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EXTERNAL COSTS OF ENVIRONMENTAL POLLUTION EMITTED BY ROAD TRANSPORT. MODELING BASED ON THE INTERSECTION UNDER REAL TRAFFIC CONDITIONS

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ABSTRACT: Environmental pollution is a negative external effect associated with road transport. The subject of the article concerns the economic aspects of air pollution caused by road transport. The aim of this study is to determine the size and costs resulting from the emission of pollutants in exhaust fumes emitted by road transport for a selected intersection under real traffic conditions. The work concerns the estimation of the costs of pollution, in conditions of flowing traffic, generated from motor vehicles, based on research conducted in real traffic conditions on the example of the intersection in Rekowo Górne. The added value and own contribution of the article result from the authors' focus on the local scale. The result of the analyses is the total annual cost resulting from the emission of harmful compounds, which is the external cost of environmental pollution by road transport. The formula presented in the article can be used to calculate the costs of pollution at selected intersections under real traffic conditions. The study, in addition to its theoretical contribution, therefore also has an application dimension and fits into the issues related to sustainable development.

KEYWORDS: cost of exhaust emissions, real traffic conditions, environmental pollution, road transport, vehicle modelling, sustainable development

Introduction

Road transport is a necessary condition for socio-economic development, but it is also a source of many negative external effects, both for society and the entire economy. Significant traffic volume adversely affects not only the efficiency of the transport system, but also the natural environment. Air pollution, as a result of exhaust emissions, entails high social costs, which are not reflected in either market prices or in the costs of all road users. The harmful effects of road transport manifest themselves not only in the form of air pollution, but also in the impact on the use of land for infrastructure, through the degradation of natural terrain and landscape. A particular area of negative impact of road transport is its impact on human health and life.

The latest research of the GUS (Główny Urząd Statystyczny – Central Statistical Office) on estimating the external costs of air pollution from road transport[1] states that Polish society was burdened with costs in the amount of PLN 32.2 billion (data for 2015), of which PLN 18 billion were costs from passenger transport. Passenger cars had the largest share in these costs, which constituted 48% of the above-mentioned amount. The share of trucks in this amount was 31%, light commercial vehicles 13%, buses 7%, and motorcycles 1%. Almost 80% of the total external costs of air pollution, i.e. almost PLN 26 billion, were generated by diesel cars. From the point of view of pollutant emissions, the highest value, estimated at PLN 16 billion, was attributed to nitrogen oxide emissions, two-thirds of which concerned passenger cars and trucks. At the same time, the external costs of air pollution from road transport amounted to 26 groszy (1 PLN = 100 groszy [gr]) per passenger-kilometer in the case of passenger transport (Kacperczyk, 2018). It is worth adding that each liter of fuel used in the combustion process produces over 2 kg of various organic compounds, carbon monoxide and dioxide, lead compounds, sulfur and many other substances contributing to atmospheric pollution and having a negative impact on human health (Adamkiewicz, 2014; Filipowicz et al., 2017).

The subject of this study is the analysis of air pollution caused by road transport. Emission of toxic exhaust components from road transport contributes to air pollution in the form of CH_4, CO_2, N_2O, NO_x, PM2.5, PM10 (particulate matter with diameters no larger than 2.5 and 10 μm, respectively) and NMVOC (non-methane volatile organic). It should be emphasised here that during the operation of combustion engines, primarily nitrogen dioxide and soot are produced, which are components of suspended particulate matter (PM10). The amount and costs resulting from harmful substances generated by motor vehicles depend primarily on the intensity of road traffic. That is why it is vital to take into account real traffic conditions. The study focuses on the traffic flow at the intersection in Rekowo Górne in the gmina Puck in 2024.

The subject of the article is related to the socio-economic aspects of the external costs of environmental pollution generated by road transport. The study presents external costs of road transport in terms of emissions of harmful substances from vehicles into the atmospheric air at the national level, and then calculates the cost resulting from harmful substances at the analysed intersection. The aim of the study is to build a model that will allow determining the emission of car exhaust fumes from the point of view of their quantity and costs, taking into account the actual traffic conditions for the selected intersection.

Literature review

External costs of environmental pollution emitted by road transport

Road transport emissions have health and climate effects, which in turn cause specific economic losses. Transport activities are primarily associated with air pollution, but also water and soil pollution; noise emissions; occupation and changes in landform and landscape degradation; congestion; climate change and road accidents (Martino et al., 2009). Identification, estimation and internalisation of external costs is the basis for implementing the idea of sustainable transport development and achieving the Sustainable Development Goals in the aspect of the existence of a relationship between economic growth and clean air (Poliński, 2012; Dang et al., 2020). Access to those was defined by the

1 The exact external costs of air pollution from road transport are presented in the later (research) part of this study.

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resolution of the United Nations General Assembly, stating that every inhabitant of the planet has the right to a healthy environment (UN, 2022).

The external costs of environmental pollution emitted by road transport are part of social costs. In their calculation, it is crucial to conduct a cost analysis in relation to the expected effects of the action. The consequences of exposure to environmental pollution can be partially valued in the context of the market value of medical services resulting from health damage and a decrease in the quality of life due to air pollution. The costs of the effects of air pollution include, among others: days off work, increased risk of neonatal death, hospital stays due to respiratory, cardiovascular, digestive system diseases, malignant tumours, and allergies. Among selected economic indicators used to calculate costs emissions from air pollution there are: VSL (value of statistical life), YOLL (increased mortality risks), VOLY (value of life-year), COI (cost of illness), WLD (work day loss), netRADs (netto Restricted activity days), MRAD (minor restricted activity days), increased mortality risk (infants), new cases of chronic bronchitis, hospital admissions (CVD, respiratory) (de Bruyn, de Vries, 2020; FPPE, 2022). Environmental pollution has measurable economic effects and affects socio-economic development. The total costs resulting from air pollution in Poland are estimated at 10% of GDP (300Gospodarka, 2024). The external costs from road transport include primarily human health costs and material damage costs.

The structure of pollutants emitted into the air by road transport depends on the type of motor vehicles. In Poland, the methodology and estimation of external costs of pollutant emissions into the atmospheric air from road transport vehicles were developed by the GUS. These studies show that more than half of the air pollution from road transport in Poland comes from passenger cars. On rural roads, the largest pollutants are emitted by buses and coaches. CO_2 dominates in the emission of harmful substances, followed by CO and NOx. Nitrogen oxides are considered the most hazardous to health (Kacperczyk, 2018). EU emission standards are being introduced in the European Union, the aim of which is to reduce exhaust emissions from vehicles. It should be noted that in terms of reducing the negative impact of road transport on the environment, pro-ecological solutions inside and outside the engine will be key (Elektromobilni.pl, 2023; Król, 2017).

In the literature, there are examples of modelling emissions of substances harmful to the environment due to the organisation of vehicle traffic at intersections (Chłopek & Polichnowski, 2002; Mądziel, 2017; Jaworski, Lejda, & Mądziel, 2017). These studies lead to the conclusion that modifying the organisation of traffic, aimed at making it flow, changes the nature of vehicle driving and affects the reduction of the average intensity of emissions of substances harmful to the environment. For example, using the A-7 sign (give way) lowers the emissions in comparison with the STOP sign (Mądziel, 2017). In studies on the external costs of environmental pollution emitted by road transport, the age and mileage of vehicles are also considered (Kuranc, 2011). The studies also assume the values of the intensity of passenger car exhaust emissions based on tests conducted in real traffic conditions, taking into account the share of vehicles meeting the latest exhaust toxicity standards, as well as the nature of changes in the length of the route covered by vehicles, using the example of the Poznań agglomeration (Merkisz et al., 2012). In the literature, the authors draw attention to the inaccuracies in determining the input values of the model, which ultimately contribute to the multiplication of the error in determining the result values (Chłopek, 2010).

At the same time, there is a lack of a model in the literature that would address the problem of exhaust emissions from an economic point of view, and which would result in a specific value understood as the amount given in PLN regarding the pollutants emitted at an intersection by vehicles passing through it. The authors of this article tried to fill this research gap, taking into account the results of their own empirical study, which was conducted in 2024.

Research methodology

The subject of the analysis is the intersection of regional road 216 with municipal roads: Lipowa (C in Figure 1) and Rekowska (A in Figure 1), which is located in the Pomeranian Voivodeship, in the gmina Puck, in the town of Rekowo Górne. The analysed intersection leads to Reda (D in Figure 1) and Puck (B in Figure 1). The aim of the study was to determine the amount and costs of pollutant emissions in exhaust fumes emitted by road transport for the analysed intersection during a year and at rush hour. The result of the own research is a model that allows estimating the costs resulting from pollution in conditions of flowing traffic.

Traffic measurement at the intersection in Rekowo Górne was performed manually. The aim of the study was to obtain, based on direct measurements, the most important parameters and characteristics of road traffic. Traffic measurement was performed taking into account the following type structure of vehicles: SO – passenger cars and minibuses, SD – light trucks, SC – trucks without trailers, SCp – trucks with trailers, A – buses. The study adopted conversion factors for equivalent vehicles (Table 1), which allows treating all vehicles as passenger cars.

Table 1. Conversion factors for conventional vehicles

category	group	factor
SO	Passenger cars	1.0
SD	Light trucks up to 3.5 t	1.0
SC	Trucks weighing over 3.5 t without trailers	2.0
SCP	Trucks weighing over 3.5 t with one or more trailers, tractor units with semi-trailers	2.5
A	Buses	2.0

Source: authors' work based on WR-D-13-01, Góralski et al. (2023), table 4.3.1., p. 28.

Taking into account daytime, evening and night-time traffic, the distribution of daily traffic of equivalent vehicles was estimated (Table 2), which shows that 66% of traffic took place between 6:00 a.m. and 6:00 p.m., evening traffic accounted for 18%, and night traffic for 16%. Table 3 presents the results of the vehicle survey, divided into vehicle types. The number of vehicles is going to be denoted as , where is the vehicle category. For example, is the number of passenger cars.

Table 2. Daily traffic distribution

Time of day	Traffic percentage	Equivalent vehicles per day
Daily traffic 6-18	66%	14,439
Evening traffic 18-22	18%	3,937
Night traffic 22-6	16%	3,501
SUM	**100%**	**21,877**

Source: authors' work based on traffic measurement research.

Table 3. Daily traffic distribution by vehicle structure

	SO	SD	SC	SCP	A	SUM
Daytime traffic: 6:00 a.m. – 6:00 p.m.	10,976	1,686	724	983	70	14,439
Evening traffic: 6:00 PM – 10:00 PM	2,993	460	197	268	19	3,937
Night traffic: 10pm-6am	2,661	409	176	238	17	3,501
Vehicles per day	**16,630**	**2,555**	**1,097**	**1,489**	**106**	**21,877**

Note: SO – passenger cars and minibuses, SD – light trucks, SC – trucks without trailers, SCp – trucks with trailers, A – buses
Source: authors' work based on traffic measurement research.

As can be seen from the data in Tables 2 and 3, 21,877 vehicles passed through the intersection in question during the day. Table 4 contains the conversion of real vehicles into equivalent vehicles for daytime traffic. In order to determine the rush hour using the recommended conversion factors for non-urban areas (Table 1), the data containing the real vehicles were converted into equivalent vehicles (Table 4), and then the traffic was summed up for the periods of the hour in a 15-minute interval (Góralski et al., 2023).

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Table 4. Conversion of real vehicles into equivalent vehicles

time	real vehicles					equivalent vehicles	time	real vehicles					equivalent vehicles
	1.0	1.0	2.0	2.5	2.0			1.0	1.0	2	2.5	2	
	SO	SD	SC	SCp	A	E		SO	SD	SC	SCp	A	E
6.00 – 6.15	135	35	6	7	1	202	11.45 – 12.00	177	33	6	17	1	267
6.15 – 6.30	157	30	2	10	1	218	12.00 – 12.15	207	30	7	3	1	261
6.30 – 6.45	232	40	1	9	1	299	12.15 – 12.30	191	30	13	15	0	285
6.45 – 7.00	235	40	2	1	0	282	12.30 – 12.45	214	42	6	13	1	303
7.00 – 7.15	181	29	4	9	2	245	12.45 – 13.00	222	43	9	12	0	313
7.15 – 7.30	207	45	7	6	0	281	13.00 – 13.15	216	48	5	9	1	299
7.30 – 7.45	204	42	7	11	0	288	13.15 – 13.30	261	34	11	11	2	349
7.45 – 8.00	188	44	4	8	0	260	13.30 – 13.45	243	34	10	5	1	312
8.00 – 8.15	160	46	10	10	3	257	13.45 – 14.00	248	36	4	3	0	300
8.15 – 8.30	152	36	3	10	0	219	14.00 – 14.15	304	22	8	8	1	364
8.30 – 8.45	180	31	3	14	1	254	14.15 – 14.30	388	41	12	5	2	470
8.45 – 9.00	168	36	7	9	0	241	14.30 – 14.45	275	26	7	1	0	318
9.00 – 9.15	153	37	10	11	1	240	14.45 – 15.00	231	29	15	10	1	317
9.15 – 9.30	142	39	9	7	0	217	15.00 – 15.15	251	35	8	8	1	324
9.30 – 9.45	173	37	15	7	1	260	15.15 – 15.30	375	39	11	7	1	456
9.45 – 10.00	205	40	4	4	1	265	15.30 – 15.45	305	34	12	5	1	378
10.00 – 10.15	159	49	8	11	0	252	15.45 – 16.00	341	32	13	13	1	434
10.15 – 10.30	204	46	7	12	0	294	16.00 – 16.15	362	46	6	2	1	427
10.30 – 10.45	179	32	12	12	1	267	16.15 – 16.30	388	41	10	7	0	467
10.45 – 11.00	196	28	9	9	1	267	16.30 – 16.45	272	25	4	4	0	315
11.00 – 11.15	186	36	14	14	0	285	16.45 – 17.00	283	22	5	5	2	332
11.15 – 11.30	202	38	13	8	1	288	17.00 – 17.15	316	38	5	4	1	376
11.30 – 11.45	178	29	10	13	0	260	17.15 – 17.30	243	26	3	7	0	293
							17.30 – 17.45	257	23	2	5	0	297
SUM	SO	SC	SC	SCp	A	E	17.45 – 18.00	230	12	3	2	1	255
	10,976	1,686	362	393	35	14,439							

Source: authors' work based on traffic measurement research.

The conducted research shows that the rush hour was between 15:30 and 16:30, where 1706 equivalent vehicles were calculated (Appendix 1). Additionally, Figure 1 presents a cartogram for the peak hour. The traffic distribution in the peak hour is presented in Table 5.

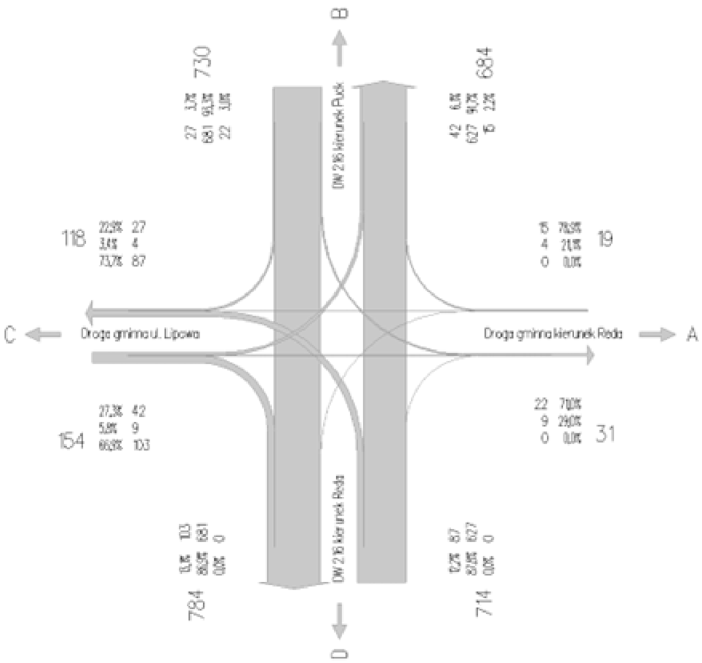

Figure 1. Cartogram for the peak hour

Source: authors' work based on traffic measurement research.

Table 5. Traffic distribution during rush hour

	SO	SD	SC	SCP	A	sum
15.30 – 15.45	305	34	24	13	2	**378**
15.45 – 16.00	341	32	26	33	2	**434**
16.00 – 16.15	362	46	12	5	2	**427**
16.15 – 16.30	388	41	20	18	0	**467**
						1,706

Source: authors' work based on traffic measurement research.

In order to achieve the objective of the study, which was to determine the size and costs resulting from the emission of pollutants in exhaust gases emitted by road transport for the analysed intersection during the day and during peak hour, the authors took into account the following environmental pollutants: CH_4, CO_2, N_2O, NO_x, PM2.5, PM10 and NMVOC.

Economic aspects of the emission of harmful exhaust components by motor vehicles

At the analysed intersection, the COPERT program calculations presented in the report *Development of the methodology and estimation of the external costs of air pollution emitted from road transport at national level* (GUS, 2019) were adopted to calculate the costs of pollutant emissions in the form of CH_4, CO_2, N_2O, NO_x, PM2.5, PM10 and NMVOC. The calculations from this report primarily come down to information on the annual external costs resulting from pollutant emissions, divided into the introduced vehicle categories. The purpose of the COPERT program is to develop a homogeneous method for estimating air pollutant emissions from transport and external costs stemming from those for all EEA (European Environment Agency) member states. The COPERT software can be used to calculate various variants of the road network, divided into urban and rural areas, as well as motorways and expressways. Additionally, it is possible to take into account the impact of various factors, such as variable temperature or road slope, on the value of costs resulting from pollutant emissions.

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Using the above-described data and information on the average annual mileage and the number of vehicles in every category (Table 6), the annual cost for one vehicle per kilometer was calculated, depending on the vehicle category and type of pollution (Table 7). It is worth noting that converting to equivalent vehicles would give a significantly different result – for example, the costs for a truck weighing up to 3.5 t are not equal to the costs for a passenger car, as would result from the coefficients presented in Table 1. Hence, it is important to conduct cost analysis on precisely conducted measurements, without introducing misleading generalisations.

The values presented in Table 7 are going to be referred to as unit cost (UC) for a given vehicle category and a given type of pollution and they are going to be denoted as , where is the type of pollution (CH_4, CO_2, N_2O, NO_x, PM2.5, PM10, NMVOC) and is the vehicle category (SO, SD, SC (including SCp), A). For example, the unit cost for buses from NOx is going to be denoted as .

Table 6. External data for calculations

vehicle category	average annual mileage [km]	number of vehicles [–]	annual cost [PLN million]						
			CH_4	CO_2	N_2O	NO_x	PM2.5	PM10	NMVOC
SO	38,382	17216420	2.7	1872.4	12.1	2328.0	416.9	484.3	57.2
SD	35,537	1522458	0.1	301.4	1.2	566.8	152.9	162.7	4.3
SC + SCp	94,355	679174	1.2	1132.1	13.0	3690.7	389.8	456.3	16.3
A	88,451	67732	0.1	70.3	0.5	285.8	27.8	28.7	1.3

Source: authors' work based on the report Kacperczyk (2018).

Table 7. Annual cost of road transport pollution in [gr/vehicle/km]

vehicle category	CH_4	CO_2	N_2O	NO_x	PM2.5	PM10	NMVOC	SUM
SO	0.0004	0.2834	0.0018	0.3523	0.0631	0.0733	0.0087	**0.7829**
SD	0.0002	0.5571	0.0022	1.0475	0.2825	0.3007	0.0079	**2.1982**
SC + SCp	0.0019	1.7666	0.0203	5.7591	0.6083	0.7120	0.0254	**8.8936**
A	0.0021	1.1735	0.0080	4.7708	0.4643	0.4796	0.0212	**6.9193**
SUM	0.0082	3.9578	0.0333	12.0754	1.5093	1.6621	0.2056	**19.45**

Results

Table 8 presents the annual cost resulting from road transport pollution for the analysed intersection in Rekowo Górne, assuming that the intersection has a total length of 1 km (250 m per inlet). The results were divided into vehicle categories and by type of pollution. The value in every cell was obtained from multiplying the number of vehicles in a given category by a corresponding unit cost. The total annual costs amount was calculated according to the formula:

$$\begin{aligned}TOTAL\ ANNUAL\ COST\ &= n_{SO} \cdot (UC_{SO}^{CH4} + UC_{SO}^{CO2} + UC_{SO}^{N2O} + UC_{SO}^{NOx} + UC_{SO}^{PM2.5} + UC_{SO}^{PM10} \\ &+ UC_{SO}^{NMVOC}) + n_{SD} \cdot (UC_{SD}^{CH4} + UC_{SD}^{CO2} + UC_{SD}^{N2O} + UC_{SD}^{NOx} + UC_{SD}^{PM2.5} + UC_{SD}^{PM10} \\ &+ UC_{SD}^{NMVOC}) + n_{SC} \cdot (UC_{SC}^{CH4} + UC_{SC}^{CO2} + UC_{SC}^{N2O} + UC_{SC}^{NOx} + UC_{SC}^{PM2.5} + UC_{SC}^{PM10} \\ &+ UC_{SC}^{NMVOC}) + n_{A} \cdot (UC_{A}^{CH4} + UC_{A}^{CO2} + UC_{A}^{N2O} + UC_{A}^{NOx} + UC_{A}^{PM2.5} + UC_{A}^{PM10} \\ &+ UC_{A}^{NMVOC}) = \\ &= \sum_{i=SO}^{A} \left(n_i \cdot \sum_{j=CH4}^{NMVOC} UC_j^i \right).\end{aligned}$$

From there, the total annual costs for the analysed intersection amount to nearly PLN 300, to which passenger cars have the largest contribution in terms of vehicle category (44%), and in terms of type of pollution – NO_x (53%). Figure 2 presents the share of types of pollutants in the costs. Hence, it can be seen that the contribution of CH_4 and N_2O is negligible and therefore, in Figure 3, presenting data from Table 8 in the form of a column chart, the two above-mentioned components of pollution have been omitted.

Table 8. Annual cost resulting from road transport pollution in [PLN] for the analysed intersection

vehicle category	CH_4	CO_2	N_2O	NO_x	PM2.5	PM10	NMVOC	SUM
SO	0.07	47.12	0.30	58.59	10.49	12.19	1.44	130.20
SD	0.01	14.23	0.06	26.76	7.22	7.68	0.20	56.16
SC + SCp	0.02	20.19	0.23	65.83	6.95	8.14	0.29	101.65
A	0.00	0.62	0.00	2.53	0.25	0.25	0.01	3.67
SUM	0.10	82.17	0.60	153.71	24.91	28.26	1.94	291.69

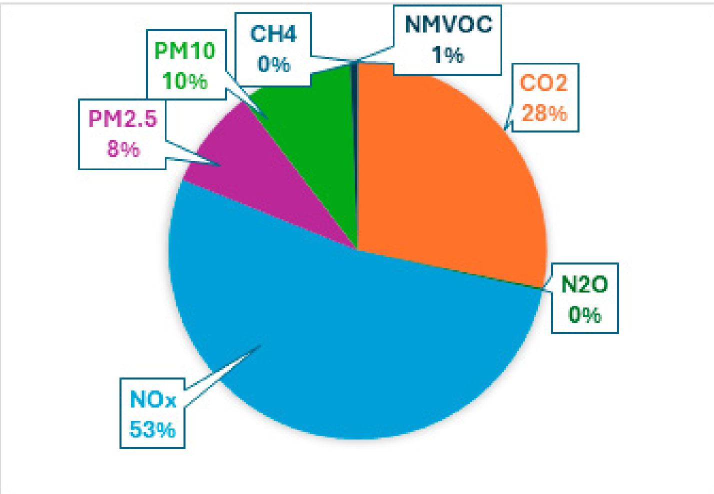

Figure 2. Share of pollutant types in external costs for the analysed intersection

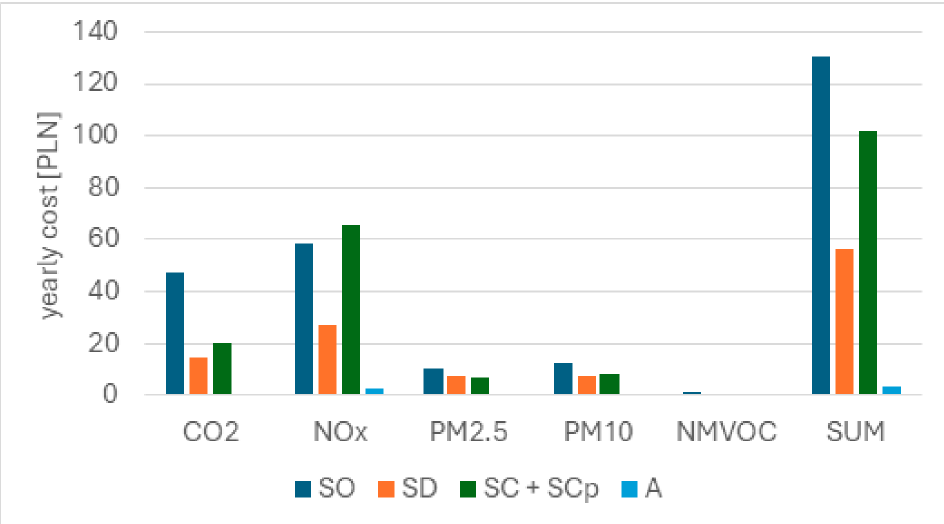

Figure 3. Annual cost of the analysed intersection

For additional verification, the obtained results were compared with the average values for a regional road. Differences between the results are expected, for example, due to the fact that the analysed intersection does not consist exclusively of regional roads. However, the obtained order of

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magnitude is similar, and in the case of total costs from all types of pollution, the difference is only 3%. This confirms that the calculations were carried out correctly.

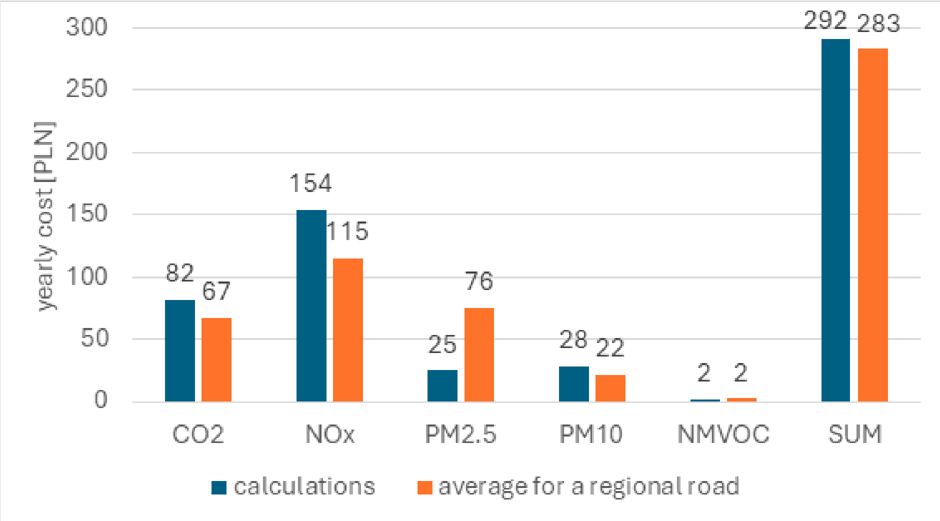

Figure 4. Comparison of results with the average values for the national road

In the case of the analysis of the rush hour (Table 9), it turns out that the largest contribution to the total costs resulting from pollution is made not by passenger cars, but by trucks weighing over 3.5 t. In terms of the type of pollutants, the largest contribution is again made by NO_x.

Table 9. Annual cost resulting from road transport pollution in [PLN] for the analysed intersection in Rekowo Górne during rush hour

	CH_4	CO_2	N_2O	NO_x	PM2.5	PM10	NMVOC	SUM
SO	0.0057	3.96	0.0256	4.92	0.88	1.02	0.121	**10.93**
SD	0.0003	0.85	0.0034	1.60	0.43	0.46	0.012	**3.36**
SC + SCp	0.0028	2.67	0.0306	8.70	0.92	1.08	0.038	**13.43**
A	0.0001	0.07	0.0005	0.29	0.03	0.03	0.001	**0.42**
SUM	0.01	7.55	0.06	15.50	2.26	2.59	0.17	**28.14**

Table 10 presents a traffic forecast for the following years until 2049 at the analysed intersection. The traffic forecast was prepared using a simplified method of GDP growth rates. Then, the results were presented in the form of a chart in Figure 5. Hence, the assumed almost linear increase in traffic in each vehicle category is visible. In the perspective of 25 years, the increase in external costs resulting from pollution at the analyzed intersection is estimated to rise from less than PLN 300 to over PLN 450.

Table 10. Traffic forecast at the intersection in Rekowo Górne

Years	SO	SD	SC	SCp	A	SDR
2024	16,630	2,555	548	595	53	20,382
2025	17,124	2,583	555	617	56	20,935
2026	17,648	2,612	562	640	59	21,521
2027	18,086	2,639	569	660	62	22,016
2028	18,535	2,666	576	681	65	22,523
2029	18,980	2,693	583	702	68	23,026

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Years	SO	SD	SC	SCp	A	SDR
2030	19421	2719	589	723	71	23523
2031	19857	2745	595	744	74	24015
2032	20286	2770	601	765	77	24499
2033	20725	2795	607	786	80	24993
2034	21190	2821	613	809	83	25516
2035	21648	2847	619	831	86	26031
2036	22116	2873	625	854	89	26557
2037	22594	2899	631	878	92	27094
2038	23064	2924	637	901	95	27621
2039	23544	2950	643	925	98	28160
2040	24034	2976	649	950	101	28710
2041	24554	3003	656	976	105	29294
2042	25085	3030	663	1003	109	29890
2043	25607	3056	670	1030	113	30476
2044	26140	3083	677	1057	117	31074
2045	26663	3109	683	1084	121	31660
2046	27175	3134	689	1111	125	32234
2047	27697	3159	695	1138	129	32818
2048	28229	3185	701	1166	133	33414
2049	28771	3211	707	1194	137	34020

Source: authors' work based on traffic measurement research.

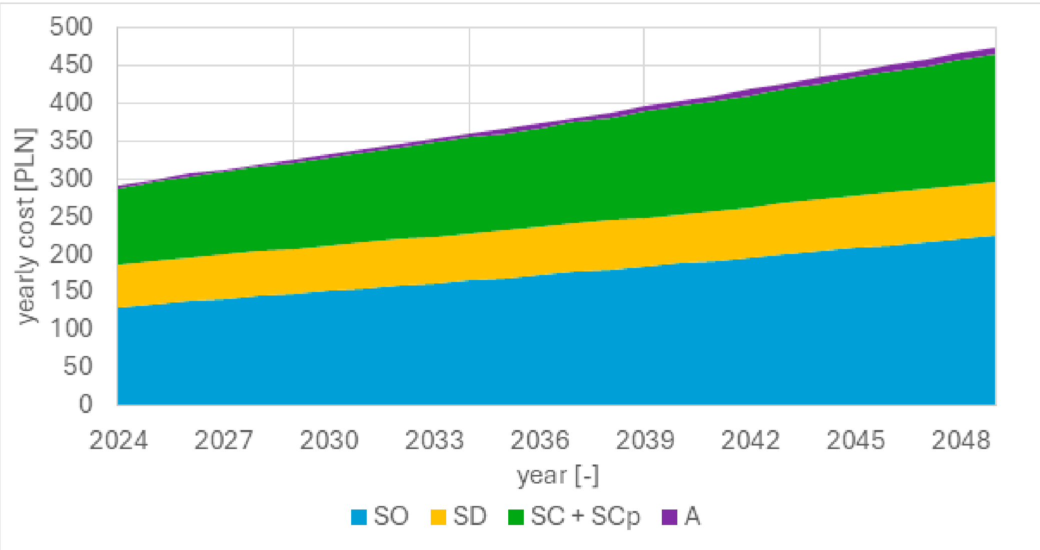

Figure 5. Traffic forecast at the analysed intersection in Rekowo Górne

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Discussion

The model proposed in this study assumes flowing traffic. In real conditions, emissions may be higher when traffic flow is disrupted due to intersection modernisation, e.g. by traffic lights, stop signs, right-of-way signs, roundabouts, etc. It has been established in the literature that aggressive driving, i.e. with frequent sudden accelerations and braking, increases fuel consumption by about 40% (SGI, 2024). At the same time, a reduction in pollutant emissions from cars can be achieved by increasing vehicle efficiency or changing the fuel used.

The modification of traffic organisation at the intersection is an important determinant of the average speed of cars passing through. Increasing this speed will result in a reduction of the generated pollutants. This is the starting point for further considerations regarding economic and ecological activities concerning environmental pollution. The reconstruction should consist of changing the location of inlets and the bus bay, and building traffic lights. In addition to sections of regional road 216 and municipal roads, a number of elements of the existing technical infrastructure will be subject to construction and reconstruction. The effect will be the improvement of the safety and comfort of road users. On the other hand, the issue of the costs coming from environmental pollution will be a new topic in this context. The value of road transport exhaust emissions depends on many factors. At intersections, vehicles usually slow down or stop, which leads to disruption of the flow of traffic and an increase in pollution. However, the start-stop systems in new types of cars, which are used to automatically switch off the engine when stationary and switch it on again when starting, should also be taken into account. In addition to the type of intersection used, these factors include the volume of road traffic, types of cars, weather conditions and driver behaviour (Januszkiewicz, 2021). In summary, exhaust emissions and fuel consumption depend to a large extent on the specific vehicle or driver behaviour.

Conclusions

Environmental pollution is a negative external effect of road transport. Air polluted by exhaust emissions increases the risk of many diseases and has a negative impact on the landscape. From an economic point of view, we are talking about the external costs of environmental pollution emitted by road transport. The study draws attention to air pollution with harmful substances from fuel combustion. At the same time, it is worth pointing out a future research field in the context of environmental pollution, which is the emission of particulate pollutants generated during the abrasion of tires and brake pads (AutoŚwiat, 2020). Paradoxically, electric cars may turn out to be less ecological in this aspect.

In terms of the results of the study in real traffic conditions, the intersection in Rekowo Górne generates external costs of approximately PLN 300 per year. These costs result primarily from NO_x emissions, and the dominant vehicle category in generating them is passenger cars. In the next 25 years, it is predicted that the costs will increase to approximately PLN 450 per year, i.e. by 50%. The analysis for the rush hour shows that most of the pollution (and consequently costs) results from the movement of trucks weighing over 3.5 t.

In accordance with the aim of the study, it was shown that the results obtained using the COPERT program allow for the construction of a model that can be applied to the conditions of actual traffic. Thanks to this, it is possible to estimate the external costs resulting from the emission of pollutants by road transport. The main limitation, however, is the fact that the obtained values assume flowing traffic, which is impossible to achieve at the intersection. Hence, the results can be treated as the minimum value of costs, which will be higher in the conditions of actual traffic. In order to increase the accuracy of the model, it would be necessary to conduct a detailed analysis of the speeds achieved by vehicles passing through the intersection, and in particular to record their braking and acceleration. Based on that, it would be possible to include changes in speed in the generated costs, which would allow for the construction of a more precise model. At the same time, it is important to maintain a balance between the accuracy of the model and its complexity. As such, the complexity of the issue is a good starting point for further analyses and research in this area. The model proposed in

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this study may be helpful in the reconstruction of intersections aimed at reducing pollution generated at them to contribute to sustainable development, which means protection of the environment and achievement of safe and smooth traffic flow.

The contribution of the authors

Conception, S.P.-K., K.K.; literature review, S.P.-K., K.K.; writing, S.P.-K., K.K.

The authors have read and agreed to the published version of the manuscript.

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Annex 1

Peak hour selection

Time	Equivalent vehicles	Time	Equivalent vehicles
6:00 – 7:00	1,000	11.45 – 12.45	1,114
6:15 – 7:15	1,043	12.00 – 13.00	1,161
6.30 – 7.30	1,106	12.15 – 13.15	1,199
6.45 – 7.45	1,095	12.30 – 13.30	1,263
7.00 – 8.00	1,073	12.45 – 13.45	1,272
7.15 – 8.15	1,086	13.00 – 14.00	1,258
7.30 – 8.30	1,024	13.15 – 14.15	1,324
7.45 – 8.45	990	13.30 – 14.30	1,445
8.00 – 9.00	971	13.45 – 14.45	1,451
8.15 – 9.15	953	14.00 – 15.00	1,468
8.30 – 9.30	951	14.15 – 15.15	1,428
8.45 – 9.45	956	14.30 – 15.30	1,414
9.00 – 10.00	981	14.45 – 15.45	1,474
9.15 – 10.15	993	15.00 – 16.00	1,591
9.30 – 10.30	1,070	15.15 – 16.15	1,694
9.45 – 10.45	1,078	15.30 – 16.30	1,706
10.00 – 11.00	1,079	15.45 – 16.45	1,642
10.15 – 11.15	1,113	16.00 – 17.00	1,540
10.30 – 11.30	1,107	16.15 – 17.15	1,489
10.45 – 11.45	1,099	16.30 – 17.30	1,315
11.00 – 12.00	1,099	16.45 – 17.45	1,297
11.15 – 12.15	1,075	17.00 – 18.00	1,220
11.30 – 12.30	1,071		

Source: authors' work based on traffic measurement research.

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Sylwia PANGSY-KANIA • Katarzyna KANIA

KOSZTY ZEWNĘTRZNE ZANIECZYSZCZENIA ŚRODOWISKA EMITOWANE PRZEZ TRANSPORT DROGOWY. MODELOWANIE NA PRZYKŁADZIE SKRZYŻOWANIA W RZECZYWISTYCH WARUNKACH RUCHU

STRESZCZENIE: Przedmiotem artykułu są społeczno-ekonomiczne aspekty zewnętrznych kosztów zanieczyszczenia środowiska generowanego przez transport drogowy. W opracowaniu przedstawione zostały koszty zewnętrzne transportu drogowego w zakresie emisji substancji szkodliwych z pojazdów do powietrza atmosferycznego w postaci CH_4, CO_2, N_2O, NO_x, PM2.5, PM10, NMVOC – na poziomie krajowym, a następnie wyliczona została wartość szkodliwych substancji na analizowanym skrzyżowaniu w ciągu roku oraz w czasie doby, uwzględniając godzinę szczytu. Celem opracowania było zbudowanie modelu, który umożliwia określenie emisyjności spalin samochodowych dla wybranego skrzyżowania. Ograniczeniem badania jest założenie zakładające płynny ruch samochodowy. Badanie ma wymiar aplikacyjny i wpisuje się w zagadnienia związane ze zrównoważonym rozwojem. W literaturze przedmiotu brakuje bowiem modelu, który ujmowałby problem emisyjności spalin z ekonomicznego punktu widzenia, czyli jako konkretną kwotę w PLN dotyczącą emitowanych zanieczyszczeń na skrzyżowaniu przez przejeżdżające przez nie pojazdy. Autorzy niniejszego artykułu starali się tę lukę badawczą wypełnić, biorąc pod uwagę wyniki własnego badania empirycznego przeprowadzonego w 2024 roku.

SŁOWA KLUCZOWE: wartość emisji spalin, rzeczywiste warunki ruchu, zanieczyszczenie środowiska, transport drogowy, modelowanie pojazdów, zrównoważony rozwój

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