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Systems and tracks of self-powered suspended monorails for transportation of people in horizontal workings and workings with inclination up to 45°

The article presents the number of transport systems and the length of the routes on which people are transported in Polish mines. A legal status in Poland and China and the guidance of the Regional Office of Arnsberg in Germany were presented. The actual speed as a function of time recorded during exploitation of the suspended monorail in the mining conditions is shown. A technical potential maximum velocity of the suspended drivetrains is identified. Extended criterial model for assessment of effects of overloads to operators and transported team as well as algorithm for identification of effects of dynamic overloads are presented. Example of simulation result, i.e. behaviour of virtual model of Hybrid III dummy during its transportation in a cabin on a curve, is given.

key words: *underground mining, suspended monorail, virtual prototyping, FEM*

1. THE USAGE OF SYSTEMS AND TRACKS OF SELF-POWERED SUSPENDED MONORAILS FOR TRANSPORTATION OF PEOPLE IN POLISH MINES

The analysis of the transportation track length and the number of self-powered suspended monorails in horizontal workings and workings with inclination of up to 450 was conducted in the period from 2000 to 2012, with reference to the total length of transportation tracks and the number of active mines in service (Fig. 1, Table 1) [1,2].

The analysis (Table 1, Figure 1) indicates that, with the closing of mines, the total length of tracks decreased, while the length of self-powered suspended monorail tracks is increasing regardless of the decreasing number of active mines still in service.

The total length of tracks decreased from 2,217 km in 2000 to 1,753 km in 2012, i.e. by approximately 21%. Within the same period, the number of active mines decreased from 42 to 31, i.e. by approximately 24%. On the other hand, the length of transportation tracks of self-powered suspended monorails was systematically extended from 152 km in 2000 to 826 km in 2012, i.e. approximately 5.5 times. The average track length of self-powered suspended monorails per one mine increased from 3.6 km in 2000 to 26.6 km in 2012, i.e. approximately 7.4 times. The number of self-powered suspended monorails rose from 211 in 2007 to 471 in 2012, i.e. approximately 2.2 times.

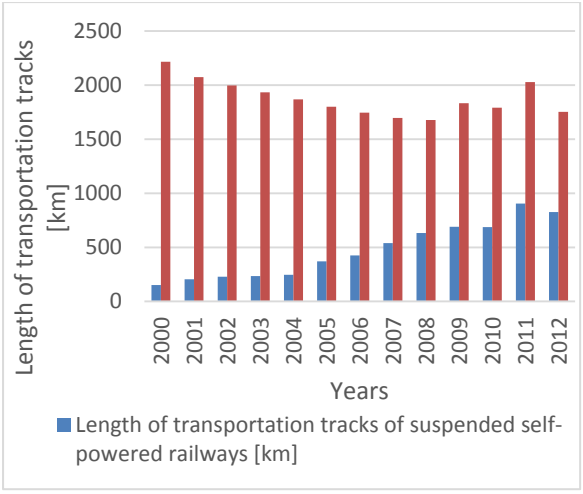

Fig. 1. The length of transportation tracks of suspended monorails in horizontal workings and workings with inclination of up to 450 [1, 2]

Table 1.

The length of transportation tracks and the number of self-powered suspended monorails in horizontal workings and workings with inclinations up to 45° [1,2]

No.	Year	Length of transportation tracks of self-powered suspended monorails [km]	Total length of transportation tracks [km]	Number of self-powered suspended monorails [pcs]	Number of mines [pcs]	Average track length of self-powered suspended monorails per one mine [km]	Number of self-powered suspended monorails [pcs]
	1	2	3	4	5	6	7
1	2000	152	2217	-	42	3.6	-
2	2001	204	2074	-	42	4.9	-
3	2002	228	1997	-	41	5.6	-
4	2003	235	1933	-	39	6.0	-
5	2004	246	1868	-	35	7.0	-
6	2005	371	1801	-	33	11.2	-
7	2006	425	1745	-	33	12.9	-
8	2007	540	1697	211	32	16.9	6.6
9	2008	632	1677	246	31	19.8	7.7
10	2009	691	1833	286	31	22.3	9.2
11	2010	688	1792	322	31	21.5	10.1
11	2011	905	2029	394	31	29.2	12.7
12	2012	826	1753	471	31	26.6	15.2

On average, the number of self-powered suspended monorails per one mine increased from 6.6 in 2007 to 15.2 in 2012, i.e. approximately 2.4 times.

The analysis conducted indicates that there is a dynamic growth in the transportation by self-powered suspended monorails, particularly in the years 2005-2012.

The number of transportation systems and track length of self-powered suspended monorails for people transportation in the individual organisational units of the coal industry in 2013 is presented in Table 2 [2].

The analysis shows that in coal mines in 2013, the personnel was transported by self-powered suspended monorails in 81 transportation systems with the total track length of 159.5 km [2].

Table 2.

The number of transportation systems and the length of tracks for people transportation [2]

No.	Organisational unit	Number of transportation systems [pcs]	Length of tracks for people transportation [km]
	1	2	3
1	KW S.A.	37	72.3
2	JSW S.A.	21	28.4
3	KHW S.A.	3	9.8
4	PKW S. A.	3	7.2
5	LW Bogdanka S.A.	12	37.1
6	PG Silesia	4	3.5
7	ZG Siltech	1	1.2
	Total	81	159.5

2. THE RULES FOR USING SUSPENDED MONORAILS IN UNDERGROUND PARTS OF MINES

The analysis of selected issues concerning the transportation by self-powered suspended monorails has been conducted on the basis of the applicable legal acts in Poland [12, 14, 19], Germany [18], Russia [5], China [6] and Vietnam [5].

Particular attention was put on the provisions regulating the speed of people transportation by self-powered means of transport and the conditions of its fulfilment. The normative documents [6, 18] indicate that the travelling speed of diesel-powered suspended monorails should be lower than 3.0 m/s, while the source documents [5, 12, 14, 19] stipulate that it cannot exceed 2.0 m/s.

2.1. Legal status in Poland

The specific provisions concerning traffic regulation and management of deposits in underground mining plants producing hard coal and lignite, developed according to the Decree No. 38 of the Minister of Mines and Energy dated 10.10.1973, in force since 01.01.1974 [14], specify that the monorail speed while transporting materials and people should not exceed 2 m/s.

It was also found that the distance between the most protruding part of the monorail or the material transported and the support or other equipment should be at least 0.4 m, and not less than 0.8 m in the reloading area (Fig. 2).

The provisions specified that, in the case of people transportation, there should be a passage in the boarding and alighting areas, which is at least 1.0 m wide (counting from the contour of the transportation cabin) and 1.8 m high, while the distance between the floor and the bottom edge of the passenger cabin or the material container of the monorail should not be less than 0.5 m (Fig. 2). The guidelines for using suspended monorails, the Ministry of Mines – the Mining Department, Katowice, November 1978 [19], superseding the "Temporary Guidelines for using suspended monorails issued by the Mining Department of the Ministry of Mines and Energy (MGiE) in 1971 received a new provision stipulating that the inclination of workings where a monorail is intended to be installed should not exceed 45^0, while the monorail speed during transportation of materials and people should not be greater than 2 m/s. Changes in the transportation equipment used, particularly related to the replacement of floor-mounted and suspended monorails with rope drive into self-powered railways began in 2003. The regulations governing monorail transportation were also amended.

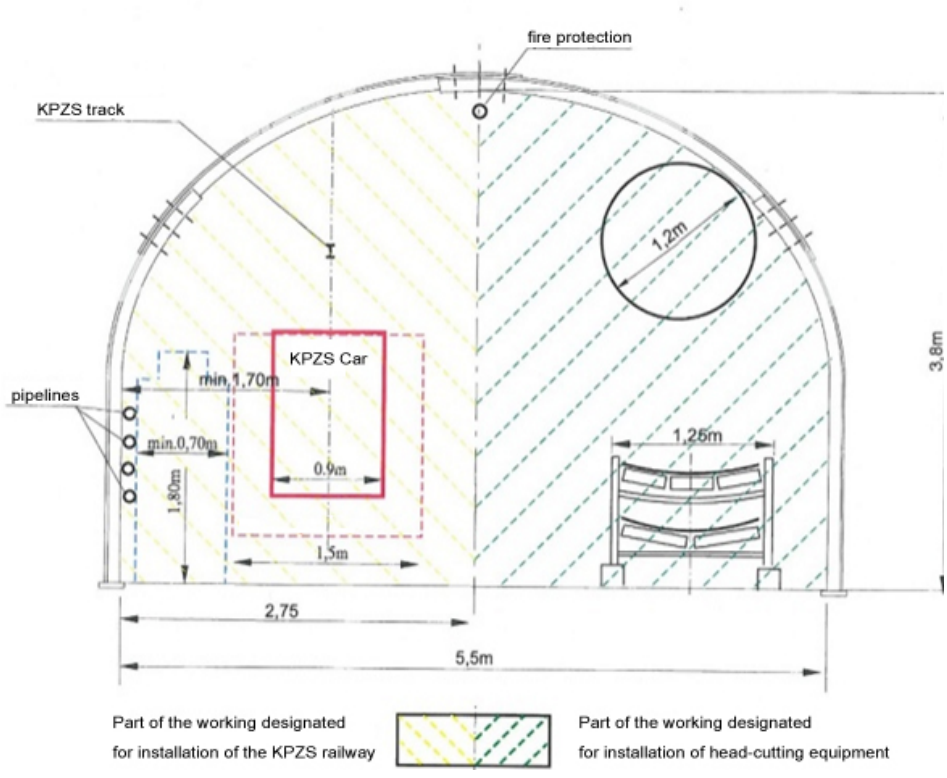

Fig. 2. Cross-section of the working with equipment constructed of a V/10 support [2]

The requirements related to the commissioning and operational safety of transportation systems were specified in the Regulation of the Minister of the Economy of 25 June 2010 concerning occupational safety and health, traffic regulation and specialised fire-fighting protective equipment in underground mining facilities, Dz. U. *[Journal of Laws]* No. 139, Item 1169 [13]. The requirements for operational safety specified in the Regulation govern, amongst others, the issues concerning:

- maintenance of the technical condition and the principles of operating and servicing in accordance with the specifications of the operation and maintenance manual (DTR);
- maintenance of workings and system installations to ensure that the dimensions of workings for transportation are secured (Fig. 2);
- the obligations of traffic supervisors and service staff related to the organisation of works and the inspections of the means of transport;
- provision of signalling, communication and traffic protection devices;
- organisation and conditions for the transportation of materials or people, where the speed of people transportation by rope-driven and self-powered means of transport cannot exceed 2 m/s.

The rules for using suspended monorails in underground parts of mines were also specified, amongst others, in the following normative acts [1, 2, 20]:

- Directive 2006/42/EC – The safety of machinery, introduced by the Regulation of the Minister of Economy, Labour and Social Policy of 21 October 2008 concerning the fundamental requirements for machines (Dz. U. [Journal of Laws] No. 199, Item 1228),
- Directive 94/9/EC of the European Parliament and of the Council of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres, introduced by
- Regulation of the Minister of the Economy of 22 December 2005 concerning the fundamental requirements for equipment and protective systems intended for use in potentially explosive atmospheres (Dz. U. *[Journal of Laws]* No. 263, Item 2203),
- Directive 97/23/EC of the European Parliament and of the Council of 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment, introduced by the Regulation of the Minister of the Economy of 21 December 2005 concerning the fundamental requirements for pressure equipment and assemblies (Dz. U. *[Journal of Laws]* No. 263, Item 2200),
- The Regulation of the Minister of the Economy of 19 August 2005 concerning the specific requirements for combustion engines in terms of limiting the emission of gaseous and particulate pollutants from combustion engines (Dz. U. *[Journal of Laws]* No. 202, Item 1681).
- PN, PN-EN, material and subject standards for the components used in the construction of monorails.

The safety requirements for operating the means of transport in the underground parts of mines included in the normative acts forced the producers of drivetrains and their users to limit the speed of people transportation to 2 m/s in the case of rope-driven and self-powered means of transport. They also forced the users to construct and maintain workings and install the transportation systems in a manner to ensure that the dimensions of workings for transportation are secured [1, 2, 20, 21].

2.2. Legal status in Germany – Guidelines by the Regional Office in Arnsberg

The provisions included in the guidelines by the Regional Office in Arnsberg, the Division of Mining and Energy in Nordrhein-Westfalen (NRW) [18], for battery-powered and diesel-powered suspended railways in underground facilities of coal mines from 14.12.2005 (Guidelines for a suspended monorail) indicate that the transportation speed of rope-driven and self-powered means of transport cannot exceed 3.0 m/s. On the other hand, an increase in the travelling speed of drivetrains and railways to over 2.0 m/s makes it necessary to extend the clearance gauge to the dimensions presented in Fig. 3 [18].

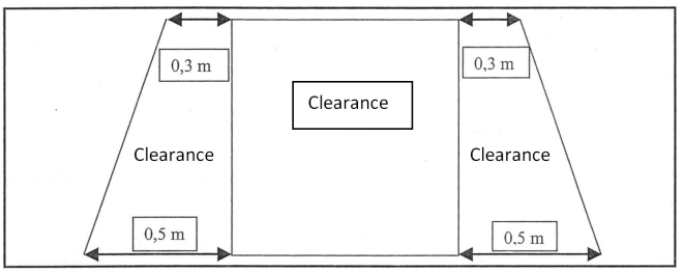

Fig. 3. Spatial profile for the travelling speed > 2.0 m/s [18]

2.3. Legal status in China – Normative documents of the Mining Industry Standard of the People's Republic of China

The safety status of transportation equipment in coal mining is based on the "Normative documents of the Mining Industry Standard of the People's Republic of China" (date of issue: 08.12.2000) [6]. The normative documents [6] indicate that the travelling speed of diesel-powered suspended monorails should be lower than 3.0 m/s (Table 3).

Table 3.

Transportation parameters for self-powered suspended monorails [6]

Maximum drawbar pull [kN]		15	30	60	90	120	160
Maximum speed [m/s]		≤3					
Inclination [°]		≤25					
Rail type		I 140 E					
Turning radius [m]	in a vertical plane	8					
	in a horizontal plane	4					
Standard for the rail		I 140 E DIN 20593					

3. IDENTIFICATION AND MONITORING OF THE OPERATING PARAMETERS OF SUSPENDED MONORAIL DRIVETRAINS

Diesel self-powered suspended mining drivetrains equipped with recorders of operational parameters installed in the power supply unit of the control and diagnostic system may be used for verifying the performance of machines. The data which are registered and stored on a memory card or transmitted to a selected recipient make it possible to analyse the values of pressure, temperature, travelling speed, rotational speed of the engine (RPM) as well as emergency states and faults of the drivetrain. Moreover, the data allow for evaluating the control function of the machine. In order to send the data in a particular frequency band, it is necessary to choose a proper data transmission system. The signals generated in the control system of a diesel-powered drivetrain may be visualised, for example in a control room. Depending on the user's communication structure, a diesel-powered drivetrain can be optionally equipped with devices for transmitting the performance parameters of the drivetrain via the following modems: UHF, VHF, Wi–Fi and a docking station.

For example, the publications [20, 21] present the analysis of people transportation speed. The speed of people transportation primarily ranged between 1.1 and 1.5 m/s. Figure 4 presents a sample graph showing the variable speed of people transportation in a mine.

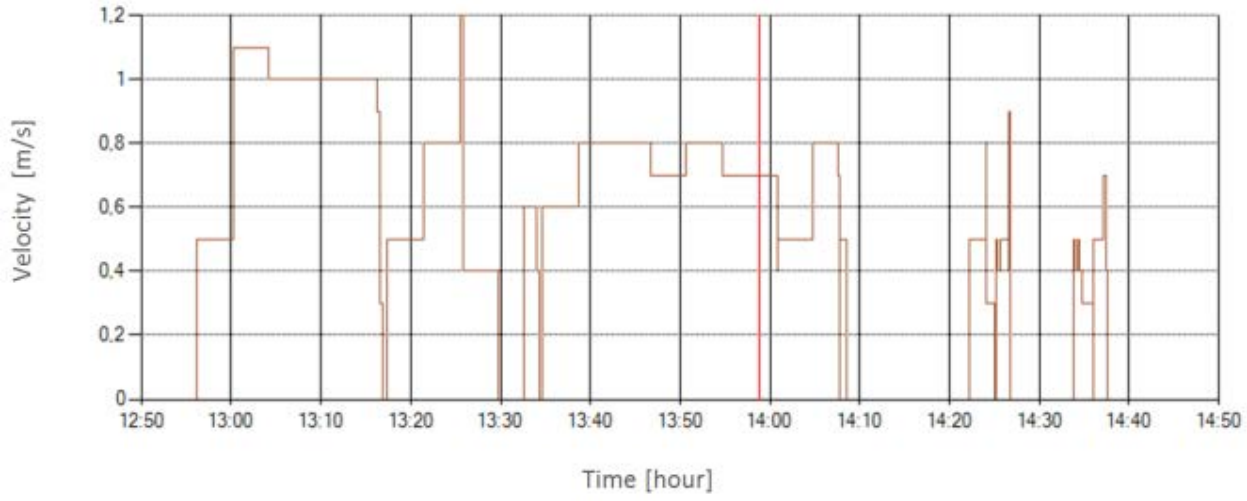

Fig. 4. The graph of velocity of people transportation registered in the mine

4. TECHNICAL FEASIBILITY OF INCREASING THE SPEED OF PEOPLE TRANSPORTATION BY SUSPENDED MONORAILS

The suspended drivetrains are self-propelled diesel machines used for the transportation of materials and people [7, 8]. They have a modular design which makes it possible to adapt their configuration to transportation systems. The suspended drivetrains type KP may be installed in three versions, depending on the mining and geological conditions as well as on the design of the drive: KPCS – drivetrains equipped with friction drives, KPZS – drivetrains equipped with HZA gear drives as well as KPCZ – drivetrains equipped with friction and gear drives. The drive units of a drivetrain are powered from a diesel-hydraulic aggregate with an anti-explosion structure, with power ratings of 95 or 148 kW. The nominal drawbar pull for the particular types of drives is equal to 20 kN (for a single friction drive) and 30 kN (for a single gear drive) [7, 8]. Growing transportation weight makes the drawbar pull of suspended monorails increase in a systematic manner. This can be attributed, amongst others, to the load exerted by a longitudinal force on the rail joint [9, 10, 11]. The basic parameters of the KPCS-148 type drive include: the power of the combustion engine equal to 148 kW and the nominal drawbar pull of 4 friction drives equal to 80 kN. The calculations verifying the possibility to transport people in eight 8-person cabins with two drivetrains having the drawbar pull of 40 kN, with the weight of 9,520 kg (total weight: 18,020 kg), presented in Figure 5 [1, 2, 20, 21], indicated that it was technically possible to reach the travelling speed of 3.9 m/s for self-powered drivetrains. With inclinations of the transportation route exceeding 10°, the speed must not be greater than 2.0 m/s (Fig. 5).

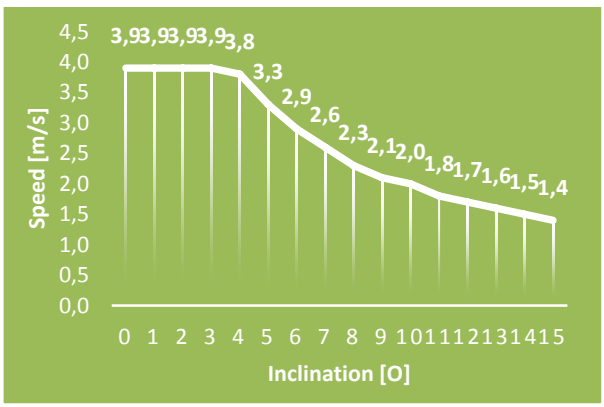

Fig. 5. The travelling speed of self-powered means of transport versus track inclination [1, 2, 20, 21]

The technical analysis of the locomotives in terms of the travelling speed indicates that it is possible to increase the speed of transporting people by self-powered means of transport.

5. IMPACT OF TRANSPORTATION MEAN ON SUSPENDED TRACK AND ON USERS OF THIS TRANSPORTATION MEAN

Means for transportation of people and materials in horizontal workings and workings inclined up to 45° in underground mining plants should be equipped with emergency braking devices, according to the requirements included in the Regulation of the Minister of Economy [4]. Besides driving-and-braking systems, which are present in drivetrains, the suspended monorail is equipped with braking cars, which additionally protect the transported team. Most often they are installed in front of and behind the cabins for transportation of people. After exceeding the speed settings the braking systems are activated automatically, i.e.:

- braking systems of drivetrain:
  - inductive sensors are activated at speed 2.5-2.6 m/s,
  - mechanical centrifugal detectors of rotational speed are activated at speed 2.7-2.8 m/s
- braking cars or systems of braking cars are activated at speed 3.0±0.2 m/s.

Each emergency braking is spontaneous, what results in dynamic overloads having impact both on suspended track as well as on frames of mine yielding support, which is commonly used in roadways of hard coal mines in Poland. According to the Annex No. 4 *Detailed rules for management of operation in workings* to the Regulation [4], the load to support arches should not exceed 40 kN. This load limit has not been changed for many years despite the fact that in this time the conditions of underground suspended transportation as well as parameters of roadway supports changed in the result of new technical and material solutions. At the same time, in the last years, the size of frame as well as cross-sections of yielding support sections increased. In the past, steel arch yielding supports of KS, KO18 or KO21 profile were used in roadways. In 1980-ties the transportation workings and near-wall roadways were made of support of frame size 7, while at present the dimensions of workings for transportation significantly increased and their frames are of size 9, 10 or bigger. With time, due to increasing demand for transportation of more loads, the cross-section of transportation workings was increased. It also required increase of cross-section of the sections

used to build the arches of roadway support. From stand tests that were carried out at the Central Mining Institute it results that load-bearing capacity of arch supports (rigid supports) for V29 and bigger profiles exceeds 800 kN [14], while from simulations made at the KOMAG Institute of Mining Technology it results that FEM computational model of a single arch of roadway support in a yielding state losses its stability at load of about 300 kN. Deformation of support arch is presented in Fig. 6.

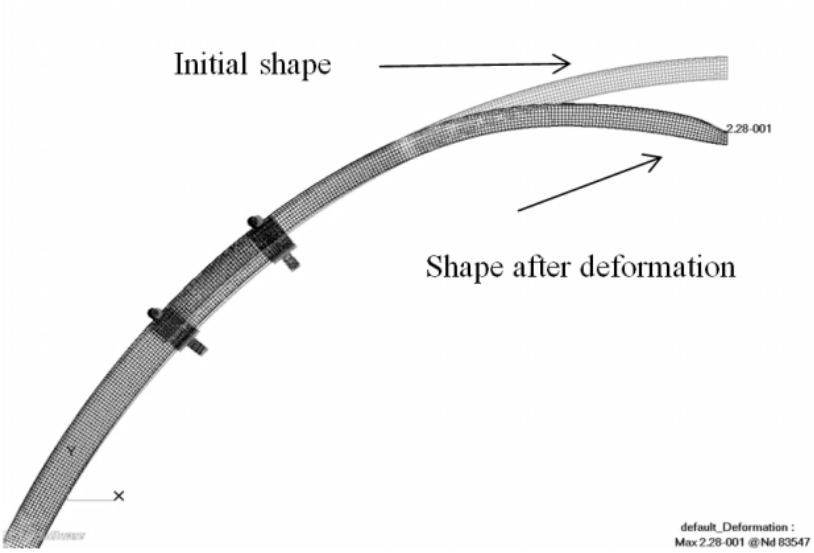

Fig. 6. Deformation of support arch under concentrated load 300 kN [16]

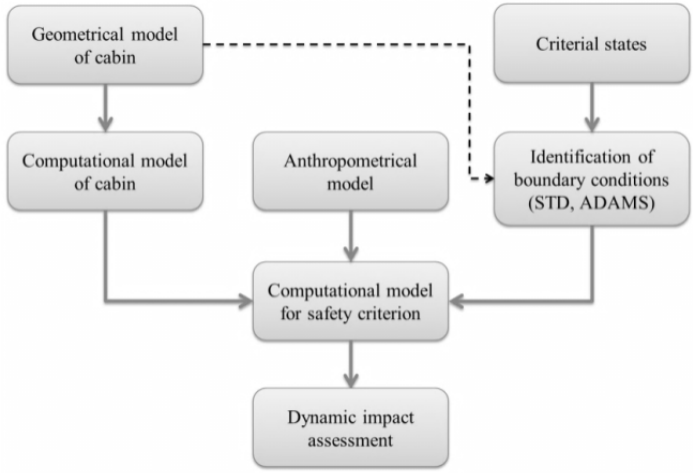

Fig. 7. Algorithm for identification of results of dynamic overloads [16]

Moreover, from MBS numerical simulations it results that load to one suspension caused by transportation system, which in static conditions is of 50 kN, increases maximally by 50% in the case of emergency braking. This increase depends on the method of installation and stabilization of suspended track.

Due to longer way to the workplace, the time of effective work of mining team shortens. However, increase of speed of suspended monorails transporting people extends that time.

Increase of travel speed requires simulation and experimental tests to assess the impact of emergency braking on the transported team. Computer simulations enable to calculate the man-machine relative displacements during braking and their impact on human body. So-called extended criterial models, including the model of geometrical features of machine and model of anthropometric features, are used for that purpose. Extended criterial models enable assessment of safety of operators and team during transportation. It especially refers to the emergency states with accompanied dynamic overloads. For that purpose it is necessary to combine the MBS method with the FEM method according to the presented algorithm, Fig. 7.

Characteristics of acceleration determined by MBS method are boundary conditions in computational models used in FEM. Computational models of operators' cabins or cabins for transportation of people are completed with virtual counterparts of HYBRID III dummies [3]. In this way they create an anthropotechnical system [17]. The example of anthropotechnical system, including 50th percentile dummy model of anthropometric features placed in a cabin for transportation of people, is given in Fig. 8.

Numerical simulations enable assessment of safety of use of transportation mean in critical states, which can cause injuries to user of this transportation mean and which cannot be assessed in real conditions, e.g.: sudden braking or acceleration, derailment, collision or ride on a curve at exceeded speed. Sample results of simulation of transportation of a virtual dummy model placed in a cabin on a curve of radius 4 m at speed 0.5 m/s, 2 m/s and 5 m/s are given in Fig. 9.

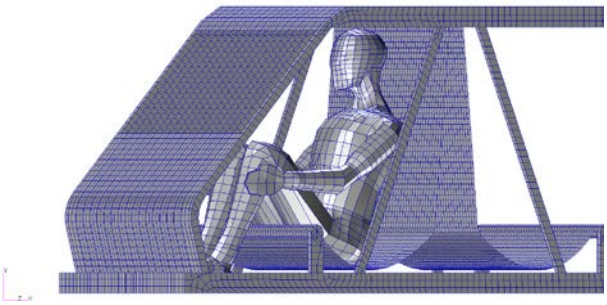

Fig. 8. Virtual counterpart of Hybrid III dummy placed in a suspended monorail's cabin for transportation of people [15]

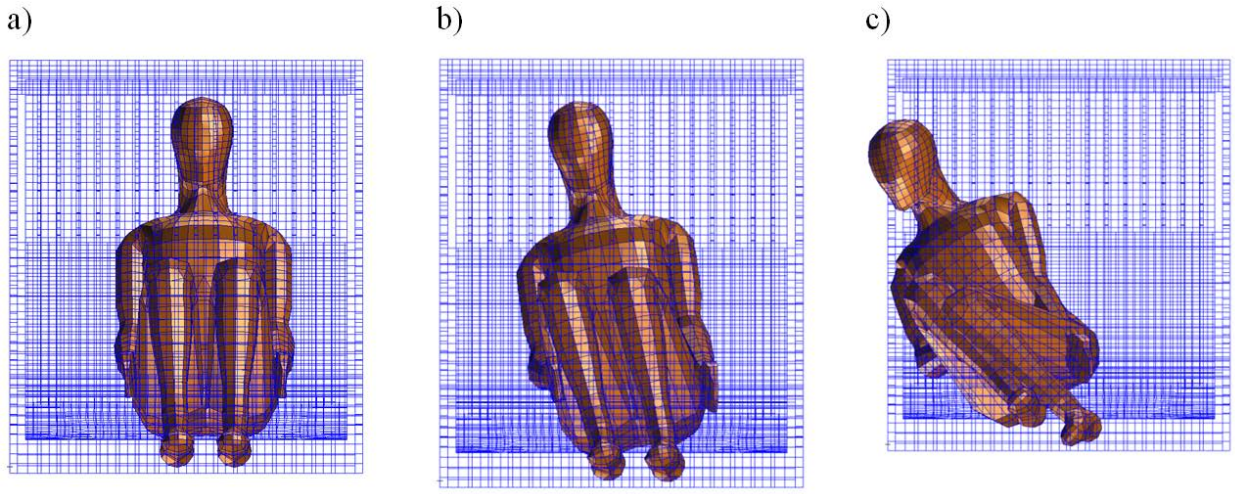

Fig. 9. Behaviour of a virtual model of Hybrid III dummy during travel in a cabin on a curve at speed: a) 0.5 m/s, b) 2m/s, c) 5m/s [15]

Use of extended criterial model is also useful in assessment of passive safety systems in cabins, e.g. automatic seat belts and other protective components installed in a passenger space of cabins for transportation of people or cabins' operators. These assessment is realize by means a quantitative method – e.g. a HIC (Head Injury Criterion) parameter is calculated [12].

6. SUMMARY

Suspended monorails are developed in the quickest way among all auxiliary transportation means in the Polish hard coal mining industry. They are used for transportation of more and more people, while their tracks are still extended. It is a long-term trend and thus the work on increasing the speed of transportation of people by suspended monorails with own drive should be intensified. State-of-the-art software tools enable assessment of impact of speed of transportation mean on safety of its users (operators and transported team) with significant reduction of underground tests. Guidelines for designing the suspended transportation systems, which will enable faster and safe travel, will be the result of this assessment. It requires collaboration between scientific centres, i.e. technical universities and research institutes as well as manufacturers of transportation systems.

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