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Analysis of benefits and drawbacks of using hybrid drive special purpose vehicles

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The article aims to analyze and assess the economic and ecological advantages and disadvantages of switching from conventional drives to hybrid drives and hydrogen fuel cells in special purpose vehicles used in railway maintenance. The environmental regulations regarding exhaust emissions restrict the rolling stock options for rail operators. However, legislation alone is insufficient to further promote the use of more ecological vehicle drive solutions. Hence it is necessary that such new vehicles are also able to offer economic and operational benefits, that can encourage their adoption into the rolling stock. Such cost-benefit analysis was conducted to assess the likelihood and rate of adoption of this type of technology. This included a literature analysis, fuel, hydrogen and electricity cost projections and a SWOT analysis of the vehicles. The cost predictions of analyzed fuels varied significantly, in most cases electric energy being the cheapest, and the most expensive case of diesel fuel still remaining cheaper than hydrogen fuel.

1. Introduction

Special purpose rail vehicles in use today are mostly powered with conventional combustion engines. Due to growing need to reduce the ecological impact of the work performed by vehicles, especially in urban agglomerations where their emissions directly affect many people, efforts have been made to research and evaluate new modern drive systems for their potential applications in these types of vehicles. As the legislation continues to reduce the limit values of harmful exhaust emissions new replacement technologies for vehicle drives must be adopted and phased in. However, the choice of technological solutions needs to be informed by their economic viability, as well as the reliability and performance required for the expected tasks. Many papers have been published on the emerging technologies in rail vehicle drive systems [10], and others that discussed the future of rail vehicles [2, 9, 13] and related rail infrastructure [11, 15]. Studies have also been performed in efforts to maximize the efficiency and energy loss on each of the drive system components [4]. The most obvious solution to the exhaust emissions problem in rail transport would be electrification of rail lines. It is, however, not always an economically viable solution, as many rail lines are not in use enough to justify the high upfront cost of electrification, and even less the ongoing maintenance costs. Hence, new alternatives had to be considered. Multiple such alternative technologies exist, however, currently the research and development efforts have been mostly focused on new alternative fuels and drive systems. New hybrid drives [7, 12], fuel additives [17], and hydrogen fuel cell systems [14, 16] have been developed and are being tested for their applicability in rail transport.

2. Aim of study

The authors chose to assess the viability of implementing two alternative drive solutions to special purpose rail vehicles from the perspective of their economic viability. The drive systems selected for comparison were: a conventional existing vehicle powered by a combustion engine, a hybrid vehicle with both a combustion engine and a pantograph to be powered

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from the overhead catenary whenever applicable, and a vehicle powered by hydrogen fuel cells using fuel held in tanks onboard the vehicle. This was achieved by considering the running costs for vehicles with different drive systems per km of distance based on fuel, electricity, and hydrogen prices in Poland. These results can be further evaluated for other countries, however, due to the large variation in prices of fuel and electricity in different EU countries the authors have limited the scope to just costs in Poland.

Further aspects of replacing the existing fleet of special purpose rail vehicles with new models powered by novel drive systems were considered using a three-way SWOT analysis for the three selected drive systems. SWOT analysis is a technique used to identify and juxtapose strengths and weaknesses of a project or solution. The analysis was performed using information discussed in scientific literature regarding novel and hybrid drive systems for rail vehicles. Many of the problems and disadvantages of the analyzed solutions have been taken as research problems and analyzed through studies. Furthermore, data from leading producers and manufacturers of engines and drive systems provided additional information about the current state of technology, and the main directions taken by the industry in further developments. Price analysis in this article relied on data from models and calculations that were performed as a part of two distinct research projects. The first was a project aimed at creating a hybrid drive special purpose vehicle, powered by the electrified line whenever possible and using a combustion engine when outside the coverage of the electrified rail network. The other was a project aimed at remotoring a special rail vehicle by removing the combustion engine and replacing it with a fuel cell system and on board hydrogen storage, with the ultimate goal of achieving the same operational range as the original combustion engine system.

3. Fuels for modern drive systems

3.1. Diesel fuel

Currently the most commonly used fuel in rail transport is the standard diesel oil. As a fossil fuel, combustion of diesel fuel generates GHG (greenhouse gases) as well as a number of toxic exhaust compounds. Those toxic compounds include: CO (carbon monoxide), NO_x (nitrogen oxides), HC (hydrocarbons), and PM/PN (particulate matter/particulate number). Diesel fuel is used to power compression ignition (CI) or diesel engines, which also requires the fuel used to have physiochemical properties within a certain range, as not all fuels can reach auto-ignition in a standard CI engine. The use of diesel fuel is ubiquitous in transport and vehicles, with the exception of air transport, which uses mostly kerosene. The high level of reliance on one type of fuel can cause certain problems in the case of supply chain disruptions, as well as depending on the changes in market price of crude oil, of which diesel fuel is a product. Oil prices can vary widely depending on supply and world situation, shifting by a wide margin in relatively short periods of time, such as after the COVID pandemic (Fig. 1).

Fig. 1. Changes in oil prices 2020–2021 [18]

Use of diesel fuel is also associated with the added costs of using exhaust aftertreatment systems, to reduce the harmful impact of diesel exhaust fumes on humans and the environment. Attempts to offset the environmental costs of using diesel fuel have led to new fuel blends with the addition of various types of biodiesel. Although, the CO_2 emission cost of biodiesel fuel is lower than that of regular diesel, the overall environmental cost of biodiesel was found to still be slightly higher than for regular diesel [20]. In this study the regular going price for locomotive diesel fuel in Poland was taken as the benchmark for calculations. For this purpose, costs were calculated using the available projected price trends, for high (0.752 euro/kg), reference (0.555 euro/kg), and low (0.352 euro/kg) price range (Fig. 2).

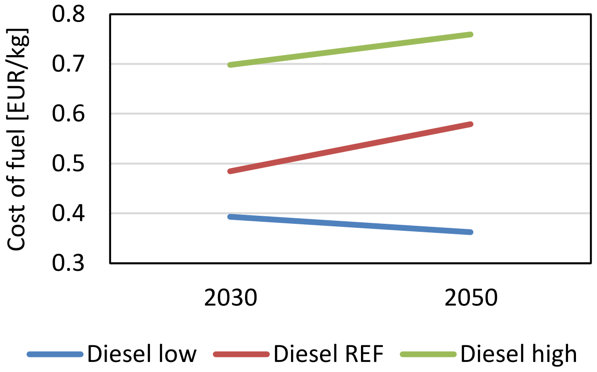

Fig. 2. Projected price of diesel fuel for years 2030 and 2050 [1]

3.2. Electric energy

Aside from diesel powered locomotives and rail vehicles, an equally common drive system in rail transport is the electric drive, typically powered using an overhead catenary. Electric locomotives are in common use in most countries in the world, but the level of electrification of rail lines varies greatly depending on the country, with countries like the US, or Latvia in Europe having a very low number of electric rail vehicles in operation, while countries like Switzerland use almost exclusively electric rail vehicles [5]. While electrifying a rail line is a costly infrastructure undertaking, this article does not consider the costs of converting rail lines or rail vehicle fleet to electric-powered in its calculations. The assessment was performed purely based on current running costs of each type of solution, irrespective of the current readiness of the existing infrastructure. As such, the price of electric energy must be taken into account, which can vary between countries.

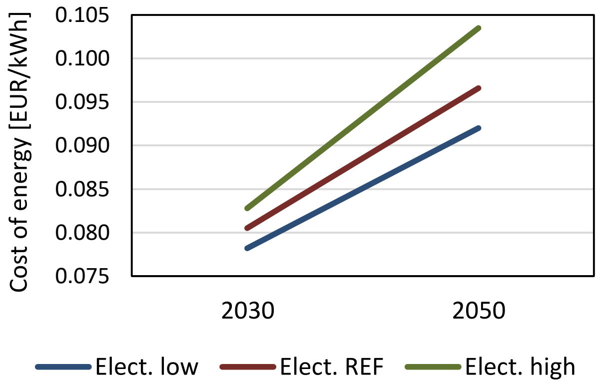

Fig. 3. Projected price of electricity for years 2030 and 2050 [19]

For this example, the projected price of electricity in Poland for the year 2030 and 2050 was used, showing the price of diesel fuel as being between 0.092 and 0.103 euro/kWh in 2050 (Fig. 3).

3.3. Hydrogen fuel

Hydrogen as fuel has only been attempted in a handful of projects and prototypes of rail vehicles. Although the technology is being rapidly developed, there are already a few commercially available hydrogen locomotives and railcars, such as the American hydrogen shunting locomotive Green Goat marked as HH20B, the Coradia iLint produced by Alstom or a new SM42 6Dn locomotive produced by PESA Bydgoszcz among others [16]. Due to the relative novelty of fuel cell powered rail vehicles the corresponding hydrogen production technology has not yet been developed to the point that would strongly reduce the price of hydrogen fuel. Projected trends for 2030 and 2050 indicate that hydrogen prices are expected to continue to decrease as the technology is developed, however, there is a wide gap in expectations for how significant the drop in hydrogen price will be, thus leading to a wide range between the higher and lower estimates, where the price is expected to reach anywhere between 1.5 and 4.8 euro/kg (Fig. 4).

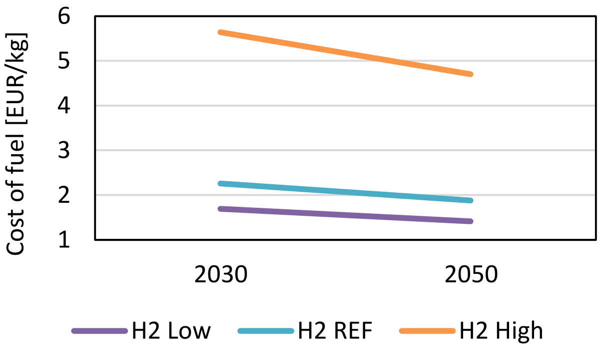

Fig. 4. Projected price of hydrogen fuel for years 2030 and 2050 [3]

Hydrogen can be used as fuel in several ways. Most common solutions involve hydrogen fuel cells (FC) of different designs, hydrogen as an admixture to conventional fuels, or hydrogen burned in a dedicated hydrogen internal combustion engine. While adapting existing engines to use hydrogen as fuel might be more readily available than developing systems based on fuel cells, hydrogen combustion is still not clean, despite not containing carbon. As with any combustion engine the high temperatures cause the nitrogen in air to oxidize into nitrogen oxides, and the lubricating oils used to ensure proper piston operation will generate trace amounts of carbon-based exhaust emissions, such as CO, HC, and PM. For this reason, most of the current hydrogen fuel technology development focuses on hydrogen fuel cells. There are several technologies of fuel cells, that operate at different temperatures, with different efficiencies, and require different materials to manufacture [6]. Most commonly used in transportation are the proton exchange membrane fuel cells (PEMFC).

Each of the analyzed fuels/power sources had some advantages and disadvantages. For diesel fuel the main benefits were the fairly low cost, readiness of technology, and reliable supply. But its ecological indicators were the worst. For hydrogen fuel the technological readiness and availability were low, and the price was high, but the ecological indicators were significantly better. Electric energy usually had the lowest cost, but the availability of infrastructure to enable its use was limited and expensive to expand. Furthermore, the ecological impact of electric energy production varies widely depending on the overall electric grid supply sources used. Electric power does boast the potential of being the most environmentally friendly solution, provided the infrastructure limitations are overcome. This, however, relies completely on switching to a fully green or renewable energy grid, which has a whole set of its own limitations, from costs to technological limitations of its own. Ultimately, aspects of ecology, economy, safety and convenience all need to be achieved on a satisfactory level, and not all possible solutions would be able to provide that as a result of their adoption. Overall, the energy costs of transporting 1 ton of cargo was estimated to be approximately 0.117 kWh/tkm for diesel trains, 0.083 kWh/tkm for hydrogen trains, and 0.052 kWh/tkm for electric trains, where electric and diesel costs were based on a case study results from Spain [8] and hydrogen costs were estimated based on own data and technical specifications of available hydrogen fueled rail vehicles (compared to the average range of 0.02–0.14 kWh/tkm as stated in Springer's The Future of Transport Between Digitalization and Decarbonization Trends, Strategies and Effects on Energy Consumption, by Michel Noussan, Manfred Hafner and Simone Tagliapietra).

4. Fuel cost analysis

The values presented in Fig. 2–4 were analyzed and compared. Due to the difference in units, where electricity was measured as cost per kWh, the whole analysis was first converted into average cost/distance travelled. Distance was calculated using data obtained from fuel consumption measurements from previous research done on representative rail vehicles travelling in real conditions, performing regular work, with the exception of cost of travel for a hydrogen powered vehicle, where the fuel consumption was estimated based on extrapolation of existing data for hydrogen prototypes and hydrogen-powered municipal buses. For the hybrid vehicle a 50/50 use of both diesel engine and electric drive were assumed (as it was close to the use share of electric drive in tested hybrid vehicles 43%), splitting the cost calculation for simplicity. The resulting data of fuel economy was calculated in EUR/km of distance travelled for vehicles powered by the three selected fuel types (Fig. 5).

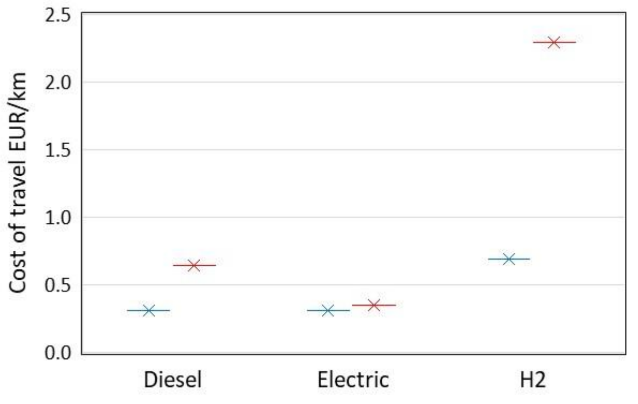

Fig. 5. Cost of travelling 1 km in a vehicles powered by diesel oil, grid electricity, and hydrogen fuel cells projected for the year 2050

5. SWOT analysis

A SWOT analysis was conducted for the hybrid diesel-electric rail vehicle, compared to a conventional and a hydrogen fuel cell powered rail vehicle (Table 1).

The main advantages of using a hybrid drive is the extension of vehicle range while on electrified tracks. While the impact of this feature depends largely on the rate of railway line electrification, a hybrid drive system would provide more options under most circumstances. Use of electric power drawn from the grid also reduces the exhaust emissions as well as providing redundancy in terms of the drive system. Thanks to lower costs of travel on electric power, compared to diesel oil, such a solution is also cheaper in the long run. It does, however, still remain more expensive than a regular electric vehicle. Compared to electric locomotives a diesel-electric hybrid is heavier, more complex to repair and maintain, requires fuel infrastructure, and produces more emissions. Repair personnel of a hybrid vehicle needs to be skilled at fixing issues with both a diesel engine and an electric pantograph system. Not to mention, that the lower emissions argument only applies when the grid electricity is produced from lower emission sources, ideally from renewable sources.

Table 1. SWOT analysis comparing a hybrid-electric rail vehicle to a hydrogen vehicle

	Positive	Negative
Internal	Longer combined range Lower travel cost Drive system redundancy More economically viable	Greater weight due to batteries More complexity More difficult and costly maintenance Battery size and charge limitations
External	High access to overhead power infrastructure Less difficult to manage than hydrogen drive Lower risk of fire/explosion when in enclosed spaces	Requires more skilled maintenance crew Electric Energy drawn from the grid is not usually green

Table 2. SWOT analysis comparing a hybrid-electric rail vehicle to a conventional diesel vehicle

	Positive	Negative
Internal	Longer combined range Lower travel cost Better environmental indicators Drive system redundancy More economically viable	Higher purchase cost Greater weight due to batteries More complexity More difficult and costly maintenance Battery size and charge limitations
External	High access to overhead power infrastructure Less harmful when operated in urban areas and agglomerations More in line with EU ecological policy on reducing emissions Isn't fully reliant on fossil fuel imports	Requires more skilled maintenance crew Electric Energy drawn from the grid is not usually green

The solution is still technologically more familiar and well tested than a fuel cell based hydrogen powered rail vehicle. Due to the many difficulties in ensuring safe and reliable hydrogen storage a hybrid drive remains cheaper and boasts greater operational range than any current or proposed hydrogen rail vehicle. Hydrogen as fuel is also the most costly solution, even at the lower end of the cost predictions for 2050, and those were made with the assumption that hydrogen fuel cell technology develops rapidly.

6. Conclusion

The high cost of hydrogen fuel, even considering the lowest predicted price for year 2050 which is still predicted to be greater than the highest predicted price for diesel oil, indicates that its adoption in the transport sector could only be justified by aspects other than economic. In order to allow the growth of hydrogen fuel in transport political actions would be necessary, either relating to fuel types or exhaust emission standards. The EU's target goal to stop the sale of cars with conventional combustion engines by 2035 is an example of such an approach which, if it comes into effect as planned, will greatly incentivize the switch to electric and hydrogen based transport. While the rail transport sector is not subject to such plans as of yet, this may also change eventually. Although changes in the rail transport sector typically tend to be slower and take longer than in road transport, in part due to the centralized ownership of rail vehicles giving operators a much greater negotiating power, and in part due to the much longer average lifespan of rail vehicles. The calculations made, based on the projected fuel cost data, allowed to draw a basic line of comparison of average cost of travel for rail vehicles with different propulsion and drive systems. Despite the many ecological advantages, hydrogen is not expected to be economically viable without completely outlawing other forms of locomotive power. The hydrogen cost predictions were also most varied, with a wide projected price range from 0.69 to 2.29 euro/km. Diesel fuel had a much smaller range of projected price (from 0.31 to 0.64 euro/km). Meanwhile the cost of travel for electric rail vehicles had the most narrow projected range from 0.31 to 0.35 euro/km. This means that a hybrid drive rail vehicle (assuming half the distance travelled using diesel engine power) would average a cost in the range of approximately 0.31 to 0.50 euro/km.

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