



# Article Using Battery-Powered Suspended Monorails in Underground Hard Coal Mines to Improve Working Conditions in the Roadway

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Abstract: Transporting materials and mine staff is a vital link necessary to the production process in underground mines. Deteriorating climatic conditions, mainly due to the increasingly deep mining and the usage of machines, force us to look for solutions to improve the underground mine environmental situation. Another essential factor responsible for deteriorating working conditions is harmful substances and exhaust fumes emitted from diesel engines. Supplying the workplaces with air quantity exceeding requirements such as the minimum velocity of air movement or gas and climatic conditions will allow for maintaining the gas concentration at the appropriate level. One possible way to solve the problems mentioned above is to replace suspended monorails powered by internal combustion engines with new solutions of electrically battery-powered monorails. Electric monorails are not yet widely used in mines; nevertheless, they have many advantages. This article analyzes the exhaust gas parameters from monorail locomotives operating in a hard coal mine and determines the required airflow to maintain permissible concentrations of harmful gases. It also focuses on a comparative analysis of climatic conditions in the development heading, considering the roadway's functioning with and without using diesel or electric monorail. The study consists of the methodology for predicting climate conditions. Based on the performed analysis, it was shown that using electric monorails could significantly improve working conditions.

**Keywords:** underground mine; climatic hazard; underground climatic conditions; gas concentration; airflow; suspended monorail; electric battery-powered monorails

### 1. Introduction

Conducting highly efficient production in every mine is impossible without using the appropriate technology during all concurrent processes. Therefore, carrying out activities such as transporting materials and the crew and proceeding with other works in development headings or roadways in longwall panels is essential to the production process. Therefore, suspended monorails have been a popular means of transport in mines for many years.

Suspended monorails are the most effective solution for transporting crew and materials in mining excavations. As a result, the crew transport time to the roadway development headings and mining areas shortens significantly, and the energy expenditure of employees related to reaching the workplace reduces. Monorails also allow for the efficient transport of heavy materials and devices. Thanks to them, devices often do not need to be disassembled and can be transported as a whole, including powered support sections [1]. Usually, a few to a dozen suspended monorails work in each Polish mine, but some mines use even more. Therefore, they constitute a significant source of transport in mines.

So far, the most widely used monorails are powered by diesel engines. Their primary advantages include high mobility and range, as they have appropriate fuel tanks. However,



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the main disadvantage of diesel monorails are issues related to fuel combustion and heat emission (sensible and latent) and, additionally, the emission of exhaust gases containing harmful (including toxic, carcinogens) gases. The harmfulness of diesel engine exhaust is the subject of much research and publications [2,3]. The abovementioned aspects make the intensive ventilation of the excavations where they work required. Exhaust emission increases when the engine wears out, and its efficiency decreases [4]. Monorails powered by diesel engines worsen climatic conditions in the mine workings, which is significant in every excavation, but especially at a considerable depth with high virgin rock temperatures. Wei et al. [5] presented the thermal contribution rate of heat sources (surrounding rocks, air self-compression, equipment and personnel) in the deep mine, defined as the percentage of the total heat transferred to the airflow by the particular heat source. This research shows that in deep mines, 30% of heat, on average, is released from equipment. In some cases, it was more than 60%. It shows that equipment is a significant source of heat emission in mines. Another one of their disadvantages is noise generation [6].

One way to improve climate conditions in excavations may be using electric suspended monorails. However, in the case of electric monorails, there is a problem plugging into the electricity via a power cable. That reduces their range and constitutes a mobility problem. The use of battery power could potentially eliminate this problem. However, such a solution would require providing places equipped with an appropriate infrastructure of chargers. In the latest monorails, this problem was solved by charging batteries directly from the mine power network with a voltage of 500 V. Battery-powered suspended monorails have many advantages that make such machines more and more considered for application in mines. However, those solutions of monorails are not yet widely used in mines. So far, there has been no analysis of the effect of their use on improving working conditions in excavations.

Issues related to the using suspended monorails in mining are rarely discussed in the worldwide literature. Some previous publications take into account issues connected with turning systems [7], speed of transportation [8], and also breaking or acceleration systems [9–11]. However, those articles only raise the mechanical aspects of suspended monorails. They do not mention the issue of harmful emission substances and their influence on the climate in the mine atmosphere.

Another group of articles concerns the diffusion and distribution of diesel exhaust particulates in excavations [12] and requirements for diesel drives used in underground mines [13]. However, in those publications, there is no reference to the possibilities of mine ventilation and the consequences of using diesel-powered monorails to air quality in excavations.

Aspects of dilution of diesel exhaust fumes are taken into account by Wallace et al. [14]. However, the authors focused on using modelling software to support the calculation of required airflow based on heat generated by the equipment and the removal of fumes from the working environment. The authors pointed out that in some cases, there is a possibility of reducing the total airflow, but without modelling software, determining the required quantity is a slightly more complex and time-consuming process.

Tokarczyk et al. [15] presented Safe Trans-System used in planning, organization, and training for safety management transportation in underground mines. The computer program presented in the article allows for minimalizing errors during the configuration of suspended monorails and conducting traction calculations, consequently improving the safety level.

Other literature focuses on the climate conditions in advanced development roadways [16–18] but without considering the impact of additional devices and equipment. For example, monorails are most often not included in excavation equipment, so their influence on climate conditions is neglected. However, not considering them can significantly underestimate the results of climatic conditions forecasts, especially regarding air humidity.

Currently, many mines are considering accumulator-powered suspended monorails as an alternative to diesel-powered ones. However, the lack of experience with electric monorails determines the necessity of performing appropriate analyses to determine the possible benefits of its use.

The article presents a comparative analysis of the operation of diesel and electric monorails in the underground workings of hard coal mines, carried out for the roadway with forcing auxiliary ventilation. The most significant difficulties arise in ensuring air quality and thermodynamic parameters in the excavation with auxiliary ventilation. Therefore, the analysis primarily took into account the influence of the operation of battery-powered suspended monorails on climatic conditions, including air temperature and humidity, and the emission of pollutants into the mine's atmosphere. Because it is impossible to perform direct comparative measurements of climatic conditions in the mine for the article, the method of predicting climatic conditions (changes in temperature and air humidity) for reference roadway is adopted. Figure 1 summarizes the article's main scope and research objectives.



battery-powered suspended monorails instead of diesel-powered monorails?

Figure 1. Scheme of article's scopes and research objectives.

### 2. Background

Currently, diesel-powered suspended monorails are the most commonly used in Polish hard coal mines. The history of work with diesel-powered suspended monorails dates back to the 1970s [6]. However, the development of those monorails in Polish hard coal mines took place in the mid-1990s. Therefore, it is difficult to answer how many suspended monorails work in Polish mines these days. Pechora and Seffner [6] estimate that at the end of 2016, there were over 560 diesel suspended monorails (locomotives). The leading suppliers of these devices are Becker-Warkop Sp. z o.o., Famur S.A., Scharf, Bevex, and Ferrit.

The main advantages that influenced the popularization of suspended monorails were their own source of power and fuel tank, the ability to work for many hours thanks to the appropriate fuel supply, the ability to transport along an unlimited length and branched route, the ability of the driver to continuously observe the road, relatively easy and quick lengthening or shortening the road, easy loading and unloading, ease of suspending various loads, high efficiency, the ability to transport thanks to high pulling force and the ability to transport mining machinery and equipment in its entirety, the ability to change the speed of the locomotive smoothly, direct access to the development heading face and close to the intersection of the roadway and the longwall [19].

The main disadvantages of locomotives powered by combustion engines include the emission of exhaust gases containing harmful gases (poisonous, suffocating, carcinogens)

and suspended dust, as well as the generation of noise. Another significant disadvantage is the emission of both sensible and latent heat.

Most of the diesel monorail locomotives used in mines have four- or six-cylinder turbocharged diesel engines with a displacement of approximately 4000–7000 cm<sup>3</sup> and power ranging from 80 kW to almost 150 kW. The machine's pulling power is provided by one engine. During the operation of such an engine, from 210 g/kWh to about 260 g/kWh of fuel is consumed. At idle speed, the engine speed is 800–900 rpm, and the nominal rate is 2000–2600 rpm. The movement speed of suspended monorails is within a range of 1.4–3.1 m/s. However, in most solutions, it does not exceed 2.5 m/s [1]. The basic parameters for diesel-powered monorails are presented in scientific publications [1,4,6] and catalog cards of manufacturers (including Becker-Warkop Sp. Z o.o., Famur S.A., Scharf, Bevex, and Ferrit).

Diesel-powered monorails take air from the excavation, which after the fuel combustion process in the engine, is returned to the excavation via the exhaust system. To burn 1 dm<sup>3</sup> of diesel oil, assuming a double excess of air-fuel during combustion in an engine, we need approximately 30 m<sup>3</sup> of air. In 80 kW power machines, we will need to provide about 500 m<sup>3</sup>/h of air; in the case of 150 kW power, even 1200 m<sup>3</sup>/h of air will be required. Therefore, the volumetric flow of exhaust gases generated in the excavation will be slightly higher, which is consistent with the manufacturers' data of suspended monorails and exceeds 1400 m<sup>3</sup>/h for 150 kW engines. Table 1 presents the primary technical parameters of explosion-proof diesel monorail locomotives manufactured by Becker-Warkop.

Туре	Engine Power	Engine Version	Number of Cylinders	Engine Displacement	Maximum Pulling Force of One Drive	Nominal Engine Speed	Fuel Consumption
	kW			cm <sup>3</sup>	kN	1/min	g/kWh
KP-95	95	Four-stroke, turbo-charged, diesel engine	4	4764	20—Friction drive 30—Toothed drive	- 2300	229
KP-148	148		6	7146	20—Friction drive 30—Toothed drive		

Table 1. Basic parameters of diesel monorail locomotives manufactured by Becker-Warkop [20].

Limitations to the use of diesel-powered suspended monorails presented in the introduction contributed to the development works and the industrial application of batterypowered electric monorails. Their construction is similar to a diesel monorail, except the monorail has a battery assembly section. At the same time, the combustion engine is usually replaced by several (from 4 to 6) asynchronous or synchronous electric motors. The first battery-powered electric locomotives were developed at the end of the 20th century. Currently, we see their dynamic development. The leading manufacturers use lithium cells to construct batteries for such machines. The battery cells are placed in a flameproof casing. They can be charged from the mains and simultaneously recharged while driving, using an energy recuperation system (e.g., braking while driving after a fall). The state-of-the-art solutions enable the machine to be charged directly from the mine's power grid with a voltage of 500 V or 1000 V [21] because the locomotive has a charger, which is closed like a battery in a flameproof housing.

The Becker-Warkop CA-190 locomotive is one example of a modern electrically powered suspended monorail. It is powered by a VOLTER lithium battery (142 kWh) and has 4 two-engine friction drives, with 11 kW single engine power, giving a total drive power of 88 kW. The maximum speed of the locomotive is 2.0 m/s. These parameters indicate that such a monorail may be an alternative to diesel engine monorails with similar technical parameters. Table 2 shows the basic parameters of the battery-powered CA-190 electric suspended monorail manufactured by Becker-Warkop.

Parameter	Value and Unit		
Drive pulling force	80 kN—for 4 friction drive		
Maximum speed	2.0 m/s		
Minimum radius of horizontal curvature	4 m		
Minimum radius of vertical curvature	8 m		
Maximum route inclination	$\pm 30^\circ$		
Nominal battery charging voltage	500 V		
(directly from the mine's electric grid)			
Accumulator type (VOLTER)	lithium		
Battery capacity	142 kWh		
One drive engine power	11 kW		
Power (with 4 two-engine friction drives)	88 kW		
Dimension (height/width/length)	1275/800/15,340 mm		
Total weight (with 4 two-engine friction drives)	11,110 kg		

**Table 2.** Technical parameters of the CA-190 cordless locomotive powered by a VOLTER lithium battery [21].

While proceeding with analyses of the monorail working influence on the thermal condition in the mine roadway, technical parameters presented in this section are considered.

#### 3. Materials and Methods

#### 3.1. Aspects of Using Combustion Engines in Mines Due to Exhaust Fumes

During the operation of the combustion engine emits exhaust fumes containing harmful gases and solids. Therefore, the Polish national standard defines the requirements for diesel machines designed for underground excavation [22]. According to its provisions, engines intended for mining diesel vehicles for operation in mining excavations should be designed in such a way that the content of toxic substances in the exhaust gases in any given engine operating state does not exceed 500 ppm for carbon monoxide, 750 ppm for nitrogen oxides, 200 ppm for hydrocarbons and 3rd soot blackness according to the Bosch scale.

The use of internal combustion engines with higher concentrations of toxic substances in their exhaust gas is permitted, provided that devices reducing the content of these substances to the permissible values are used in their exhaust systems. The content of harmful substances in the exhaust gas is measured following the relevant standard [23]. This standard specifies where they operate, and the gas analyzers used.

According to the current Polish mining regulations [20], all accessible workings and spaces are ventilated in such a way that the oxygen content in the air is not less than 19% by volume. The gas concentration in the air is not greater than 1% for carbon dioxide, 0.0026% for carbon monoxide (26 ppm), 0.00026% for nitric oxide (2.6 ppm), 0.000075% for sulfur dioxide (0.75 ppm) and 0.0007% hydrogen sulfide (7 ppm).

In addition, the mining regulations [24] specify that in mines using machines with a combustion engine, the content of nitrogen oxides is determined based on the concentration of nitrogen dioxide.

Among the nitrogen oxides in the exhaust gas, nitrogen dioxide is the most dangerous gas, as it is highly toxic. Of the remaining oxides, nitric oxide also has an irritant effect, but its impact on the human body is much smaller. In addition, it oxidizes rapidly in the air into nitrogen dioxide. The proportion of nitrogen dioxide in exhaust gases is 5–10% compared to nitrogen oxide.

Their composition was analyzed based on the measurements of undiluted exhaust gases carried out cyclically in one of the hard coal mines in the Upper Silesian Coal Basin (USCB) in Poland. The measurements covered an annual period. Measurements were conducted following the requirements of the standard [23]. They were carried out for 10 suspended monorails in use in the mine. The machines tested included the locomotives produced by Becker-Warkop (KP-95, KP-148) and Ferrit (DLZ 50F, DLZ 130F, DLZ 210F).

The analyses included measurements of the concentration of oxygen, carbon dioxide, carbon monoxide, and nitrogen dioxide for the idle speed and nominal machines' speed. Additionally, the temperature of exhaust gases and hydrocarbons was measured. The measurement results are presented in the next section of the article. This analysis's main objective is to determine the necessary volumetric airflow in the excavation to ensure the permissible concentrations of harmful gases emitted in the exhaust fumes.

#### 3.2. Aspects of Using Monorails in Mines Due to Climate Conditions

Climatic conditions in the excavation are shaped by many factors, both natural and technical. To the greatest extent, these conditions depend on the depth of exploitation and the associated virgin rock temperature. In addition to the virgin rock temperature, several other factors affect the climatic conditions in the excavation. The most important of them are thermo-physical parameters of the rocks, the temperature of the air flowing, the lifetime of workings, heat from machines and power machinery devices, diesel-powered machines, pipelines transporting various media, water evaporating in the excavation, and air pressure changes during the flow with inclined gas desorption.

This article analyzes the impact of suspended monorails on climatic conditions in reference roadway. The comparison was made for the diesel and electric-powered suspended monorails. The heat transferred to the air by machine drives depends primarily on their power, mechanical efficiency, the method of converting the supplied energy into heat, and the unevenness of the load over time.

During the process of internal combustion in diesel engines, the power supplied to the drive is equal to the calorific value of the fuel and several times higher than the useable power of the engine. In general, machines powered by diesel engines transfer about 3 times more heat to the environment than machines powered by electric motors of the same useable power. The calorific value of diesel fuel, which is a diesel engine fuel, is 45.6 MJ/kg. Fuel consumption in overhead diesel engines ranges from 210 g/kWh to around 260 g/kWh (average 235 g/kWh). Therefore, for 1 kW of engine power, it consumes fuel containing the following amount of energy:

$$\frac{0.235 \cdot 45600}{3600} \cong 3.0 \text{ kW}_{\text{fuel}} / \text{kW}_{\text{engine}}$$
(1)

The amount of energy calculated with the relationship (1) in about 1/3 is converted into the useful work of the machine. At the same time, the remaining 2/3 is transferred to the excavation area through heat by hot engine components and exhaust emissions. In addition, part of the heat generated during combustion is transferred to the air in a latent form. It means that burning 1 dm<sup>3</sup> of diesel fuel results in releasing about 1 kg of water vapor into the air. Therefore, diesel engine machines significantly affect climatic conditions during operation in the context of increasing air temperature and humidity.

Measurements carried out in German mines by Voß [25] show that 30% of the heat released due to the machine's operation is transferred outside the excavation area with the transported output. About 10–25% of the remaining part is released into the air as sensible heat and about 90–75% as latent heat. The experiences of the authors of the article, resulting from measurements carried out in mines, also indicate such ranges for the share of sensible and latent heat increase in areas where machines operate. Based on the phenomena mentioned above, it was possible to determine the relation enabling the determination of the rise in temperature  $\Delta t$  and air humidity  $\Delta w$  caused by the operation of drives and mechanical devices [26]:

$$\Delta t = \frac{7.0 \cdot (0.1 - 0.25) \cdot \Delta Q_m}{\dot{V}_a \cdot \rho_a \cdot c_{pa}}$$
(2)

$$\Delta w = \frac{0.7 \cdot (0.9 - 0.75) \cdot \Delta Q_m}{\dot{V}_a \cdot \rho_a \cdot r_w} \tag{3}$$

where  $\Delta Q_m$  is energy converted into heat in a device with mechanical or electric drive in kW,  $\dot{V}_a$  is volumetric airflow in the excavation in m<sup>3</sup>/s,  $\rho_a$  is the density of air in the excavation in kg/m<sup>3</sup>,  $c_{pa}$  is the specific heat of the air in kJ/(kg·K), and  $r_w$  is the heat of water vaporization in kJ/kg.

In the case of electric machines, some of the drive energy is converted into heat directly in the motor. This process determines the device's efficiency, which manifests in higher engine temperature than ambient temperature. The efficiency of electric motors depends on their structure, engine speed, power, and load concerning the nominal power. Fully loaded ring and squirrel-cage asynchronous motors with a nominal power of hundreds of kW reach efficiency levels exceeding 90%. In the motors, losses occur in the winding and the magnetic circuit (the copper and the iron losses). Winding losses are usually the greatest and vary with the square of the current. When the engine load is reduced compared to the nominal power, its efficiency decreases.

In the case of an incomplete load of machines, the engine unevenness coefficient can be introduced, equal to the ratio of the engine operation time to the working shift time.

The article presents a comparative analysis of the influence of the suspended monorail on climatic conditions in the reference advanced development heading. For this purpose, a forecast of climatic conditions was made for a reference 1000 m of the roadway, supported with arch support yielding steel sets with a cross-section of 17.8 m<sup>2</sup>. In the roadway forcing auxiliary ventilation system is used.

Authors adopted an authorship method to forecast the climate condition [27]. This method is based on the methodology widely used in polish mines for predicting climate conditions. Authorship modification concerns its adaptation to the roadways with auxiliary ventilation. Additionally, the methodology includes increasing temperature and moisture content in the air connected with the working monorail, according to Equations (2) and (3). The forecast considers both temperature and air humidity changes.

Predicted air temperature was calculated according to the following formula:

$$t_{air out} = t_{air in} + \Psi \cdot \Delta \theta_r + \Omega \cdot \Delta t_{ad} + \phi \cdot \Delta t_w, \quad C$$
(4)

where  $t_{air in}$  is the temperature of the air at the beginning of a considerate section of excavation in degrees of Celsius,  $\Psi$  is the coefficient depending on the Kirpichev number,  $\Delta \theta_d$  is the temperature differential between virgin rock temperature and air temperature at the beginning of a considerate section of excavation in the degree of Celsius,  $\Omega$  is coefficient depended on the Kirpichev number,  $\Delta t_{ad}$  is air temperature increase resulting from the operation of additional heat sources in the considerate section of excavation (time of excavation existence),  $\Delta t_w$  is a change of air temperature associated with the difference in the state of aggregation of water in the air in the degree of Celsius.

Coefficient  $\Psi$  was calculated from the formula:

$$\Psi = 1 - exp[-K(Fo, Bi) \cdot \overline{x}]$$
(5)

where *K* is the Kirpichev number depending on the Fourier and Biot numbers,  $\overline{x}$  is a distance coordinate calculated as:

$$\overline{x} = \frac{2 \cdot \pi \cdot \lambda \cdot l}{\dot{m} \cdot c_p} \tag{6}$$

where  $\lambda$  is the thermal conductivity coefficient of rocks in W/(m·K), *l* is excavation section length in meters, *m* is the mass airflow in kg/s and  $c_p$  is the specific heat of the air in K/(kg·K).

Coefficient  $\Omega$  was calculated from the formula:

$$\Omega = \frac{1 - exp[-K(Fo, Bi) \cdot \overline{x}]}{K(Fo, Bi) \cdot \overline{x}}$$
(7)

The air temperature increase resulting from the operation of additional heat sources in the considerate section of excavation was calculated from the formula:

$$\Delta t_{ad} = \frac{Q_1 + Q_2 + Q_3 + Q_4}{\dot{m} \cdot c_p}$$
(8)

where  $Q_1$  is the heat emitted from machines and electric devices in kW,  $Q_2$  is the heat emitted from the carbon oxidation process in kW,  $Q_3$  is the heat emitted from pipelines in kW, and  $Q_4$  is the heat emitted from transported coal in kW.

Coefficient  $\phi$  was calculated from the formula:

$$\phi = \varepsilon' \cdot \Omega \cdot \left( 1 - \frac{K(Fo, Bi)}{Bi} \right) \tag{9}$$

where  $\varepsilon'$  is the empirical coefficient dependent on ventilation time of excavation (time of excavation existence)—value from the range from 0.16 to 0.8.

Change of air temperature associated with the difference in the state of aggregation of water in the air was calculated as:

$$\Delta t_w = -\frac{a' \cdot \Delta w \cdot l}{c_p} \tag{10}$$

where a' is a heat of water vaporization in kJ/kg,  $\Delta w$  increase in the moisture content in air in kg/(kg·m).

The analysis was conducted for two cases:

- Case 1—excavation in which the temperature of 28 °C is maintained throughout the entire length of the roadway without the use of the suspended monorail;
- Case 2—excavation performed in difficult climatic conditions, where the temperature of 28 °C is exceeded in the normal state without using the suspended monorail.

The climate condition forecast was carried out in 100 m sections, taking into account the tightness of the duct and changes in air parameters in excavation. In addition, the appropriate working time of the excavation on its individual sections was assumed, taking into account the progress of the face and the work of electric machines and transformers. The forecast for both cases was made in the following order:

- forecast for the excavation without a working monorail;
- forecast for the excavation, assuming the operation of a 95 kW diesel monorail;
- forecast for the excavation, taking the operation of an electric monorail with a total engine power of 95 kW.

In Figure 2, the situation in the analyzed reference excavation is shown. The drawing shows the direction of airflow and the location of the suspended monorail.



Figure 2. Layout of the analyzed excavation.

The calculations consider the continuous operation of the monorail in the excavation. It was assumed that 20% of the machine's generated heat is transferred to the air as sensible heat and 80% as latent heat. Moreover, the heat generated during the operation of the monorail is not taken from the excavation together with the coal output, i.e., the authors considered the maximum possible heat increase in the excavation.

Calculations were made to increase the heat flux in the excavation in connection with the operation of the suspended monorail, considering both the sensible and latent heat increase in the case of the diesel monorail.

### 4. Results and Discussion

# 4.1. Analysis of Exhaust Fumes from Diesel Engine Monorails in Terms of Ensuring Appropriate Ventilation Conditions

The exhaust gas temperature for all tested monorails ranged from 47  $^{\circ}$ C to 49  $^{\circ}$ C, depending on the engine speed. The analyzes also indicated that the content of hydrocarbons in the exhaust gas was negligible. Methane was found in one measurement but with concentrations of hundredths of a percent.

Figures 3–6 show the diagrams of the registered gas concentrations using frame diagrams for oxygen, carbon dioxide, carbon monoxide, and nitrogen dioxide, respectively. The charts cover the entire period of measurements, and the data in the charts have been divided into individual machines and engine speeds. In the graphs, the point represents the mean value, the box shows values within the 95% confidence interval, and the whiskers shows the minimum and maximum values for a given monorail.



Figure 3. Graph of oxygen concentration in exhaust fumes emitted by suspended monorails.

The analyses carried out for all monorails show that the oxygen concentration level in the exhaust gas is on average 17.13% at idle speed and 16.72% at a nominal rate. In the case of carbon dioxide, concentrations reach an average of 2.71% at idle speed and 3.21% at nominal speed. In the case of carbon monoxide concentration, it was on average, 207 ppm at idle and 266 ppm at nominal revolutions. On the other hand, the recorded concentrations of nitrogen dioxide were on average, 32 ppm at idle speed and 47 ppm at a nominal rate.

The measurements and analysis of the average values of concentrations of harmful gases in the exhaust gas show that during the machine operation the concentration of the emitted gases is, in most cases, much lower than assumed in the Polish standard [22]. Nevertheless, the concentration of carbon monoxide is sometimes close to the limit values provided for in the standard.



Figure 4. Graph of carbon dioxide concentration in exhaust fumes emitted by suspended monorails.



Figure 5. Graph of carbon monoxide concentration in exhaust fumes emitted by suspended monorails.



Figure 6. Graph of nitrogen dioxide concentration in exhaust fumes emitted by suspension monorails.

The Becker-Warkop company made available to the authors the results of the exhaust gas analysis of new diesel monorails used to work in mining excavations. The investigation

was carried out both at idle speed and nominal speed. The exhaust gas temperature during the tests varied from 33.6 to 43.8 °C, oxygen concentration from 13.0% to 17.0% (higher at idle speed), carbon dioxide concentration from 2.93% to 5.87% (higher at a nominal rate), the concentration of carbon monoxide from 136 ppm to 242 ppm (higher at nominal speed), the concentration of nitrogen oxides from 157 ppm to 219 ppm (higher at idle speed). The exhaust gas analyses show that the tested monorail locomotives with an allowance meet the standard's requirements [22].

In the excavation with a working diesel engine monorail, it must be ensured that the airflow is sufficient to maintain the permissible concentrations of harmful gases emitted in the exhaust fumes. The airflow  $\dot{V}_a$  necessary to dilute the harmful components of the exhaust gas is calculated as:

$$\dot{V}_a = k \cdot q_f \cdot \left(\frac{c_1}{c_1_{per}} + \frac{c_2}{c_2_{per}} + \dots + \frac{c_n}{c_{n_{per}}}\right), \ \mathbf{m}^3 / \mathbf{min}$$
(11)

where *k* is the correction factor for non-uniformity mixing of the exhaust gases in the mine atmosphere,  $q_f$  flue gas volume flow in m<sup>3</sup>/min,  $c_i$  is the concentration of the *i*-th harmful component in the exhaust gas in ppm, and  $c_{i per}$  is the permissible concentration of the *i*-th element in the mine atmosphere in ppm.

Based on the average values of gas concentrations obtained from the measurements and taking into account the 95% confidence interval, the required airflow was calculated following the relevant Equation (9). Due to the harmful nature of exhaust gas components, the required airflow for individual ingredients (carbon monoxide and nitrogen dioxide) was summed up. Additionally, the correction factor (k = 1.5) was taken into account, taking into account the emission unevenness, the efficiency of exhaust gas dilution, and the harmfulness of the substance. The results of variant calculations of the required airflow for the average CO and NO<sub>2</sub> concentrations values from the measurements and the variable flux of exhaust gases emitted for the engine running at idle and at nominal speed are presented in the form of a diagram in Figure 7.



**Figure 7.** The required airflow for the average values of CO and NO<sub>2</sub> concentrations from measurements and the variable flux of emitted exhaust gases.

The airflows presented in Figure 7 show that to dilute the harmful components of exhaust gases during the monorail operation in the excavation, from 400 m<sup>3</sup>/min to even 1100 m<sup>3</sup>/min of air may be needed. Such an expenditure significantly exceeds the required air stream resulting from the necessity to ensure the air velocity required by law [24] in the excavation of the methane fields (0.3 m/s). For example, for a cross-section of 14 m<sup>2</sup>, the required airflow is 252 m<sup>3</sup>/min, and for a cross-section of 20 m<sup>2</sup>, it is 360 m<sup>3</sup>/min.

It follows that the operation of the diesel engine monorail significantly interferes with the process of ensuring appropriate conditions during excavation. Supplying airflows exceeding all other criteria will allow diluting of the gases emitted in the exhaust gas. Providing the

all other criteria will allow diluting of the gases emitted in the exhaust gas. Providing the proper ventilation conditions in remote parts of the mine may sometimes be challenging. In this aspect the use of battery-powered suspended monorails will help improving air quality in the excavation and in some cases will enable reducing the required airflow.

# 4.2. Distribution of Gas Concentration in Excavation with Operating Diesel Engine Suspended Monorail

Calculations of the airflow carried out in point 4.1 refer to the continuous operation of the machine in the excavation at a given point of the excavation, at full load. It is known that machines, particularly suspended monorails, move in excavations, making determining the concentration of gases in a given part of the excavation more complicated. The distribution of the concentration of gases emitted by the suspended monorail locomotives in the exhaust gas will depend on the excavation air velocity, the monorail's speed, and the direction of its movement [28]. The concentration distribution may also be influenced by the fact that many machines with an internal combustion engine are operated during excavation. A generalized graphic interpretation of various cases of machine motion concerning the direction and velocity of the air flowing in the excavation is shown in the figures in Table 3. The figures show that, over time, during the continuous operation of the line, the gas concentration will stabilize at a certain level and a distance behind the line, depending on ventilation conditions in excavation. Detailed solutions of the equations concentration values to be calculated were included as part of the work [28].

**Table 3.** Cases of the movement of suspended monorails in the excavation in relation to the direction of airflow.





List of symbols used in Table 3: *x*—the current coordinate for roadway, m; *c*—gas concentration, % or ppm; *q*—mass emission of gas during the operation of the monorail locomotive, kg/m<sup>3</sup>;  $\tau$ —moment in time; ( $\tau_2 > \tau_1$ ), s; *s*—excavation cross-sectional area, m<sup>2</sup>;  $V_a$ —air volume flow, m<sup>3</sup>/s;  $\rho$ —air density, kg/m<sup>3</sup>;  $\rho_{ex}$ —exhaust gas density at the exit from the exhaust pipe, kg/m<sup>3</sup>;  $v_{mon}$ —speed of the moving monorail, m/s;  $v_{air}$ —air velocity, m/s.

Keeping concentrations at a permissible level allows for achieving the most favorable distribution of gas concentrations in the working atmosphere when the monorail moves against the current of the flowing air. The least favorable variant is when the monorail moves in the direction of the airflow, and the speed of the monorail is equal to the velocity of the flowing air.

# 4.3. Comparison of the Climatic Conditions in the Roadway during the Operation of the Diesel and Electric Suspended Monorail

The article analyzed two cases for reference roadway. In both cases, the same values were established for implementing the predicting climate condition for some parameters. Other parameters depend on the analyzed case. The same parameters in both cases are:

- time of excavation existence—from 1 to 10 months depending on the section,
- > thermal conductivity coefficient of rocks— $\lambda = 1.92 \text{ W}/(\text{m}\cdot\text{K})$ ,
- mass of transported coal—110 t/d,
- three pipelines in excavation with a diameter of 100 mm.

The technical and ventilation parameters and the characteristics of the factors influencing the climatic condition for the roadway analyzed in case 1 are presented in Table 4. In addition, graphical summaries of temperature and air humidity forecasts are presented in Figures 8–10. Figure 8 shows the estimates for the roadway without the monorail operation, Figure 9 with the diesel monorail operation, and Figure 10 with the electric monorail operation.

**Table 4.** Characteristics of the roadway—case 1.

Parameter	Value	Unit
Roadway length	1000	m
Roadway cross-section area	17.8	m <sup>2</sup>
Volumetric airflow in advancing face	600	m <sup>3</sup> /min
Main auxiliary fan volume flow rate	800	m <sup>3</sup> /min
Virgin rock temperature	32	°C
Total machine power working in the roadway face	300	kW
Air temperature in the roadway face	25	°C
Air humidity in the roadway face	65	%



Figure 8. Forecast of air temperature and humidity in the roadway (case 1).

The analysis of Case 1 shows that the heat gain caused by using a diesel engine monorail in the roadway is about 181 kW. The increase in sensible heat is about 24 kW, and the remaining heat is latent heat caused by the rise in the moisture content in the air. The air temperature at the exit from the roadway increased by  $1.5 \,^{\circ}$ C, while the moisture content in the air increased by approximately  $4.6 \,\text{g/kg}$  of dry air. On the other hand, this translated into a significant increase in relative humidity (approximately 12%). In the case

of the electric monorail, the heat increase in the section is 18.5 kW in total, with a 2.5 kW sensible heat increase, while the remaining part is latent heat. According to the forecast, the air temperature at the exit from the excavation increased by 0.1 °C, while the moisture content in the air by about 0.5 g/kg of dry air. Due to the increase in temperature and moisture content, the relative air humidity at the excavation's exit remained practically unchanged when the monorail was not in operation.



**Figure 9.** Forecast of air temperature and humidity in the roadway with the operation of the diesel monorail (case 1).



**Figure 10.** Forecast of air temperature and humidity in the roadway with electric monorail operation (case 1).

The comparison shows that it is possible to provide more favorable climatic conditions for roadways by using an electric-powered suspended monorail in preference to a dieselpowered one.

The second case analyzed is a similar roadway in difficult climatic conditions. The technical and ventilation parameters and the characteristics of the factors influencing the

climate condition for the analyzed roadway in case 2 are presented in Table 5. In addition, graphical summaries of temperature and air humidity forecasts are shown in Figures 11–13. Figure 11 shows the forecast for the roadway with no monorail, Figure 12 using the diesel monorail, and Figure 13 using the electric monorail.

Parameter	Value	Unit
Roadway length	1000	m
Roadway cross-section area	17.8	m <sup>2</sup>
Volumetric airflow in advancing face	600	m <sup>3</sup> /min
Main auxiliary fan volume flow rate	800	m <sup>3</sup> /min
Virgin rock temperature	42	°C
Total machine power working in the roadway face	550	kW
Air temperature in the roadway face	26	°C
Air humidity in the roadway face	65	%

Table 5. Characteristics of the roadway—case 2.



Figure 11. Forecast of air temperature and humidity in the roadway (case 2).

The analysis of Case 2 shows that the heat increase caused by the use of monorail in the roadway is approximately 169 kW. The increase in sensible heat is about 21 kW, and the remaining heat is latent heat. The air temperature at the exit from the excavation increased by 1.3 °C. In contrast, the moisture content in the air rose by about 4.6 g/kg of dry air, which translated into a significant increase in relative humidity (higher by about 16%). In the case of the electric monorail, the heat increase in the section is in total, as in Case 1, 18 kW, with a sensible heat increase of less than 2.5 kW, while the remaining part is latent heat. According to the forecast, the air temperature at the exit from the excavation increased by about 0.1 °C, while the moisture content in the air increased by about 0.5 g/kg of dry air. Due to the increase in temperature and moisture content, the relative air humidity at the exit of the roadway remained practically unchanged concerning the situation in which no monorail was used.

The comparison performed, as in Case 1, shows that it is possible to provide more favorable climatic conditions for excavation thanks to using an electric-powered monorail in preference to a diesel-powered one. The lower heat increases at the exit from the excavation in this case, and also for both monorail drive solutions, in comparison to Case 1, are because the additional heat increase from the monorails resulted in a lower heat increase from other sources in the excavation, most of which came from the rocks. In the case of

excavations carried out in difficult climatic conditions, the influence of additional heat sources is, therefore, more minor and has a lesser impact on the deterioration of climatic conditions. However, this does not change the fact that electric monorails have a less negative effect on climatic conditions during excavation.



**Figure 12.** Forecast of air temperature and humidity in the roadway with the operation of the diesel monorail (case 2).



**Figure 13.** Forecast of air temperature and humidity in the roadway with electric monorail operation (case 2).

## 5. Summary and Conclusions

The analyzes performed as part of the article concerned the operation of suspended monorails in mining excavation, with particular emphasis on climatic conditions and the emission of pollutants. Based on them, one can conclude that the use of battery-powered electric monorail instead of diesel monorail has a more positive effect on the microclimatic conditions and the improvement of air quality during excavation. The high efficiency of electric drives causes them to emit much less heat into the excavation area than diesel monorails. As part of this article, comparative analyzes of heat gain were performed for 1000 m of a roadway, where 28 °C is ensured without the monorail operation along its entire length, and for excavation carried out in difficult climatic conditions. In the first case, the temperature increase at the excavation exit during the diesel monorail operation was 1.5 °C. In the case of an electric train, it is about 0.1 °C. Along with a deterioration in climatic conditions during excavation, the impact of the monorail operation is slightly smaller. In the second case, the temperature increase at the exit from the roadway area during the operation of the diesel monorail was 1.3 °C. During the operation of the electric monorail, it was about 0.1 °C. The lower temperature increases during roadway in difficult climatic conditions are due to the heat increase caused by the operation of the monorail inhibiting heat inflow from other sources, especially the rock mass.

One of the undisputed advantages of electric monorails is the lack of steam, which increases the moisture content in the air. Its humidity is crucial if it is necessary to use air cooling in workings. When it is high, the cooling capacity of the built-in air conditioning system coolers is used to lower the air humidity (air drying) rather than the temperature. The total heat gain (sensible and latent) in the first case analyzed was 181 kW and 18.5 kW for the diesel and electric monorails, respectively. In the second case, the total heat gain was 169 kW and 18 kW, respectively.

Using electric monorails also eliminates the emission of harmful gases into the ventilating air, significantly improving air quality during mining operations. Moreover, it is possible to reduce the airflow in selected excavations—provided, of course, this is possible even given other requirements stipulated by applicable regulations or the occurrence of natural hazards.

Due to the advantages of electric monorails above diesel ones presented in the comparison, they are likely to gradually replace diesel engine monorails operating in mines in the coming years.

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