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Conditions for the construction of monorails in Poland

Abstract: The article presents an overview of monorails. The technological conditions for their construction have been taken into account. The conditions for the construction of cableways in Poland were analyzed. In Polish law, there are general provisions specifying and defining monorail, however, to enable the development of this technology in Poland, it is necessary to introduce additional separate regulations. It seems reasonable that a monorail should be treated similarly to a cable car, with some solutions borrowed from the classic.

Keywords: Monorail; Cableway

Introduction

Recently, interest in monorail solutions has increased significantly - almost 30 new monorail lines are under construction, testing, conceptual planning, or awaiting construction. This technology is found on every continent in the world, not counting Antarctica. Currently, there are approximately 56 monorail lines in operation, of which as many as 26 are located in Asia, 13 in Europe, 10 in North America, 3 in South America, and 2 in Africa, Australia, and Oceania. [14,23]

A monorail is a type of means of transport that uses vehicles that run on a single rail for the transport of passengers or goods. The rail is a beam structure made of prestressed concrete or steel, which is supported on relatively densely arranged supporting structures, creating a flyover. This solution makes it possible to run a monorail route over highly urbanized areas, i.e. in large cities and urban agglomerations. [4]

The most developed monorail systems are found in two regions - Asia (Chongqing, China) and South America (Sao Paulo, Brazil). Currently, at least 9 companies are offering their solutions on the monorail market. They are: Bombardier, Scomi, Hitachi, BYD Skyrail, CRRC, FCF SpA, Intamin Transportation Ltd. Mitsubishi, and Morton [24]

The monorail can also include the magnetic railway, however, taking into account the lack of physical contact between the vehicle and the rail (magnetic levitation), the lack of wheel-rail friction and rolling resistance, as well as much higher speeds (400-500 km/h), magnetic railways cannot qualify as a monorail. [7] In addition, the current legal system in Poland clearly distinguishes between monorail, air cushion, and magnetic rail.[12,16]

Monorail construction technology

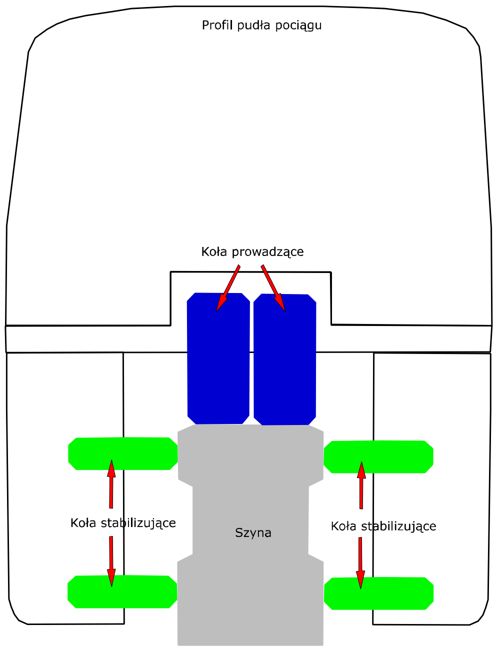
System solutions

Monorail vehicles can be suspended to a rail (beam) or based on a saddle, hence two types of railroads are distinguished: suspended, where the vehicle is suspended from the rail (beam), and a saddle, where the vehicle is supported on a saddle beam. Monorail lines (suspended and saddle type) usually consist of two tracks (one in each direction) and are completely collision-free. [2]

Currently, the most commonly used type of monorail is the saddle type, which is characterized by greater stability in curves. The name of this solution is related to the shape of the trolley, which covers the trolley on three sides. The most famous monorail solutions are: ALWEG, Steel Box Beam, and Inverted T. [23]

The most popular monorail saddle system is the solution of the ALWEG company. The vehicles run on a concrete rail, on two parallel wheels in two trolleys, and the wheels placed perpendicularly on both sides of the rail below play a stabilizing role. The ALWEG company withdrew from activity in the 1960s, but their solutions are constantly produced by other companies, such as Hitachi, Bombardier, or Scomi. The analysis of the beam dimensions in the currently available ALWEG systems solutions showed that the maximum width difference between the largest (90 cm) and the smallest (66 cm) rail is 24 cm. [7,23]

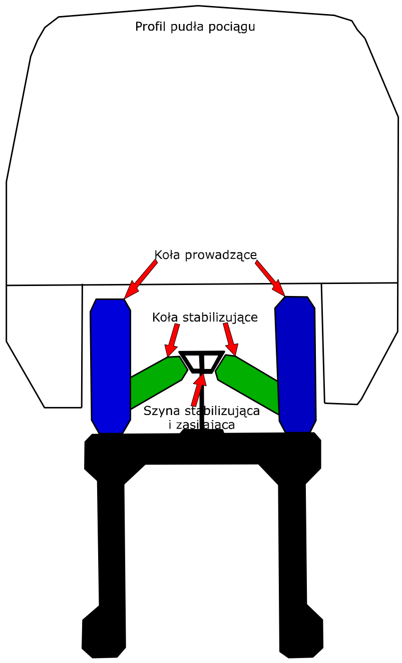
All monorail vehicles produced in this technology have the same basic suspension - two bogies (front and rear), consisting of vertically mounted pneumatic rubber tires, allowing rail travel as well as load and power transmission. Horizontal tires, usually on the top and bottom of the rail, are responsible for stabilizing the vehicle. A simplified diagram of the ALWEG system is presented below (Figure **1**). [7,23]



1. Simplified diagram of the "ALWEG" system for monorail
Source: own study based on [7]

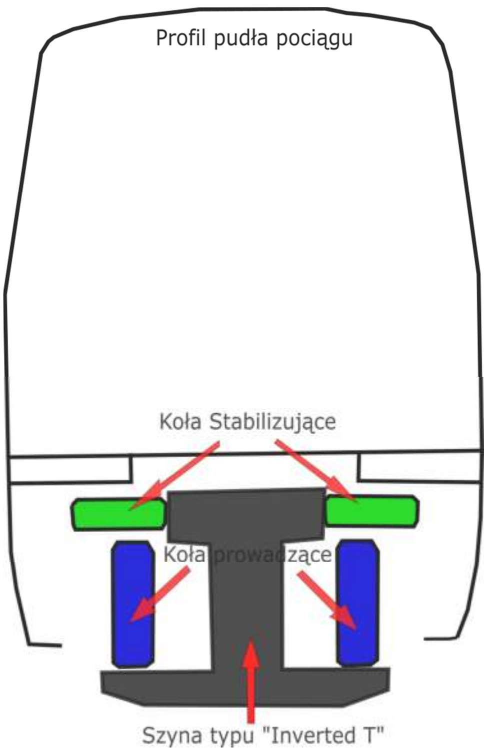
The "Steel Box Beam" system uses a steel beam made of a box girder, on which a trolley moved with two pneumatic traction wheels, guided by four horizontal stabilizing wheels. Currently, this solution is mainly used to support people mover systems, serving relatively small areas such as airports, downtown districts, and amusement parks (e.g. Savio, Italy). The trolleys are arranged between the wagons and house the drive unit and are equipped with air springs with automatic load compensation.[23]

A variation of the above system was a solution called "Urbanaut", which used a concrete or steel box beam with a single rail on top for guidance (stabilization) and power. The system was built in South Korea in the city of Incheon but was abandoned due to design errors. The simplified diagram of the Urbanaut system is presented below (Figure **2**). [7,23]



2. Simplified diagram of the "Urbanaut" system for monorail
Source: own study based on [7]

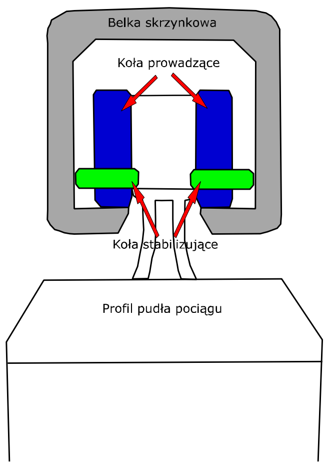
Another solution used in the saddle monorail is the "Inverted T" system, ie a beam (rails) resembling an inverted letter T, which can be made of concrete or steel. The vertical element of the guide serves to support the trolley's stabilizing wheels, while the lower edges of the guide support the load wheels. A simplified diagram of the Inverted T system is presented below (Figure **3**). [23].



3. Simplified diagram of the "Inverted T" system for monorail
Source: own study based on [23]

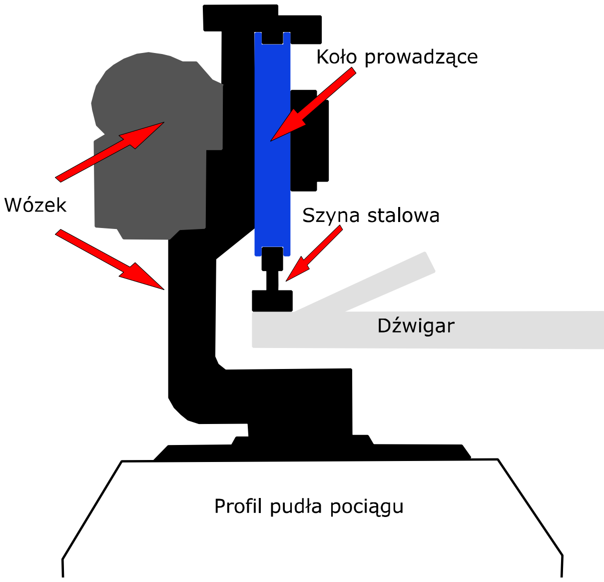
A less common type of monorail is the suspended type, in which the vehicle runs suspended on a rail and the drive unit is located on the roof. The most famous suspension rail systems include the following systems: SAFEGE, Double-flanged, and a cable car.[23]

The most widespread monorail suspension system is the "SAFEGE" type solution. In this system, an empty box girder was used to suspend the trolley, in which there was a slot in the lower part through which the suspension of the wagons was passed. Inserting the trolleys inside the spar provided them with protection against adverse weather conditions, such as rain, frost, or snow. The use of rubber tires guarantees good braking and acceleration parameters as well as low noise, while the pendulum-type suspension with air springs allows for stability and comfort for passengers. There is also an additional rail in the box girder that supplies electricity to the vehicles. Trolleys are equipped with several sets of wheels moving in the vertical plane - road wheels, transferring mainly vertical loads, and horizontally - stabilizing and guiding wheels, ensuring the stability of the vehicle in the vertical and transverse plane of the track and limiting the roll. The "SAFEGE" system is used, among others, by monorails in Japan and China. A simplified diagram of the "SAFEGE" system is shown below (Figure **4**) [23].



4. Simplified diagram of the "SAFEGE" system for monorail
Source: own study based on [22]

Another suspension monorail system is the "Double-flanged" solution. Each vehicle has two two-wheeled trolleys to which steel wheels with double rims are mounted. The wheels run on one steel rail placed on a beam (girder). Both trolleys are powered by a single motor with a worm gear. A characteristic feature of this system is the free rolling of vehicles under the tracks, however, the inclination does not exceed 15 degrees. This system is used in the oldest functioning monorail in the world - in Wuppertal, Germany. A simplified diagram of the "Double-flanged" system is shown below (Figure **5**) [23].



5. Simplified diagram of the "Double-flanged" system for monorail
Source: own study based on [22]

6. Monorail in Wuppertal (Germany) using the "Double-flanged" system”
Source: website [27]

In the urban communication system, a rare solution for suspended monorail is a cable car, which is mainly used to connect places with large differences in level. The monorail cableway consists of a monorail guide which is driven by drive units in stations via steel cables. The oldest existing monorail cable car is the Dresden suspension railway in Germany, which is 274 meters long with a gradient of 39.2%. Cableway technology was also used to connect the city of Memphis with a river park on Mud Island (USA). Vehicles simultaneously move between stations on parallel tracks [23].

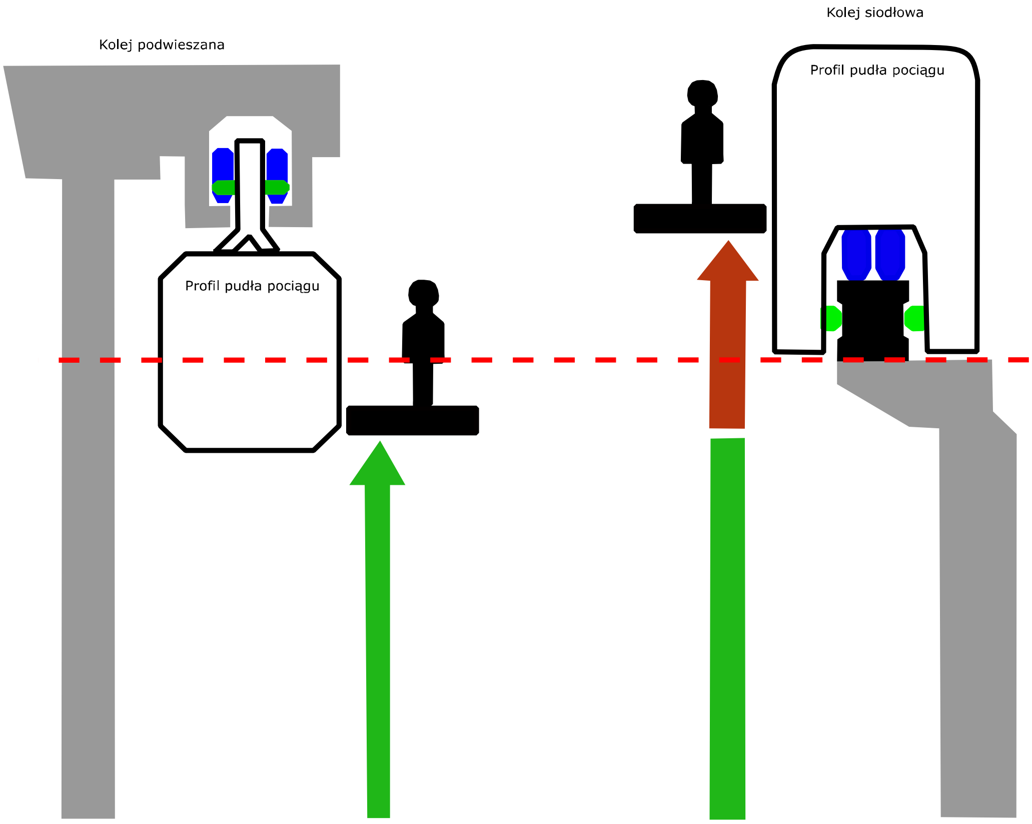
7. Dresden (Germany) monorail cableway
Source: website [23]

Construction of flyovers, supports, and stations

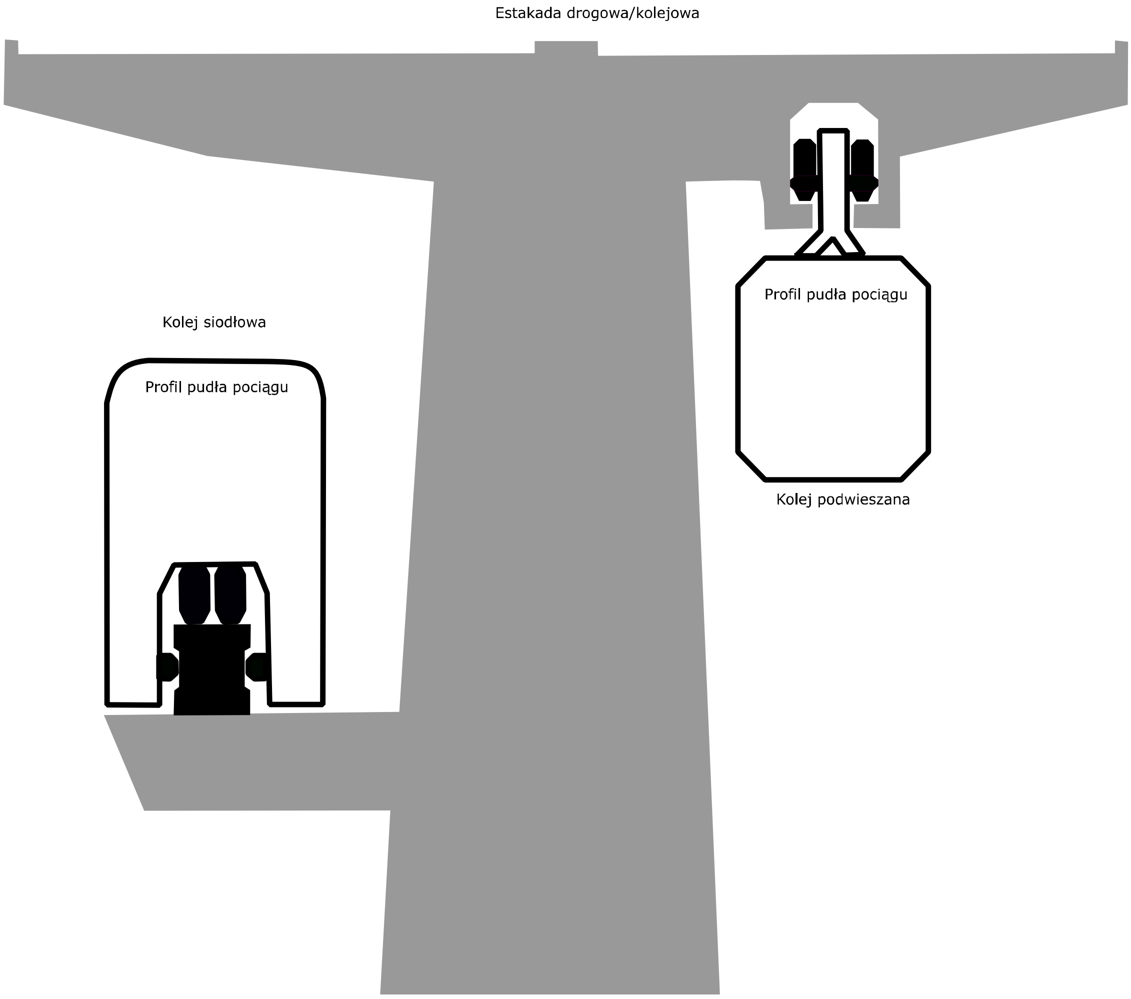
The structure of monorail flyovers is usually made of prefabricated steel or concrete elements. Regardless of the type of monorail (suspended, saddle) and the system used, the construction of the line is very similar. T-shaped supports are used for the construction of a double-track line, and Γ-shaped supports when the line will be single-track. If it is not possible to place supports directly under the line, frame solutions (frame supports) are used, which enable the line to be traced, e.g. over other infrastructure. The height of the supports should be selected adequately to the immediate vicinity of the line, however, the recommended minimum support height should be 5-9 meters, depending on the type of monorail. [4,8]

The advantage of the monorail is the ability to overcome large inclines, even up to 10% (in practice, the maximum inclination used is 6%). On the other hand, the small minimum turning radius of 50 m makes it much easier to route in dense urban areas. [6,16]

The difference between the two types of monorail (saddle and suspended) is related to the height of the supports. The supports for suspended railways are much higher than for saddle railways, which results from the applied technical solutions. The height of the station is also an element differentiating these two types of a monorail. In the case of a fifth wheel, the platforms must be situated higher than for the suspension railway. The differences in the height of the supports and platforms are presented in the diagram below (Figure **8**). Additionally, for the construction of a monorail, it is possible to use the existing road or rail infrastructure (Figure **9**). [4]



8. Comparison of the support heights and the location of the platforms for suspended and saddle railways
Source: own study based on [4]



9. Use of road/rail infrastructure for monorail
Source: own study based on [4]

Monorail stations are usually spaced from 0.5 km to 3.5 km. They are usually located above the terrain, at the height of the railway line, with the use of supports similar to those on the trail. In special cases, they can also be located on the ground level or below the surface. [4]

Depending on the anticipated type of railroad and rolling stock, various shapes and types of contact beam (rails) are used. In the case of suspended railways, steel or composite beams are most often used. Fifth wheel manufacturers most often use a prefabricated prestressed concrete beam with a fixed or variable height. Variable beam height enables more effective use of the structure cross-section. The average height of the beam supporting structure (rail) is 1.5 m. The width of the rail, depending on the selected system, may vary from 0.6 to 0.9 m, and its length ranges from 20 to 30 m. Use of long elements enables the creation of a multi-span system ensuring continuity of beam deformation and minimizing vibrations. [4,7,11]

Turnouts

The most important element of the monorail infrastructure is the turnouts enabling the change of direction. The oldest monorail solutions did not provide for the possibility of changing the direction of traffic, therefore vehicles move on these lines in a loop (Wuppertal, Germany) or between two fixed stations (Seattle, USA). [4,23] The current solutions of the monorail allow for a smooth change of track and direction of travel.

In the case of the SAFAGE suspended monorail system, the beam structure allows the use of a movable spire, similar to the turnouts of a classic railway. The turnout is equipped with movable horizontal plates which act as sliding surfaces in both directions of the turnout. The SAFEGE system turnout in the extreme positions is presented below (Figure **10**). [4,23]

10. SAFEGE turnout in extreme positions
Source: website [20]

Saddle rail switches use more complex solutions. The most frequently used solution in Japan is a segmented (strip) monorail. The solution was invented by the ALWEG company in the 1950s. The segment switch, made of a steel section of rail made of movable segments, allows you to change the curvature and thus change the direction of travel in about 7 seconds. A turnout using a segment coupler in the ALWEG system is presented below [4,23].

11. ALWEG system segment switch (Kuala Lumpur, Malaysia)
Source: website [23]

Another solution used to change the direction of travel of the fifth wheel is the use of a sliding mechanism, the movement of which deflects a straight section of the beam to the side, and a curved section moves in its place (and vice versa). In this system, the complete switching of the turnout takes 12 seconds. The turnout using a sliding mechanism is presented below (Figure **12**). [7,23]

12. Turnout using a sliding mechanism
Source: website [28]

A solution used in a monorail to change the direction of travel is also a rotary switch, which rotates around its horizontal axis replaces a straight section of a rail with a curved section (arc). This technology was used, among others railroad linking Newark Airport. [23]

Vehicle

Monorail vehicles are characterized by a relatively large weight compared to the weight of the contact beam (rail), which results in a significant impact of dynamic loads on the rail stress state. In addition, monorail vehicles have a greater width compared to the track on which they run, which means that they are exposed to lateral deflection when driving (mainly in curves). [4]

In the latest vehicles, both for the suspended and fifth wheel type, in order to prevent transverse deflection, bogies have been equipped with sets of wheels moving in the vertical (road wheels) and horizontal (stabilizing wheels) plane. In the ALWEG system, the trolley usually consists of four vertical road wheels (two tires on each axle) and six additional wheels (three on each side of the beam), which are responsible for stabilization and side guidance. Two wheels touch the upper part of the running beam, and the remaining wheels touch the lower part, ensuring stability. Trolleys in the SAFEGE system (suspended railway), have four road wheels (two tires on each axle) and four tires (two on each side of the beam) to stabilize the vehicle. [9]

Most monorail vehicles are powered by electric motors capable of speeds up to 80 km/h (commercial speed is 30-50 km/h). The speed of acceleration and braking varies within the following limits: respectively 3.5 m/s2 and 4 m/s2. Electricity is supplied from rails running on both sides of the running beam. These rails are powered by direct current. [4.9]

Most monorail vehicles are equipped with two independent braking systems, i.e. a mechanical brake and an electric brake which acts as an emergency brake operated by the driver or from the train control center. [11]

Monorail construction safety

Monorail is currently considered to be one of the safest means of transport. The structure and route of the route basically prevent a collision with other means of transport. However, there were several serious accidents on the lines that are currently operating. In 2009, there was a collision of two vehicles in the Walt Disney World theme park, in which one of the vehicle's drivers was killed. The cause of the accident was negligence committed by employees responsible for traffic control, as well as deficiencies in safety procedures related to the reversal of vehicles. In 2005, in Seattle (USA), one train collision was reported as a result of a design error due to line reconstruction in the 1980s (insufficient track spacing). The passengers were not seriously injured during the incident. The most tragic accident happened in 1999 on the oldest monorail line - in Wuppertal (Germany). As a result of the train derailment, 5 people were killed and 47 were injured. The reason for this event was negligence on the part of the team supervising the renovation works. As a result of leaving a metal element on the rail, the train ran out of the rail and fell into the river (Figure **13**). [3,4,6,15,19]

13. Derailment of a monorail train in Wuppertal (Germany)
Source: website [21]

Locating the monorail infrastructure on the supports carries greater risks, in particular when it is necessary to evacuate or assist passengers trapped between stations. Lowering the monorail vehicle in an emergency is difficult due to the considerable distance from the ground. The cause of such an emergency stop may be a vehicle breakdown, power failure, or fire. [3,4,15]

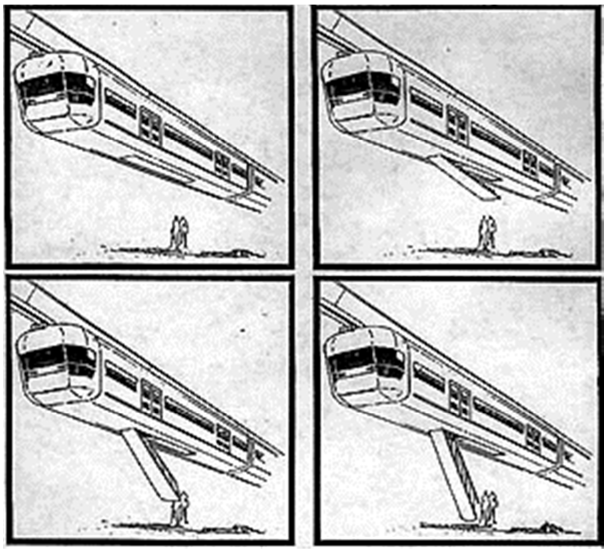
With the above in mind, any monorail system should have a safe and effective means of evacuating passengers at any point along the line.

Two evacuation directions can be distinguished: horizontal and vertical. The quickest and most effective method of evacuating from a monorail vehicle is to use an emergency walkway mounted on the outside of the track or between the track beams. In the event of an emergency, the pavement allows you to leave the vehicle very quickly and reach the nearest station. During the normal operation of the line, these pavements can be used for inspections and repairs. An example of an escape walkway is presented below (Figure **14**). [2,3,4,15]

14. Escape walkway along the monorail line in Saõ Paulo (Brazil)
Source: website [25]

Another way to evacuate horizontally is to use the platform as a transition to a roadworthy vehicle that is on the same or adjacent track. The need to properly adjust the platform from the other vehicle makes this solution unsuitable in the event of a failure on the curve of the line (Figure 13). [1,3]

The use of an appropriate method of vertical evacuation depends largely on the development of the area located under the railway line where the vehicle has stopped. The most commonly used vertical evacuation solutions are: an evacuation spiral, the use of vehicles with a ladder, bringing passengers using a harness. However, in suspended railways (SAFEGE system), it is possible to use design solutions in the form of a ramp (gangway), which is part of the vehicle floor. In the event of a breakdown, the ramp located in the aisle between the seats is unfolded enabling safe evacuation of the vehicle (Figure **15**) [1,3,10].



15. Escape ramp in the SAFEGE suspension rail system
Source: website [23]

In the event of a malfunctioning unit on the route, it can be towed or pushed to the nearest station/depot with the use of other vehicles operated on a given railway line. This solution enables the track to be unblocked quickly and the trains to run back to normal. [1]

Monorail stations, due to their location, should be equipped with platform doors (or half-doors) that prevent inadvertent falls from the platform edge. The door completely closes the edge of the platform and is synchronized with the opening and closing of the vehicle door to allow entry and exit. [13]

16. Half-platform doors at the monorail station in Daegu (South Korea)
Source: website [65]

Additionally, railway stations should be equipped with diagrams to facilitate orientation, signage showing the escape route, and finished with materials of appropriate fire resistance. [5]

Monorail vehicles must be constructed of fire-resistant internal materials and equipped with high-pressure sprinklers and fire-extinguishing systems. Vehicle bogies are equipped with additional sets of wheels or tires with a reinforced and stiffened structure of sidewalls (the so-called run flat), which enable the vehicle to safely reach the nearest station. In addition, monorail vehicles are equipped with advanced traffic control systems, including those enabling completely maintenance-free system operation (CBTC - Communication Based Train Control). On-board and track-side devices allow for accurate real-time determination of the location of trains and their key parameters. [3,5,10,13]

Possibilities of using monorail technology in Poland

An important aspect of introducing a new means of transport to the existing transport system of cities and entire agglomerations is the analysis of transport needs. This analysis should include the appropriate identification of areas in terms of the possibility of building the entire railway infrastructure in response to the existing, currently unmet, and foreseeable future transport needs. It should also provide answers on how the introduction of a new transport subsystem will solve the existing communication problems and prevent public transport passengers from being taken over by individual road transport, with particular emphasis on the alternative of modernizing or expanding the already existing public transport systems in the analyzed location.

Running a monorail route on supports above the street level is subject to several urban and spatial conditions. The best terrain for a monorail is a wide boulevard or a road with a lane separating the road, thanks to which the occurrence of expropriation or demolition is limited. In addition, the proposed route should run through densely populated areas, i.e. commercial and residential areas, which will guarantee an appropriate demand, as well as ensure the intermodal nature of the transport system, i.e. include connections with other means of transport (conventional rail, airport, bus, metro, tram).

The key issue in the process of introducing a new technology is the appropriate location of requirements and solutions in the applicable legal system. An analysis of the available legal solutions in the world has shown that the approach to the monorail is different. Monorail railway is sometimes treated as a light railway (Italy), on a par with tram transport (Germany), or as a traditional railway (Japan).

The analysis of the currently binding legal regulations in Poland has shown that there are regulations covering monorail in its scope. These are:

- The Act of December 16, 2010, on public collective transport,[16]
- Regulation of the Minister of Transport and Maritime Economy of September 10, 1998, on technical conditions to be met by railway structures and their location (Journal of Laws of 1998, No. 151, item 987, as amended).[12]

According to [16], monorail is classified as other rail transport, which is defined as "the transport of people by means of transport that run on rails or railroad tracks, including trams or subways, or the transport of people by means of transport that run on one rail or on airbags or magnetic, other than rail transport and rope-off-road transport ".

According to [16], other rail transport, and thus monorail, is classified as public collective transport as generally available regular passenger transport performed at specified intervals and along a specific communication line (communication lines or communication networks), i.e. communication along with the network of public roads, lines: railway, other rail, cable, rope and off-road; sea basins or inland waters, together with designated places for boarding and disembarking passengers.

The regulation [12] defines monorail as an unconventional railway, which is defined as:

- a railway vehicle moving on a non-railroad surface, while maintaining the condition of connecting the road with the vehicle through a special structure of the vehicle and road unit, or
- a railway vehicle that does not have traction and friction driving wheels to convert the torque generated by the traction motor into translational motion.

It should be noted that the Polish legal system already has general provisions that define and define monorail. However, to enable the development of this technology in Poland, it is necessary to introduce executive regulations that define the basic requirements, construction and safety rules, and other necessary solutions necessary to launch this means of transport in Poland. Taking into account the technical solutions used in the monorail and the existing legal regulations in Polish regulations, it seems reasonable that the new technology should be treated in a similar way as a cableway, with some solutions borrowed from the traditional one (e.g. regarding the safety or risk assessment).

Treating the monorail on a similar basis to the cableway will require the introduction of organizational changes resulting from the expansion of the competencies of some authorities and entities responsible for rail transport in Poland, including, in particular, the Railway Transport Office (UTK) and the Transport Technical Inspection (TDT),

Under the Act on Technical Inspection [17], the scope of activities of the Transport Technical Inspection includes technical supervision, inter alia, over technical devices installed in the railway area, in railway rail vehicles, on railway sidings, and over passenger and goods cableways. Technical devices are subject to inspection in the course of their design, production, including the production of materials and components, repair and modernization, trade and operation.

According to [18], the Office of Rail Transport, in the field of cable transport, is responsible for safety, interoperability, and technical coherence of rail transport as well as for issuing licenses and certificates to train drivers. In the field of cableways intended for passenger transport, UTK is a body specialized in conformity assessment, authorization, and notification, as well as control of compliance by these railways with essential and detailed requirements.

The analysis of the current duties and competencies of the above-mentioned entities responsible for the supervision of cableways showed that in the event of the introduction of a new transport system, which is a monorail, it will be necessary to expand the qualifications and increase the staff.

Summary

Monorail can be considered one of the safest means of transport in the world. The design and route of the route allow for tracing lines with large longitudinal slopes (up to 6-10%), small radius of bends (minimum turning radius 50 m), additionally they prevent collisions with other means of transport, which is why monorail is often chosen in dense agglomerations, business centers, and residential areas. The most widespread monorail system used all over the world is the fifth wheel system - ALWEG, while the SAFEGE system (suspended type) is most often used in locations with less favorable weather conditions. The offered monorail solutions are complete, i.e. they include all the elements necessary for the operation of the system, i.e. vehicles, infrastructure, stations, power supply, and traffic control systems..

In Polish law, there are already general provisions that define and define monorail. However, to enable the development of this technology in Poland, it is necessary to introduce executive regulations that define the basic requirements, construction and safety rules, and other necessary solutions necessary to launch this means of transport in Poland. The launch of the monorail in Poland will also involve the introduction of regulations extending the competencies of the authorities responsible for safety in rail transport (TDT, UTK).

It seems reasonable that a monorail should be treated in a similar way to a cable car, with some solutions borrowed from the classic ones (safety issues, risk assessment, or flammability of materials).

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