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Application of alternative drive systems in modern special-purpose rail vehicles

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Abstract: In response to the market demand for modern special-purpose rail vehicles, an overview of the rolling stock available on the European and world markets was developed, along with an analysis of the scope of works they performed. The need for new alternative forms of propulsion in line with the development directions, taking into account EU and national environmental goals was discussed. The paper presents a design of a proprietary modern special-purpose vehicle with an alternative drive. It discusses it compared to other special-purpose vehicles regarding their parameters and the viability of different drive systems, including hydrogen fuel cells.

Keywords: special-purpose vehicle, alternative drive, energy storage, hydrogen fuels

1. Introduction

The development of alternative drive systems in means of transport is mainly observed for road vehicles [1-3]. Knowledge, experience, and technological solutions developed for the needs of new road vehicle drives often become a precursor to developing drives for Non-Road vehicles [4], including rail vehicles. New solutions are already being introduced in the form of alternative drives, adapted to alternative fuels [5], such as hydrogen or biofuels, hybrid drives [6], and multi-drive systems for passenger and freight rail vehicles [7-9]. The applied drive system solutions are selected based on the performance characteristics and the tasks performed for a given type of vehicle [10-12]. Hence, it can be expected that alternative drives would also be designed for use in special-purpose vehicles. In the case of vehicles of this category, it is possible to apply various solutions, allowing for an increase in the utility, range, or reduction of the environmental impact of these vehicles [13-14].

Changes introduced due to the adopted climate policies and sustainable development goals result in the accelerated implementation of new propulsion technologies in various transport sectors. Several innovative activities are under consideration where solutions with

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zero emissions or in line with the principles of a circular carbon dioxide economy are considered the end goal [15]. Transitional solutions that are supposed to modernize the vehicle fleets already in use, reducing their environmental impact, also exist in parallel [16]. Such solutions usually do not fully eliminate CO_2 emissions involved with their operations. For this reason, the currently proposed alternatives must combine environmental benefits and other advantages such as lower cost, greater efficiency, longer lifespan, greater versatility, greater safety, or greater range [17-19]. Any offered changes and modifications to existing vehicles and powertrains [20] must be cheap, effective, and safe to implement to make them competitive. Some solutions and vehicle options offered on the railway market or still being developed meet these assumptions and can compete with conventional drive systems based on internal combustion engines and electric motors.

2. Existing solutions for special-purpose rail vehicles

The solutions appearing in the rolling stock, using new alternative drive systems, are considered mainly in terms of their applications for passenger and freight transport and shunting vehicles. Hence, in the case of special-purpose vehicles, such solutions are relatively rare and few. One example is the MG11 special rail milling vehicle (Fig. 1), powered by hydrogen cells and fueled with hydrogen [21]. The vehicle is equipped with a 150 kW fuel cell system and an energy storage system enabling it to perform work of up to 60 kWh (Table 1).

Table 1. Technical specifications of the special-purpose vehicle MG11-H2 from Lisinger (source: [21])

Parameter	Value
Service mass	39 t
Max. speed (self-propelled)	50 km/h
Tractive power	150 kW fuel cells; 60 kWh batteries
Max. track gradient	40‰
Gauge	1000 to 1668 mm
Max. track cant value (for 1435 mm)	150 mm

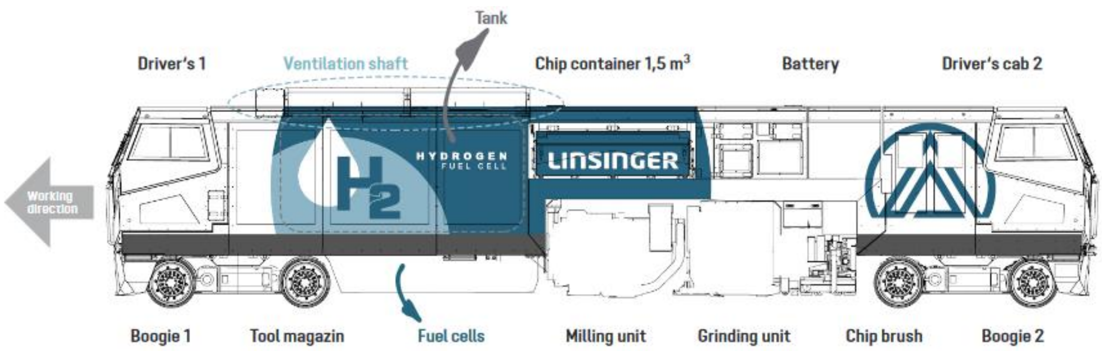

Fig. 1. The MG11 vehicle from Lisinger (source: [21])

A similar solution was used in the PESA Bydgoszcz SM42 6Dn shunting locomotive presented at TRAKO 2021 rolling stock trade fair (Fig. 2). The new version of the SM42 locomotive is powered by hydrogen fuel cells with a total power output of 170 kW and an on-board energy storage system, thus allowing for off-grid work. Refueling requires fuel in the form of hydrogen and has a fuel tank with a hydrogen fuel capacity of 175 kg. The locomotive data are listed in Table 2.

Fig. 2. The SM42 6Dn hydrogen locomotive presented at the TRAKO 2021 fair in Gdańsk (source: [22])

Table 2. Technical specifications of the SM42 6Dn shunting locomotive powered with hydrogen fuel (source: [22])

Parameter	**Value**
Service mass	<70 t
Max. speed (self-propelled)	90 km/h
Hydrogen fuel cells power	85 kW x2
Expected fuel consumption	<0,08 kg/kWh
DC power supply voltage	<800 V
Intermediate battery capacity	>160 kWh
Hydrogen fuel tanks capacity	175 kg
Fuel cells operating temperature	-40 °C to +85 °C

Another special-purpose vehicle currently in development is the new proprietary 501EH model with a hybrid propulsion system [27] supported by energy storage devices designed for diagnostics and track analysis. The prototype of such a vehicle is being created as part of the cooperation between ZPS Sp. z o.o. and the Poznań Institute of Technology from the Łukasiewicz Research Network, marked with the project number POIR.01.01.01-00-1601/20. In its basic version, the vehicle is to act as a platform on which specialized components for the construction, diagnostics, and measurements of railway infrastructure will be installed (Fig. 3). The possible applications of such a vehicle can be adapted to the operator's needs by installing the appropriate elements for the construction or diagnostics of tracks, including elements such as basket crane (Fig. 4). This vehicle is designed to be able to reach a maximum travel speed of 160 km/h. Its parameters are described in Table 3.

Using energy storage in the vehicle structure enables it to work in zero-emission mode, which is necessary for the so-called "Green zones". It will lead to a general reduction of environmental impact from operating a specialized rail vehicle. This solution differs from a hydrogen-powered solution in operational and environmental aspects. Hydrogen fueling is more difficult to implement, and the fuel is more expensive. However, hydrogen can still generate electricity in power generators for the utility grid during increased demand. This application of hydrogen fuel could reduce the need to rely on power from dynamically operating gas power plants. If a railway line is partially or fully electrified, using hydrogen cells in the vehicle is a less economical solution than using a pantograph for power supply from the network. Using an electric energy receiver from the overhead contact line reduces costs and the difficulties resulting from hydrogen fuel distribution.

Table 3. The target technical specification of the proposed 501EH vehicle

Parameter	Value
Service mass	65 t
Max. speed (self-propelled)	160 km/h
Tractive power	65 kW electric motor; 340 kW combustion engine; 100 kWh batteries
Max. track gradient	30‰
Gauge	1435 mm
Max. track cant value	180 mm

Fig. 3. Basic version of a special hybrid vehicle with a loading platform

A similar example of using energy storage in rail vehicles is the new version of a vehicle by the NEWAG company that is being tested. The Impuls EN63H-008 vehicle uses super-capacitors to store energy instead of batteries [28]. These devices have very different current-voltage characteristics [47]. Their power density is much higher, with lower capacity and greater losses of stored electricity over time [29].

Another currently developed technology uses ammonia instead of hydrogen due to its higher energy density (12.7 MJ/l compared to hydrogen with an energy density of 8.5 MJ/l) and easier of meeting condensation conditions [26]. In the case of hydrogen, storage, and transport requires special conditions such as high pressures of up to 700 bar (gaseous hydrogen) or low temperatures of down to -250°C (liquid hydrogen). The production of ammonia and its further distribution is much easier. It only requires a temperature of -33°C at atmospheric pressure or 10 bar pressure at a temperature of 25°C. The ammonia can then be split back into hydrogen and nitrogen for use as a fuel, or even the use of ammonia alone in solutions based on appropriate types of fuel cells [23] or directly in the internal combustion engine [24-25]. The main challenge of using hydrogen as the primary fuel is the energy cost of its liquefaction, which is even 40% of the energy contained in the fuel [26]. It means that for every 1J of hydrogen energy, at least 1.4J of energy is needed for production, plus additional energy for its transport. The higher energy density of ammonia avoids some of these costs. Unfortunately, ammonia is a toxic and corrosive substance, significantly reducing the chances of its widespread commercial use. In addition, transporting energy in the form of ammonia fuel requires several steps, which result in numerous energy losses associated with the conversion of hydrogen to ammonia and then back to hydrogen. The American Chemical Association estimated that because of these losses, conversion to ammonia and back to hydrogen reduces the amount of usable energy at the target point to 61.0-68.5% compared to using hydrogen fuel alone without conversion [26].

Fig. 4. A special-purpose diagnostic rail vehicle after the installation of a crane arm for work at heights

3. Costs and applicability of hydrogen fuels for electric vehicles

The use of electric drives powered using the overhead catenary is possible only in countries where a sufficiently large portion of the railway lines is electrified. Currently, around 60% of the length of railways in the EU is electrified, which accounts for around 80% of all conducted transport activities [30]. Nevertheless, infrastructure is not evenly distributed, as there are areas with a high level of electrification, such as Luxembourg (97%), and areas with a low level of electrification, such as Lithuania (8%). As a result, in some cases, the use of vehicles powered by electric traction may not be possible in most of the country or may require expensive expansion of the railway infrastructure (modernization and electrification). In these areas, hydrogen-fueled vehicles, despite the energy loss in conversion, technological difficulties in storage, and higher distribution costs, can still be considered the main alternative to rail vehicles powered by fossil fuels. In 2022 the International Council on Clean Transportation (ICCT) estimated the at-the-pump price of green hydrogen in Europe varying from 8.5€/kg in Germany down to 6€/kg in Poland. But to make green hydrogen competitive as fuel for long-haul trucks, it must reach a Total Cost of Ownership (TCO) parity with diesel fuel, which means an average price point of 4€/kg. For this, the highest break-even price for hydrogen was 5€/kg in the UK (down 2.19€/kg from the current price), and the lowest was 3.5€/kg in Poland (2.48€/kg lower than the current price). It means that significant drops in green hydrogen costs are still necessary to consider it competitive in the current transport sector of European countries. The rail transport sector faces a similar problem, with green hydrogen fuel still being too expensive to reach the break-even point with diesel fuel. Hence, using electrified lines wherever possible proves generally more cost-effective for rail transport and is likely to be the primary solution. Nevertheless, lines with partial or no electrification will require diesel-powered locomotives or their replacement with either electric vehicles equipped with battery systems or hydrogen-powered vehicles with fuel cells. This approach, however, runs into the problem of economies of scale, where both hydrogen fuel and hydrogen fuel cells are unlikely to drop in price to competitive levels without widespread adoption.

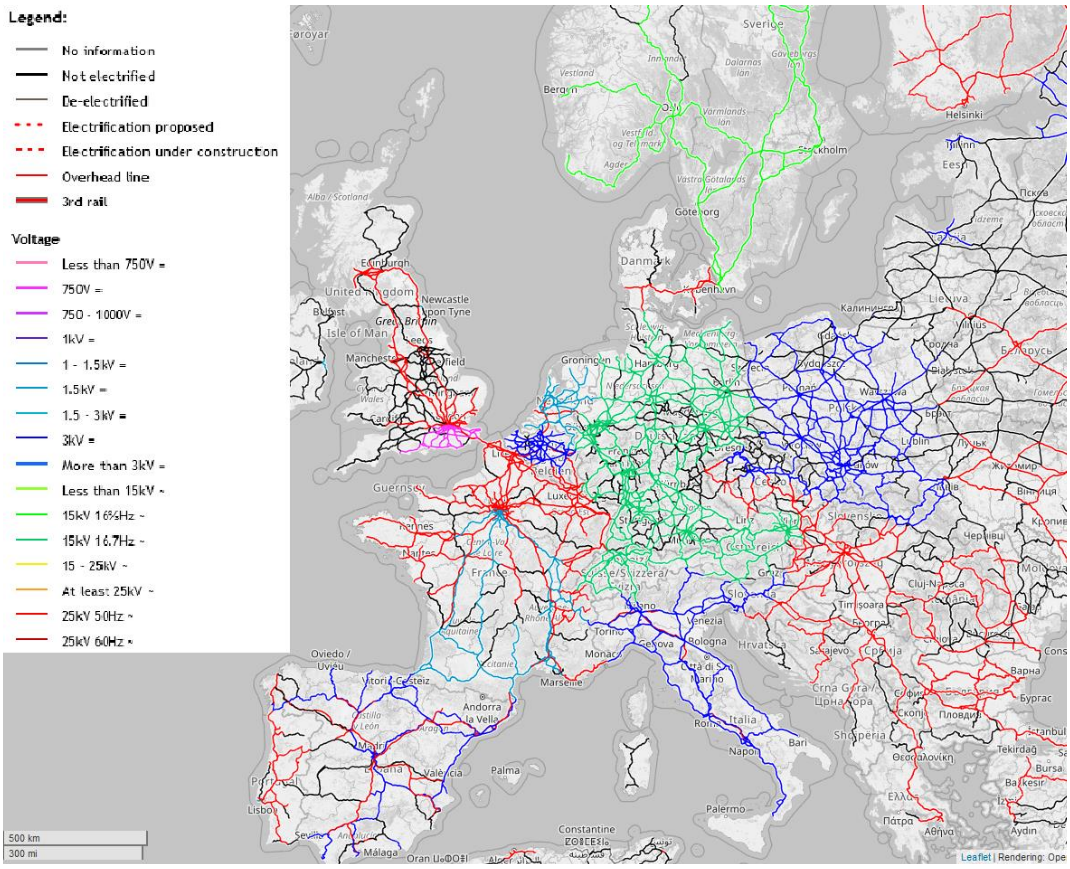

Fig. 5 Map of rail line electrification voltage in Europe (source: [31])

Another significant challenge that still needs to be overcome is the differentiation of electric traction voltage in the territory of the EU Member States. Electrified routes in the European Union operate using multiple different voltages: 750 V, 1.5 kV, 3 kV, 15 kV, and 25 kV (Fig. 5) [31]. Due to the wide variation in the voltage supply of electric traction, using electric rail vehicles to an EU-wide extent or on most lines crossing national borders is currently not feasible. On the other hand, hydrogen fuel requires a distribution network specific to that type of fuel to be created. There is currently only a residual amount of such infrastructure, which the EC plans to use as a starting point in developing a full hydrogen network. To this end, the FCH JU (Fuel Cells and Hydrogen Joint Undertaking) [32] partnership has been established, bringing together state and private actors in the EU to establish a common direction for developing hydrogen fuel in the EU. This program was given a budget of € 1.3 trillion and runs alongside other national hydrogen development programs in the EU. Despite the allocation of large funds and numerous planned investments, the current state of hydrogen infrastructure development in Europe is still lower than in the US. According to data [33], about 30 companies in Europe are currently dealing with various aspects of hydrogen applications (production, distribution, hydrogen cells, components, etc.). At the same time, in the US, there are more than twice as many (Fig. 6). Hydrogen use strategies and plans for its implementation in transport are described in more detail in the European Directives [34]. It can directly impact the rate of adoption and the price point of hydrogen fuel and hydrogen fuel cell technology in the automotive industry.

It should be noted that, due to the different geography of the United States, the extent of electrified railway lines is much smaller. As a result, hydrogen fuel is more competitive for many of the operated rail lines. Green hydrogen was estimated to cost around $5/kg in the USA, compared to 6-8€/kg in Europe, despite the currencies being nearly equal in value.

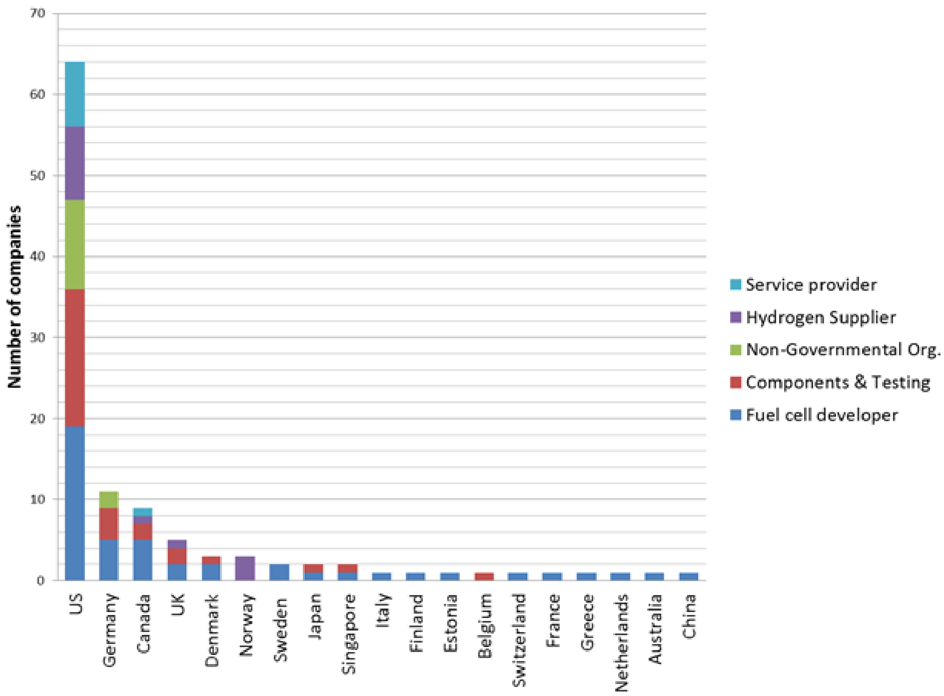

Fig. 6. Number of companies, enterprises, and organizations operating in the field of hydrogen as fuel (source: [33])

4. Use of hydrogen in combustion engines

The use of hydrogen in conventional internal combustion engines is usually considered to supply an already ignited mixture of hydrogen and air in the form of a burning stream into the combustion chamber. The aim is to improve the combustion performance of conventional hydrocarbon fuel. This experiment uses a modified combustion system with an additional pre-chamber to prepare and ignite the stream, which ignites the fuel in the cylinder. The studies available in the literature indicate such a technological solution can achieve more favorable combustion process parameters. Indicators that were noted to achieve more favorable values include faster flame front propagation, lower ignition delay, shorter combustion time, higher maximum pressure in the cylinder, and lower emission of toxic compounds [35] [36]. It should be emphasized that the most important observation resulting from the research of hydrogen-burning engines with a pre-chamber is the increase in the engine efficiency, which is confirmed by numerous publications, such as [37] and [38]. Despite the advantages of pre-chamber solutions, studies in the literature are mainly limited to engines used in road vehicles. However, work is underway to introduce a solution for more powerful engines for off-road use [39-40].

It can be assumed that despite some differences in high-power engines used in linear and shunting locomotives or special-purpose rail vehicles, the discussed technical solution should be feasible and enable similar results in improving the thermal efficiency of the drive unit [41]. The main limitation of the wide application of such a combustion system in engines is the need to modify the engine and add a pre-chamber to prepare and ignite the initial fuel dose [42]. Therefore, pre-chamber engines do not gain an advantage over other new drive systems. They are not backward compatible or cannot be retrofitted without replacing the entire engine unit.

Another proposed solution is to supply internal combustion engines with hydrogen only, without using conventional fuels. Many studies conducted to modify internal combustion engines to run on pure hydrogen fuel have also resulted in several versions offering engine conversion without replacing it with a new unit. Examples of such a concept are the works of A. Boretti [43-44], although most research agrees that a new purpose-built engine is necessary. The influence and possibilities of using hydrogen as a fuel in conventional combustion engines without modification are described in [45]. The introduction of hydrogen fuel into the combustion chamber can be done in different ways. Research is being carried out on injecting hydrogen into the intake manifold in a gas or liquid form and on direct injection into the hydrogen combustion chamber at a 15-30 MPa [46]. Despite this, the possibility of using hydrogen to power existing internal combustion engines is significantly limited by design requirements. Due to the differences in the hydrogen combustion process, the hydrogen-powered engine must have greater stroke volume than its equivalent fueled by diesel oil to maintain the same power output. In addition, component changes necessary for the safe and efficient use of hydrogen in an internal combustion engine must be considered. The main changes made as part of converting a conventional engine to hydrogen combustion require the replacement of components such as valves with seats, connecting rods, spark plugs and ignition coils, injectors, crankshaft damper, head gasket, and intake manifold. Using original parts from regular combustion engines is not impossible, but the engine lifespan can be significantly reduced. The lubricating oil may also need to be changed to a more resistant version to higher temperatures.

5. Conclusions

The paper presents various solutions through new drive systems and technologies. The currently popular uses of hydrogen as a fuel were divided into two categories: based on hydrogen combustion in a cylinder or on fuel cells. As the efficiency of the drive systems based on hydrogen cells is higher at low loads, the cells have more useful operating parameters for low-power vehicles. The high efficiency of the combustion engine powered by hydrogen is obtained only at higher engine load values. Thus it is a solution more suited to heavy vehicles and non-road mobile machinery (NRMM). Despite such operating characteristics, hydrogen-powered combustion engines also require larger dimensions to achieve nominal power comparable to their conventional counterparts. Hence, hydrogen as a fuel for special-purpose rail vehicles would significantly affect the rolling stock's capabilities and performance. The applied hybrid, three-drive solution, together with energy storage, enables the maximum use of power from the network in accordance with the availability and level of electrification of a given section of the railway line. Coupled with this, the 501EH also can run on conventional engine power. At some stage in the development of the hydrogen fuel distribution network, it can be expected that modifying an internal combustion engine to run on hydrogen fuel will become a cost-effective solution for further converting a special purpose vehicle to a zero carbon emission vehicle.

Based on the presented data and comparisons, it was found that the numerous advantages of new technologies of drive systems, including mainly hybrid drives combining three power sources, make their introduction into operation lead to a significant reduction of the environmental impact of vehicles performing special track works, to reduce exhaust emissions, to reduce noise and improve safety during vehicle operation. This solution is in line with the current efforts of zero-emission transport, assuming electricity production is carried out using "green" sources (Green Energy). The proposed solution allows the vehicle to work temporarily outside the power grid and does not require the expansion of the hydrogen or ammonia distribution network.

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