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POLICY OF DECARBONISATION OF THE TRANSPORT SECTOR OF THE ECONOMY OF UKRAINE: PROBLEMS AND PERSPECTIVES

Abstract: Practically, the strategic guideline for a transformation of transport sector of the Ukraine's economy is the reduction of the transport carbon footprint. The decarbonisation policy of the Ukrainian transport sector is characterised in the present paper. Moreover, inefficiency of the current policy is proved. The authors created the mathematical model of structural improvement in road transportations by redistribution of transportations volumes between the motor transport and the railway. Guided by the scenario approach, the three most probable scenarios for traffic optimisation are developed, such as pessimistic, basic, and optimistic. The carbon reduction percentage is computed in each of these scenarios. In addition, the priority vectors of the policy of the structural optimisation of the road transport by redistribution of traffic volumes between the motor transport and the railway are determined.

Keywords: air pollution, emissions of greenhouse gases, decarbonisation, Ukraine, transportation

Introduction

The future of present and future generations is largely determined by the "well-being" of the planet, which, unfortunately, is becoming more difficult every day due to significant greenhouse gas (GHG) emissions, global warming and the degradation of the climate crisis. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC) [1], global warming in this century will lead to irreversible changes in the structure of precipitation, oceans and winds in all regions of the world. Europe and, in particular, Ukraine expect an increase in temperature by almost 2 °C, an increase in the frequency and intensity of extreme weather events, which will have critical consequences for the environment, humanity and economies of countries [2].

The UN Secretary-General Antonio Guterres called the IPCC report a "red code for humanity" and called the humanity to come to their senses, as the alarms are deafening, and the evidence is conclusive: GHG emissions choke our planet and put billions at risk [2].

According to John Kerry, the US president's special envoy for climate change, the report "clearly shows" that the climate crisis will continue to escalate, so anti-crisis climate actions over the next decade will be decisive.

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The Prime Minister of the United Kingdom Boris Johnson has the same opinion, speaking in climate change meetings, he has repeatedly claimed that the next decade will indeed be "key" to the future of the planet, and how quickly humanity will respond to the growth of GHG emissions, will depend on the activity of global warming [3].

Charles Michel at the 76th session of the UN General Assembly which took place in New York (USA) on 14-27.09.2021, accented that the immediate, rapid, and large-scale reduction of GHG emissions and achieving zero CO_2 emissions can limit global warming, climate change and their consequences [3].

The Ukraine's road transport sector GHG emission and the transportation structure are examined in the present paper with the goal to prove the truth of the hypothesis that the strategic focus on reducing the carbon footprint of the transport sector of the Ukrainian economy requires the implementation of a decarbonisation policy based on the decoupling effect to redistribute the traffic volumes between road transport and railway, which will ensure the achievement of the climate neutrality by the industry and the fulfilment of Ukraine's obligations according to the Second National-Defined Contribution (hereinafter - NDC2).

Literature review

Realising the seriousness of the situation, the European Parliament has now decided to increase climate ambitions, namely, to reduce GHG emissions by 2030 by 55 % compared to 1990 and achieve a net zero emissions balance. However, achieving such ambitious goals is not an easy task. Therefore, the European Parliament at the legislative level (namely the European Climate Act) [4] identifies those measures to combat climate change should be integrated into all sectors of the economy, and especially those that are the biggest polluters of air, in particular in the sector of transportation. The decision of the European Parliament accented to strengthen measures to limit the impact of transport on the environment by moving transport to an eco-friendly mode. In addition, due to the change in the overall structure of EU transport by rail, which prompted Parliament to adopt the economic development of the countries of EU and the smart mobility and to declare 2021 like the year of the European Year of Railway Transport.

According to the study [5], the main sources of atmospheric emissions are thermal power plants, coal-fired power plants, industry, household heating and transport. According to the International Green Transport Council, in 2018, domestic and international transport accounted for 29 % of total EU GHG emissions. The largest share (namely 18 %) of all GHG emissions belonged to vehicles [6].

Unfortunately, over time, the situation has not improved. In 2020, compared to 1990, the emissions from road transport in the EU increased by 33%. Not surprisingly, as European Commission President Ursula von der Leyen [7] said at the meeting with US President Joe Biden during the Washington-based International Energy and Climate Forum, EU is significantly worried about changing trends of GHG emissions from transport and intends to strengthen measures to limit the impact of transport on the environment in the near future [7]. For example, the European Parliament recently presented a new package of proposals under the European Green Deal [8], which contains much stricter requirements for vehicles than those set by EURO 1-7 standards of fuel quality requirements.

However, it does not mean that Europe approaches the problem of GHG emissions by transport in fragments, on the contrary, its actions are systemic and comprehensive and include measures [6] such as:

- to promote electric cars;
- to stimulate the scaling of charging points for electric vehicles;
- partial or complete ban on the production of gasoline and diesel cars;
- on the introduction of restrictions on GHG emissions at the level of motor vehicle production;
- to create zones with low emissions;
- to increase the tax pressure on the environmental taxes;
- on the limitation of quotas for transportation by the territory of the EU countries.

However, the main measure, as noted by Ursula von der Leyen, in solving the problem of GHG emissions is the transition of transport to eco-friendly mode, and primarily due to changes in the overall structure of EU transport by rail [7]. This is what prompted the European Parliament to adopt a policy of sustainable transport as a basis for economic development, to determine the vectors of the European strategy for sustainable and reasonable mobility and to declare 2021 as the European Year of Railway Transport.

The transport sector is the second most important sector contributing to the production of CO_2 emissions worldwide, and it is responsible for more than one third of the total energy consumption within the country-members of the European Environment Agency [9]. It was investigated the effects of environmental policy stringency, climate change mitigation technologies, and investments in rail, inland waterways, and roads on the amount of CO_2 emissions caused by the transport sector in 12 European countries from 1994 to 2014 [9].

Through the analysis in [9], the policies and technological innovation factors are important for a low carbon economy. However, sometimes the results provide evidence that environmental policy has a negative impact on GHG emissions, which uncovers an efficient environmental outcome from regulation in Portugal [10].

The paper [10] was focused on the assessment of environmental taxes (energy, transport) as the most important economic instrument used in Latvia's environmental policy to reduce transport-related emissions using regression analyses. The non-linear multifactor regression showed that the fuel consumption factor has the most significant effect on GHG emissions. Therefore, to achieve a result of zero emissions, a significant reduction in fuel consumption is required [11]. Thus, innovation investment is one of the key factors to control the rise in CO_2 emissions and the impact of innovation on carbon emissions of the transport sector in Mediterranean countries was investigated in [12]. To combat CO_2 emissions from transport sector, new innovative technologies have been developed recently, that was shown by the effect of innovation on CO_2 emissions of OCED countries from 1990 to 2014 [13].

Thus, the study of the impact of transport to the environment in Ukraine is relevant, also using the experience of European countries, as well as through its transition to eco-friendly operation, taking into account the impact of investment.

Ukraine, ranked 8th in Europe and 43rd in the world among the countries with the most polluted air in 2020, fully supports the European strategy of sustainable and smart mobility, and has significant potential for rail transport, also intends in the near future to redistribute transport traffic between road and rail transport. According to experts, the country's annual losses from environmental pollution by vehicles are estimated

at 2.5 billion euros. This situation is caused, first of all, by the aging of vehicles, because the average age of the car fleet in Ukraine is 22.7 years, which is two times higher than the average in the countries of EU (11.5 years) [6].

Therefore, the carbon trace of road transport in Ukraine is terrible. In addition, according to experts of the Centre for Environmental Initiatives "Ekodia", there is a real threat to its further growth, and primarily due to the development of branches of international road transport corridors passing through the territory of Ukraine:

- Pan-European Transport Corridor No. 3 (Cretan No. 3);
- Pan-European Transport Corridor No. 5 (Cretan No. 5);
- Pan-European Transport Corridor No. 9 (Cretan No. 9);
- Europe - Caucasus - Asia (ROUTE);
- Gdansk-Odessa (Baltic Sea-Black Sea) and others [14, 15].

Of course, the Ministry of Environmental Protection and Natural Resources of Ukraine (hereinafter the Ministry of Environment of Ukraine) within the development of the NDC2 [16] to the Paris Agreement [17], forecasts an annual increase in electric vehicles. However, at the level of 3 %, it is expected to achieve a certain amount of reduction of GHG emissions by vehicles is almost impossible, and therefore expect to reduce them by stimulating the promotion of electric vehicles and charging stations, as provided by the Law of Ukraine No. 3476 "On Amendments to of the Tax Code of Ukraine and some legislative acts of Ukraine on stimulating the development of electric transport in Ukraine" dated 14.05.2020 under No. 3476 [18] (hereinafter - the Law of Ukraine No. 3476) and the Law of Ukraine "On Amendments to the Customs Code of Ukraine to stimulate development of the electric transport industry in Ukraine" from 14.05.2020 for No. 3477 [19] (hereinafter - the Law of Ukraine No. 3477), is not worth it.

The NDC2 targets assume that the level of CO_2-equivalently in the transport sector in 2030 will not exceed 42.2 million tonnes ([t] = tonne = 10^6 g = Mg), which will be 38 % of the 1990 level. At the same time, the Ministry of Environment of Ukraine in the Draft Analytical Review of the Second Nationally Determined Contribution of Ukraine to the Paris Agreement [17] recognises that the main factors influencing the reduction of GHG emissions from road transport are:

- change in the total number of kilometres travelled (usually associated with a change in the number of vehicles in Ukraine);
- change of fuel used, for example, electricity instead of diesel ("fuel switch");
- change in the amount of energy consumed per kilometre ("energy efficiency") [20, p. 24].

Instead, considering that even with pessimistic forecasts, annual Gross Domestic Product (GDP) growth is expected to exceed 3% and, accordingly, traffic growth possibly does not reduce, but rather increases GHG emissions in 2030.

The authors [21] found that significantly low concentrations of ozone are observed with a large load of vehicles. The use of a "fuel switch" will undoubtedly reduce GHG emissions, but only by 12 % [20, p. 24], and therefore, to fulfil Ukraine's obligations under NDC2 in such conditions is almost impossible.

It will not significantly reduce carbon emissions and increase the energy efficiency of vehicles, because even with the accelerated pace of renewal of the country's fleet, in the next decade the percentage of its aging will remain high. Therefore, perhaps the only right solution in this situation is to support Ukraine's EU initiative to develop rail transport.

Instead, such a decision needs to be clarified: the density of railways and their capacity; readiness of the railway to increase the volume of cargo and passenger transportation; the expected effect and balancing the interests of stakeholders; investment needs, etc. So, let us focus on their study.

According to the Global Competitiveness Report [22], in 2018 Ukraine ranked 23rd among 140 countries in the ranking of railway tracks (35.8 km of tracks / km^2 of land area), compared to 93.4 km of tracks / km^2 in Germany (5th position), 58.9 km of tracks / km^2 in Poland (12 position), 54.7 km of tracks / km^2 in France (15 position) and 55.7 km of roads / km^2 in Italy (14 position), etc. [22]. This gives grounds to state that the existing potential of Ukrainian railways is not fully used, and therefore, Ukraine has the opportunity to make changes to the structure of transport and ensure its optimisation.

Instead, the optimisation of the transport structure should be determined by the effect of decoupling, which exists when the positive dynamics of economic growth indicators of negative impact on the environment remain stable or show a downward trend over the same period [23, 24].

Given the sustainable development of the economy, attention should be focused on establishing the relationship between economic growth and existing (expected) environmental threats [25]. Therefore, the assessment of the GHG emission impact on the environment should be carried out by the decoupling effect [23, 25]. Authors of [26, 27] agree with the need to assess the relationship between economic growth and environmental threats and give preference to the Decoupling Index, determining the density of economic growth and anthropogenic pressure on the environment. The aim of the paper [28] is to evaluate the decoupling of economic growth (in terms of GDP) from the environmental impacts due to EU-28 consumption, assessed by means of life cycle assessment.

It was conducted a survey of recent (1990-2019) research on decoupling in Web of Science and reviewed the results in the research according to the categorisation of the different kinds of decoupling, with regard to their relevance [29]. The reviewed 179 articles contain evidence of absolute impact decoupling. The drivers of decoupling economic growth from carbon emission were researched and made an empirical analysis of 192 countries [30].

The expediency of using decoupling analysis in the development of anti-carbon policy of multimodal transportation was considered in [31] and cocoupling in [32]. However, the complex approach using decoupling to optimise the railway and road transport structure has not yet been considered. To solve such research gap, this paper assesses the decoupling in the Ukrainian transport sector and the following forecast based on investment. Despite the fact that numerous works are devoted to this topic, the approach proposed by the authors has a high degree of novelty, which limits the possibility of a more detailed connection with previous findings.

Data, variables and methodology

According to the OECD methodology [33], the effect of decoupling is estimated by the Decoupling Index (hereinafter - *DecInd*) and is defined as:

$$DecInd = \frac{\left(\frac{EP}{DF}\right)_e}{\left(\frac{EP}{DF}\right)_b} = \frac{K_{EP}}{K_{DF}} \ [-] \tag{1}$$

where *EP* is an indicator of the anthropogenic pressure on the environment (environmental pressure), natural units; *DF* - an indicator of economic growth (driving force), it is displayed most often through the Gross Domestic Product (GDP, given in monetary unit); K_{EP}, K_{DF} - the rate of increase in the general indicators in the ending and base (beginning) periods of time [years].

The next values are notated to measure a *Decoupling Index*: K_{CO2} is the chain growth rates of emissions of CO_2 from the railway transport of the country [%], K_{GDP} is the chain growth rates of the country's GDP [%].

Decoupling Index is calculated by a formula similar to formula (1):

$$DecInd\ (t) = \frac{K_{CO2}(t)}{K_{GDP}(t)}\ [-] \tag{2}$$

where *t* is the time [year].

The chain growth rate of the corresponding indicator, K_t is given by:

$$K_t = T_t - 100\ [\%] \tag{3}$$

where T_t is an index of the corresponding indicator

$$T_t = \frac{y_t}{y_{t-1}} \cdot 100\ [\%] \tag{4}$$

where y_t is the value of the corresponding indicator in the considered year, y_{t-1} is the value of the corresponding indicator in the previous year.

Decoupling analysis will be carried out in countries that are close to Ukraine in the length of the railway network (Table 1).

Table 1

The length of the railway network of Ukraine and countries close to this indicator [34]

Country	The length of the railway network [km]
France	29,640
Italy	20,182
Ukraine	21,733
Romania	22,298
Poland	19,837
United Kingdom	16,837
Spain	16,102

Guided by the official statistics [16, 35-37], presented in the Table 2, let us consider the current trends in the reduction of carbon emissions by rail in the countries selected for the study.

Also, the following methods were used at the present work: economic and mathematical modelling abased on correlation and regression analysis - by constructing a mathematical model of the dependence of the volume of GHG emissions on the volume of freight and passenger turnover of the railway and capital investments; the comparative analysis - by studying the decoupling effect of GHG emissions in countries with a length of railways close to Ukraine; the scenario forecasting - by determining alternative scenarios of changes in GHG emissions during the redistribution of traffic volumes between road transport and the railway, the abstract-logical - by generalising the research results and formulating conclusions.

Table 2

Railroad carbon emissions during 1990-2019 [38]

Years	Emissions CO_2 [kt]						
	Ukraine	**Romania**	**Italy**	**Poland**	**France**	**United Kingdom**	**Spain**
1990	3433.0896	451.89865	613.32569	1623.6691	1078.4307	1471.82	421.72
1991	2860.6131	381.82751	613.32569	1168.8954	1044.6291	1514.39	414.11
1992	2453.7862	1016.3522	603.93805	820.6511	994.73156	1527.24	410.98
1993	1868.0978	971.27105	588.29199	802.4282	920.42179	1463.77	354.07
1994	1511.5727	873.58546	594.55041	891.2241	854.69653	1405.25	330.03
1995	1179.5779	881.32895	600.80884	866.6136	816.60272	1485.89	328.73
1996	1197.9407	905.25056	538.22458	735.3687	790.84915	1570.36	319.72
1997	1221.3918	908.53293	600.80884	661.0267	783.33769	1639.18	325.29
1998	1195.8866	774.38515	594.55041	618.6588	745.51214	1748.52	327.51
1999	1224.8484	629.84992	434.96057	573.534	751.14573	1685.64	324.38
2000	1242.5112	903.83346	432.31449	525.7395	764.55905	1702.94	308.34
2001	1363.6871	449.96796	375.51404	512.9943	727.00176	1767.68	317.54
2002	716.59612	600.77101	384.98078	487.5039	748.46307	1731.97	307.73
2003	866.33014	532.84165	416.53659	512.9943	716.27111	1752.13	312.67
2004	835.54832	612.42645	362.89172	512.9943	705.54045	1827.66	308.49
2005	786.82212	228.46866	306.09128	503.4354	638.47387	1873.12	310.66
2006	829.14786	225.53577	353.42498	462.0135	614.05365	1903.93	308.51
2007	772.77018	564.02517	331.33592	455.6409	575.50461	1991.77	303.06
2008	742.82125	527.53992	220.89061	398.2875	583.1315	1981.31	292.39
2009	446.74188	393.84029	189.33481	385.0236	530.09746	1973.90	273.19
2010	489.17241	444.02214	198.80155	356.14683	502.49634	1986.34	269.59
2011	475.69188	600.12767	142.00111	368.98095	512.61454	1893.38	277.42
2012	340.15794	572.88096	169.83969	343.31271	499.70615	1947.70	258.30
2013	392.08628	488.54948	119.51682	317.64447	493.87426	1947.00	243.28
2014	405.69086	325.12379	56.613231	285.55917	417.81627	1984.82	247.51
2015	405.97905	333.36394	69.193949	261.2766	411.86707	1923.48	244.18
2016	424.92571	353.06054	47.177692	261.2766	416.55962	1899.69	233.55
2017	497.07865	370.551	103.79092	267.84038	441.99842	1875.82	243.73
2018	512.28687	280.32564	138.3879	322.34523	394.28169	1773.85	251.62
2019	530.00806	393.77144	135.24272	267.92304	395.32264	1679.04	245.37

Correlation and regression analysis is constantly developing and improving for different applied models [39, 40]. Innovative ideas regarding the formulation and estimation of regression decomposition developed in [41]. Time series processing is a comprehensive and relevant problem in economy data analysis [42]. The works [25, 28] showed how difficult questions could be answered by developing simple models with simple interpretation of parameters for diversity of applications. Due to the smoothing process of the time series [39], correlation and regression analysis was performed, the results of which determined the coefficients of multiple nonlinear regression, after the initial linearisation and then using the generalised least squares method in matrix form. Choosing the form of nonlinear models was done with the help of the developed software algorithm by the directed enumeration method of power dependencies [32, 43, 44]. The criterion for the best fit of the model to reality is the least sum of squares of residuals in comparable models (minimisation of potentials between the points) [45].

Results and discussion

The data presented in the Table 2 gives grounds to state that during the period studied for each of the studied countries, there is a significant reduction in GHG emissions. However, if in European countries the reduction of carbon emissions was achieved due to the modernisation of infrastructure and the railway network, then in Ukraine a significant reduction in CO_2 emissions was the result of:

- firstly, the decline in the volume of cargo and passenger transportation, as a result of: the crisis state of the economy and, above all, of the industry; falling of the GDP volumes; the deterioration of the railway infrastructure; a shortage of freight and passenger cars that are out of service faster than they arrive; a constructive deterioration and obsolescence of the rolling stock of railway transport, which does not allow the delivery of goods quickly, on time and without losses; providing passengers with the advantage of air transport for long-distance transportation and road transport - for short distances (as faster and more convenient);
- secondly, the annexation of Crimea by Russia and hostilities in the east of the country [46];
- thirdly, the state monopoly on the main activities of a single production and technological complex to ensure the transportation of goods and passengers of the Ukrainian railways joint stock company Ukrzaliznytsia (here and after Ukrzaliznytsia), which led to curbing competition and slowing down the development of railway transport, preventing its effective functioning in the context of the active development of the international market of transport services [46];
- fourthly, the low level of organisation of the transportation process and ineffective work of railway transport;
- fifth, the direct protectionist policy of Russia in relation to its own ports and railways, etc.

To form a clearer idea of the trends in the volume of carbon emissions by rail transport in countries that are close in terms of the length of the railway network in Ukraine, they are graphically presented in Figure 1.

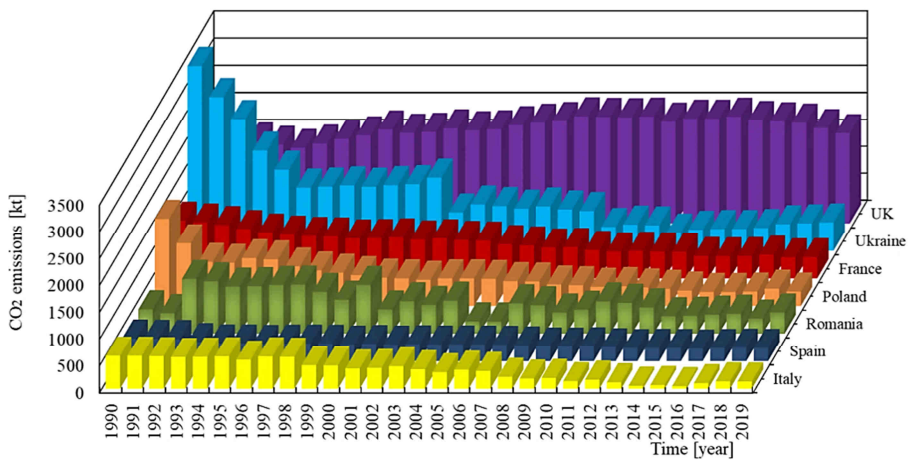


Fig. 1. Carbon trace of European countries participating in the Paris Agreement, close in terms of the length of the railway network in Ukraine during 1990-2019

Table 3

Chain rates of GDP growth during 1990-2019 [47]

Years	Chain GDP growth rates [%]						
	France	Italy	Poland	Romania	Ukraine	United Kingdom	Spain
1990	2.9239	1.985774943	0	0	–6.34524	0.733755503	3.781393378
1991	1.0482	1.538447558	–7.015578796	–12.9182	–8.41064	–1.103121655	2.546000548
1992	1.5993	0.834275454	2.514978612	–8.76723	–9.699	0.401082104	0.929215549
1993	–0.6287	–0.852805764	3.738310308	1.528834	–14.2261	2.48983093	–1.031491863
1994	2.3583	2.151023638	5.292802058	3.931943	–22.934	3.846009131	2.383195397
1995	2.1067	2.886836759	7.102865538	6.233511	–12.2	2.531670077	2.757493994
1996	1.4130	1.266784802	6.115380709	3.907702	–10	2.491610855	2.660524453
1997	2.3363	1.830212234	6.449059835	–4.84906	–3	4.975295008	3.702580285
1998	3.5886	1.810615162	4.640634369	–2.02981	–1.9	3.707771046	4.393037351
1999	3.4214	1.625727599	4.654826659	–0.37666	–0.2	3.29520162	4.490491316
2000	3.9237	3.786955143	4.561025468	2.461263	5.9	3.506217426	5.24599468
2001	1.9837	1.951371556	1.258472694	5.218136	9.203695	2.730335651	3.932948843
2002	1.1355	0.253942999	2.035903501	5.702992	5.249341	2.178744368	2.731022232
2003	0.8232	0.138626891	3.498399184	2.341147	9.515923	3.321881725	2.981894836
2004	2.8297	1.423594158	4.982822123	10.42811	12.10877	2.286278175	3.122795242
2005	1.6632	0.817848974	3.506847453	4.668148	2.9973	2.955691743	3.652032674
2006	2.4493	1.790639681	6.131143946	8.028811	7.439918	2.693800367	4.102727115
2007	2.4247	1.48707298	7.061543813	7.233808	7.59352	2.360575861	3.604687971
2008	0.2549	–0.962012841	4.199962292	9.307467	2.304025	–0.278780161	0.887145182
2009	–2.8733	–5.280937208	2.832184589	–5.51739	–14.7586	–4.113949331	–3.763231927
2010	1.9494	1.713295839	3.740517779	–3.90124	3.834393	2.074050953	0.163010231
2011	2.1927	0.707333347	4.757638004	1.906068	5.465502	1.275708411	–0.814373455
2012	0.3131	–2.980905768	1.324890828	2.040665	0.238682	1.430396029	–2.959441302
2013	0.5763	–1.841065451	1.125767836	3.770962	–0.0267	2.186113352	–1.435394259
2014	0.9562	–0.004547542	3.378578073	3.608724	–6.55263	2.862728671	1.383907943
2015	1.1129	0.778304351	4.236326306	2.953674	–9.77296	2.363069511	3.83517266
2016	1.0955	1.293462732	3.141731229	4.702998	2.235068	1.722385904	3.03130133
2017	2.2914	1.667859041	4.83065457	7.319449	2.466036	1.740309443	2.973641191
2018	1.7929	0.941737193	5.353704746	4.474524	3.405296	1.252590613	2.430047145
2019	1.5086	0.287449937	4.540919514	4.127451	3.221483	1.370814722	1.950126894

Among the listed factors that had a significant impact on changes in the volume of freight and passenger traffic in Ukraine, the most influential are the changes in the volume of GDP. To be convinced of the correctness of this statement, guided by the data of the State Statistics Service of Ukraine for the period 1990-2019, presented in Table 3, we will analyse the chain rates of GDP growth over the previous year and establish the relationship between its changes and the carbon trace of railway transport.

Let us note that according to the World Bank, Ukraine's GDP in 1990 at current prices, it was $ 77.4 billion, which is almost 1.5 times the volume of Israel's GDP ($ 59.1 billion) and the volume of Singapore's GDP ($ 45.5 billion). However, over the years of independence, the Ukrainian economy "survived" several severe crises - in the first half of the 1990s (the collapse of the USSR), during the period 2008-2009 (there was Global financial crisis) and between 2014 and 2015 (there was an Active anti-terrorist operation in the east of the country), which resulted in a significant drop in GDP, as evidenced by the chain growth rates of these years. On the other hand, since 2015, the growth rates of Ukraine's GDP are characterised by positive changes, although clear trends in their changes have not yet been formed. According to the results of 2019, the volume of Ukraine's GDP

amounted to $ 153.9 billion. At first glance, there is a positive trend, however, the GDP growth rate is too low. The volume of GDP of the Israel in 2019 reached the level of $ 394.7 billion. And the GDP of Singapore is $ 374.4 billion [47]. Thus, the reduction in the carbon trace of rail transport over the period studied should be recognised as a common consequence of a decrease in GDP and, accordingly, transport traffic.

Guided by formula 2 and preliminary calculations on the chain rates of CO_2 and GDP growth, let's determine the *Decoupling Index* (Table 4) and, accordingly, the decoupling effect of rail transport in each of the countries selected for the study.

Table 4

Dynamics of the *Decoupling Index* for rail transport in the countries participating in the Paris Agreement during 1991-2019

Years	***DecInd* [–]**						
	Ukraine	**Romania**	**Poland**	**UK**	**Italy**	**France**	**Spain**
1991	1.982638	1.200316	3.992402	–2.62154	0	–2.99027	–0.70855
1992	1.466303	–18.9548	–11.8461	2.116773	–1.83466	–2.98659	–0.81405
1993	1.677813	–2.90128	–0.594	–1.66928	3.037824	11.88283	13.42476
1994	0.832166	–2.5579	2.090745	–1.03948	0.494569	–3.02788	–2.84897
1995	1.80029	0.1422	–0.38878	2.266745	0.364631	–2.11564	–0.14329
1996	–0.15567	0.694594	–2.47647	2.281571	–8.22292	–2.23196	–1.02939
1997	–0.65254	–0.07478	–1.56759	0.880824	6.353311	–0.40654	0.469922
1998	1.099056	7.274226	–1.38115	1.799108	–0.57531	–1.34556	0.155331
1999	–12.1089	49.55259	–1.56697	–1.09133	–16.5108	0.220867	–0.21238
2000	0.244415	17.67377	–1.82707	0.292647	–0.16064	0.455113	–0.94274
2001	1.059629	–9.62328	–1.92634	1.392478	–6.73305	–2.4763	0.758857
2002	–9.03953	5.876596	–2.44066	–0.92722	9.927458	2.59969	–1.13116
2003	2.195812	–4.8297	1.494615	0.350328	59.12793	–5.22507	0.537632
2004	–0.29343	1.432274	0	1.885547	–9.04667	–0.52942	–0.42729
2005	–1.94563	–13.4303	–0.53135	0.841535	–19.1382	–5.71524	0.192566
2006	0.723036	–0.15989	–1.34198	0.610598	8.635974	–1.56157	–0.16935
2007	–0.89543	20.74735	–0.19533	1.954303	–4.20289	–2.58906	–0.48929
2008	–1.68207	–0.695	–2.99703	1.882513	34.64957	5.198171	–3.96919
2009	2.700721	4.59347	–1.17585	0.090897	2.705148	3.165229	1.744833
2010	2.476996	–3.26606	–2.00507	0.303837	2.918352	–2.67092	–8.09044
2011	–0.50421	18.44486	0.757435	–3.6688	–40.3932	0.918313	–3.5681
2012	–11.9372	–2.22484	–5.25064	2.005745	–6.57669	–8.04174	2.329847
2013	–5.71804	–3.90367	–6.64137	–0.01642	16.09374	–2.025	4.050381
2014	–0.52953	–9.26954	–2.98972	0.678633	11.57363	–16.106	1.257508
2015	–0.00727	0.858073	–2.00729	–1.30797	28.5521	–1.27942	–0.3507
2016	2.088038	1.256312	0	–0.71804	–24.5992	1.040049	–1.43689
2017	6.885598	0.676821	0.520053	–0.72178	71.94853	2.665107	1.466844
2018	0.898459	–5.44169	3.801059	–4.33979	35.39558	–6.02147	1.331753
2019	1.073801	9.804912	–3.71801	–3.89918	–7.90652	0.175005	–1.2746

To describe the decoupling effect of transportation by rail, we will use the classification of decoupling types according to Tapio [23]. Depending on the density of the relationship between economic growth and the rate of nature of the *DecInd*, researchers distinguish four subcategories and eight logical degrees (Table 5).

According to Tapio's classification during the period 1990-1993 the development of transport transportation by rail in Ukraine was accompanied by *a recessive decoupling-effect.* The characteristic features of which are a simultaneous drop in the rate

of economic development and GHG emissions when the rate of decline of the latter exceeds the rate of decline in economic growth of the railroad (Fig. 2a).

Table 5

Categories of Decoupling Index by Tapio [23]

Weak $0 < DecInd < 0.8$	Strong $DecInd < 0$	Recessive	Expansive
Positive *DecInd*		Coupling effect $1.2 > DecInd > 0.8$	
observed if the condition of simultaneous growth of economic growth rates and GHG emissions, but when the growth rates of the former exceed the latter	observed if conditions of growth of economic growth rates and simultaneous decrease in rates of GHG emissions	observed if the rate of economic growth and GHG emissions tend to decrease	observed if the rate of economic growth and GHG emissions tend to increase
Negative *DecInd*		Decoupling effect $DecInd > 1.2$	
observed if the rate of economic growth and the rate of change of GHG emissions tend to decline, but when the rate of decline of economic growth exceeds the rate of decline of GHG emissions	observed if the rate of economic growth tends to decline, and the rate of change in GHG emissions to increase	observed if with a simultaneous decline in economic growth and GHG emissions, but when the rate of decline in GHG emissions exceeds the rate of decline in economic growth	observed if the rate of economic growth and the rate of change of GHG emissions tend to increase, but when the growth rate of the latter exceeds the former

At the end of the 90s, the situation changes - the economic development of the railway network and railway infrastructure is accompanied by a weak overcoupling-effect, when the rates of economic development of the railway and the rate of changes in GHG emissions simultaneously tend to decline. However, when the rate of decline of the former exceeds the rate of decline in GHG emissions.

The beginning of the XXI century was marked by a strong overcoupling-effect in certain years of the economic development of the railway transport in Ukraine, in which the rates of economic development of the railway are characterised by a fall, and the rate of changes in GHG emissions, on the contrary, by their growth.

Nevertheless, with the reform of Ukrzaliznytsia, which began in 2016, the situation is changing dramatically. The economic development of rail transport is accompanied by a recessive decoupling-effect, when the rate of decline in GHG emissions exceeds the rate of decline in cargo and passenger traffic by rail. Therefore, only since 2016, we observe the adoption by the government of Ukraine of actions to "green" transport traffic.

The situation in European countries is absolutely opposite. In particular, in Romania (Fig. 2b) during the period, the development of rail transport was studied in most years, which is characterised by a *weak decoupling-effect*. That is, an excess of the economic development of rail transport over the growth rate of GHG emissions, as well as a *strong decoupling-effect* according to which the rate of economic growth of the industry is accompanied by a decrease in the rate of GHG emissions. The achievement of a *weak*- and strong decoupling-effect is the result of the introduction of a balanced and clear anti-coal policy in the country. The situation is similar in Poland (Fig. 2c), Italy (Fig. 2e), United Kingdom (Fig. 2d), France (Fig. 2f) and Spain (Fig. 2g).

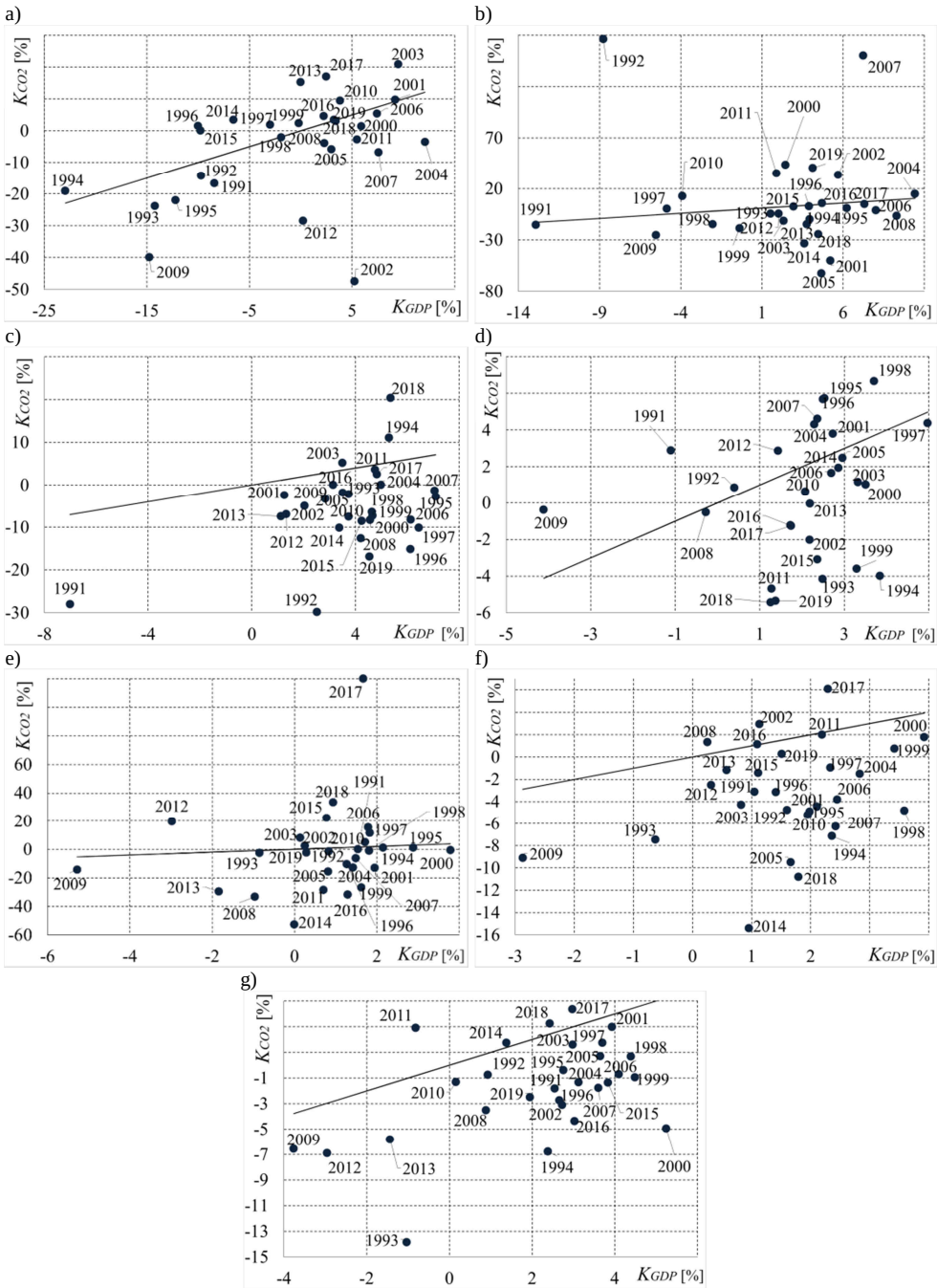


Fig. 2. Dynamics of the growth rate of CO_2 emissions from GDP in Ukraine and countries close to the length of railways: a) Ukraine, b) Romania, c) Poland, d) United Kingdom, e) Italy, f) France, g) Spain

To establish the dependence of CO_2 emissions on the volumes of freight and passenger traffic by rail in Ukraine (Table 6), we proposed to use the integral indicator of the factors of freight and passenger traffic as their geometric mean when calculating the *Decoupling Index* [31]. We considered the statistics of the passenger-distance, which is the distance travelled by passengers on transit vehicles; determined by multiplying the number of unlinked passenger trips by the average length of their trips, units of measurement in transportation is passenger-kilometres [pkm] (pkm = passenger · 10^3 m) and payload-distance. Freight is measured in mass-distance in transportation statistics. A simple unit is the tonne-kilometre [tkm] (tkm = 10^6 g · 10^3 m = 10^9 g m), the service of moving one tonne of payload a distance of one kilometre.

Table 6

Dynamics of indicators of railway and road transport in Ukraine between 1990 and 2019 [34-36]

Years	Railway transport				Road transport			
	Freight turnover [10^9 tkm]	**Passenger turnover [10^9 pkm]**	**Capital investments [10^6 USD]**	**Emissions of CO_2 [kt]**	**Freight turnover [10^9 tkm]**	**Passenger turnover [10^9 pkm]**	**Capital investments [10^6 USD]**	**Emissions of CO_2 [kt]**
1990	475.3	68.9	4980.2	3433.0896	76.9	86.9	2150.9	59,916.59
1991	398.1	67.3	3765.2	2860.613	58.6	68.9	1620.3	45,482.65
1992	340.6	65.6	3221.4	2453.786	49.8	44.3	1270.1	37,224.11
1993	246.9	63.8	2703.1	1868.0978	30.1	38.2	833.2	23,829.21
1994	215.7	62.2	1980.5	1511.5727	25.2	36.1	718.1	21,083.19
1995	163.2	62.7	1598.6	1179.5779	25.9	39.5	700.4	20,274.29
1996	171.5	58.5	1552.3	1197.9407	27.6	33.2	733.1	20,826.63
1997	167.4	54.4	1598.4	1221.3918	22.1	27.1	673	18,349.80
1998	164.9	54.5	1524.3	1195.8866	18.6	30.1	585.1	15,494.68
1999	171.8	52.8	1600	1224.8484	20.1	27.4	588.9	17,028.91
2000	172.8	51.8	1609	1242.5112	19.3	28.8	531.8	15,399.47
2001	177.5	49.7	1249.3	1363.6871	18.5	31	685.1	17,246.87
2002	193.1	50.5	1704.2	716.59612	20.6	35.8	862.1	19,552.79
2003	225.3	52.6	1809.1	866.33014	24.4	40.1	1299.1	20,744.19
2004	234	51.7	2599.8	835.54832	28.8	47.5	1462.6	21,949.67
2005	224	52.7	3463.1	786.82212	35.3	52.5	1918	21,624.22
2006	240.8	53.2	6683.5	829.14786	40.6	54.2	3442.7	23,112.19
2007	262.5	53.1	8549.3	772.77018	46.6	56.1	3831.3	29,283.45
2008	257	53.1	3597.3	742.82125	54.9	61.4	1651.8	30,064.88
2009	196.2	48.3	5734.8	446.74188	49.2	55.3	3055.1	27,548.75
2010	218.1	50.2	3738.5	489.17241	53.9	52.1	1200.7	28,173.26
2011	243.9	50.6	5187.7	475.69188	38.4	51.4	1693.3	27,677.61
2012	237.7	49.3	2107.1	340.15794	39.2	50.4	1572.6	28,390.38
2013	224.4	49	1281.5	392.08628	40.5	49.1	1448.7	28,154.45
2014	210.2	35.9	1045.2	405.69086	37.7	42.7	1470.5	26,075.24
2015	195.1	35.4	1509.8	405.97905	34.4	34.8	3378.8	22,250.21
2016	187.6	36.8	9487.7	424.92571	37.6	34.5	3587.7	23,348.22
2017	191.9	28.1	15384.9	497.07865	41.2	35.4	4428.6	24,026.50
2018	186.3	28.7	22961.7	512.28687	42.6	31.8	5819.6	24,071.95
2019	181.8	28.4	15771.4	530.00806	48.9	33.9	5240.5	25,945.95

FT_{RW} *is a* freight turnover in railway transport of Ukraine [10^9 tkm], PT_{RW} is a passenger turnover in the railway transport of Ukraine [10^9 tkm].

The geometric mean of several real numbers is a number that can replace each of these numbers by the way that their product does not change. Applying the chain growth rate of

the corresponding indicators calculated by formula (4), we propose the following formula to find an integrated indicator of the growth rate of rail transport, T_{Integ} [%]:

$$T_{Integ} = \sqrt{T_{FT_{RW}} \cdot T_{PT_{RW}}} \ [\%] \tag{5}$$

where $T_{FT_{RW}}$ is an index of a freight turnover in railway transport of Ukraine [%]; $T_{PT_{RW}}$ is an index of a passenger turnover in railway transport of Ukraine [%].

Guided by formula (3), let's find an integral indicator of the growth rate of negative factors, K_{Integ} [%]:

$$K_{Integ} = T_{Integ} - 100 \ [\%] \tag{6}$$

Table 7

Dynamics of decoupling of volumes of cargo and passenger handling by rail in Ukraine during 1990-2019

Year	$DecInd_{Integt}$ [−]	$DecInd_{FT}$ [−]	$DecInd_{PT}$ [−]	$DecInd_{IFP}$ [−]
1991	1.73387	1.931169	0.293478	1.143476
1992	1.638204	1.489185	0.260935	0.895068
1993	1.494438	1.933788	0.182518	1.122705
1994	2.451221	0.551002	0.116235	0.33949
1995	1.741026	1.99503	–0.07586	1.034039
1996	–1.55926	–0.50858	0.673029	0.099838
1997	–0.41422	0.79689	2.335196	1.575356
1998	3.021608	0.786015	–0.06199	0.363732
1999	4.234752	–20.9218	14.57665	–2.85942
2000	–1.92681	0.098656	–0.34937	–0.12685
2001	–13.4548	0.295523	–0.44048	–0.07875
2002	–9.23553	1.674255	0.30664	0.978778
2003	2.040674	1.752357	0.436996	1.076023
2004	–3.4269	0.318903	–0.1413	0.085627
2005	4.786366	–1.42578	0.645326	–0.40649
2006	1.289111	1.008076	0.127524	0.560879
2007	–1.57744	1.186752	–0.02475	0.56765
2008	3.679887	–0.90938	0	–0.4571
2009	2.391264	1.602974	0.612495	1.129412
2010	1.26854	2.911042	1.025912	1.952635
2011	–0.44665	2.164382	0.145789	1.128883
2012	11.14884	–10.6503	–10.764	–10.7071
2013	–4.87109	209.5779	22.79279	117.3871
2014	–0.20223	0.965717	4.079994	2.618387
2015	–0.0164	0.735052	0.142511	0.443264
2016	–225.376	–1.71994	1.769433	–0.00926
2017	–1.46119	0.929472	–9.58677	–4.71232
2018	–7.22386	–0.85696	0.627033	–0.12437
2019	–1.99636	–0.7498	–0.32448	–0.53788

We propose to calculate the integral *Decoupling Index* by a formula similar to formula (2):

$$K_{Integ} = DecInd_{Integt} = \frac{K_{CO2t}}{K_{Integt}} \ [-] \tag{7}$$

From here:

$$DecInd_{FT} = \frac{K_{FT_{RW}}}{K_{GDP}}\ [-], \qquad DecInd_{PT} = \frac{K_{PT_{RW}}}{K_{GDP}}\ [-], \qquad DecInd_{IFP} = \frac{K_{Integ}}{K_{GDP}}\ [-] \qquad (8)$$

The results of the calculations for the period 1990-2019 are summarised in the Table 7.

The schematic representation of the dependence of GHG emissions on GDP is shown in Figure 3a. The dependence of the volume of passenger and cargo transportation on the volume of GDP is characterised by the data presented in Figures 3b and 3c. The relationship between the integral indicators of transportation by rail is shown in Figure 3d.

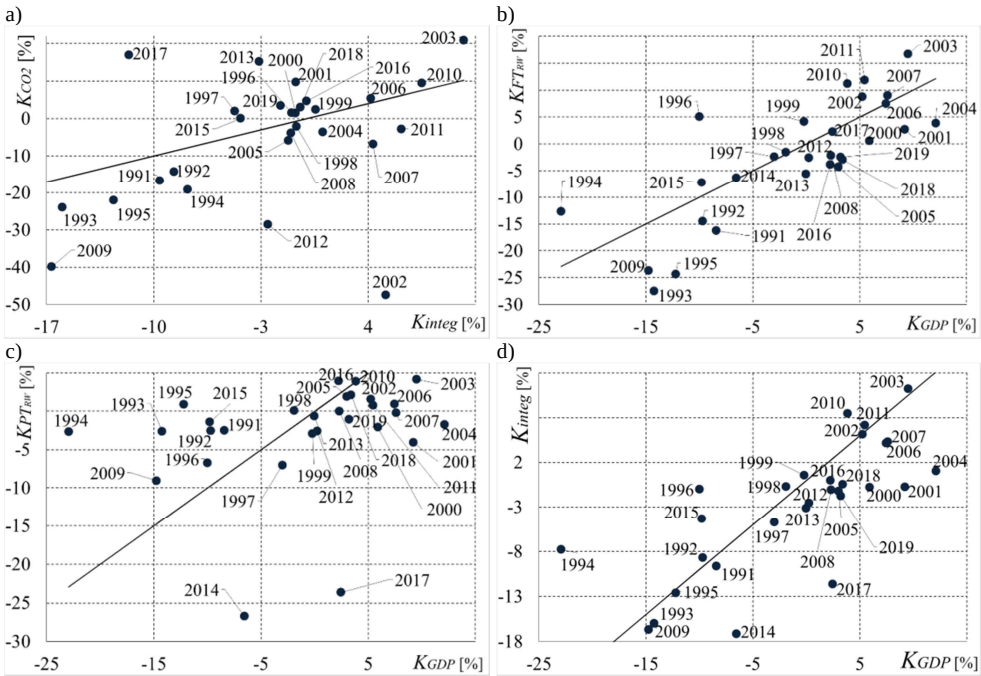


Fig. 3. Dynamics of the growth rate of: a) CO_2 emissions from the volume of freight and passenger turnover; b) the volume of freight, c) passenger turnover and d) both from the GDP of Ukraine by railway transport

Observing the idea of the dependence of CO_2 emissions on the volume of freight and passenger traffic, by rail, we will attempt to build a mathematical model to improve the structure of road transport by redistributing traffic volumes between road and rail which allow to achieve climate neutrality in the long term and reduce CO_2 emissions not less than 55 %, as provided by NDC2 with the Paris Agreement [17].

Let us note that a number of components, each of which, respectively, is characterised by a set of properties (indicators), characterises the volume of GHG emissions. However, the ability to quickly and completely obtain statistical information is complicated by trade secrets [48]. This is why the need arises to indirectly assess a number of processes occurring during the emission of GHG by transport.

The selected factors are chosen for modelling (Table 6) should be dimensionless quantities [49], while the initial indicators may have different dimensions. Therefore, all the selected constituent indicators for mathematical modelling will be reduced to a dimensionless value and obtained by the ratio to the base value. We consider it expedient to choose the value for 2001 as the basic values (the beginning of the fifth cycle of the Kondratyev long wave curve [50]), which does not change the dynamics of the process modelled.

Using correlation-regression analysis [40], the authors proposed the following nonlinear regression models:

$$E^*_{CO2RW} = -0.268 + 0.072 \cdot FT^{*3}_{RW} + 0.695 \cdot PT^{*2}_{RW} - 0.005 \cdot I^{*0.2}_{RW} \ [-] \quad (9)$$

$$E^*_{CO2RT} = 0.992 + 0.027 \cdot FT^{*3}_{RT} + 0.088 \cdot PT^{*2}_{RT} - 0.005 \cdot I^{*}_{RT} \ [-] \quad (10)$$

where E_{CO2RW} is the volume of CO_2 emissions in the railway transport of Ukraine [kt], E_{CO2RT} is the volume of CO_2 emissions in road transport of Ukraine [kt], PT_{RT} is the passenger turnover in road transport of Ukraine [10^9 pkm], FT_{RT} is the freight turnover in road transport of Ukraine [10^9 pkm], I_{RW} is capital investments in railway transport [10^6 USD], I_{RT} is capital investments in road transport [10^6 USD], * denotes a dimensionless quantity:

$$E^*_{CO2} = \frac{E_{CO2}(current\ year)}{E_{CO2}(2001)} \ [-], \qquad FT^* = \frac{FT(current\ year)}{FT(2001)} \ [-],$$

$$PT^* = \frac{PT(current\ year)}{PT(2001)} \ [-], I^* = \frac{I(current\ year)}{I(2001)} \ [-]$$

The coefficients of multifactorial nonlinear regression (9)-(10) after the initial linearisation are found by the generalised least squares method in matrix form [40]. The type of nonlinear models was chosen by the method of directed enumeration of power and logarithmic dependences, calculating the deviation potentials [45]. The criterion for the best fit of the model to reality was chosen the closest value of the determination coefficient to one (Table 8). This coefficient determines the proportion of variation of one of the variables, which is explained by the variation of other variables, that is, it measures the proportion of the variation relative to the mean, which is "explained" by the regression [51]. Checking by Fisher's criterion, $F > F_{cr}$, showed that with a reliability of 95 % (the level of significance a = 0.05 can be considered that the corresponding ones R^2 are statistically significant and mathematical models are proposed that are adequate to statistical data and on the basis of the adopted system of simultaneous regressions, economic analysis can be carried out.

Table 8

Coefficients for analysing the adequacy of the proposed mathematical model

No. of regression equation	R^2 [-]	F [-]	F_{cr} (a = 0.05) [-]
(9)	0.833	43.244	2.98 (k_1 = 3, k_2 = 26)
(10)	0.895	73.687	

Developing a forecast, an assessment of its accuracy must be carried out in advance (a priori), when the true value of the predicted value is still unknown. Accordingly, another indicator of the quality of the regression equations is the relative forecast error, V [40]:

$$V = \frac{\sqrt{\sum_{i=1}^{n}(y - \hat{y})^2 / k_2}}{\bar{y}} \; [-] \tag{11}$$

It is clear that the lower the error calculated by formula (11), the higher the forecast accuracy. In our case, the value of the relative forecast error is approximately 0.343 for regression (9) and 0.121 for (10) one.

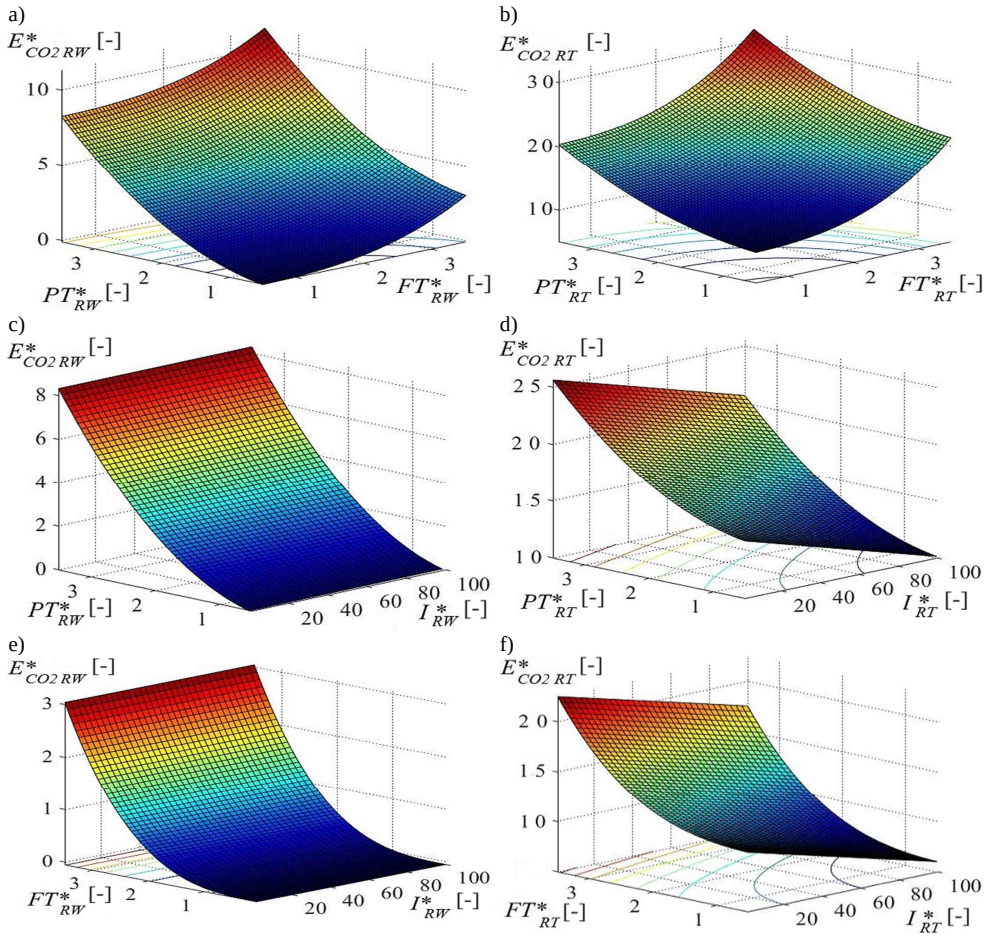


Fig. 4. The regression surfaces of CO_2 emissions with constant values of the indicators of 2019, which are absent on the axes correspondingly: a) I^*_{RW} = 12.624 [-]; b) I^*_{RT} = 7.649 [-]; c) FT^*_{RW} = 1.024 [-]; d) FT^*_{RT} = 2.643 [-]; e) PT^*_{RW} = 0.571 [-]; f) PT^*_{RT} = 1.093 [-]

The regression surfaces of CO_2 emissions (vertical axis) are demonstrated in Figure 4: in the railway (Fig. 4a, c, e) and the road transportations (Fig. 4b, d, f), with constant values of the indicators of 2019, which are absent on the axes correspondingly. The comparison of regression equations (9) and (10) in Figure 4a, respectively, we see that they are quite similar in nature. Both factors *PT* and *FT* are in regressions (9) and (10) cause an increase

in CO_2 emissions (Fig. 4). That is, the influence of changes in freight and passenger traffic on railway and road transport is similar, which can be seen from the uniformity of the corresponding power-law dependences in Figure 4. The minus sign in front of the coefficients in regression (9) and (10) means that capital investment reduce CO_2 emissions due to modernisation and design innovations in transport. A smaller coefficient and a lower degree for capital investments in rail transport means their smaller impact on CO_2 emissions compared to road transport, since road transport requires large investments in transitions to alternative green fuels, in particular electricity, and rail transport is already less harmful to the environment.

Nevertheless, when there are investments, first, the question of the efficiency of railway transportation arises. In 2018, Ukraine ranked 37th in terms of Efficiency of train services, while Germany - 9th, France - 14th, etc. The main reason for this was the relationship between the government and the Ministry of Railways. Until 2021, the government of Ukraine did not give railway enterprises the freedom of commercial activity. As part of political intervention to achieve urgent goals, the authorities over the past decade have only supported unprofitable transport services, in particular, passenger services. The investments in the development of railways and railway infrastructure were usually insufficient or misdirected, which resulted in the bankruptcy of Ukrzaliznytsia [52, p. 10].

However, it is not the only problem for Ukrzaliznytsia, caused by ineffective government regulation. In particular:

- The disruption of the healthy balance in the system occurred due to the government oppression of the railway in favour of other industries, in particular, motor transport;
- Financing of the construction and reconstruction of main railway lines, mobilisation facilities, the acquisition of rolling stock, etc., is prescribed by the Law of Ukraine "On Railway Transport" dated 04.07.1996, No. 273/96-BP [53] on the state budget at the very the case was not carried out;
- Harsh regulation made the road clumsy, but sufficiently resistant to ineffective management decisions.

The deterioration of the infrastructure and rolling stock of railway transport has reached a critical state. Therefore, this together with a catastrophic lack of investment resources for their restoration and modernisation, create a large-scale state problem and an obstacle in the transportation structure optimisation of the road transport in Ukraine (extremely necessary to ensure the reduction of CO_2 emissions), which is impossible today to solve without the involvement of outside help (the donor countries and foreign investors) [46].

However, the constant attempts of the railway, manoeuvring between the existing regulatory framework and the desire to increase the profitability of transportation, to change the terms of contracts led to the main problem - the loss of confidence of market participants in the railway as a reliable partner. The terms of contracts change so quickly and unpredictably that the market simply does not have time to adapt [54]. Therefore, the investors expect effective legislation and a favourable investment environment.

Therefore, the government of Ukraine should understand that it is the volumes of capital investment in the renovation and modernisation of the railway network and infrastructure of Ukrzaliznytsia that determine the scenarios for the transportation structure optimising of road transport of the country, and, consequently, Ukraine’s commitments to reduce carbon emissions for the period up to 2030 and 2050.

In addition, according to UIF estimates, the Ukrainian economy will face three most likely development scenarios until 2030: pessimistic, basic and optimistic. The optimistic scenario assumes that a comprehensive economic strategy will be implemented in Ukraine, in which the nominal GDP will increase to $ 1.2 trillion; according to the basic scenario - up to $ 1 trillion, and with the pessimistic scenario not less than $ 330 billion [55, p. 66]. Each of these scenarios provides different values of the volume of rail traffic. In particular, according to the pessimistic scenario, the volume of transportation by rail will decrease by 13 %, according to the basic scenario, it will grow by 20 %, and according to the optimistic scenario, the growth will triple [55, p. 68]. However, our focus is not on the expected changes in transport volumes due to economic growth, but on changes in the volumes of rail transport because of their redistribution between road and rail, as a more environmentally friendly mode of transport.

Therefore, guided by the scenario approach [55], taking into account the expected volumes of capital investment in the development of railway transport in Ukraine, we have developed scenarios for optimising the structure of transport by road in the country for the period up to 2030, which are presented in the Table 9.

Table 9

Scenarios for optimising the structure of road transport of Ukraine for the period up to 2030

Influencing factors	**Scenarios for optimising the structure of transport transportation for the period up to 2030**		
	Pessimistic	**Basic**	**Optimistic**
The volume of passenger traffic by rail [10^9 pkm] [54]	27.265	33.981	47.441
Volume of freight transportation by rail [10^9 pkm] [54]	176.985	220.579	307.954
Change in the volume of passenger traffic by road due to rail transport [10^9 pkm]	1.435	–1.860	–6.725
Change in the volume of road transport by road due to rail transport [10^9 pkm]	9.315	–12.926	–43.656
Capital investments in railway transport [10^6 USD] [54, p. 11]	18,369.36	47,314.23	126,171.21
Forecast of CO_2 emissions from railway transport [kt]	484.98	252.18	994.96
Forecast of CO_2 emissions from road transport [kt]	32,755.11	21,411.88	17,572.28
Total forecast of CO_2 emissions from road and rail transport [kt]	33,240.09	21,664.06	18,567.24
Expected changes in total CO_2 emissions in 2030 compared to 1990 due to the redistribution of transport volumes [%]	–47.5	–65.8	–70.7

We consider that the main factors that will affect the change in the range of investments in the renovation and modernisation of railway transport and its infrastructure are the tariff policy, the existing and projected shortage of traction and wagons, the aging of the railway infrastructure, etc. This means that the government of Ukraine urgently needs to take measures in terms of:

The tariff regulation. The efficiency of the capital invested in the Ukrainian railways is primarily determined by the efficiency of the tariff policy, since tariffs are one of the key sources of income for railway transport. In Ukraine, tariffs for rail transportation are much lower those of European countries. In particular, tariffs for rail transportation of industrial goods in Ukraine and some EU countries in 2020 (US dollars per 1 t per 500 km) were: Ukraine - $ 38.69, Poland - $ 81.69, Slovakia - $ 63.43, Hungary - $ 83.78, Romania - $ 48.3, etc. [56]. The higher transportation charges allow European carriers to reinvest the revenues generated in the modernisation of rail transport and rail infrastructure.

Consequently, one of the first steps of the Ukrainian government to optimise the structure of road transport in Ukraine should be the revision of tariffs for transport by rail.

However, an equally important step in solving the issue of optimising transportation and reducing emissions by the transport sector of Ukraine is overcoming the discrimination of tariffs for the transportation of certain classes of goods by abolishing the class system of tariff pricing and moving to a single tariff for all types of goods with market regulation. Under such conditions, the tariffs will be formed depending on market conditions, and all participants in the transportation market will be on equal terms [55, p. 30].

Overcoming the traction deficit. One of the main challenges in optimising the structure of transportation by road is the shortage of locomotive traction, which is aggravated every year due to the retirement of traction from the operating railway fleet due to aging. The actual wear rate of electric freight locomotives is now up to 90 %. According to the Investment Program of Ukrzaliznytsia until 2021 for the renewal of rolling stock, the purchase of 262 locomotives is envisaged. However, with 400 units of locomotives written off in recent years each year, the deficit of locomotive is becoming more acute, and this is because of a decrease in the efficiency of using the railway carriages of Ukrzaliznytsia and private companies. According to UIF estimates, there are two options for reducing the deficit of locomotive traction for Ukrainian railway transport, namely, viewing planned purchases of locomotives or restoring their own production.

Overcoming infrastructure challenges. The development of international relations and international transport railway corridors provoke infrastructure challenges, in particular, such as: the transition to European-style railways, the introduction of high-speed transport, the need for railway "dry ports", the introduction of digitalisation of railway infrastructure, etc. Over the past two decades, the Ukrainian government's ignorance of these challenges has led to the loss of Ukrainian iron positions in the world ranking of railway infrastructure. Therefore, during the period from 2014 to 2018, Ukraine yielded 12 positions, from 25th place in 2014 to 37th in 2018 [55, p. 51]. Moreover the main reason for this was the deterioration of the main and regional routes. The share of tracks still in need of repair and modernisation is more than 40 %, and in case of failure to repair them in 2025, this figure will increase to 70 %. With such a level of wear and tear, the railway will not be able to provide even the minimum volume of traffic envisaged under the pessimistic scenario, which means that most of the traffic will be carried out by road, which will entail a large-scale impact on the volume of carbon emissions by the transport sector of the country's economy.

Equally important for optimising the transportation structure and reducing CO_2 emissions is the complete transition of locomotive traction to electrified tracks. According to official statistics, the length of electrified tracks has increased slightly by 25 % over the past two decades. Of course, with such a pace of electrification of the tracks, it is not worth talking about the redistribution of transport traffic between road transport and the railway. According to the UIF, for 100 % electrification of Ukraine's railways, up to $\$ 5\ 10^9$ is needed, which is possible only if private investment, funds from international development banks, etc. are attracted.

The development of high-speed transport also needs significant investments necessary for the transition to a new infrastructure with high-speed parameters and higher throughput [55, p. 55], and the reliability and safety of transportation encourages the widespread use of digital technologies, etc. (Fig. 5).

Consequently, overcoming the challenges of the railway infrastructure should be resolved not in fragments, but in a comprehensive manner in close interaction of the state, Ukrzaliznytsia, business and private investors.

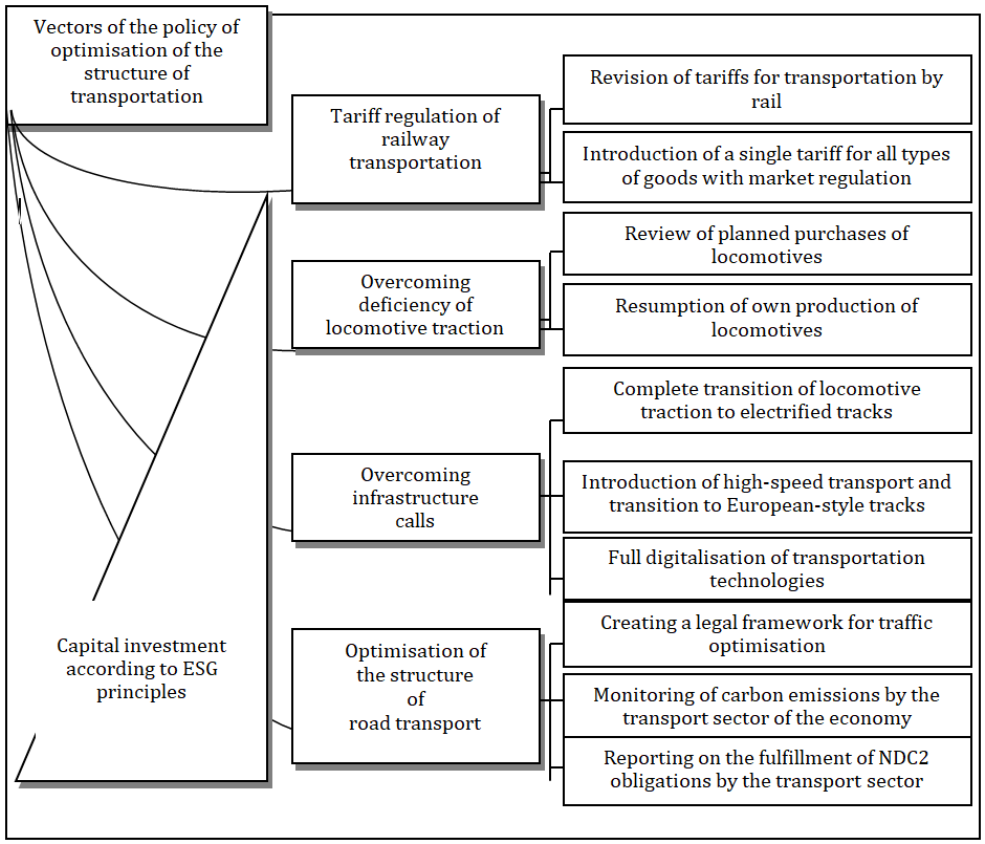


Fig. 5. Vectors of the policy of optimisation of the structure of transportation in the conditions of decarbonisation of the transport sector of the Ukrainian economy

Conclusion

Thus, according to the results of the study, it was stated that the government of Ukraine fully supports the European Strategy for Permanent and Reasonable Mobility. Therefore, the strategic guideline for the transformation of the transport sector of the Ukrainian economy has so far been chosen to reduce the carbon trace of transportation.

The truth of the hypothesis has been proved that the almost only correct solution to reduce carbon emissions by the transport sector of Ukraine's economy in accordance with certain obligations of the NDC2 under the Paris Agreement is to implement the decarbonisation policy to the road transport aimed at optimising their structure by redistribution of traffic by road and rail. The author's economic-mathematical model is offered for transportation structure optimisation based on the decoupling effect to

redistribute the volumes of transportations between motor transport and the railway. The application of the created model has allowed us to develop three most probable scenarios for the optimisation of the transport sector (pessimistic, basic and optimistic). Consequently, the percentage reduction was evaluated for each of the scenarios in carbon emissions by the Ukraine's transport sector and their compliance was estimated with the commitments with NDC2 under the Paris Agreement. The priority vectors of the decarbonisation policy for the road transport were determined. It has been emphasised that the effectiveness of the system of monitoring, reporting and verification of greenhouse gas emissions is necessary for the implementation of the authors' decarbonisation policy for road transport. That is, the lack of responsible monitoring in the limitations of this methodology.

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