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The sensors-based artificial intelligence Train Control and Monitoring System (TCMS) for managing the railway transport fleet

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Railways deliver a safe and sustainable form of transport and are typically pointed as one the safest form of transportation. Nevertheless, train accidents still happen, and when they happen, the consequences concern serious fatalities and injuries. Since every case is unique, the most frequent causes of train accidents are mechanical derailments, failures, as well as human errors and ignorance. In order to mitigate the risks posed by both physical and human related factors, various technological advancements have been designed and implemented. Among many existing Train Control and Monitoring Systems (TCMS), one can observe that recently developed artificial intelligence (AI) methods are also considered to be integrated part of the modern TCMS solutions. Following recent AI improvements and trends, in this paper we aim to present and discuss our newly developed TCMS system. In particular, both the system architecture and features are described along with the expected benefits of its implementation.

1. Introduction

Global rolling stock market value in 2020 was estimated to be worth around 51.6 billion U.S. dollars [4]. Around the globe, passengers traveled over three-and-a-half trillion passenger kilometers on railway networks in 2019, where China, India and Japan have had the highest passenger traffic [8], while in Europe, in total on railways passengers traveled around 643 billion passenger kilometers in 2019 [5]. On the other hand, in 2020, on the global scale the rail freight market was worth some 247.4 billion USD, and is projected to grow to almost 280 billion USD in 2026 [6].

Despite many technological advancements and innovations, the major concern raised throughout the on-going discussion among both researchers and manufacturers is still the safety [7]. The safety of rail traffic depends on a number of factors, which concern performance of duties by involved employees, and the organization of traffic and rail transport, as well as on the technical condition of the railway infrastructure and the rolling stock [9]. Hence, one can classify the safety factors twofold: firstly, as human-related, and secondly as technical. Obviously, the intersection between these two groups is something natural and inherent, and as a whole should be considered as one "living organism".

Nevertheless, incidents (event with no harmful consequences) and accidents (event with harmful consequences) continue to occur in the railway system. In general, among derailment-causes are determined to three causal factors, including infrastructure defects, operations related factors, and rolling stock [1]. To tackle these issues, the on-going research and development activities have been undertaken to increase the body of knowledge and use it to devise new applications. In this line of thinking, in this paper we aim to present and discuss both the design and features of the recently developed information TCMS system.

The rest of the paper is structured as follows. In Section 2 we present the TCMS architecture. In Section 3 the system features and capabilities are discussed. In Section 4, we conclude the paper by

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providing the expected benefits of the system implementation.

2. TCMS System architecture, deployment and configuration

2.1. Software architecture

To implement the TCMS system the following three technologies have been used.

1. **Angular** is a component-based development platform for developing scalable web applications, including a collection of the integrated libraries that cover features such as routing, forms management, client-server communication; we chose Angular since any project can be scaled from single-developer to enterprise level applications, as well as due to its support by the world-wide community.
2. **Spring** is an open-source application framework which provides infrastructure support for developing Java-based high performing applications; we chose Spring is considered to be a low-cost, flexible and secure framework.
3. **PostgreSQL** is an object-relational database system which takes advantage and extends the SQL language combined with many other features; the system is an open-source, secure and scalable solution with strong support from the developers community.

To sum up. Our TCMS system combines the recent advances in front-end and back-end technologies with the best practices and ideas adopted and adapted from the open-source projects.

2.2. Hardware architecture

By definition, a sensor is “a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control)” [3].

The GeoTrainAI (see Fig. 1) is a high-tech, autonomous sensors-based locator device. By design, being relatively small and having robust cover, protecting against rain, snow, hail, and dirt, is supplied with the energy from the built-in solar cells, located on the visible part of its cover (see Table 1 for details).

Fig. 1. The GeoTrainAI device

Each active device collects and integrates localization data with the accuracy up to 1.5 meter, and afterwards transmits every 5 minutes the data packages to the TCSM system, where they are further processed using machine learning algorithms. Eventually, the system shares and visualize the data, and generates accurate vehicle information, and in case of occurrence, an anomaly detection messages.

The GeoTrainAI device specification is provided by Table 1 below.

Table 1. The GeoTrainAI device specification

Parameter	**Value**
Size (length × width × height)	115.76 × 78.16 × 33.7
Weight	~ 350 g
Acceptable temperature	–20 – +80 degrees Celsius
Battery capacity	6800 mAh
Installation	Neodymium magnet
Certification	
CE	Compliant
RoHS	Compliant
IP Grade	IP67
GPS specification	
GPS	Compliant
GLONASS	Compliant
Galileo	Compliant
SBAS	
Accuracy placement in the optimal conditions: 1.5 m	
Connection	
GSM	Compliant
SIM	Varied, depending on the applications
Environment attitude	
Housing	PC material, UV resistant, IP 67 compliant
Power Supply	Solar cell, electrical supply

The GeoTrainAI device utilizes the following five sensors which have been developed as part of the research and development activities. In the near future, these newly developed devices are going to replace the existing ones.

First, a **loading sensor** to determine whether a wagon is loaded or empty; in addition, this sensor returns information about the total weight of the wagon, by design with an accuracy on the level at least of 30%. The purpose of the real-time "weighing" on the railroad is twofold: to measure the weight of the load and to check the correct internal distribution of the load in the individual vehicles. The measurement of the weight of the load, primarily for the purpose of calculating the charges for the transported load, is carried out by means of static or dynamic scales mounted on the tracks. The second key objective is to check the correctness of the axle load of the wagons and the distribution of the load in the wagon, which has a significant impact on the wear of tracks, as well as on the vehicle parts. Thus, due to the TCMS system implementation, the traffic safety is leveraged. Eventually, a loading sensor aims to detect anomalies, which not detected in a timely manner on the railroad may lead to derailment and a railway disaster. If the wagon is overloaded on one side, the other side of the wagon will be "unloaded" and the raised flange of the wheel may run over the rail and derail the wagon, leading to a railway disaster.

Second, an **acoustic (vibration) sensor** aims to detect wheel performance anomalies, such as thickening, flattening, or cracking. The sensors will be designed to monitor flat spots and so-called "stickers" on the rolling surface of the wheelsets. The sensors will catch the so-called. "rhythmic tapping" after the impact of wheel bumps on the rail. This phenomenon is very dangerous, it can cause heating of the "stub axle", breakage of the axle, damage to track equipment, rail cracks, etc.

Third, an **axlebox temperature sensor** is to monitor the bearings' performance, mounted in the individual wagon. If there is an increase in temperature on the bearings then the vehicle (wagon) should be stopped, taken out of service and the bearings replaced with new ones. In general, the replacement of bearings is carried out during the inspection repairs of railroad vehicles (static). During the operation of the vehicle (wagon) - in operation, between overhauls, it is possible to monitor the proper functioning of bearings at some railroad stations through the use of "measurement zones", where sensors are installed along the tracks to measure the temperature of the bearings of passing vehicles (railcars) in motion.

Fourth, a **wheel temperature sensor** aims to monitor the brakes performance, in particular whether the brakes are jammed. In the case of emergency braking of a vehicle (wagon), there is an inability to decelerate with the combination brake or hand brake during driving, there is intense friction of the brake pads against the wheel surface and an associated significant increase in temperature. Once the vehicle is stopped and a successful brake test is performed, the vehicle can continue driving. However, prolonged tightening of the brakes results in a so-called "flat spot" on the rolling surface of the wheel and the vehicle (wagon) must be taken out of service and referred for revision and careful inspection. Flat spots on the wheel rolling surface must be removed by rolling the wheelset and compared with the diameter of the adjacent wheel set.

Fifth, a **geolocation sensor**, which serves as a central unit with the ability to analyze and process data collected from other sensors by means of the embedded artificial intelligence methods.

2.3. GeoTrainAI deployment and configuration

The GeoTrainAI device physical installation on train is a straightforward activity (see Figure 2) since each particular device is to be manually mounted to the vehicle, and is supported by the built-in strong neodymium magnet.

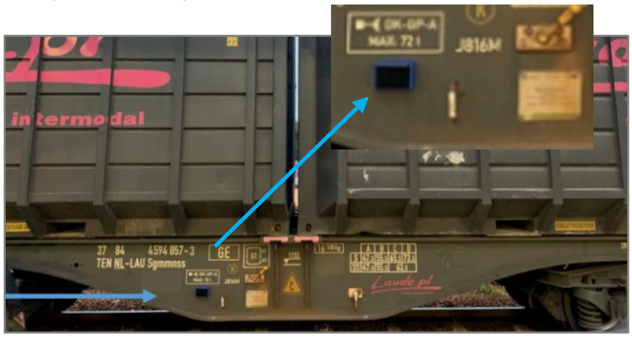

Fig. 2. A view on the mounted GeoTrainAI device (on the right of the blue arrow, located in the bottom left); a magnified view is given on the right part of the car

If one has mounted all the necessary devices, the account for a user (client) is created, along with additional information. Therefore, a separate and self-managed instance of the TCSM system is ready for use. After a short period of time, the system dashboard, fueled by collected data streams, becomes fully operational.

3. GeoTrainAI features

3.1. Maps

The feature Maps allows a user to choose the available maps and available sensors. On the other hand, a user can create a new Map by defining its name and description, along with providing its width, length and height. Moreover, the system allows a user to select appropriate shapes, colors, or lines in order to enhance the map's visualization capacity.

Selecting the Map List tab allows a user to preview the available maps. It defines their Name, Author, Gates and Sensors. By using the Edit Map option, it is possible to edit an area, while by using the Delete Map option, it is possible to permanently delete an area.

Selecting the Railway Map tab allows us to observe sensor data and control the location and speed at which the vehicle is traveling. It is updated through Open Railway Map and Google Maps on-line tools (see Fig. 3 for details).

In order to read the speed and battery condition of a particular sensor, a user can simply click on the sensor's dot. The shape of the dot along with an arrow indicates that the particular vehicle on which the sensor is attached is moving. In the current version, the reading of the location of the sensor with the cell in the case when "the vehicle is moving" is done every 10 minutes, in the case when the train is standing the time is 1.5 h.

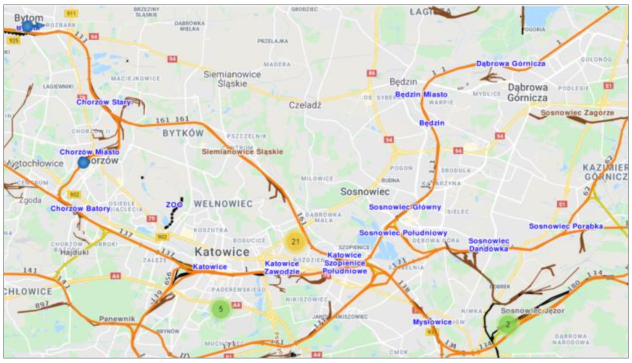

Fig. 3. A view on the railroad map, along with active sensors devices (marked by the green circle and the unique identifier inside)

The history function allows a user to indicate the location of a particular sensor at a defined period of time; more specifically, it also is possible to enable (or disable) labels and select their type, as well as enable (or disable) sensor grouping (see Fig. 4 for details).

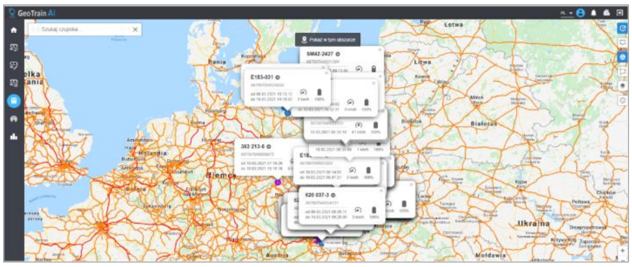

Fig. 4. The effect of sensors grouping in order to get a summary view of the railway transport fleet, managed by a particular user

It is possible to add an area and select its geographic points, as well as select the type of satellite and the type of railroad map which can use three different palette colors, namely: default, satellite and grayscale (see Fig. 5 for details).

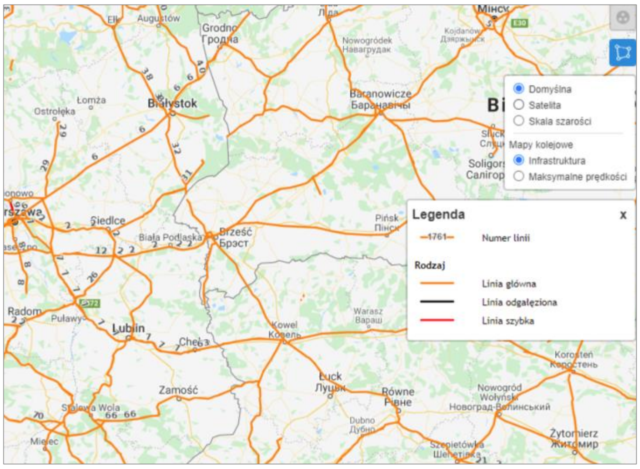

Fig. 5. A view on selecting the type of map, with the corresponding legend

Moreover, a user can create a new zone from the railroad maps or vehicle maps, where the Road Map tab allows a user to observe sensor data and control the location and speed at which a road vehicle is traveling, covering both the European and Asian continents.

3.2. Sensors management

The second feature of the TCSM system is the Sensors Management. Here, by management, we understand the data view on all the user's sensors collected in the database, including: sensor's type/subtype sensor, name, serial number, description, battery status, software version, last location and last report (see Fig. 6 for details).

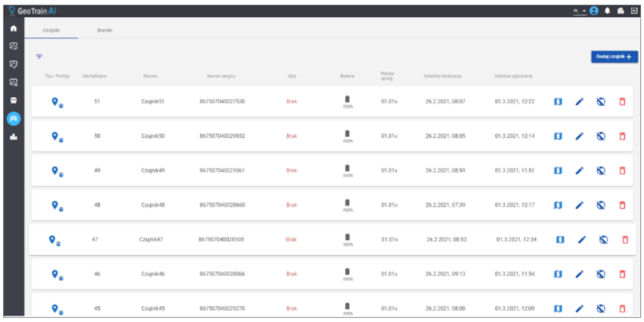

Fig. 6. A view on the sensors management dashboard

In order to manage all registered sensors in the system, a user is able to perform the CRUD (create, read, update and delete) operations.

By applying the options located in the right corner marked with 3 vertical dots: Edit Sensor, Deactivate Sensor, Delete Sensor, a user can edit, deactivate or permanently delete a particular sensor, respectively.

By selecting the Add sensor option it is possible to go to a window that allows adding a new sensor and its description, which includes, among others: Name, Subtype, Identifier, Serial Number, License, Start Distance, Last Inspection Date, and Description.

In order to get more information about the parameters of a particular sensor, you need to indicate the sensor of your choice. Once this is done, it is possible to preview the sensor in question and obtain information regarding its name, subtype and ID.

Selecting the Attributes option allows us to control the location of a particular sensor and the condition of its battery. It is possible to get an accurate reading of the battery on a daily, weekly and monthly basis.

By selecting the Gateways tab, it is possible to access the gateways. We have 2 types of sensors, which are geostationary (satellite) sensors and UWB sensors. The aforementioned sensors connect by radio to gateways, which determine the positions of these UWB sensors based on the collected measurements, and then collectively send the data.

3.3. Events

By selecting the Events tab, it is possible to create our own precedent. To do this, select Add Event, which is located in the upper right corner of the screen. By default, a user is redirected to an option enabling adding a new event, along with an action pattern and the reactions (see Figure 7 for details).

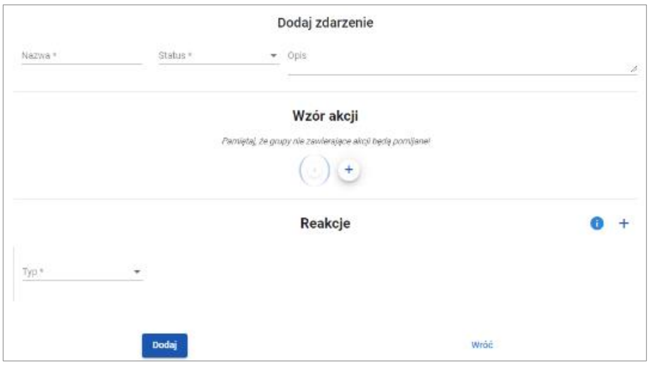

Fig. 7. A view on the sensors management dashboard

Enter the appropriate Name, Status and Description. Then assign an Action Pattern from either AND / OR. Select the corresponding Action Type: Sensor Value, Sensor Attribute, Sensor Position. The available options of the Sensor Value tab are: Serial Number, Identifier, Name, Battery Level, Temperature, Last Inspection Date (see Figure 8 for details).

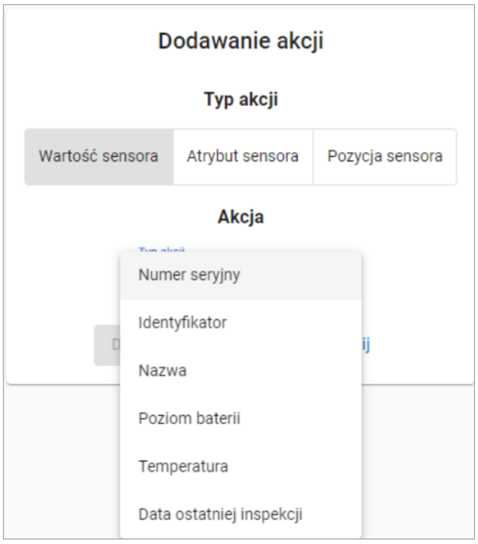

Fig. 8. A view on the Add Action configuration window

Available options of Sensor Attribute tab are: Color, Failure date, Wheel Size, Operational.

Example: Assigning action Serial number equals (type the appropriate text to be displayed). In addition, you can make a selection of the Action Operator from: contains, does not contain, equal, unequal, starts with, ends with. The Action Operators on the Sensor Attributes tab are: equal, unequal, greater than, greater than or equal to, less than, less than or equal to.

After pointing to the Sensor Position tab, you will be redirected to a window illustrating the position of the given sensors. It is possible to add an action operator from among: at entry, within, at exit. It is also possible to add a new area and create its name and description. The next step is to assign a given reaction after performing the action we indicated. Enter the appropriate Type.

Let us consider the following example. Figure 9 below depicts the Type of the reaction, which is by an email message; afterwards a user is asked to define its Recipients, Title and Content.

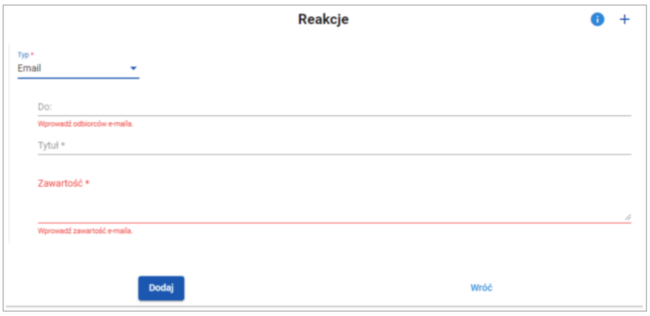

Fig. 9. A view on the reaction configuration window

3.4. Reports

The Reports feature allows to control the distance covered by the vehicle with the mounted sensor. The available summary shows detailed information of the registered sensors, including: Identifier, Name, Serial Number, Distance, Stop Duration, Moving Duration (see Figure 10 for details).

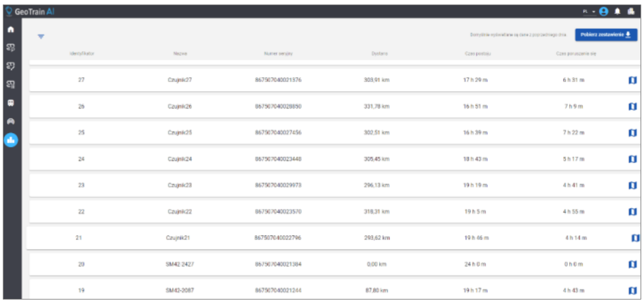

Fig. 10. The summary of the registered sensors in the GeoTrainAI

Through the **Show on Map** function, it is possible to be automatically redirected to a map, depicting the selected sensor by a user (see Fig. 11 for details).

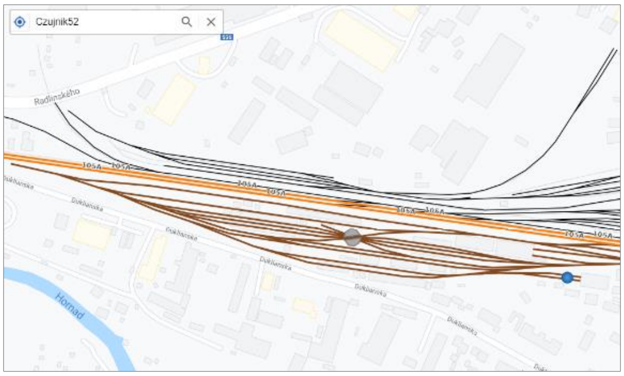

Fig. 11. A detailed physical localization of the Sensor52 (marked by the blue circle on the map)

Moreover, for the selected sensor(s) by a user, it is also possible to download detailed measurement report, in the XLSX data format.

3.5. Availability

The "Availability" tab presents a summary of the entered users. The screen view will display the information in columns: E-mail, Name, Status, Rules. The feature "User accessibility rules" allows a user to set rules regarding areas, attributes and colors. The other information concerns failure date, wheel size, status, locomotive and vehicle type.

It should be noted here that the TCSM system provides the variety of the built-in wizards, which serve as the user-friendly setup assistants in the form of a dialog box that leads the user through a sequence of configuration steps.

3.6. Machine-learning feature

The main idea, underlying the architecture and design of the TCSM system, was the assumption of incorporating the modern machine learning (ML) techniques, with respect to the particular railway transport safety issues. Having said that, the role of the ML component is to detect anomalies in input data, classify the anomaly, and inform a user. Since the time is a crucial factor in human cognition [2], the duration of data processing has been a major issue during the component design and testing activities.

We have assumed that an anomaly occurs when at least one physical parameter deviates from what is standard, normal, or expected. These three states (categories) have been used to describe the current status of the processes, described by the quantitative data delivered by the five different sensors, namely: loading sensor, acoustic (vibration) sensor, axlebox temperature sensor, wheel temperature sensor, and a geolocation sensor.

Due to the intellectual property rights, we are not allowed to present and discuss the full picture of the ML features. Nevertheless, interested readers can be informed directly by the Meritus representatives, in case of receiving more information.

4. Conclusions

The recipients of the our TCSM system are rail carriers owners and operators who wish to reduce the cost of the consequences of serious breakdown, since the system allows in advance to prevent emerging faults by real-time monitoring the current state of specific physical components, and recognizing their abnormal states and behavior.

Implementing the TCSM system, along with deployment of the network of physical sensors bring the following benefits. Firstly, a user is able to monitor key parameters of vehicles, control their technical condition, track routes, increase transport efficiency and comprehensively manage your fleet using a single system. Secondly, a user gains the ability to draw virtual boundaries for moving vehicles, as well as receiving zone alerts when units cross a given area. Thirdly, a user is able to determine train (car) localization 24/7, in particular the ability to track the location of vehicles on maps with an accuracy of up to 1.5 meters, thanks to geolocation feature operating in the real-time mode. With the system you will support the work of dispatchers and logisticians. Fourthly, a user is able to minimize the risk of downtime related to vehicle breakdowns, and you will have the ability to conduct a proactive maintenance strategy, which results in minimizing, or even eliminating unscheduled stops.

Eventually, due to the implemented artificial intelligence techniques, the key advantage of sensors is to inform railway carriers in advance about the impending malfunctions and failures of the specific vehicle parts, which in return could prevent from occurring greater repairs and replacements. Therefore, the risk of withdrawing railroad cars from traffic for a longer period of time is reduced which in return will contribute to downsizing the maintenance costs.

To conclude our paper, the presented TCSM system, by combing and utilizing artificial intelligence techniques and recent telecommunication advancements, has the capacity to collect highly precise data streams directly from the track, which in turn significantly leverage the efficiency, safety and attractiveness of rail freight transportation. By raising the level of technology, rail carriers can not only increase the efficiency and safety of their shipments, reduce costs and build a strong competitive advantage, but also divert business and transported cargo from road routes to rail tracks, which is key to achieving sustainable development of freight transportation.

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Nomenclature

AI artificiall intelligence
ML machine learning
TCMS train control and monitoring system

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