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Design of an electric propulsion system for a subway-type means of transport

Diseño del sistema de propulsión eléctrico para medio de transporte tipo metro

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Abstract: This document presents the design of an electric propulsion system for a metro-type transport. For this design, a route was proposed that evaluates the energy demand of passenger mobility in the city of Villavicencio (Colombia). The foregoing allows choosing the technical characteristics necessary to satisfy the quality of the service provided. For this, a mathematical model of the longitudinal dynamics of the vehicle was exposed, which studies the forces of interaction through Gillespie simulation, obtaining relevant information on its behavior compared to its operation, the above is determined by means of a computer simulation. The energy study performs the reading of the altimetry data of the chosen route, together with the inclination angles, through the variation of heights and distances. The simulated simulation executes the different data of the chosen train together with its respective trailer, following the trajectory of the chosen route, in order to quantify the forces, power and energy necessary to carry out the total route.

Keywords: Design, Energy efficiency, Vehicle electrification, Propulsion system, Sustainable transport.

Resumen: Este documento presenta el diseño de un sistema de propulsión eléctrico para un transporte tipo metro. Para este diseño se planteó una ruta que evalúa la demanda energética de la movilidad de pasajeros en la ciudad de Villavicencio (Colombia). Lo anterior permite elegir las características técnicas necesarias para satisfacer la calidad de servicio brindado. Para esto se expuso un modelo matemático de la dinámica longitudinal del vehículo que estudia las fuerzas de interacción mediante la ecuación de Gillespie, permitiendo obtener información relevante de su comportamiento frente a su operación, lo anterior se determina mediante una simulación computacional. El estudio energético realiza la lectura de los datos de altimetría de la ruta elegida, junto con los ángulos de inclinación, por medio de la variación de alturas y distancias. La simulación diseñada ejecuta los diferentes datos del tren elegido junto a su respectivo remolque, siguiendo la trayectoria de la ruta elegida, con el fin de cuantificar las fuerzas, potencia y energía necesarias para realizar el recorrido total.

Palabras clave: Diseño, Eficiencia energética, Electrificación vehicular, Sistema propulsión, Transporte sostenible.

1. INTRODUCTION

In recent years, global freight and passenger transportation has increased mainly in urban areas [1], [2], generating high traffic congestion and low energy efficiency. Therefore, different studies are trying to look for energy sustainability within automotive propulsion systems [3]. The automotive industry is one of the most energy-consuming industries, so lately research is trying to find affordable, sustainable and reliable solutions by providing alternatives to the use of petroleum-based fuels [4], [5].

Transportation is one of the largest consumers of energy and producers of greenhouse gas emissions, [6], [7]. In order to reduce these high consumptions and emissions, strategic models need to be designed for technological intervention, such as the electrification of used engines [8], [9], and improvements in the longitudinal dynamics of vehicles, in order to optimize performance standards during operation [10], [11].

Looking for more efficient options in passenger mobility, we have one of the oldest and most used, such as "the train", due to the possibility of transporting large weights in load and giving an energetically viable option in mass passenger transportation [12], [13]. Over time, this type of transportation has undergone technological improvements, especially in its energy source, using electric energy as shown in [14], [15].

An important precedent is given with the project presented in Portland Oregon, in which data were taken for modeling the energy consumption of an electric train taking into account the efficiency of instantaneous regenerative braking. It was found that energy recovery reduces the total energy consumption by 20%, thus improving the energy efficiency of the system [16].

On the other hand, in Ukraine, diesel shunting locomotives were modernized by replacing a direct current generator with an asynchronous electric traction motor, thus reducing energy consumption, improving efficiency and reducing the negative impact of the railway system on the environment [17].

With the urban rail system in China, more than 35 cities were expanded with new metro lines [18]. The first energy tramway with electric double-layer capacitor (EDLC) was realized in Guangzhou Metro Corp. by Zhuzhou Electric Locomotive CO, generating energy efficiency and network performance. It generated the design of a stationary charging station for urban rail vehicles with the EDLC storage system.

The stationary charging station is designed with two small chargers in parallel. The circuit topology of each charger is simplified, optimizing costs and improving reliability. A hybrid charging station is intended to be realized in the future, which requires further research [19].

Studies have been conducted on the advantages of having hybrid vehicles, giving the possibility of having a greater opportunity in the automotive market [20], [21]. This allows generating lower maintenance costs, and in turn, improving the environmental impact generated by the continuous emission of particulate gases from fully combustion vehicles such as those seen in [22]-[24].

There are several software and hardware tools that model the operation of the electric drive, where you can perform a computer analysis of the behavior of the designs made, in order to obtain a more efficient design, as demonstrated [25]-[27], a subway power supply system is described a model for a traction motor control system, thus performing different calculations with different loads, this in order to make better use of power [28]-[30].

In 2016, the international congress of industrial engineering, applications and manufacturing, presented a paper where a real-time simulator was projected, demonstrating the different mathematical models with different types of electric drive for a shunting locomotive [31].

2. METHODOLOGY

Based on information from a train manufacturer with an excellent track record in mobility, it was decided to search for a train that complies with the specifications of a diesel engine, with the objective of seeing a change when the transition to an electric system is made. Table 1 shows all the specifications and technical characteristics of the chosen train series.

Table 1: *Technical Specifications*

DATA SHEET (9000 SERIES)	
BUILDERS	
Mechanical parts	Alsthom
Diesel Engine	S.A.C.M
Transmission	Alsthom
Brake	Jourdain-Monneret
GENERAL INFORMATION	
Locomotive Type	BB 48 t
Rated Power (wheels)	625 CV
Wheel Diameter	950 mm
Pneumatic Brake	DUAL Air and Vacuum
Dynamic Brake	Does not have
Sandboxes (number)	4
Dead Man System	Hollande type
Multiple Command	Up to 2
Speed Recorder	Teloc
TRACTION	
Maximum Speed	70 km/h
Tensile stress Start-up	11.500 Kg
Tensile Stress Continuous	11.000 Kg
Tensile Stress at Max. Speed.	2.400 Kg
DIESEL ENGINE	
Quantity	1
Builder	S.A.C.M.
Tipe	MGO V 12 ASHR
Number of Times	4
Number of Cylinders	V 12
Nominal Power	925 CV
Nominal Speed	1.500 rpm
Power Utilization	850 CV

Within the technical specifications of the train, the manufacturer Alstom was chosen for the transmission and mechanical parts, and for the diesel engine, the company S.A.C.M. These factories have worldwide recognition in their respective areas.

2.1. Route and dimensions

In this phase of the project, we proceed to the definition and detailed establishment of the fundamental requirements that will guide the development of the prototype, which are classified in four categories:

1. User´s: Focus on the specific needs and preferences of the end users of the system, ensuring an intuitive and satisfying experience.
2. Functional: They detail the specific functions and operations that the system must perform to fulfill its main purpose.
3. Quality: They establish criteria and standards that will guarantee the efficiency, reliability and safety of the system.
4. Implementation: Addresses practical and technical considerations essential for the successful execution of the project.

This requirements definition process lays the foundation for a structured and results-oriented development, aligned with the key expectations and needs identified.

As is known, in Colombia, the Medellin subway is used as a reference, which was taken into account for the maximum number of wagons chosen for the proposed design.

The project is to be established in the city of Villavicencio (Colombia), which has one-eighth of the inhabitants of the city of Medellín (531,275). The rail line will be established between the Porfía neighborhood and the city center, due to the high traffic congestion in this area. The train will be designed with 2 traction wagons and 2 trailer wagons.

The dimensions of the proposed train are shown in Table 2.

Table 2: *Train dimensions*

DIMENSIONS TRACTION	
Weight	11.5 Tn
Height	3.7 m
Width	2.8 m
Length	11.36 m
TRAILER DIMENSIONS	
Weight	6.5 Tn
Height	3.9 m
Width	2.9 m
Length	20.49 m

Source: *own elaboration.*

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2.2. Mathematical model

To start the mathematical model, the loads or forces on the vehicle axle are determined, being fundamental the analysis of the acceleration and braking performance. These analyses determine the axle loads and tractive effort that affect acceleration, slope, maximum speed and drawbar effort. Fig. 1 shows the free body diagram of the complete vehicle train.

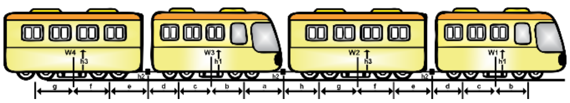

Fig. 1. Free body diagram of the complete train

In order to find the equations for the slope capacity, first the free body analysis of each of the wagons (trailer and traction) is performed to find the forces.

The free body diagram of wagon 1 (traction) is shown in Fig. 2.

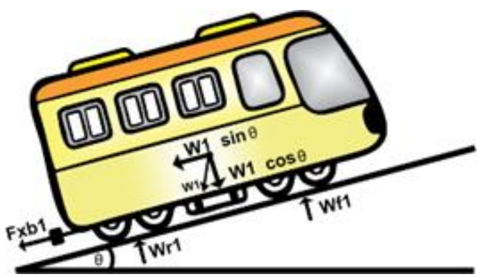

Fig. 2. Free body diagram wagon 1 (traction)

Taking the moments on the contact point of the rear tire, as shown in equation (1), we obtain:

$$\sum Ty = 0 = W1h1sin\theta - W1Ccos\theta + Fxb1h2 \ + Wf1(b+c) \quad (1)$$

On the other hand, the moments on the front axle of the traction wagon is obtained using equation (2):

$$\sum Ty = 0 = W1h1sin\theta + W1bcos\theta + Fxb1h2 + Wfr1(b+c) \quad (2)$$

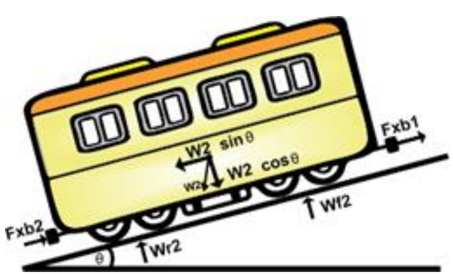

Fig. 3. Free body diagram wagon 2 (Trailer)

As for the moments on the contact point of the rear tire of the trailer wagon, equation (3) is obtained. The free body diagram of wagon 2 (trailer) is shown in Fig. 3.

$$\sum Ty2 = 0 = W2h3sin\theta - W2gcos\theta - Fxb2h3 - Fxb1h3 + Wf2(g+f) \quad (3)$$

The moments on the front axle of wagon 2 (trailer), equation (4) is obtained:

$$\sum Ty2 = 0 = W2h3sin\theta + W2fcos\theta - Fxb2h2 - Fxb1h3 + Wfr2(g+f) \quad (4)$$

As shown in equation (5), the equilibrium of forces along the longitudinal axis of the train trailer is obtained. Fig. 4 presents the free body diagram of wagon 3 (traction).

$$\sum Fx = 0 = Fxb1 + fxb2 - W2sin\theta \quad (5)$$

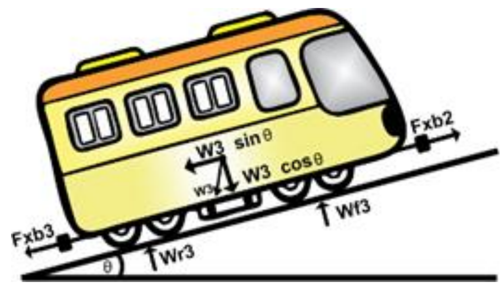

Fig. 4. Free body diagram wagon 3(traction)

Taking moments on the contact point of the rear tire of the traction wagon 3, equation (6) is obtained:

$$\sum Ty3 = 0 = W3h1sin\theta - W3Ccos\theta + Fxb3h2\ fxb2h2 + Wf3(b+c) \quad (6)$$

Taking the moments at the contact point of the rear tire of traction wagon 3, equation (6) is obtained.

$$\sum Ty3 = 0 = W3h1sin\theta + W3bcos\theta + Fxb3h2 + fxb2h2 + Wfr3(b+c) \quad (7)$$

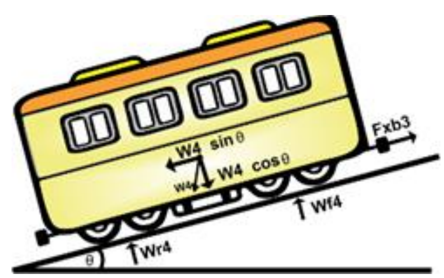

Fig. 5. Free body diagram wagon 4 (Trailer)

Taking moments on the contact point of the rear tire of the trailer wagon 4, equation (8) is obtained:

$$\sum Ty4 = 0 = W4h3sin\theta - W2gcos\theta - Fxb3h3 + Wf2(g+f) \quad (8)$$

Finally, the moments on the front axle of the trailer wagon 4 are obtained by equation (9):

$$\sum Ty4 = 0 = W4h3sin\theta + W2fcos\theta - Fxb3h3 + Wfr2(g + f) \quad (9)$$

Equation (10) gives the equilibrium of forces along the longitudinal axis of wagon 4 (trailer).

$$\sum Fx = 0 = fxb3 - W4sin\theta \quad (10)$$

It is essential to understand the importance of vehicle dynamics. Thomas D. Gillespie stated the equation (11) that provides an expression for the tractive force that can be obtained from the engine.

$$Max = \frac{W}{g}ax = Fx - Rx - DA - Rhx - W\ sin\theta \quad (11)$$

Where:

M = Mass of the vehicle - W/g

ax = Longitudinal acceleration (meters/sec2)

Fx = Traction force on the ground

Rx = Rolling resistance forces

DA = Aerodynamic drag force

Rhx = Hitching forces (towing)

Ø= Angle of inclination of the route

2.3. Altimetry

According to the trajectory defined for the simulation of the project, Google Earth is used as a computational tool to take the height and distance of the route, presented in Fig. 6 and Fig. 7. These data are organized in an Excel table for analysis in Matlab®, where we proceed further to calculate the angle.

Fig. 6. Route traced

Fig. 7. Height and distance of the route

2.4. Stations

From the above, the projection of the first metro line was made, having a total distance of 9 km, according to the pre-established route, selecting 10 stations along the route with a separation between them of 1 km, which are listed as follows:

1. Ciudad Porfia
2. Roundabout entrance to Ciudad Porfia
3. Samán de la Rivera
4. Montecarlo sector 3
5. Gazel Gasoline Station
6. Serramonte 1
7. Fundadores park
8. Llanocentro
9. Unicentro
10. Fire Station

2.5. Topology

For this electric propulsion system, a conventional three-phase inverter topology was chosen, in order to convert the energy supplied by the catenary or batteries to the AC motors, as shown in Fig. 8. The conventional bidirectional three-phase inverter allows transforming the power from the alternating current source and vice versa, thus taking advantage of the moments where regeneration occurs due to the negative powers during the subway route in the different stretches between stations.

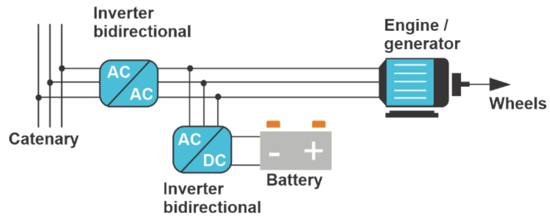

Fig. 8. Bi-directional inverter topology driving the AC motor

3. RESULTS

According to the data obtained from the train, in addition to the altimetry data, it was organized and entered into the chosen program, in this case Matlab®. From the above, different results were obtained following the methodology described below:

Altimetry data were entered into Matlab®, performing an interpolation to obtain a greater number of samples to the original entered, from 163 data to 936 data, shown in Fig. 9.

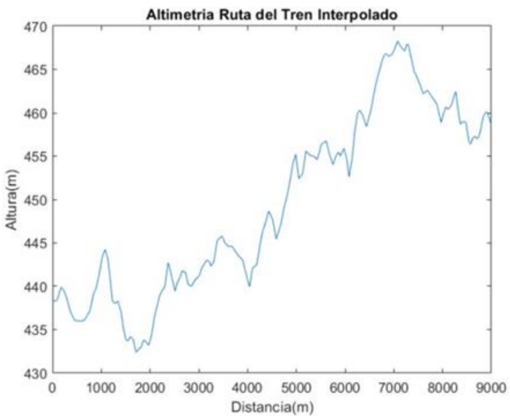

Fig. 9. *Altimetry of the preselected route for the metro line.*

According to the above, we proceeded to find the different angles during the course by means of the inverse trigonometric tangent inverse function. To achieve this, the angles for each section are divided in order to analyze the so-called driving cycle. As each station has on average a distance of 1 km, the driving cycle is standard for each leg. Fig. 10 shows the driving cycle with respect to the time per section traveled, with a maximum speed of 70 km/h.

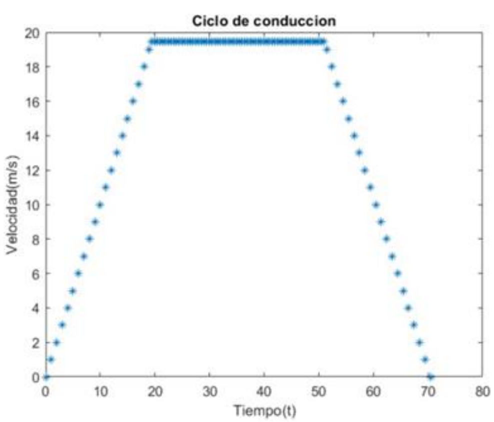

Fig. 10. *Driving cycle*

On the other hand, the forces exerted by the train in each section were found by means of equation (11), from which it was obtained that during the route in section 1 (located between the Ciudad Porfía station and Roundabout entrance to Ciudad Porfia) there is a greater applied force of 16.1 kNm, as shown in Fig. 11. The force is higher due to the need for the train to overcome a route with a greater degree of inclination.

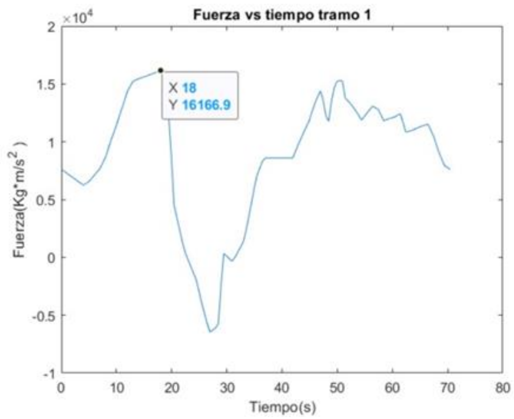

Fig. 11. *Highest force obtained pre-selected route. Section 1*

Similarly, the section where the subway has the highest total force consumed during the route is analyzed, spending 959.04 kNm (from Gazel Gasoline Station to Serramonte 1 Station), as a result of overcoming the altimetry to accelerate the train. See Fig. 12.

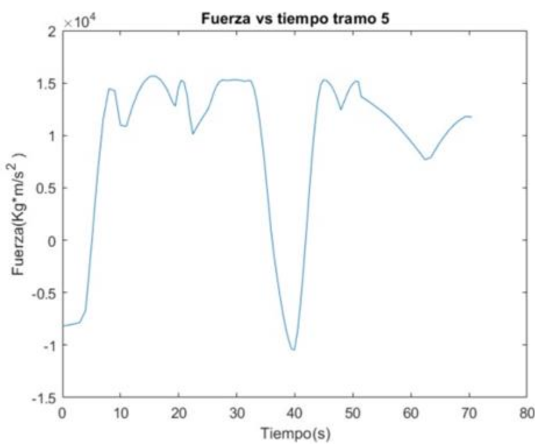

Fig. 12. *The most power consumed in a route section. Section 5*

With the above, we proceed to calculate the different powers consumed during the tour of the stations, using equation (12), taking as a reference the driving cycle shown in Fig. 10.

$$P = F * V \tag{12}$$

On the other hand, the maximum power (Pmax) consumed by the metro during the trip is determined. This high consumption occurs between Ciudad Porfía station and Roundabout entrance to Ciudad Porfia, with a value of 301 kW. This parameter allows the selection of the propulsion motors. Fig. 13 shows the aforementioned section.

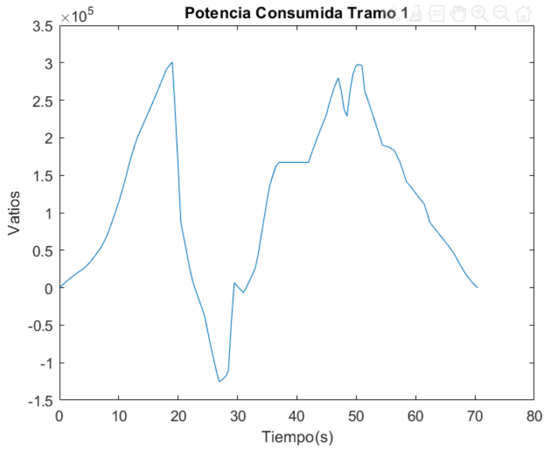

Fig. 13. *Section with the highest power consumption on the road. Section 1*

By design criteria, the power of the motors must be oversized by 10%, which is calculated above. Therefore, it is required that the four motors exert a total power of 331.1 kW, allowing an ideal performance during the driving cycle. After finding the power required for the displacement of the subway, it is integrated to quantify the energy consumption in each section, according to equation (13).

$$Etotal = \int_0^t Pdt \qquad (13)$$

When calculating the total energy consumed per section, it is determined that the maximum value is 4.45 kW/hour corresponding to section 5 (located from Gazel Gasoline Station to Serramonte 1 Station). Subsequently, performing an analysis of the average energy consumption between stations, the autonomy of an energy storage system for 500m is determined. From the above, a requirement of 2.23 kWh is obtained.

4. CONCLUSIONS

One of the advantages of this electric propulsion system, conversion system and Battery Energy Storage System (BESS), is that it has a higher energy efficiency than a combustion vehicle, close to 70%. In the case of the subway, it will have an exclusive lane without affecting the daily traffic. This advantage can be reflected in a decrease of stress caused by vehicular congestion and experiences in public service, making Villavicencio a more sustainable city with better quality of life.

The selection of the first metro line was established as a future mobility strategy between the sectors of Ciudad Porfía and the center of the city of Villavicencio. This is intended to improve the mobility of approximately 15,000 travelers during the metro service day (5 am to 11 pm), taking an average of 18 minutes between stations. It is important to highlight that the delay in conventional vehicular traffic (not motorcycles) would be approximately 30 minutes.

The project proposes four motors per wagon, with the Weg motor reference SD125363CQA being selected. These four motors add up to a total power of 480 kW to serve the metro with a maximum power consumption of 330 kW.

The topology chosen, conventional three-phase inverter, allows the use of the negative powers derived from the altimetry of the terrain and its kinetics, taking advantage of the bidirectionality of the energy flow.

In the event of a power failure, a battery system with an autonomy of 500 m is chosen, taking as a reference the stretch with the highest energy consumption for the necessary storage calculation. A battery with a capacity of 2.23 kWh at 12V and 200A is chosen. The selected reference is the LiFePO UU-200Gp battery.

Both routes, Ciudad Porfía - Centro and vice versa, were simulated, from which it is obtained that the energy consumption is lower (18.55 kWh) between the stations Centro to Porfía, compared to 26.32 kWh between Ciudad Porfía and Centro due to its altimetry is descending. This makes it possible to quantify 29.5% less energy consumption for this route.

As a recommendation for future projects oriented to massive electromobility of passengers, we recommend an analysis of metro materials to reduce its weight, making it a lighter vehicle.

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REFERENCES

[1] ABBEL, “Global mobility trends and analyses: The impact of COVID-19 on

mobility," netherlands, 2021. [Online]. Available: https://www.government.nl/documents/reports/2021/12/31/global-mobility-trends-and-analyses-the-impact-of-covid-19-on-mobility

[2] T. Denne and L. Wright, "Public and Passenger Transport : historical trends and drivers of deman," New zealand, 2017. [Online]. Available: https://www.researchgate.net/publication/315695317%0APublic

[3] J. W. Detlev Mohr, Vadim Pokotilo, "Urban Transportation Systems of 25 Global Cities," Nueva York, 2021. [Online]. Available: https://www.mckinsey.com/~/media/mckinsey/business functions/operations/our insights/building a transport system that works new charts five insights from our 25 city report new/elements-of-success-urban-transportation-systems-of-25-global-cities-july-2021

[4] D. Liyuan, Q. Yue, W. Wenjing, and Q. Guoliang, "Current situation of energy saving and emission reduction of urban public transportation and green development suggestion," in *International Conference on Intelligent Transportation, Big Data and Smart City, ICITBS 2016*, 2017, pp. 14–17. doi: 10.1109/ICITBS.2016.17.

[5] C. Di Palma, V. Galdi, V. Calderaro, and F. De Luca, "Driver Assistance System for Trams: Smart Tram in Smart Cities," Madrid, Spain, 2020. doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160780.

[6] M. Jacyna, M. Wasiak, K. Lewczuk, and G. Karoń, "Noise and environmental pollution from transport: Decisive problems in developing ecologically efficient transport systems," *J. Vibroengineering*, vol. 19, no. 7, pp. 5639–5655, 2017, doi: 10.21595/jve.2017.19371.

[7] R. Borck, "Public transport and urban pollution," *Reg. Sci. Urban Econ.*, vol. 77, pp. 356–366, 2019, doi: 10.1016/j.regsciurbeco.2019.06.005.

[8] M. P. Carter *et al.*, "Energy and Environment," in *PUBLIC TRANSPORTATION American Public Transportation Association Vice Presidents*, 55th ed., no. Marzo, American Public Transportation Association, 2004, pp. 26–27.

[9] M. Kubański, "Prospects for the Use of Electric Vehicles in Public Transport on the Example of the City of Czechowice-Dziedzice," *Transp. Res. Procedia*, vol. 44, no. 2019, pp. 110–114, 2020, doi: 10.1016/j.trpro.2020.02.016.

[10] V. Ferencey and M. Omachelová, "Mathematical modelling of the motion dynamics in the longitudinal direction of the electric vehicle," in *2016 Cybernetics and Informatics (k&I)*, 2016, pp. 1–6. doi: 10.1109/CYBERI.2016.7438632.

[11] D. Vosahlik, T. Hanis, and M. Hromcik, "Vehicle longitudinal dynamics control based on LQ," in *2019 22nd International Conference on Process Control (PC 19)*, 2019, pp. 179–184. doi: 10.1109/PC.2019.8815044.

[12] Vukan R. Vuchic, "Streetcars/Tramways," in *Urban Transit*, Copyright, Ed. New Jersey: Copyright, 2007, pp. 32–38. doi: 10.1201/9781420041217.ch61.

[13] S. Zieger y N. Niessen, "Opportunities and Challenges for the Demand-Responsive Transport Using Highly Automated and Autonomous Rail Units in Rural Areas," *2021 IEEE Intell. Veh. Symp.*, pp. 77–82, 2021, [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9575561&isnumber=9575130%0A

[14] G. S. Zinoviev and S. I. Salva, "Ways of modernization of systems of electro-supply and electric equipment high-voltage electric locomotives of constant voltage," *IEEE 11th Int. Conf. Actual Probl. Electron. Instrum. Eng.*, pp. 207–210, 2012, doi: 10.1109/APEIE.2012.6629082.

[15] M. Carmen, R. Lamedica, R. Bartoni, and G. Maranzano, "Energy management in metro-transit systems : An innovative proposal toward an integrated and sustainable urban mobility system including plug-in electric vehicles," *Electr. Power Syst. Res.*, vol. 81, no. 12, pp. 2127–2138, 2011, doi: 10.1016/j.epsr.2011.08.004.

[16] J. Wang and H. A. Rakha, "Electric train energy consumption modeling," *Appl. Energy*, vol. 193, pp. 346–355, 2017, doi: 10.1016/j.apenergy.2017.02.058.

[17] V. Kuznetsov *et al.*, "Method of Selecting Energy-Efficient Parameters of an Electric Asynchronous Traction Motor for Diesel Shunting Locomotives—Case Study on the Example of a Locomotive Series ChME3 (ЧМЭ3, ČME3, ČKD S200)," *Energies*, vol. 15, no. 1, p. 317, 2022, doi: 10.3390/en15010317.

[18] W. Wang, W. Du, K. Liu, and L. Tong, "The Evolution of China's Railway Network (CRN) 1999-2019: Urbanization Impact and Regional Connectivity," *Urban Rail Transit*, vol. 8, no. 2, pp. 134–145, 2022, doi: 10.1007/s40864-022-00168-9.

[19] H. Li, J. Peng, W. Liu, and Z. Huang, "Stationary charging station design for sustainable urban rail systems: A case study at zhuzhou electric locomotive co., China," *Sustain.*, vol. 7, no. 1, pp. 465–481, 2015, doi: 10.3390/su7010465.

[20] R. León, C. Montaleza, J. L. Maldonado, M. Tostado-Véliz, and F. Jurado, "Hybrid Electric Vehicles: A Review of Existing Configurations and Thermodynamic Cycles," *Thermo*, vol. 1, no. 2, pp. 134–150, 2021, doi: 10.3390/thermo1020010.

[21] A. Stanescu, N. Mocioi, and A. Dimitrescu, "Hybrid Propulsion Train with Energy Storage in Metal Hydrides," IEEE, bucuresti, 2019. doi: 10.1109/EV.2019.8892853.

[22] Y. Zhang, S. Yu, W. Wang, Y. Fu, and W. Chen, "Fast matching design on fuel cell hybrid system of tram," in *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific(ITEC Asia-Pacific)*, 2017, pp. 1–5. doi: 10.1109/ITEC-AP.2017.8080855.

[23] J. J. Mwambeleko and T. Kulworawanichpong, "Battery and accelerating-catenary hybrid system for light rail vehicles and trams," in *2017 International Electrical Engineering Congress (iEECON)*, 2017, pp. 1–4. doi: 10.1109/IEECON.2017.8075778.

[24] Y. Yan, J. Liu, Q. Li, and W. Chen, "Research on hierarchical energy management strategy in fuel cell hybrid tram system," in *Proceedings - 2017 Chinese Automation Congress (CAC)*, 2017, pp. 1630–1634. doi: 10.1109/CAC.2017.8243029.

[25] A. Y. Zakharov, N. V. Potekhin, and V. V. Korolev, "Simulation of control system for traction electric motors control of subway cars," in *2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus)*, 2019, pp. 747–751. doi: 10.1109/EIConRus.2019.8656704.

[26] H. Zhipeng, J. Xin, and S. Haiming, "Analysis of Control Strategies of an AC All Electric Propulsion System without Converters," in *2022 Power System and Green Energy Conference (PSGEC)*, 2022, pp. 1004–1011. doi: 10.1109/PSGEC54663.2022.9881082

[27] S. Valadkhani, O. Alkandri, Z. Akhmetov, and Z. Pantic, "Comprehensive Analysis and Modeling of Conventional and Hybrid Electric Ferry Power and Propulsion Systems," in *2023 IEEE Electric Ship Technologies Symposium (ESTS)*, 2023, pp. 99–106. doi: 10.1109/ESTS56571.2023.10220506.

[28] W. Wang and P. Bao, "Research on Improving Transient Characteristics of Electric Ship Propulsion System by Using Flywheel Energy Storage System," in *2023 10th International Forum on Electrical Engineering and Automation (IFEEA)*, 2023, pp. 185–189. doi: 10.1109/IFEEA60725.2023.10429231.

[29] K. M. Sidorov, A. G. Grishchenko, B. N. Sidorov, and V. I. Stroganov, "Electric Propulsion System Simulation as Basis for the Electric Vehicle Digital Twin Development," in *2021 Systems of Signals Generating and Processing in the Field of on Board Communications*, 2021, pp. 1–6. doi: 10.1109/IEEECONF51389.2021.9416111.

[30]Y Hong and W Shi, "Impulse Load Energy Supply Strategy of Ship Regional Distribution Power System Based on Flywheel Energy Storage

Technology", Ship Engineering, vol. 45, no. 1, pp. 103-109, 2023.

[31] K. E. Nesterov, M. V. Mudrov, and V. I. Zelentsov, “Simulator of the shunting locomotive’s electric drive,” *2016 2nd Int. Conf. Ind. Eng. Appl. Manuf. ICIEAM 2016 - Proc.*, pp. 7–10, 2016, doi: 10.1109/ICIEAM.2016.7911523.