Development of transport infrastructure of urban mobility based on cable metro technology

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Abstract. The article presents materials on the use of cable metro technology in a highly urbanized environment, as an improvement in urban mobility in the format of a smart city. The presented transport system is significantly different from the traditional cablecar, which is described in the comparative characteristics of each system. The article describes the principle of operation of the cable metro, based on the use of mechatronic motion modules.

1. Introduction
Social and economic transformations, together with achievements in the field of transport technologies, social networks, wireless services and cloud spaces, contribute to the growth of human mobility in the urban environment. More and more people use Web applications, choosing the most convenient option for moving, optimizing it for cost, travel time, waiting time, number of transfers, etc.

According to the results of a social survey [1], 83\% of respondents said that innovative transport is a key feature of a smart city, and almost half (45\%) of the respondents believe that the city can never reach a world class level without good digital communications.

Currently, smart cities are characterized by six key indicators - smart economy, smart mobility, smart environment, smart people, smart living, smart government.

Each indicator is determined by factors. There are special indicators to assess the level of development of a factor in a particular city. Of the six key characteristics, let us focus on smart mobility [2]. To assess the level of smart mobility in practice for a particular city, we use the following factors:

1) the ability to easily get to all areas and significant places of the city;
2) openness and accessibility of the city at the national and international levels;
3) the availability of information infrastructure (Internet, GLONASS, GPS, etc.);
4) the availability of a sustainable, innovative and safe transport system.

Mobility is a key component of a “smart city”, which must be adapted to the information infrastructure of the city. Public transport is the most effective way of moving a person in megacities.

With the development of transport technologies, a new type of passengers appears who are configured to receive information about the route in real time and no longer want to travel without continuously receiving data throughout their movement.
Transport logistics are becoming a “multimodal multiplier” for smart cities, increasing the efficiency of public transport [3,4]. Digitization of the urban transport system through real-time information transfer, the introduction of mobile applications and other technologies improves the quality of passenger service and allows them to receive more thoughtful and effective solutions along the travel route. By receiving and using real-time data using predictive analytics, transporters can significantly change their work in a positive direction.

Public transport, cities and society are on the verge of rapid change, as advances in mobility and technology are increasingly used in our lives. The growth of urbanization in our cities will continue to influence the development of innovations in the transport sector [5,6].

2. Analysis of the transport infrastructure of urban mobility

Today, engineering can offer a person different options to move in an urbanized environment: railways, road, water, air transport, high-speed railways, magnetic suspension trains, monorail, trolleybus, high-speed tram, rail bus, string transport, cable cars. 13 structurally different modes of transport in total. Together with various constructive options, there about 200 ideas. Each has its own advantages and disadvantages.

Unfortunately, no type of transport meets the current requirements for the creation of efficient means of transportation for the conditions of large cities, megacities and urban agglomerations, which must combine environmental friendliness, safety and speed of movement of passengers, low economic characteristics of transporting passengers and cargo. Constant traffic jams, gas contamination of streets and other inconveniences of urban movement is an objective initiator of the development of new innovative types of urban transport (Figure 1).

Figure 1. Movement in an urbanized environment.

The logical direction of the fundamental overcoming of the problems associated with the use of ground public transport is the transition to another high-altitude level. The transfer of traffic flows to urban overground space still remains a promising, but little developed direction for improving the transport infrastructure of modern cities. Technically, this can be realized using cable transport technologies. One of the innovative modes of transport, which began to be introduced in the city of Moscow, is the cable cars used as urban transport.

3. Cable car technology

The cable metro is an innovative type of cable transport [5,6] (a type of passenger cable car), and is designed to carry passengers in an urbanized environment, between settlements and directly in megacities located on rough terrain, including those with the presence of water barriers (river, lake, swamp, bay, etc.), as well as trunk lines, transport and waterways, high-voltage power lines, oil, gas, water pipes, high-rise buildings and structures, taking into account safe dimensions of approximation.
The main difference between the cable metro and traditional passenger cable cars is the presence of intermediate stations designed not only for boarding and disembarking passengers in rolling stock, but also, which is a fundamental difference, for transferring passengers to other directions and forwarding the rolling stock to other routes, and also almost infinite length of transportation of rolling stock by one traction rope. A mechatronic distributed drive (“active roller battery”), installed discretely at intermediate stations or linear supports, acts as the mover of the traction rope. The design of overhead cable cars with respect to the possibility of using it as public passenger transport in large metropolitan cities, urban agglomerations and within natural territories was protected by a number of patents [3,7].

Actually, the term “cable metro” was introduced into use in scientific works [3,4,7] in the process of solving the following engineering problem: the creation of a universal passenger public transport system for an urbanized environment based on the mechatronic modular design and construction principle with the possibility of unlimited completion without limiting the shape of the profile of transport lines in plan and height, without limiting the length of the path in space, without limiting the number and configuration of special nodal stations of transport lines.

The transport system, which general structural diagram is shown in Figure 2 includes a path supported by intermediate supports, and the vehicle in the form of passenger cars is a mechatronic system. It contains mechatronic motion modules interconnected by a mechanical link in the form of a path consisting of one or more strands of an annular traction rope, and a control system based on a hierarchical decentralized network with a single protocol for the exchange of information between mechatronic modules.
Figure 2. The general structural diagram of the cable metro. Despite the fact that the cable metro looks like a traditional suspended cable car, it is based on either new or fundamentally different technical solutions (see Table 1) [12].
### Table 1. Comparative characteristics of the cable metro and passenger cableway.

|                     | Passenger cableway | Cable metro |
|---------------------|--------------------|-------------|
| **Disadvantage:**   | the use of obsolete equipment. | Advantage: the use of mechatronic technologies to create a controlled multi-rope transport system in an urbanized environment. |
| **Disadvantage:**   | limited length of the transportation route. | Advantage: unlimited length of the route, the ability to continue the metro line with the expansion of urban development. |
| **Reason:**         | the presence of one concentrated drive traction rope movement. | Reason: mechatronic motion modules implement the idea of a drive linearly distributed along the route for driving passenger cabins. |
| **Negative consequences:** | 1) with an increase in the length of the ropeway, the power of its drive increases, as well as the dimensions of the equipment and supporting metal structures and, as a result, the cost indicators of the project; 2) ropes of great length require ropes of great aggregate strength, which leads to an increase in the mass and cost of the rope, drive and metal structures; 3) therefore, on the long routes, several cable cars are installed one after another; 4) it is energy-consuming, expensive and time-consuming during construction, especially in urban environments. | Positive effects: 1) low power of one mechatronic module, since it provides the movement of the traction rope in a limited section of the route; 2) lower total power and energy consumption of mechatronic modules in comparison with traditional single drive on equal length paths (up to 30%); 3) small overall dimensions of equipment and supporting metal structures; 4) the possibility of using traction and load-bearing ropes of lower aggregate strength and, accordingly, a smaller diameter (3-5 times), dead weight (up to 7 times) and cost; 5) the possibility of increasing the distance between adjacent supporting metal structures along the route up to 3000 m; 6) improvement of dynamic characteristics by reducing the mass of moving elements. |
Table 1.

| Disadvantage: predominantly linear trajectory for passenger cabs. | Advantage: the ability to create any routes within the entire system of cable lines, including ring routes (i.e., the logistic capabilities of the cable metro are equivalent to traditional modes of transport). |
| --- | --- |
| Reason: the reciprocating movement of the traction rope between the two end points of the route. | Reason: the presence of devices to reorient the direction of movement of passenger cabins. |
| Negative consequences: 1) the lack of the ability to switch from one line of the cable car to another without a transfer; 2) the impossibility of forming an arbitrary or circular transport route. | Positive effects: 1) the ability to transfer passenger cabins to another line of the cable metro at junction stations without transferring passengers; 2) the possibility of creating sludge points for passenger cabins during the period of reduced passenger flow on the line; 3) the possibility of rapid transfer of cabins on the line of increased passenger flow, at rush hour, etc. |

Disadvantage: a complete stop of the movement of all passenger cabs on the line in the event of a drive failure of the traction rope movement.

Reason: the presence of one concentrated drive traction rope.

Negative consequences: 1) the need for urgent one-time emergency rescue and repair work along the length of the route; 2) a long duration of emergency rescue operations, disruption of passenger plans, delay, etc.; 3) a rather difficult psychological situation for passengers; 4) difficulties in organizing the system of maintenance and repair of the cableway, because carrying out these works requires stopping cabs.

Advantage: almost zero probability of cabs stopping in case of failure of the traction rope drive.

Reason: the presence of a cab motion drive linearly distributed along the route based on a plurality of mechatronic motion modules. Positive effects: 1) there is no need for urgent repair of the failed mechatronic motion module and emergency rescue operations; 2) the possibility of organizing a high-quality system of maintenance and repair of mechatronic motion modules, because its implementation is possible during the operation of the cable metro without stopping it; 3) the absence of psychological consequences and inconvenience for passengers in case of failure of the mechatronic motion module.
Table 1.

| Disadvantage | Advantage |
|--------------|-----------|
| the inability to stop the cab at the station for boarding and unloading passengers. | the ability to stop the cab at the station for boarding and unloading passengers. |
| Reason: one-piece connection of the passenger cabin to a constantly moving traction rope. | Reason: the presence of an automated control system for the movement of cabs that tracks their location and automatically performs the connection-disconnection of the cabin from a constantly moving rope. |

Negative consequences:
1) unsafe when boarding and disembarking passengers on the go;
2) it is impossible to arrange the landing of disabled people and persons with disabilities, children, passengers with prams and bulky luggage, etc.;
3) when landing several people, it is necessary to move after the cabin;
4) it is impossible to use cabins of profitable capacity (30 ... 40 people).

Positive effects:
1) the complete safety of boarding and unloading passengers in a stopped cabin;
2) safe landing of disabled people and persons with disabilities, children, passengers with prams and bulky luggage, etc.;
3) it is possible to use passenger cabins of profitable capacity (30-40 people each).

Disadvantage: lack of an automated cab movement control system. | Advantage: the presence of an automated control system for the movement of cabs. |
| Reason: the “rigid” scheme of the cableway, not implying the possibility of significant regulation of traffic parameters. | Reason: the use of information technology based on RFID tags (transponders) integrated into the traction rope and forming a solid track structure. |

Negative consequences:
1) the inability to ensure the required level of comfort and safety of passengers;
2) the inability to control the movement parameters of passenger cabins, including their stopping time, speed, etc.

Positive effects:
1) increased safety of movement;
2) the ability to track the movement and control the movement of each passenger cabin, including its location, speed, the need to stop;
3) identification of cases of disturbance in public order in the cabs, video detection and detention of violators.

4. Design features of the cable metro
The mechatronic module of the cable car is equipped with an acceleration and deceleration engine and automatic grips (Figure 3). They are mounted on the carriage, and in their number and size correspond to the threads of the annular traction rope with vehicles suspended in the form of passenger cars. Automatic grippers interact with a gripper actuation device mounted on intermediate supports.
The considered transport system of the cable metro works as follows. The paths for the passenger cab vehicles are made of strands of an annular traction rope passing over a land-based urbanized infrastructure, taking into account the permissible dimensions for approaching various types of infrastructural facilities, including those that can be based on them. The strands of the annular traction rope are connected to the vehicle by means of a carriage and automatic grippers installed on it. Pulling force or braking force on the threads of the annular traction rope is created by mechatronic modules of the annular traction rope located on the intermediate supports.

The control system uses a decentralized network with a single information exchange protocol (for example, PROFIBUS). It has an economic advantage in terms of reducing prices by reducing cable connection and reducing footprint, as well as a technological advantage in terms of reducing debugging and commissioning times, flexibility to connect additional devices to the control system, and the possibility of developing system intelligence when realizing automation tasks outside CPU unit using multifunctional controllers.

The presence of the mechatronic module of the station allows us to change the route of movement of passenger cars to other paths due to automatic “arrows” of entry-exit, paired with one of the hard tracks of the corresponding route. This function allows passengers to minimize travel time between the start and end points of the route.

Currently, several technical solutions are known aimed at the development and improvement of certain aspects of cable cars for urban environments, which should be considered as directly related to the concept of "cable metro".

A further development of the ideology of creating urban cableways for passenger transport in an urbanized environment, based on innovative technology of the cable metro, is a cableway with mechatronic propulsion devices [8,10]. The proposed technical solution is aimed at improving the reliability, safety and efficiency of controlling the mechanisms of movement of the cableway and ensuring uniform load distribution between the drives, eliminating excessive sagging and tension of the traction rope.

5. Examples of urban mobility transport infrastructure projects based on cable metro technology

To confirm the operability and verify the effectiveness of the Cable Metro transport system, the authors develop schemes for its implementation in a number of Russian cities, including Bryansk, Rostov-on-Don, St. Petersburg, Stavropol, Moscow, Sevastopol, Sochi, Yekaterinburg, Krasnoyarsk, Novocherkassk, Skolkovo, taking into account their natural and geographical features, as well as the terrain, the specifics of urban development and the location of communal infrastructure.

The concept of innovative urban transport for the development of the cable metro network in Rostov-on-Don was developed at the Don State Technical University [9].
For the developed routes we propose typical architectural and planning solutions of cable metro stations (Figure 4), integrated into the existing street and transport infrastructure of Rostov-on-Don. At cable metro stations, it is possible to place commercial and socially-oriented infrastructure for passengers in the form of cafes, shops, pharmacies, payment centers, bank branches, toilets, etc. (Figure 5).

Figure 4. Three-dimensional model of intermediate supports and rolling stock cable cars integrated in the street network of Rostov-on-Don:
    a – Krasnoarmeiskaya str.; b - Nagibina str.

Figure 5. Three-dimensional model of the internal view of the cable metro stations.

Bryansk is an ideal city for the construction of the cable metro, since in relation to its development and relief, the conditions that are necessary for the most efficient functioning of the cable metro are well suited [11]. At the same time, these same features of the city’s development and topography are a barrier to the development of its transport infrastructure based on traditional types of automobile and electric transport. The existing transport infrastructure of Bryansk is complicated by the fact that the territory of the city has significant area, and four districts are separated from each other by the Desna, Bolva and Snezhet rivers with wide floodplains and an extensive network of railways with bridges and overpasses. Due to the imperfection of the planning structure, the backbone network of the center of Bryansk is heavily congested with transit traffic. During peak hours, the speed of vehicles does not exceed 20 km/h.

Under the conditions of dense urban development in the city of Bryansk, inter-city transportation based on traditional types of ground transport has practically exhausted its capabilities for the development of passenger traffic. The growth in road transport is accompanied by an increase in the number of cars on the road. In relation to 2009, in 2018 there was an increase in the number of cars by 34%, trucks - by 38%, buses - by 20%. At the same time, the total number of passengers transported by
road and trolleybus public transport decreased from 78 million to 65.5 million, which could obviously be associated with the development of personal motor transport of city residents, leading to an additional increase in the load on the transport infrastructure of the city [11].

Taking into account the passenger flows in Bryansk, Bryansk State University named after academician I.G. Petrovsky made a preliminary assessment of the number and possible locations of the cable metro lines (Figure 6).

![Figure 6. The location of cable metro lines in Bryansk.](image)

The project for the construction of a passenger cable transport system based on cable metro technology for the city of Yekaterinburg was developed at the Novocherkassk ICC “Mysl” and LLC “Skado” in conjunction with CJSC “Ural Expert Center” (Figure 7)
Figure 7. Cable car line in Yekaterinburg along the river.

In relation to the conditions of the city of Yekaterinburg, a passenger cable car transport suspension system based on the cable metro operates as follows. Passengers come by underground metro to the Botanicheskaya station in Yekaterinburg, either by commuter trains, or by personal cars and place them in multi-storey car parks, or come to shopping centers. All of the above facilities are connected by the transport system module integrated into the passenger transport logistics of the city of Yekaterinburg. Station modules have different geometric shapes in plan and an unlimited number of levels in height for their integration into the prevailing architectural appearance of an urbanized environment, forming multimodal complexes, which allows passengers to comfortably make transfers and minimize routes when changing the mode of transport.

The project for the construction of a passenger cable transport system based on cable metro technology for the city of Yekaterinburg is integrated in the logistics of passenger transport. It suggests that one of the multimodal complexes of the cableway metro transport system should be combined with the Botanicheskaya metro station, and the path should go along Shcherbakova Street to Zimnyaya Street, with a subsequent continuation to Himmash and the Utkus skiing complex. Within the limits of the city territory, a cable metro line crosses the water barrier - the floodplain of the Iset River.

6. Conclusion

The innovative transport system "cable metro" is an important element in the development of transport infrastructure of urban mobility and can be used in the technology of "smart city", as it has several advantages over other modes of transport.

Technical and economic calculations of the expected values of the characteristics of the passenger transport system "Cable Metro" showed that it has the following characteristics [3,5,7]:

- maximum passenger traffic - 3.0 thousand passengers / hour;
- construction cost of 1 km of track - 0.3 billion rubles;
- maximum speed - 40 km / h;
- average speed - 34 km / h;
- energy efficiency coefficient - 0.42;
- specific energy consumption - 25 W • h / t • km;
• the cost of 1 pass. / km - 2.0 rubles;
• the present value of the organization of movement at the maximum passenger flow is 1.8 thousand rubles / pass.;
• present value of rolling stock - 0.4 thousand rubles / pass. / year;
• specific energy consumption - 0.3 ... 0.5 L/100 pass. / Km;
• area occupied by 1 passengers on the street - 0 m².

A comparison of the cable metro and traditional forms of urban transport for a number of basic technical and economic indicators allows us to formulate the following advantages of the cable metro:

• social:
  o the fare is at the level of traditional types of urban public transport;
  o speed (up to 50 ... 60 km / h) and clear predictability of travel time due to the absence of undetermined downtime in traffic jams, at traffic lights, etc.:
    o absence of loss of time for forced downtime and waiting in traffic jams;
    o convenience of embarkation and disembarkation, including for people with disabilities;
    o comfort and safety of movement, as the rolling stock has a smooth ride and there is no likelihood of a collision with another vehicle;
  o the ability to carry hand luggage and bulky goods;
• technical:
  o movement above the ground without intersection with the routes of other types of urban public, freight and special transport;
    o lack of traffic accidents;
    o creation of direct routes of any configuration;
  o relative energy consumption for moving (up to 40 km / h) is 5 ... 10 times lower than that of a modern car;
    o practically insensitive to terrain, ground and underground objects and communications;
    o the existing road-street network and engineering infrastructure are not violated;
    o fits well with the architectural look of the city;
    o construction of bridges, overpasses, embankments and tunnels is not required;
    o volumetric excavation, violating the landscape and requiring subsequent restoration, is not required;
  o resistance to the effects of adverse climatic factors and natural disasters (earthquakes, floods, landslides, hurricane winds, low or high ambient temperatures, etc.);
    o the use of electric traction, which does not adversely affect the environment, low noise and vibration, the absence of harmful emissions;
  o minimal need for building materials and structures, relatively low consumption of structural steels, non-ferrous metals, semi-finished products and building materials;
• economic:
  o relatively low cost of design and construction (up to 30 million rubles / 1 km of track);
  o the cost of constructing a highway with infrastructure 2 ... 5 times cheaper than modern railways and roads;
  o lowest costs for the organization of movement and the purchase of rolling stock;
  o the lowest specific consumption and the highest energy utilization coefficient for the transportation of 1 passenger;
  o savings in travel costs through the introduction of energy-efficient technologies and independence from petroleum products;
  o minimal land allocation (on average 0.1 hectares of land per 1 km of the route);
  o no redemption or alienation of expensive land plots, demolition of existing buildings and structures for laying a ground road is required;
a significant part of the areas of landing stations can be leased and used for commercial or other purposes.

An analysis of the conditions of the most appropriate use of the cable metro as an innovative transport system for regular passenger traffic, carried out in a number of works, showed that the cable metro works most effectively in cases where other types of urban transport are ineffective, in particular:

- in the presence of dense urban development with the presence of relatively narrow streets (2 ... 4 lanes for traffic);
- in the conditions of spatial dispersion of urban areas in the absence or insufficiency of alternative highways between them;
- in case of difficulty or inability to lay new highways within the urban area or between remote urban areas or satellite cities within the urban area;
- if there are wide rivers or river floodplains within the city limits;
- with a ravine or hilly terrain;
- to effectively solve the problem of ensuring environmental protection from the harmful effects of transport infrastructure on human living conditions and the environment.

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