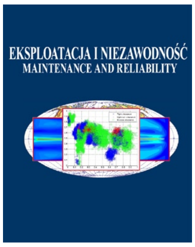

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Impact of suspension and route stabilization on dynamic parameters of self-driven mine suspended monorails

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Highlights

- An analysis of potential increase in speed of suspended monorail is presented.
- An analysis of the impact of route stabilization on dynamic loads of the support is included.
- An analysis of the impact of route stabilization on forces affecting the operator is included.
- The impact of dynamic interactions of the monorail on the biomechanical parameter is assessed.

Abstract

Impact of the method of suspension and route stabilization of suspended monorail on forces loading the roadway roof support system is presented. This is important in the context of possible increasing the speed of monorails during personnel movement. Nature of load and displacement of the route, as well as deceleration of the transport set, with a dynamic excitation - an emergency braking of the transport set, are presented. The results are presented for seven configurations of slings and lashings stabilizing the route. The Head Injury Criterion (HIC), recorded using the Articulated Total Body (HYBRID III) model, during the impact of operator's cabin against an obstacle, is presented in the further part of the article. Analyzes are aimed at developing the guidelines to ensure safety of mining personnel (without exceeding the accepted overloads) and mining infrastructure (without exceeding the maximum accepted load of the roadway support) during operation of the suspended monorail at higher speed. Analyzes are the result of the authors numerical simulations.

Keywords

coal mining, safety, suspended monorails, transport, numerical simulations

1. Introduction

Mine transport is an indispensable link in the mining process of any mining plant. While floor transport has been used since the beginning of mining development, and mine tracks appeared in the 17th century, the use of suspended transport started only in the middle of the 20th century [13]. The suspended monorails quickly became widely used underground mean of transport. The development of self-driven suspended monorails resulted in an increase in the load-bearing capacity and strength of rails and transport sets, as well as an increase in tractive force, compared to suspended cable-driven suspended monorails [12, 13]. Intensive development of suspended monorails is still observed today. This is proved by R&D work in development of electrically powered monorails [9, 13], mechanical modifications, including the possibility of travelling at higher speed or improving the comfort of travelling [21, 24]. The changes also involve introduction of innovative mechatronic solutions in monorails [1, 6, 22]. Along with the development of suspended monorails, the development of monorail routes and the methods of their suspension and stabilization gradually advanced. In self-driven monorails, their routes were standardized. Currently the most frequently used rails are those with the I155 profile, less often with the I140V profile. One of the "tasks" of the suspended monorail system is to transfer the loads, resulting from the weight of monorail unit and its movement, to the roadway roof support or directly to the rock mass, thus slings and lashings are used. The rails in the roadway are suspended on various types of slings, which, depending on the structure, can be loaded with a maximum force of 40 kN [20]. Depending on the length of rails and the configuration of slings and lashings, this force is transferred in different ways to the arches of yielding roadway roof support, which protects the transport routes against falling rocks. Moreover, to ensure stability, a suspended route must always be stabilized at the turns and the dips. It is recommended to stabilize straight sections, if necessary, at least at every 100 meters. Proper stabilization of the suspended route enables transferring the forces from the moving suspended monorail unit in the longitudinal and transverse directions. This often takes place on inclined routes, when dynamic forces dominate. Emergency braking of a transport set, during which the actuating system of brakes is activated in

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the shortest possible time is an example. This causes deceleration affecting operator and moved personnel, but also dynamic overloads in connectors, slings and lashings stabilizing the route of the suspended monorail. These situations may lead to damage, such as: deformation of rails, loss of the route continuity (splitting rails at joints) or breaking the slings. In turn, the above-mentioned damage may cause an accident. The probability of hazardous situations and their possible effects increase with the increase in the travel speed of a suspended monorail. According to legal regulations in the Polish hard coal mines [20], the maximum acceptable speed of a suspended monorail during the personnel movement is 2 m/s. Due to the systematically increasing length of the routes to the newly opened mining fields, the time needed for miners to travel to the workplace is also longer. This reduces availability of the mining personnel at workplaces and shortens the effective working time. This happens due to depletion of deposits in close proximity to the shafts where coal is transported to the surface. This affects the financial results of companies in the mining industry. Shortening the travel time of personnel to the longwall panel, e.g. by increasing the acceptable speed of the suspended monorail is the solution. The benefits of shortening the travel time to the workplace are presented in [32]. Reducing the travel time to the longwall face by 15 minutes and by 30 minutes on the way back for each shift at the IMBAT MIOMNIG Co. Manisa coal mine in Eynez, Turkey, resulted in an increase in mining capacity by 1,606.95 tons per day as mentioned in that article. In the cited example, shortening of the time to reach the workplace was associated with the use of a belt conveyor adapted to personnel movement. Therefore, increasing the maximum acceptable speed of suspended monorails is justified from an economic point of view. However, apart from economic benefits, another extremely important aspect should be ensured – safety of the moved personnel. Introduction of legal changes enabling the increase of the acceptable speed must be preceded by development of the procedures for safe method of the monorail's travel. Analyzing the impact of emergency braking on operator and personnel overloads [3] and assessing the feasibility of introducing a two-stage emergency braking system[23] demonstrated the impact of increasing the speed limit on safety.

Development of guidelines for designing the monorail route on the sections that will be passed at higher speed is one of the preparation stages to increase permissible speed. This aspect is very important, because the wrong way of suspending the monorail route may result in exceeding the permissible load of the roadway roof support's arches, which in extreme cases may lead to roadway damage. Such situations are particularly dangerous during dynamic loads, e.g. during emergency braking from higher speed. The literature on the subject includes the work related to the tests on the load-bearing capacity of the yielding roof support [4], and also related to analysis of static and dynamic loads on the roadway roof support related to transport by suspended monorails [19]. The paper [18] presents the results of research work on impact of the suspended monorail speed on forces in the selected parts of the route. However, the project did not take into account the aspects related to the possibility of using different configurations of slings of the suspended monorail route, which, according to the authors, affects the forces loading the steel arches.

The authors defined the impact of the configuration of slings and lashings on the forces acting on the curves of the roof support's arches as the objective of the work presented in this article. The article presents the difference in the load to the roadway support in relation to seven variants of the configuration of slings and lashings of the suspended monorail route. The load to the route was created by simulating emergency braking from a speed of 5 m/s in a given part of the route. Depending on the configuration of the slings and stabilizing lashings, the suspended monorail route can move within a given range. During emergency braking, especially at higher speeds, the stopped train still moves forward together with the route causing acting the forces on the slings and roadway support, and the overloads affect the operator and the moved personnel. Finding the answer to the question: "How to arrange the slings and lashings of the suspended monorail route to minimize the load to the roadway roof support arches and the overload to the people in the monorail during emergency braking at higher speed (5 m/s)?" prompted the authors to conduct a series of tests, the results of which are presented. According to the authors, the results of the tests supplement the current state of knowledge on the impact of configuration of slings and lashings of the route on roadway support and at the same time are the basis for the development of guidelines on how to properly construct the route on the sections intended for high-speed suspension of the suspended monorail.

Development of guidelines and correct configuration of slings and lashings of the route is only one of the aspects ensuring the safety of mining personnel in the operator's and passenger cabins. Additional seat belts are the second aspect of the monorail safety improvement. Currently, both the monorail operator and passengers sitting in their seats do not have the possibility of using seat belts or other measures to protect them from being injured in emergency situations, such as emergency braking or a collision with a stationary obstacle on the track. The introduction of seat belts is one of the ideas of protecting the personnel in monorails travelling at higher speeds. This aspect was the subject of further research work of the authors. Its aim was to determine the HIC describing the probability of suffering a severe or fatal head injury. The operator's cabin was tested. The virtual HYBRID III dummy was used during these numerical simulations. HYBRID III dummies are specially designed for crash tests in the automotive industry [8]. These dummies were designed in such a way as to recreate behavior of the human body during traffic accidents [2]. For each part of the dummy (body part), appropriate masses, moments of inertia and the stiffness of connections between them were defined, which corresponded to the stiffness of the joints and the muscle tension. An example of the use of dummies in safety tests in the automotive industry is analysis of the impact of velocity on the risk of injury in relation to the driver and passenger of a passenger car, presented in [33]. Other example of the aforementioned analyzes are the analyzes presented in [17] concerning the impact of position of a person in a car on the risk of injury during a road accident. Another example of the use of dummies is analysis of the impact of car seat vibrations on the comfort of a child traveling in a car, which was presented in [30]. Along with the development of computer techniques and the development of numerical computational methods, a numerical dummy model was developed, which is used for virtual crash tests and simulations aimed at analyzing the safety of a driver and passengers in new automotive solutions.

Simulations with the use of HYBRID III dummies models were also carried out in relation to mining machines used in hard coal mines. The article [28] presents the structure and the method of defining the dummy model, as well as an example of a simulation in which the HYBRID III dummy model was used during the analyzes of the floor railway operator's cabin. As regards the use of suspended monorails, the HYBRID III dummy model was used to identify hazards and to assess their effects in the event of emergency braking from 2 m/s and 4 m/s in relation to passengers traveling in one of the types of passenger cabins [27]. This article presents the results of the simulation of an impact of a monorail traveling at a speed of 5 m/s against a stationary obstacle, with the operator wearing seat belts or without the seat belts. The objective of these research work was to demonstrate the necessity to introduce seat belts as the basic and necessary equipment for the operator's cabin of monorails traveling at a speed of 5 m/s. Due to the justified efforts to increase the permissible speed of the suspended monorail, it is necessary to ensure the safety and comfort of the personnel movement while transporting people. Safety in this aspect relates both to the safety of people as well as to the safety of machines, equipment and mining infrastructure.

Developing the guidelines which determine changes in legal regulations and allow the personnel movement at higher speed in a safe way, even in the event of an emergency is a responsible and difficult task. Results of the research work presented by the authors constitute recommendations on how to configure the slings and lashings of the route to minimize the roadway support load and overloads affecting people in the monorail in emergency situations. Ensuring these recommendations will contribute to the reliable and safe operation of suspended monorails, even at higher speeds. On the other hand, the introduction of additional components, such as seat belts, in dangerous situations, will allow to minimize injuries sustained by people traveling on the monorail, as indicated by the HIC parameter, calculated in the simulations.

2. Computational models of the suspended monorail and its route

Measurement of forces acting on the slings of suspended monorail route requires installation of dedicated sensors in the monitored slings. Both due to the cost and the capabilities of the measuring equipment, the number of sensors that record the forces acting on slings is limited. conditions in which suspended monorails are used are the additional difficulty during this type of research work. The greatest limitations related to tests in in-situ conditions include the fact that the measuring equipment must meet the requirements of the ATEX directive to be used in underground mine workings. Safety requirements are another aspect that limits in-situ testing. It is often difficult to find a sufficient amount of space for the installation of measuring equipment on transport routes in hard coal mines. When testing the monorails under the operating conditions, all legal restrictions related to the movement of suspended monorails, including the speed limits for these monorails, must be met. This means that it is formally impossible to carry out driving tests at a speed 5 m/s in real conditions. In addition, in accordance with the regulations governing the traffic of monorails in mining plants, each time when emergency braking trolley is activated, it is necessary to inspect it, which generates additional costs of tests in real conditions. Testing and measuring the forces in the selected slings on a real object is easier using a special test stand. Such a stand was built under the INESI project [5]. At the stand, while maintaining appropriate safety measures, meeting the regulations required in underground mine are not necessary, and the test equipment does not have to meet the stringent requirements related to the ATEX directive. The stand built for the project was used to test a new type of 4 m elongated and reinforced rails (Fig. 1). The stand also has dedicated sensors for recording the force acting on the slings of the route. On the test stand, emergency braking was tested at a speed of 5 m/s, during which the forces acting on the slings of the route were recorded. However, for economic reasons, it was not possible to modify the method of suspending the monorail route at the stand and recording the forces acting on the slings, using a different method of stabilizing the rails. According to the authors, the method of suspension and stabilization of the rails has an impact on the forces acting on the slings in the case of dynamic excitations, such as emergency braking. Taking into account the limitations, the authors decided to develop a computational model of the suspended monorail and its route, which corresponded to the configuration on the test stand.

Fig. 1. View of the reinforced rail and double sling coupler built on a route intended for high-speeds [5]

The model of suspended monorail consisted of an operator cabin, machinery part, two gear drives, passenger cabin and emergency braking trolley. The model of the monorail route consisted of 23 straight rails, each 4 m long. The rails were placed horizontally, and to suspend them, slings in the configuration from the test stand were used. The created computational model was validated. Emergency braking from a speed of 5 m/s with the boundary conditions consistent with those on the test stand, was simulated. Validation process consisted in comparing the results of the measurements from the test stand and those of numerical simulations, and then by fine-tuning the computational model. The following parameters were analyzed in the validation process:

- acceleration, recorded in the operator cabin and in the passenger cabin (the difference in the maximum acceleration calculated by numerical method and that recorded on the test stand was 6.6% on average),
- effective value of vibrations (RMS), recorded in the operator cabin and in the passenger cabin (the difference in the effective value recorded on the test stand and calculated by numerical simulations was on average 10%),
- forces acting on the selected slings of the monorail route (the difference in maximum force in the selected sling, calculated numerically in relation to values recorded on the test stand, was on average 9%).

The detailed method of validation of the computational model and the results are included in the following sources: acceleration acting on the operator [3]; forces in route suspensions [25]; RMS acceleration [5].

After validation of the suspended monorail model, to assess the impact of configuration of the slings and the route stabilizing lashings on forces transmitted through the slings to the roof support frame, the method of suspending the route in the model was modified by defining seven variants of the computational model. Configuration of the slings on the test stand was marked as variant 6. Each variant of the monorail route suspension differed in the arrangement of the slings located directly above the rail connections and the presence and location of side lashings. Tension of the side chains was adjusted with a turnbuckle. Another, more advanced solution is the use of a yielding lashings of a specific stiffness, their changes in length under the impact of dynamic loads, reduce the peaks of the force loading the sling and the roadway roof support. This solution is definitely more expensive. However, to analyze the impact of using such an element in the lashing in variants 3 and 5, an elastic-damping element with the characteristics corresponding to available industrial solutions was introduced to the side lashings. Each variant of the suspended monorail route model is characterized by the following features:

- Variant 1 – rails are suspended on straight slings, perpendicular to the monorail route. It is the easiest option to install and at the same time the cheapest because it requires the least amount of chain for slings. Difficulties occur with the irregular pitch of the roadway roof support. A section of the route in variant 1 is shown in Fig. 2.
- Variant 2 – this variant complements variant 1 with side lashings, added to the rail No. 2 (in the initial area of the route – braking will take place after the lashing). These lashings are inclined from the horizontal upwards by an angle of 10° and have constant length, Fig. 3. The purpose of this variant is to limit the possibility of the route moving along the monorail axis. At the same time, the forces acting on the lashings during emergency braking were recorded.
- Variant 3 – both the location of the route slings and the lashings were consistent with the

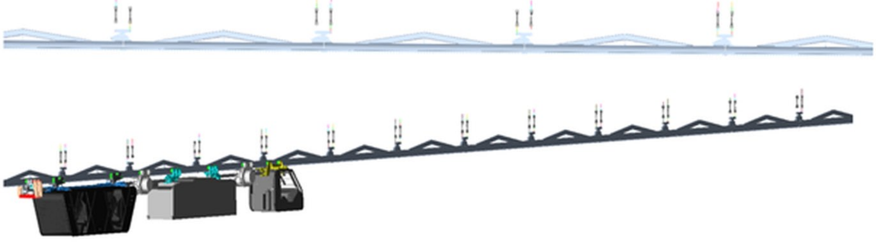


Fig. 2. A section of the suspended monorail route in variant 1, along with the suspended monorail model

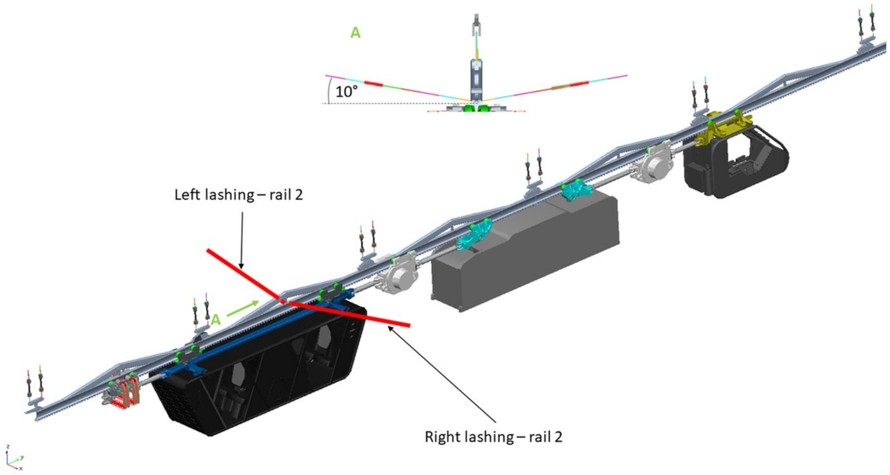


Fig. 3. Section of the suspended monorail route variant 2

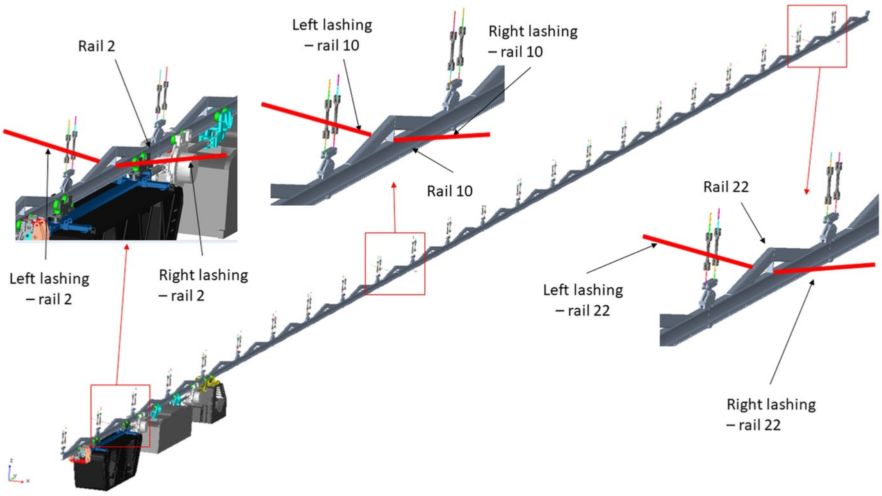


Fig. 4. Route stabilisation in the computational model for Variant 4

variant 2. The difference was the yielding of the lashings mounted on the rail 2 by introducing an elastic-damping element, enabling the lashings to be extended under the impact of external force. The modulus of elasticity in relation to the side lashings was 6.66 x 10^6 N/m. The purpose of this variant was to compare the forces and decelerations during emergency braking in relation to the configuration with fixed-length lashings (variant 2).

- Variant 4 – additional side lashings, installed on rails 10 and 22, were added to the calculation model of the suspended monorail route. The lashings were mounted in the same manner as in the previous variants (10° angle from the horizontal), Fig. 4. To identify differences in the load to the lashing located at the beginning of the route (rail No. 2), in the area of emergency braking (rail No. 10), and located at the end of the route (rail No. 22) additional slings were added. In addition, the changes in the nature of the route displacement were compared.
- Variant 5 – side lashings were modified (installed as in variant 4) by yielding. Spring elements were used with the same properties as in variant 3. The purpose of this variant was to compare the forces and decelerations during emergency braking in relation to the configuration with fixed-length lashings (variant 4). The results of this simulation may constitute an argument for the use of more expensive technical solutions in selected regions.
- Variant 6 – the computational model includes straight (perpendicular to the rails) and oblique slings placed alternately. Oblique slings were inclined at an angle of 45°; one in the direction of the monorail movement and the other in the opposite direction. This way of constructing the route was used on the test route in the INESI project [5], Fig. 5. This variant was used to validate the computational model of the suspended monorail.
- Variant 7 – all slings of the rails of the computational model are inclined at an angle of 45° in relation to the monorail route. In each pair of slings, one was deflected in the direction of the monorail movement and the other in the opposite direction, Fig. 6. The purpose of this variant is to compare the route displacement and the forces acting on the slings, in relation to the variants with side lashings.

The developed variants of the method of suspending the route of monorail enabled identifying the impact of method of suspending the route on load to the slings, and then further propagation of the load to the arches of the roadway roof support. Such analyzes are important regarding the possibility of increasing the accepted speed of suspended monorails. Situations when it is necessary to use emergency braking from higher speed seem to be dangerous. Then, sudden overloads (load peaks) may take place and that may lead to breaking of the slings and the loss of stability of roadway support. In an extreme case, in poor technical condition, roadway supports may be deformed, which leads to the destruction of the roadway and transport route [4, 18, 19]. Assessment of the impact of installation method of suspended monorail route will increase the safety of mine personnel and will enable specifying the guidelines for the route installation on the sections with increased accepted speed.

3. Numerical simulations

As part of the research work, the MultiBody System (MBS) simulation method was used in numerical simulations related to the dynamics of the presented model. In this method, on the basis of defined geometric constraints and defined excitations, the kinematic and dynamic quantities during the analyzed system operation, in the discussed case constituting the suspended monorail assembly with its route, were calculated. In dynamic simulations, the initial conditions in the form of known positions and velocities of all bodies, as well as information about the time processes of forces acting on the bodies, are the input data. Determination of motion of the MBS under the impact

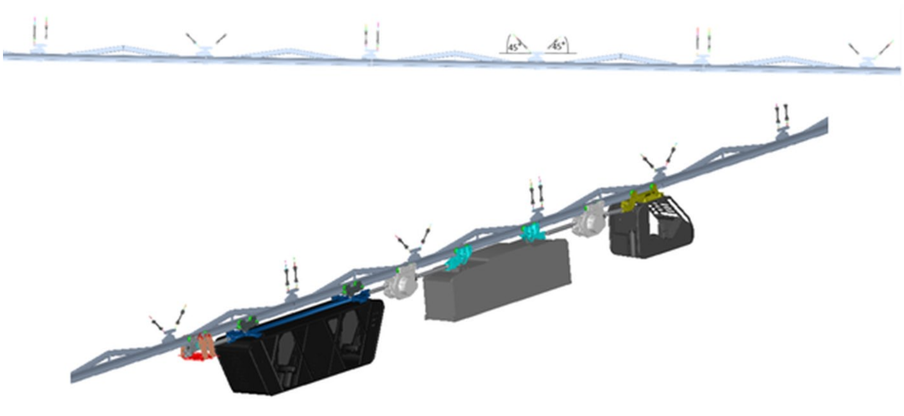


Fig. 5. View of the suspended route in variant 6

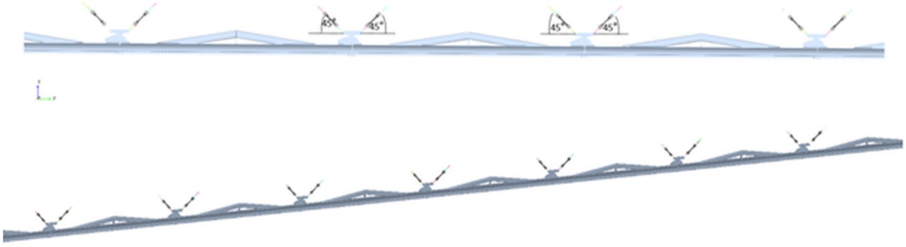


Fig. 6. Route suspensions in the computational model in Variant 7

of the forces applied to it as well as the reaction forces, in particular geometric constraints, is the result of solving the dynamics problems. From a mathematical point of view, to solve the problem of dynamics, solving the system of differential-algebraic equations is needed. In the software environment (MSC.ADAMS), the system of equations of motion of a mechanical system is formulated based on the Euler - Lagrange's equation (1) [26, 31]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)-\frac{\partial L}{\partial q}+\Phi_q^T\lambda=Q \qquad (1)$$

where:

- L – Lagrange function (2), i.e. the difference between the kinetic energy T and the potential energy V of the system:

$$L = T - V \qquad (2)$$

- λ – vector of Lagrange multipliers,
- Q – vector of generalized forces acting on MBS (3):

$$Q = Q(q,\dot{q},t) \qquad (3)$$

- Φ – vector of left sides of constraints equations (after elimination of redundant constraints) (4):

$$\Phi(\mathrm{q},\mathrm{t})=\begin{bmatrix}\Phi^K(q)\\ \Phi^D(q,t)\end{bmatrix}=0_{Nx1} \qquad (4)$$

- q – vector of generalized coordinates,
- K – number of kinematic pairs in the system,
- D – number of guiding constraints.

The solution of the formulated system of equations results in the calculation of positions, velocities, accelerations of each solid, as well as forces and moments acting in the computational model. In the numerical simulations, a computational model was used, which had previously been validated.

The simulation was the same for all variants. Emergency braking was from a speed of 5 m/s. In each variant of the route suspension, the suspended monorail was accelerated to speed of 5 m/s. Then, for approx. 1 s, the speed was constant, then emergency braking started due to the activation of two pairs of jaws in the brake trolley. An example of the monorail speed chart is shown in Fig. 7.

Until the commencement of emergency braking, the speed of the monorail was the same in all simulations. Depending on the suspension method, the route could move along the axis in the direction of the monorail movement. As a result of these movements, the curve in the speed diagram may oscillate depending on the route suspension variant.

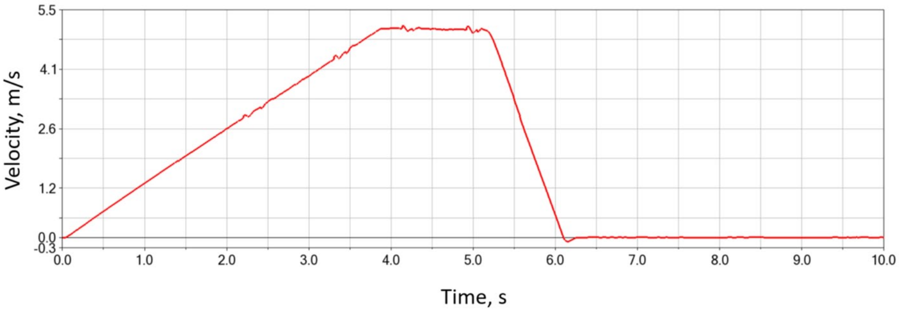


Fig. 7. The course of travel speed of suspended monorail unit in the MBS simulation

4. Results of numerical simulations

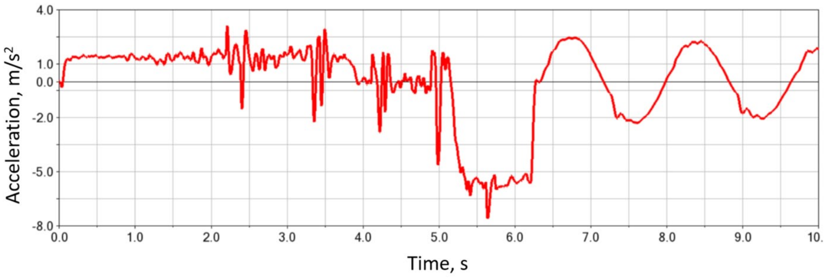
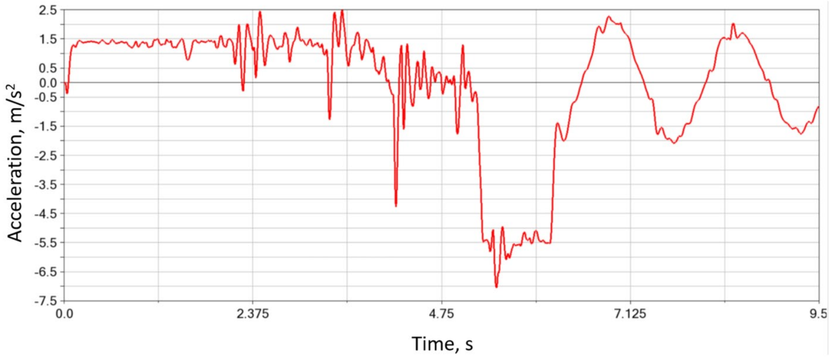
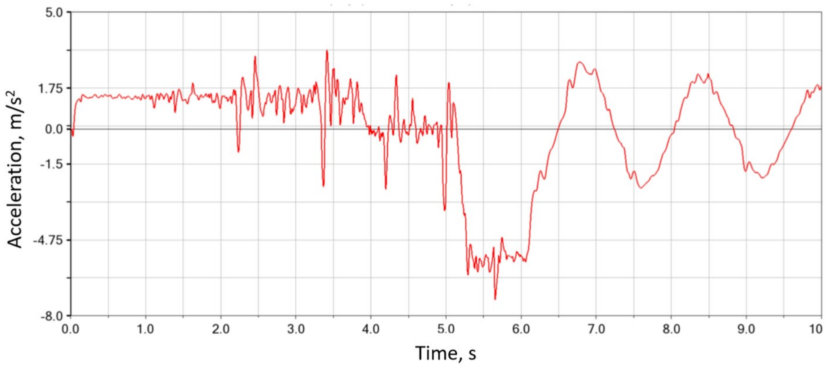
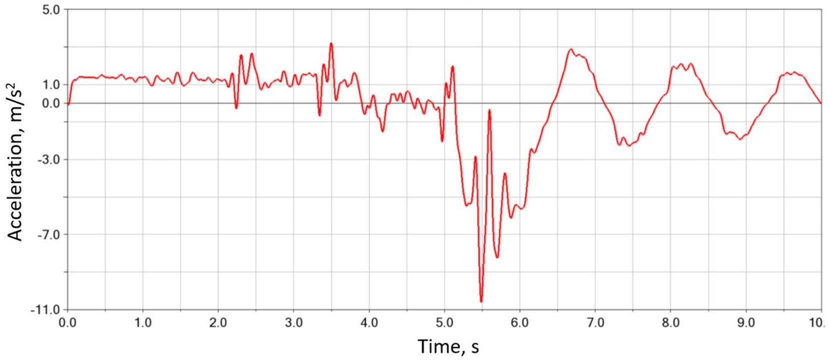
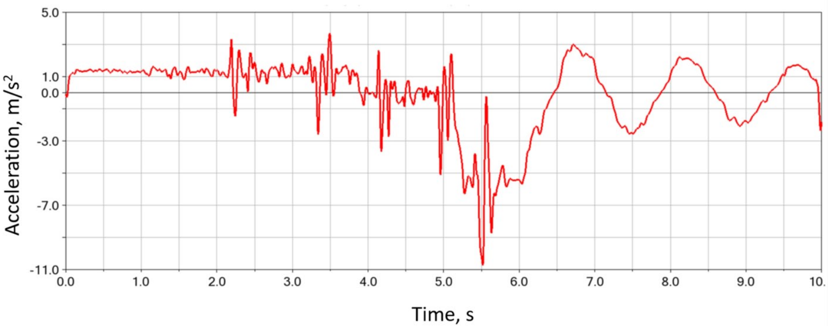
In a result of the simulations, time processes of various quantities and parameters were obtained.

This article provides the following results:

1. Curve of acceleration of the transport unit during travel and emergency braking.
2. Forces in the slings of the route.
3. Displacement of rails.

Ad. 1) acceleration of the transport unit during travel and emergency braking.

Acceleration and in particular the deceleration, affects other parameters, i.e. the forces in the route suspensions and the route displacements. The greatest changes in the acceleration of the transport set may occur in a situation other than typical operating conditions, e.g. impact loading due to rockfall, hitting an obstacle or (most often) during emergency braking. In the case of dangerous situation emergency braking starts [14]. Although, according to Annex 4 to the Regulation [20], the deceleration cannot exceed 10 m/s^2, emergency operation of the braking system results in dynamic overloads, affecting both the suspended route, the frame of roadway support, and most of all everything on the operator and passengers of the suspended

Variant	Acceleration
1.	
2.	
3.	
4.	
5.	

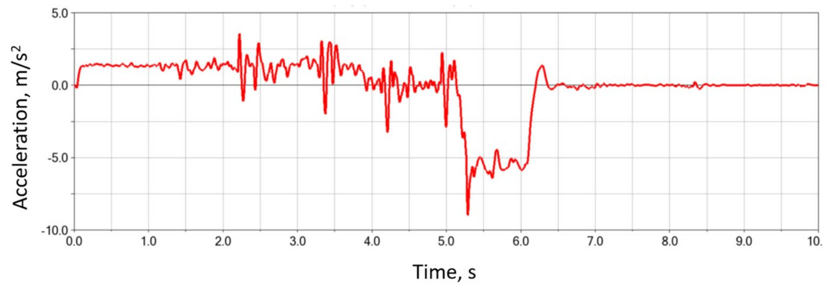
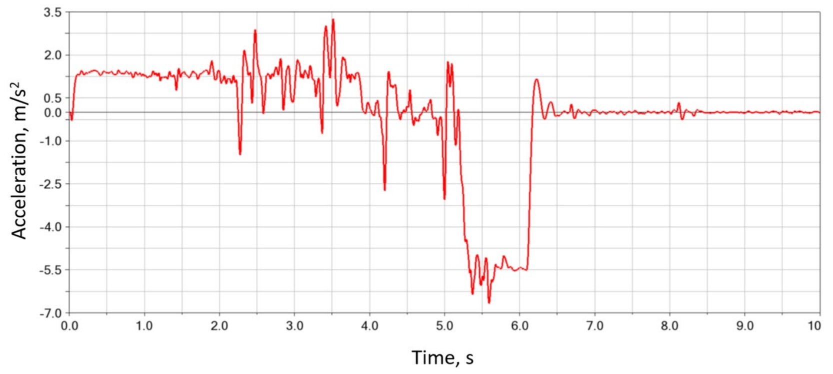
6.	
7.	

Fig. 8. Acceleration curves for each variant

monorail. Fig. 8 shows the acceleration curves of the transport set in each simulation variant. Maximum and minimum accelerations for each of the analysed variants are shown in Fig. 9.

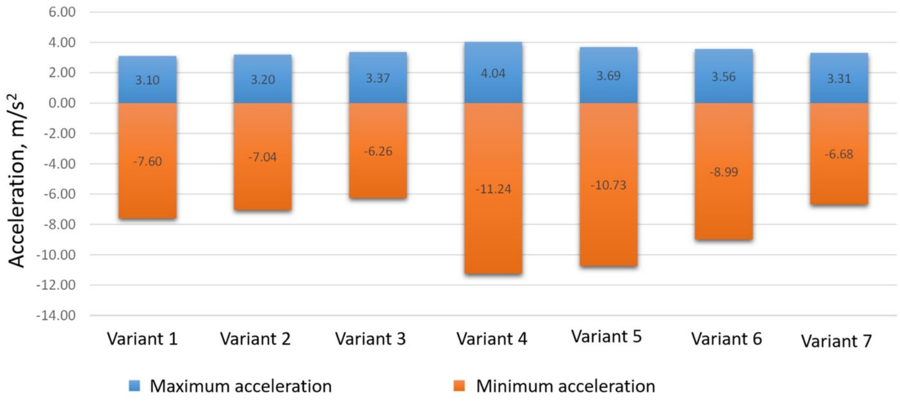


Fig. 9. Maximum and minimum accelerations for each of the analysed variants

The highest deceleration acting on the monorail operator during emergency braking was recorded for variants 4 and 5 – the variants in which 3 side lashings stabilizing the route were defined. On the other hand, the smallest decelerations affecting the operator during emergency braking were recorded for variants 2 and 3, in which one side lashing was used at the beginning of the route. Higher values were recorded in variant 7, in which all the slings were inclined, due to the fact that after braking the route moves further in the direction of monorail movement. The route was stabilized by 3 side lashings In variants 4 and 5. This eliminated the possibility of further movement of the route, what increased deceleration during emergency braking. It is worth mentioning that deceleration in these variants exceed the acceptable values regulated by law in the Polish mines. It is because the way of route installation is not proper on those route sections where a higher speed is allowed. On the other hand, in the case of variants 2 and 3, during emergency braking, the route was stabilized with one lashing, and in variant 7, with oblique slings. Such stabilization limited the effect of lifting the entire transport route upwards, as in variant 1.

As a result, the decelerations acting on the operator were minimized. Comparing variants 2 and 3, yielding of the side lashings resulted in a reduction of deceleration by approx. 11%. On the other hand, in the case of variants with three lashings (variants 4 and 5), the addition of side lashings resulted in a reduction of the deceleration affecting the operator by about 4.5%. Comparing variant 3 (with one flexible side lashing) and variant 7 (all oblique slings), the deceleration affecting the operator is about 6% higher in variant 7. However, the advantage of variant 7 is the faster stabilization of the route oscillation after emergency braking. In the case of variant 3, after stopping the monorail, transport route forward and backward movement was observed, due to changes in acceleration from positive to negative. In the case of variant 7, oscillation of the route stops with the braking. To sum up, due to minimization of acceleration acting on the suspended monorail operator during emergency braking, the most successful route was the route with straight slings and one side lashing (variant 3) and the route where all slings were installed obliquely (variant 7).

Ad. 2) Forces in route slings

Forces in each sling were another parameter recorded during the simulation. Forces in relation to slings No. 11 – 22 are presented. The slings refer to location of transport set after it stopped (they are located above the transport set). Number of each sling, depending on variant, is shown in Fig. 10 - Fig. 12.

The maximum resultant forces acting on the slings are presented in Table 1. The areas marked in green mean the slings with maximum force at a low level, in most cases not exceeding 10 kN. Yellow and orange colours represent the average range of slings loads. The slings loaded with a force in the range of 10 kN – 30 kN are in this group. It is a load greater than in the group marked in green, however, it is accepted and does not cause any dangerous situations. The areas marked in red indicate slings loaded with a force of more than 30 kN. These are the most loaded slings and special attention should be paid to them, because in these situations the accepted values may be exceeded.

Due to the stopping point of transport set, a lower load to slings numbers 19-22 was observed. The highest forces acting on the slings were recorded for pairs of slings marked as cz13 and cz14 as well as cz15 and cz16 in all variants. This results from the place, where the monorail stops during emergency braking. The heaviest component of the set (the machinery part) is on the rail located between the slings cz15 and cz18. Direction of the monorail travel determines the direction and sense of inertia force, which loads mainly slings cz15 and cz16. The highest force acting on the sling was recorded for the variant 6 in the sling cz15. Such a large value results from fact that the load from the mass of the machine, i.e. inertia force of this monorail component, and the weight of the travel route, accumulated on this sling. This unfavorable phenomenon takes place when the transport route moves forward or backward at such arrangement of the slings, and this happens during emergency braking. In such a situation, one (front) sling is partially relieved, while the other „takes" part of the first load and the function of route stabilization. In variant 6, accumulation of these loads results in exceeding the maximum accepted forces loading each sling. A similar situation takes place in variant 7, in which 400 N is below the maximum accepted force. When analyzing the force recorded in the most loaded sling, it can be observed that the introduction of one side lashing (variant 2) decreased the force in the sling cz15 by approx. 5% compared to the variant with all straight slings (variant 1). On the other hand, the introduction of 3 side lashings (variant 4) resulted in a reduction of force in the most loaded sling by approx. 16.8%, in relation to the variant without lashings (variant 1). In turn, yielding the side lashings resulted in a reduction of forces in the most loaded sling by approx. 27.5%, comparing variants 1 and 3, and about 12.8% comparing variant 1 and 5. Analyzing the recorded forces in variant 6 and 7, a significant disproportions in force between adjacent slings forming the letter "V" inclined in opposite directions can be observed. This disproportion may reach even approx. 40% as in the variant 7 and slings cz15 and cz16.

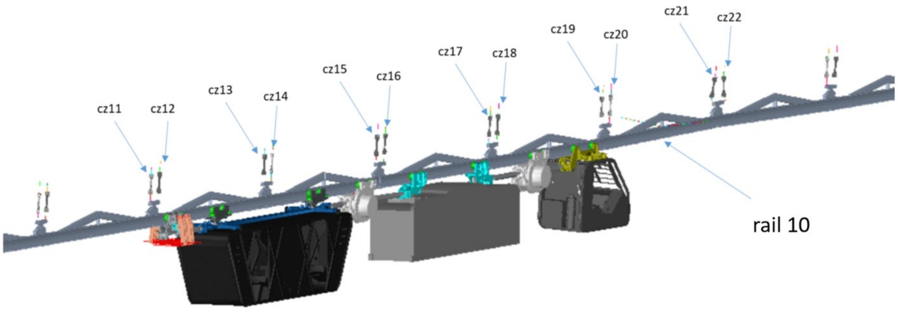


Fig. 10. Numbers of slings in variants 1 – 5

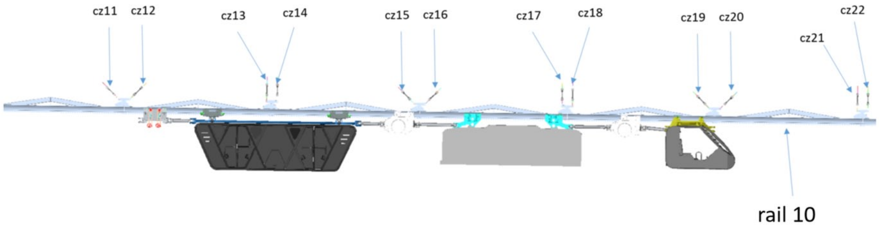


Fig. 11. Numbers of slings in variant 6

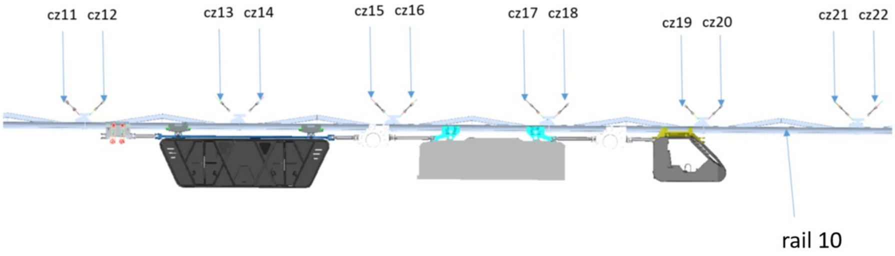


Fig. 12. Numbers of slings in variant 7

In variants 2, 3, 4 and 5 there were side lashings stabilizing the monorail route. Fig. 13 - Fig. 15 show the maximum force vector components recorded in the stabilization lashings during the emergency braking.

The force components are in the following directions:

- OY - in line with the direction of the monorail movement,

Table. 1. Maximum resultant forces in slings 11-22

Variant number	Maximum resultant force											
	cz11, N	cz12, N	cz13, N	cz14, N	cz15, N	cz16, N	cz17, N	cz18, N	cz19, N	cz20, N	cz21, N	cz22, N
1.	22052	25741	25015	23675	31789	24582	21596	18553	7384	6079	1619	1069
2.	22227	24496	25312	24801	30205	23031	17607	18622	7164	6816	1555	1377
3.	24519	24156	23947	23188	23055	19035	16939	18035	6306	5980	1474	1050
4.	19222	20777	19905	19830	26445	21541	16879	17728	6778	8171	5339	2648
5.	21733	23721	25812	25048	27732	27118	16996	18059	5784	6122	2031	4346
6.	23998	34444	23496	23471	47472	29085	17363	17316	11932	9786	1028	1014
7.	28042	26823	29308	26103	39600	24043	27935	26671	9744	8837	1839	1471

- OZ - vertical, perpendicular to the axis of the monorail route,
- OX - horizontal, perpendicular to the axis of the monorail route.

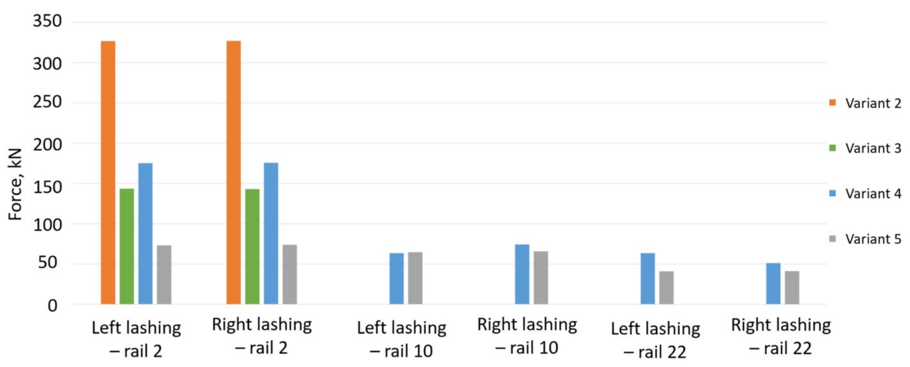


Fig. 13. Component Y of the force in lashings stabilizing the route

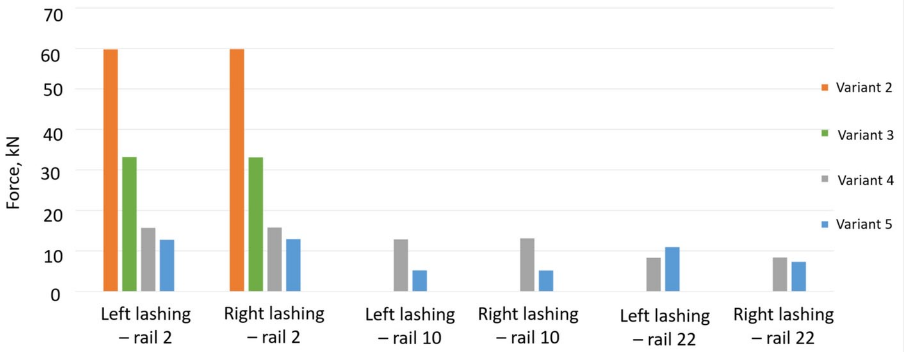


Fig. 14. Component Z of the force in lashings stabilizing the route

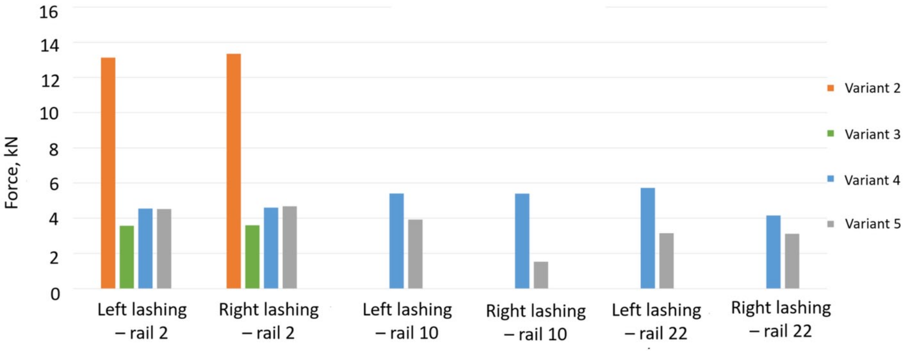


Fig. 15. Component X of the force in lashings stabilizing the route

The highest values occur in the components of the forces whose direction is consistent with the direction of movement of the transport unit. Increasing the number of lashings from 1 (variant 2) to 3 (variant 4) reduces the maximum force by approx. 46.3% in relation to the Y axis, by approx. 73.7% in the vertical axis (Z axis) and by approx. 3 % in the X axis. In addition, the introduction of yielding slings decreased the maximum forces in relation to the configuration with one sling by approx. 56% in the Y axis (in line with the direction of travel), by approx. 45% in the vertical axis (Z axis) and by approx. 73% in the X axis. In relation to the configuration with three side lashings, their yielding resulted in a reduction of the maximum forces in these lashings by approx. 46% in the Y axis, by approx. 20% in the vertical axis (Z axis) and by approx. 60% in the X axis. Therefore, it can be concluded that yielding the side lashings is an effective way to reduce the force in them. This conclusion justifies the purchase of more expensive components used in yielding lashings, especially in the sensitive places, where the roadway roof support is in a worse technical condition or in the strategic points along the suspended monorail route. The recorded results show that along with introduction of three side lashings, "tearing up" of the rail No. 10 was minimized. This is evidenced by a significant reduction in force in these lashings in the Z axis (vertical axis). The forces acting in the "X" direction have the smallest share in load to the stabilizing lashings, because the computational model covered only the straight section of the route where there were no external forces acting in this direction. The forces recorded in this axis resulted mainly from the deviation of the side lashings by an angle of 10 degrees from the horizon. Minimizing the force in the slings, which are transferred to the roadway roof support during emergency braking from speed of 5 m/s is most effective in variant 3 or variant 5. While analysing the forces in the side lashings, special attention should be paid to the large values of forces recorded in the lashings in axis of the railway movement (Y axis).

The presented forces suggest that during emergency braking from a speed of 5 m/s, the accepted loads to the roadway roof support may be exceeded. An improvement was observed in configurations with added side lashings and with the yielding of these lashings. A comprehensive solution to this problem may be designing the proper installation of the side lashings, the task of which will be to distribute dynamic loads to several adjacent roof support frames. In this way, the lashings will stabilize the monorail route and at the same time the accepted load to each roadway support arch is not exceeded.

Ad. 3) The rail further movement

In Table 2 further movement of the rail 1 and 10, in line with OY, OZ and OX directions is given.

The colours given in the table show that the greatest further movements were in Y direction, i.e. in line with the travel of the transport unit (red and orange).

Further movements in the Z direction, i.e. vertical (orange and green) were smaller and negligible ones were in the X direction (horizontal, perpendicular to the route axis). The largest further movements were in the route arranged according to variant 1 (without stabilization) and the maximum values mean a very large swing of the route, which in real conditions would not be acceptable (fields marked in red in Table 3). The introduction of one, yielding lashing reduces this value by approx. 50%, and the next two by approx. 60%. Further movements of approx. 180 mm during emergency braking do not pose any threats to the crew and passengers and at the same time they reduce the maximum force in the stabilizing lashings.

5. Analysis of the results

The cabin hitting a stationary obstacle was simulated as a part of the assessment of operator safetyin the case of an emergency braking when driving at a speed of 5 m/s. During the simulation,the Articulated Total Body (ATB) of Hybrid III dummy model was used, corresponding to a 50 percentile male.

Based on the numerical simulation, the maximum value of the Head Injury Criterion (HIC) during the collision of the cabin with

Table. 2. Maximum further movement of the route (rails No 1 and 10) in each variant of the route suspension

Variant	Maximum further movement rail 1			Maximum further movement rail 10		
	in Y axis, m	in Z axis, m	In X axis, m	In Y axis, m	In Z axis, m	In X axis, m
1.	0.365	0.132	0.005	0.365	0.132	0.001
2.	0.133	0.084	0.001	0.129	0.017	0.001
3.	0.188	0.078	0.001	0.184	0.03	0.001
4.	0.111	0.079	0.001	0.104	0.107	0.0002
5.	0.157	0.075	0.002	0.15	0.114	0.0003
6.	0.009	0.002	0.004	0.009	0.002	0.001
7.	0.005	0.001	0.002	0.005	0.001	0.002

an obstacle was determined. This is one of the injury criteria that has been established on the basis of biomechanical responses from experimental tests [7]. The HIC parameter is a function of the time and deceleration during head collision with an obstacle (5). The HIC is expressed by the following formula [11]:

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t) dt \right]^{2,5} (t_2 - t_1) \tag{5}$$

where:

- a – liner acceleration (deceleration) of head centre of gravity, in g,
- t_1, t_2 – time of starting/ending the contact of head with an obstacle or time interval expressed in sec., at which HIC is maximal (dimensionless parameter).

Exceeding the value of 1000 of HIC means significant increase in the probability of a serious head injury [10, 15, 16]. In relation to the analysed case, two simulations were carried out - the first one, in which the operator sits freely in the operator cabin and has the ability to move around; in the second,the operator is additionally secured with four-point seat belts. Fig. 16 shows the operator initial position, which was the same in both simulations. Then the operator positions are shown after collision withan obstacle comparing the variant with fastened seat belts and without seat belts. The position ofthe operator is shown in 0.15 s and in 0.21 s of simulation.

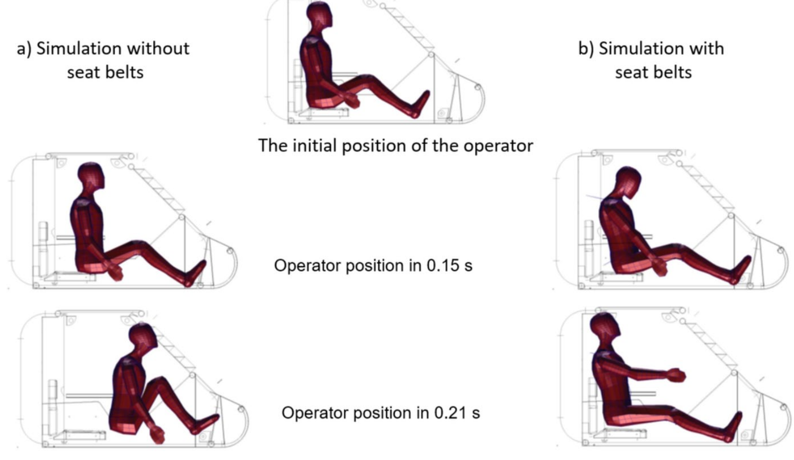


Fig. 16. Position of Hybrid III dummy during collision with the obstacle at speed equal to 5 m/s: (a) simulation without safety belts, (b) simulation with the safety belts

Fig. 17 shows the HIC parameter during the simulation of the vehicle hitting an obstacle whenthe operator does not have seat belts. The value reaches 1200, what means that there is a very high probability of serious or fatal head injury in the result of hitting the head on the cabin front.

Fig. 18 shows the HIC parameters in relation to simulation of the operator cabin collision in a situation with the seat belts fastened. In this case, the maximum HIC parameter is about 350, what means a low probability of suffering severe or fatal head injuries.

For interpretation of the above diagrams, the Abbreviated Injury Scale (AIS) for adults is used. In this way, it is possible to detail the HIC parameter impact on the damage level [16]. For example, when this parameter is equal to 1000, it means the following:

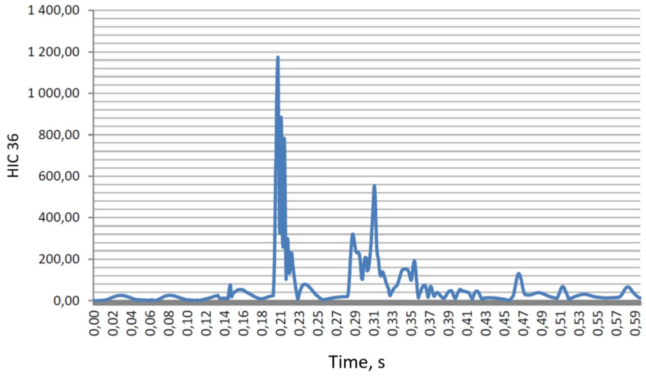


Fig. 17. The HIC parameter when simulating an impact with an obstacle at a speed of 5 m/s while traveling without seat belts

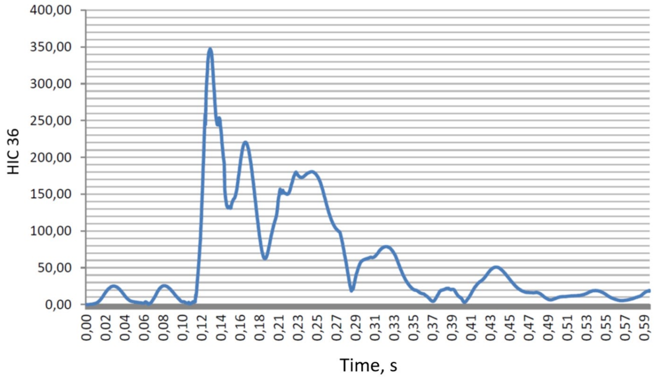


Fig. 18. The HIC parameter when simulating an impact with an obstacle at a speed of 5 m/s while traveling with the seat belts

- 18% probability of heavy head injury (AIS4),
- 55% probability of medium head injury (AIS3),
- 90% probability of light head injury (AIS2).

It is assumed that hitting the head on a non-deformable surface with a speed of at least 4 m / s may cause severe brain injuries TBI (Traumatic Brain Injury).

6. Conclusions

MBS simulation, along with the analysis of the results, enables the identification and selectionof the method of suspending and stabilization of the monorail railway route. The simulations allowfor the identification of adverse phenomena that may occur in emergency situations, such as emergency braking from higher speeds. The unfavourable phenomena include excessive further displacement ofthe route, observed in variant 1. Excessive stiffening of the route (variants 6 and 7) is also not favourable, due to generation of high forces in the lashings of the route, which may result in exceedingthe acceptable load to a single roadway roof support frame. Use of the yielding componentsin the lashings enables the minimization of the forces loading the roof support frame, which is especially important in the case of emergency. Regarding the suspension options analysed in the article, variants3 and 7 are the most advantageous regarding minimizing the overloads acting on the operator,and variants 3 and 5 regarding minimizing the forces in the slings. In turn, the smallest forces in the side lashings were recorded in variants 4 and 5. As it results from the analyses presented in the article, there is no one universal and best configuration of the suspensions of the suspended monorail route, whichin the situation of dynamic excitations would allow for the maximum minimization of all effects of this extortion. Therefore, numerical simulations should be a normal practice used by designers of transport routes in the production preparation departments of the mining plants, especially in the case of routes intended for high-speed suspension railway, used for the personnel movement. An additional advantage of using this type of simulation at the route designing stage is the possibility of checking and testing many variants of the configuration of slings and lashings proposed by the designers. Another conclusion from the analyses of forces in the side lashings is the need to use components that allow the distribution of forces resulting from dynamic forces into several adjacent roof support arches. This is a valuable information for designers of road transport at higher speed.

Simulations with the ATB, as well as the analyses of the results, indicate that the operator cabin should be equipped with additional passive safety elements, e.g. seat belts or headrests. These elements will protect the operator against severe and even fatal injuries in an emergency. The proposed additional equipment of the operator cabin significantly reduces the HIC coefficient, which should be interpretedas minimizing the likelihood of serious head injuries. Use of special numerical simulations enables both the quantitative and qualitative assessment of the impact of changed driving speed on the operator safety. Inability of this type of tests in real conditions, due to the existing regulations and ensuringthe safety of the railway operator is an another argument.

Numerical analyses enable, in a safe and effective way, analysing the level of safety and comparing various scenarios of emergency situations that may happen during operation of the suspended monorail. The analyses of forces in the slings, the decelerations affecting people traveling by the monorailand the route displacements indicate that movement of passengers by the suspended monorailat a speed of 5 m/s, is possible without reducing the level of safety under condition of ensuringthe proper design and stabilization of the suspended route as well as introduction of additional equipment (passive safety) in the transport unit. The designer should select the configuration of the slings, so that the route does not move excessively during emergencies. At the same time, care should be taken not to over stiffen the route, which will result in a significant increase in loads transferred to the frame of the roadway roof support.

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References

1. Becker F, Zell M. The state of the art in positively guided rail transport systems for underground mining. Mining Report 2014; 105(1/2): 34 – 46, https://doi.org/10.1002/mire.201400002.
2. Danelson K A, Golman A, Kemper A, Gayzik F. Finite element comparison of human and Hybrid III responses in a frontal impact. Accident Analysis and Prevention 2015, 85: 125-156, https://doi.org/10.1016/j.aap.2015.09.010.
3. Herbuś K, Szewerda K, Świder J. Virtual prototyping of the suspended monorail in the aspect of increasing the permissible travel speed in hard coal mines. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2020; 4, 610-619, http://dx.doi.org/10.17531/ein.2020.4.4.
4. Horyl P, Šňupárek R, Maršálek P, Poruba Z, Pacześniowski K. Parametric Studies of Total Load-Bearing Capacity of Steel Arch Supports. Acta Montanistica Slovaca 2019; 24(3): 213-222.
5. INESI (RFCS) – Increase Efficiency and Safety Improvement in Underground Mining Transportation Routes (Zwiększenie efektywności i poprawa bezpieczeństwa w podziemnych, górniczych drogach transportowych). Contract No. 754169. Okres realizacji: 2017 – 2020.
6. Jagoda J, Hetmańczyk M, Stankiewicz K. Dispersed, self-organizing sensory networks supporting the technological processes. Mining Machines 2021, 2: 13-23, https://doi.org/10.32056/KOMAG2021.2.2.
7. Krzystała E, Kciuk S, Mężyk A. Identyfikacja zagrożeń załogi pojazdów specjalnych podczas wybuchu. Wydawnictwo Naukowe Instytutu Technologii Eksploatacji – Państwowy Instytut Badawczy. Radom 2012, ISBN 978-83-7789-161-2.
8. Lai X, Wang Y, Zhou Q, Lin Z, Culiere P. Development of a finite element pam-crash model of hybrid iii anthropomorphic test device with high fidelity. International Technical Conference on the Enhanced Safety of Vehicles (ESV). Washington:2011: 11-0031.
9. Lutyński A. KOMAG activities in the domestic and international research areas. Mining Machines 2021; 4: 47-60, https://doi.org/10.32056/KOMAG2021.4.5.
10. Mackay M. The increasing importance of the biomechanics of impact trauma. Sadhana 2007; 32(4): 397-408.
11. National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation (DOT). Occupant Crash Protection – Head Injury Criterion. S6.2 of MVSS 571.208, Docket 69-7, Notice 17. NHTSA, Washington, DC, 1972.
12. Pieczora E, Suffner H. Rozwój napędów dołowych kolejek podwieszonych. Maszyny Górnicze 2017; 3: 44-57.
13. Pieczora E, Tokarczyk J. Development of mine underground transportation with use of suspended monorails. Mining-informatics automation and electrical Engineering 2017; 4(532): 96-117, http://dx.doi.org/10.7494/miag.2017.4.532.96.
14. PN-EN ISO 13850:2016-03 Bezpieczeństwo maszyn – Funkcja zatrzymania awaryjnego – Zasady projektowania.
15. Post A, Hoshizaki T B, Glichrist M D, Brien S, Cusimano M, Marshall S. The dynamic response characteristics of traumatic brain injury. Accident Analysis and Prevention 2015; 79: 33-40, https://doi.org/10.1016/j.aap.2015.03.017.
16. Prasad P, Mertz H J. The Position of the United States Delegation to the ISO working group 6 on the use of HIC in the Automotive Environment. Conference: SAE Government Industry Meeting and ExpositionSAE Government Industry Meeting and Exposition 1985; https://doi.org/10.4271/851246.
17. Prochowski L, Żuchowski A. Analysis of the influence of passenger position in a car on a risk of injuries during a car accident. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2014; 16 (3): 360–366.
18. Pytkik A, Rotkegel M, Szot Ł. Badanie wpływu prędkości kolejek podwieszonych na siły w wybranych elementach trasy. Przegląd górniczy 2016; 11: 30-37.
19. Pytlik A. Tests of steel arch and rock bolt support resistance to static and dynamic loading induced by suspended monorail transportation.

Studia Geotechnica et Mechanica 2019; 41(2): 81–92, https://doi.org/10.2478/sgem-2019-0009.

20. Rozporządzenie Ministra Energii z dnia 23 listopada 2016 r. w sprawie szczegółowych wymagań dotyczących prowadzenia ruchu podziemnych zakładów górniczych (Dz.U. z 2017r. poz. 1118 z późn. zm).
21. Song ZA, Jiang F. Hydraulic system elaboration and simulation for single-drive light-load monorail locomotive in fully mechanized coal mining applications. IOP Conf. Series: Materials Science and Engineering 2019; 474, http://dx.doi.org/10.1088/1757-899X/474/1/012006.
22. Stankiewicz K. Mechatronic systems developed at the KOMAG. Mining Machines 2020(162); 2: 58 -68, https://doi.org/10.32056/KOMAG2020.2.6.
23. Świder J, Szewerda K, Herbuś K, Jura J. Testing the Impact of Braking Algorithm Parameters on Acceleration and Braking Distance for a Suspended Monorail with regard to Acceptable Travel Speed in Hard Coal Mines. Energies 2021; 14, 7275 https://doi.org/10.3390/en14217275
24. Szewerda K, Tokarczyk J, Bożek P, Michalak D, Drwięga A. Vibrations diagnostics and analysis in operator's and passenger cabins of a suspended monorail. Acta Montanistica Slovaca 2020; 2: 150-158, https://doi.org/10.46544/AMS.v25i2.2.
25. Szewerda K, Tokarczyk J, Wieczorek A. Impact of Increased Travel Speed of a Transportation Set on the Dynamic Parameters of a Mine Suspended Monorail. Energies 2021; 14(6), https://doi.org/10.3390/en14061528.
26. Teixeira R R, Moreira S R D S, Tavares S M O. Multibody dynamics simulation of an electric bus. Procedia Engineering 2015; 114: 470 – 477, https://doi.org/10.1016/j.proeng.2015.08.094.
27. Tokarczyk J. Method for identification of results of dynamic overloads in assessment of safety use of the mine auxiliary transportation system. Archives of Mining Sciences 2016; 61(4): 765-777.
28. Tokarczyk J. Method for virtual prototyping of cabins of mining machines operators. Archives of Mining Sciences 2015; 60 (1): 329-340.
29. Tokarczyk J. Metodyka identyfikacji wybranych zagrożeń mechanicznych w pomocniczym transporcie podziemnych zakładów górniczych. Prace Naukowe – Monografie KOMAG, Monografia nr 52 2017; Instytut Techniki Górniczej KOMAG Gliwice.
30. Wicher J, Więckowski D. Influence of vibrations of the child seat on the comfort of child's ride in a car. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2010; 4 (48): 102–110.
31. Wojtyra M, Frączek J. Metoda układów wieloczłonowych w dynamice mechanizmów. Oficyna Wydawnicza Politechniki Warszawskiej 2007; Warszawa.
32. Yýlmaz AI, Büyükyýldýz G, Ekici A, Çalýk M, Önder Ö, Aksoy CO. Staff transportation two way on the belt conveyor. Acta Montanistica Slovaca 2013; 18: 141-150.
33. Żuchowski A. Analysis of the influence of the impact speed on the risk of injury of the driver and front passenger of a passenger car. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2016; 18 (3): 436–444, http://dx.doi.org/10.17531/ein.2016.3.16.