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EVALUATING ALTERNATIVE VEHICLE FUELS THROUGH MULTI-CRITERIA DECISION ANALYSIS

Abstract: *In the last century, alongside the development of combustion engines, researchers, engineers, and manufacturers have explored alternative fuel solutions. The results of such experiments and concepts were usually not commercialized due to a lack of awareness of the negative environmental impact of fossil fuels and insufficient technological readiness. Today, due to strict regulations and emission restrictions, the automotive industry is driven to develop and explore vehicles with more efficient engines, lower emissions, and sustainable production methods. This paper applies Multi-Criteria Decision Analysis (MCDA) to rank various propulsion options, such as electricity, hydrogen, biofuels, and synthetic fuels, based on key criteria like energy efficiency, carbon footprint, economic feasibility, technological maturity, infrastructure readiness, etc. The analysis highlights trade-offs between different power systems, emphasizing the role of policy, innovation, and infrastructure in shaping the future of mobility.*

Keywords: sustainable transportation, alternative vehicle fuels, energy efficiency, emission

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INTRODUCTION

Today's world is highly dependent on fossil fuels, and transportation is considered one of the major energy consumers, alongside the residential and industrial sectors. In the European Union, transportation accounts for around 33.1% of total energy consumption, followed by the industrial sector with 23.3% and the residential sector with 38.9% of final energy consumption (International Energy Agency, 2021). Fossil fuels, such as gasoline and diesel, remain the primary energy sources, despite their negative environmental impact. The extraction, refinement, and use of these fuels are responsible for high greenhouse gas emissions (GHG) released into the atmosphere (U.S. Environmental Protection Agency, 2023). In addition to their environmental impact, the depletion of oil reserves, which are the primary energy source for transportation, is also considered a major problem (Doğan & Erol, 2019). This has led to the development of alternative energy sources and fuels for vehicles. It should be noted that such fuels were initially developed alongside internal combustion engines but with different motivations than today, primarily to reduce dependence on oil and the oil industry. Today, environmental concerns are the main driving force for the development of alternative fuels (Towoju, 2021). Despite this, internal combustion engines fueled by fossil fuels still dominate road transportation (Flach et al., 2017). This is influenced by the lower cost of both fuel and vehicles, as well as consumer habits. To reduce greenhouse gas emissions, many countries have introduced supportive measures for purchasing vehicles powered by alternative fuels, particularly electric and hybrid ones, and have implemented various regulations in the transportation sector to reduce emissions (Towoju, 2021). Although alternative fuels can be more efficient, and there is increasing support for replacing internal combustion (IC) engines with electric ones, resistance to this transition still exists. This paper will examine different types of alternative fuels and use a multicriteria analysis to evaluate and rank them based on criteria such as environmental impact, infrastructure requirements, and other relevant factors.

ALTERNATIVE FUELS

This section will explore different types of alternative propulsion options. Some of them have become widely used by now, such as natural gas, biodiesel, and electric vehicles. In addition, this section will examine alcohol-based fuels, which are often blended with gasoline to improve fuel quality, as well as hydrogen, whose technology is still in the development stage. Toyota is actively researching this technology and introduced the first hydrogen-powered car, the Toyota Mirai (Thompson et al., 2018). While electric vehicles are expected to dominate the transport sector, particularly in passenger cars, other alternatives are still needed. Their usage will largely depend on the intended purpose and function of the vehicle (Varga, Sagoian, & Mariasiu, 2019).

Electric vehicles

Although many authors include hybrids and plug-in hybrids under the category of electric vehicles, the authors of this paper consider that these types of vehicles are already commercially available and widely used. Therefore, they will not be considered as alternatives in this paper. Electric vehicles (EVs) convert electrical energy from batteries into mechanical energy using electric motors. These vehicles emit zero greenhouse gases into the atmosphere and are considered a better alternative to IC engine vehicles, especially in urban areas, where noise is also an issue, as electric vehicles are much quieter. In addition, electric motors are significantly more efficient than IC engines, with an energy conversion rate of 80–90%, compared to just 20–30% in internal combustion engines. These types of vehicles are also considered a preferable solution because their operating costs are very low. In most cases, the cost of recharging the battery is much lower than the cost of refueling with diesel or gasoline. However, there are still several issues with electric vehicles. First, they are only truly "green" if the electricity they use comes from renewable sources (Towoju, 2021). Another challenge is the underdeveloped charging infrastructure, along with slow battery charging times. Electric vehicles also have a shorter driving range compared to IC vehicles, and face concerns regarding battery life cycles. Additionally, EVs are generally more expensive than IC or hybrid vehicles, but many countries have introduced policies and incentive programs to support the purchase of electric cars (Enoma et al., 2022).

Natural gas

Natural gas is an attractive fuel because it is domestically available in many countries, has been used in vehicles for many years, and benefits from a well-established infrastructure. It also produces minimal harmful emissions and is considered a “cleaner” fuel compared to traditional fossil fuels. It has been introduced into internal combustion engines to help reduce greenhouse gas emissions (Chen et al., 2018). Vehicles powered by natural gas typically use either compressed natural gas (CNG) or liquefied natural gas (LNG), and it is often applied in bi-fuel systems, such as diesel/CNG or gasoline/CNG, to improve engine performance and reduce emissions. One of the key advantages of natural gas is its lower cost compared to diesel or gasoline, which makes it a very appealing alternative. In addition to being widely available in many countries and regions, natural gas can be sourced from various origins, so it has the potential to be a more sustainable and renewable energy option. These sources include conventional gas wells, coalbed methane, and shale formations. Although natural gas infrastructure is relatively well developed, there are still challenges, particularly the limited number of refueling stations compared to conventional fuels, which makes bi-fuel usage (e.g. gasoline/CNG) more practical and appealing in many regions (Enoma et al., 2022).

Biodiesel

Biodiesel is currently used as a blend with standard diesel to reduce emissions, improve cold starts, and enhance fuel intake. It is blended this way because of its high viscosity and density, which can cause fuel injection problems when used on its own. In standard internal combustion engines, the use of biodiesel, depending on the blend, can reduce greenhouse gas emissions by up to 78% (Nabi et al., 2019). This type of fuel is typically derived from renewable lipid sources and is considered sustainable only when it does not compete with the food industry. There are four generations of biodiesel, each distinguished by the type of feedstock used. The first generation is produced from crops like corn, wheat, and vegetable oils. The second generation uses non-edible plants, waste oils, energy crops, and lignocellulosic biomass. The third and fourth generations are still under development. The third generation focuses on algal biomass, while the fourth involves genetically modified microorganisms (Stančin et al., 2020). Pure biodiesel is rarely used on its own in engines; it is commonly blended with conventional diesel. This is due to several challenges, including the lack of regulatory support, its high viscosity, which can clog fuel filters, and potential compatibility issues that may lead to the degradation of engine components and fuel system parts (U.S. Department of Energy, 2016).

Alcohol derivate fuels

Like biodiesel, alcohol derivate fuels have been successfully used in IC engines in blends with fossil fuels, where shares of alcohol do not exceed 20%. Commercially used is ethanol, but in this paper, methanol and dimethyl ether will be reviewed as well.

Methanol can have various roles as an alternative fuel: it was used and can be used in IC engines in blends, in fuel cells, and as a potential hydrogen carrier. Engines solely for methanol usage are under development. Methanol is a colorless, volatile, and flammable liquid that raises concerns for its storage and safety regulations. It is important to note that while methanol can be produced from a variety of feedstocks, priority should be given to producing it from renewable and sustainable sources (Stančin et al., 2020).

Ethanol is a widely used alternative fuel, typically produced from corn, sugarcane, wheat, and various forms of agricultural and forestry waste. Similar to biodiesel, it is most often blended with fossil fuels to enhance fuel quality, reduce emissions, and improve engine efficiency. The most common blend contains 10% ethanol, while higher blends require engine modifications (Enoma et al., 2022). One major drawback of ethanol is its low energy density, which leads to increased fuel consumption and the need for larger fuel tanks or more frequent refueling. Additionally, incomplete combustion of ethanol can result in the release of harmful gases into the atmosphere, such as formaldehyde (Stančin et al., 2020).

Dimethyl ether (DME) has been used as a fuel additive and has demonstrated strong performance in spark-ignition engines. It is a non-toxic, non-carcinogenic compound with a low global warming potential and a cetane number comparable to that of diesel, which makes it a promising and environmentally friendly alternative to fossil fuels. However, DME faces similar challenges as ethanol—its low energy density requires larger or reinforced fuel tanks, and its low viscosity can lead to fuel leakage issues which require the development of a new fuel delivery system (U.S. Department of Energy, 2016).

Hydrogen

Hydrogen is a promising alternative fuel that can be used in compressed, liquid, or solid form, each with its limitations. The most efficient and attractive application of hydrogen is in fuel cells, where compressed hydrogen gas is converted into electricity to power electric motors (Brooks et al., 2018). Although hydrogen has a lower energy density than fossil fuels, posing challenges for storage and distribution, it offers a significantly higher energy conversion efficiency, around 60%. When used as a fuel, hydrogen emits only water vapor and heat, without releasing any harmful gases (Enoma et al., 2022). Despite being the most abundant element in the universe, hydrogen is rarely found in its pure elemental form on Earth. It can be produced in several ways, but the most common method relies on fossil fuels, which makes the process less sustainable, though currently cheaper than renewable-based alternatives. Greater emphasis should be placed on producing hydrogen from renewables, such as through electrolysis powered by renewable energy (Stančin et al., 2020). However, hydrogen faces major challenges in terms of storage and infrastructure. Establishing a reliable hydrogen distribution network is expected to require billions of dollars in investment over the coming decades (Acar & Dincer, 2019).

METHODOLOGY

In this paper, Multi-Criteria Decision Analysis (MCDA) was used to evaluate and weigh the given alternatives. This method is usually used when is needed to evaluate alternatives and rank them based on valuation criteria with varying scales or units (Kügemann & Polatidis, 2020). MCDA methods typically rely on two main inputs: the performance of each alternative across several criteria, and the relative importance (weights) assigned to each criterion. A common approach is to combine these inputs into an overall score for each option by aggregating weighted values across the criteria. In many cases, this is done using a hierarchical structure, where the main criteria are divided into sub-criteria. Each alternative is then evaluated on these sub-criteria, and the results are aggregated step-by-step to obtain a final ranking. Several MCDA methods are commonly used for evaluating complex alternatives across multiple criteria, such as Weighted Sum Method (WSM), Weighted Product Model (WPM), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Multi-Attribute Utility Theory (MAUT), and others (Huang, Keisler, & Linkov, 2011). Among these, the Weighted Sum Method (WSM) is one of the simplest and most intuitive with straightforward calculation and ease of interpretation. It involves assigning a weight to each criterion based on its importance and then multiplying these weights by the chosen performance scores of each alternative. The total score for each alternative is obtained by summing up these weighted values and the preferred option is the one with the highest overall score (Taherdoost, 2023).

This paper applies to the Weighted Sum Method (WSM) due to its simplicity and the authors' belief that all considered alternatives have potential applications; the aim is to rank them in terms of which is likely to become the most widely used and conventional.

SELECTION OF ALTERNATIVES AND CRITERIA

Alternative propulsion options face several challenges in reaching widespread commercial adoption. The main obstacles include underdeveloped infrastructure, higher costs compared to fossil fuels, and reliance on fossil-based production methods. For alternative fuels to be considered competitive and truly sustainable, their production should move away from fossil fuel dependence and adopt more efficient, renewable-based processes. Additionally, to achieve price competitiveness with conventional fuels, government support through subsidies or tax incentives is often necessary (Hordeski, 2013).

To rank alternatives, selected criteria will focus on the next crucial criteria: emission of greenhouse gases (GHG), developed/accessible infrastructure, level of technology readiness (TRL), energy density and cost. Each criterion has been assigned a weight based on its relative importance in the current context shown in Table 1.

Table 1. *Criteria and its*

Criteria	Weight
Greenhouse gas emission (GHG)	0.25
Infrastructure	0.25
Energy density	0.2
Technology readiness (TRL)	0.15
Cost	0.15

Emissions and infrastructure are considered the most critical factors, each receiving the highest weight (0.25), due to their direct impact on sustainability and practical deployment. Energy density is next in importance (0.20), as it influences refueling logistics and overall efficiency. Technology readiness and cost are weighed lower (0.15 each), as these parameters are more likely to evolve and improve over time with further development and market dynamics. The alternatives: electricity, CNG, biodiesel, alcohol derivate fuels and hydrogen will be first evaluated against these criteria on a scale from 1 (poor) to 5 (excellent) and then multiplied by the weight of each criterion. It should be noted that the ranking is based on findings in the reviewed literature (Stančin et al., 2020; Towoju, 2021), and that the assigned scores also reflect a level of informed subjectivity based on the current development status and projected potential of each technology.

These scores reflect the perceived performance of each fuel in the respective category. For example, EVs received the highest score in GHG emissions due to their zero tailpipe emissions, but scored lower in energy density, highlighting the current limitations of battery technology. CNG and ethanol, with relatively mature infrastructure and technology, scored consistently well across most categories. In contrast, hydrogen and DME were rated lower in infrastructure and cost due to their limited commercial deployment and high production or distribution expenses.

Table 2. *Score of alternatives on each criterion*

Energy/ Fuel type	GHG	Infra-structure	Energy density	TRL	Cost
EV	5	4	2	4	4
CNG	3	4	3	5	5
Biodiesel	3	4	4	4	4
Methanol	3	2	3	4	4
Ethanol	4	4	3	5	3
DME	3	2	4	3	2
Hydrogen	5	2	3	3	2

Table 3 presents these scores normalized to a 0–1 range and then multiplied by the corresponding weights and summed to calculate an overall score for each fuel.

Table 3. *Total score for each alternative fuel*

Energy/ Fuel type	GHG	Infra-structure	Energy density	TRL	Cost	Total
EV	0.25	0.2	0.08	0.12	0.12	0.77
CNG	0.15	0.2	0.12	0.15	0.15	0.77
Biodiesel	0.15	0.2	0.16	0.12	0.12	0.75
Methanol	0.15	0.1	0.12	0.12	0.12	0.61
Ethanol	0.2	0.2	0.12	0.15	0.09	0.76
DME	0.15	0.1	0.16	0.09	0.06	0.56
Hydrogen	0.25	0.1	0.12	0.09	0.06	0.61

Based on the results, the most preferable and mature technologies are electric vehicles and compressed natural gas, followed by ethanol and biodiesel. Methanol, hydrogen and dimethyl ethyl still need further research and development to be widely commercialized.

Another approach to achieving sustainable and efficient transportation is the use of flexible fuel vehicles (FFVs). These vehicles are designed to operate on more than one type of fuel, typically a combination of gasoline and alternative fuels, such as ethanol or methanol. The main advantage of FFVs is their ability to leverage the benefits of multiple fuels, allowing for greater flexibility, improved fuel efficiency, and reduced environmental impact. By combining the best characteristics of different fuels, FFVs offer a practical solution during the transition toward cleaner energy sources in the transport sector (Hordeski, 2013).

CONCLUSION

The future of transportation will not be defined by a single dominant solution, but rather by a combination of various alternative propulsion options and technologies, each suited to different contexts and applications. Among these, although ethanol, biodiesel and CNG are widely spread and used, electric vehicles (EVs) are currently positioned as the most prominent option. This is largely due to the strong policy support provided by many governments and their technological maturity. However, the limitations of EVs, particularly in terms of charging infrastructure and long-distance travel capabilities, highlight the need for continued innovation.

Other alternatives, such as hydrogen, biofuels, and alcohol-derivate fuels, also offer distinct advantages and face specific challenges. Their adoption will depend on advancements in production efficiency, infrastructure development, and cost reduction. Flexible-fuel vehicles and hybrid systems, which allow the use of multiple fuels, represent a particularly promising direction. By combining the strengths of different energy sources, they offer greater adaptability and resilience, as seen in CNG/gasoline and hybrid-electric vehicles.

Ultimately, the success of any alternative depends not only on technical feasibility and policy support but also on consumer behavior. A lack of awareness, motivation, or confidence among buyers can significantly impact the adoption of newer technologies, particularly when conventional vehicles remain more affordable and familiar.

In conclusion, while EVs are likely to dominate in the short term, the future of the automotive industry will be shaped by a range of coexisting technologies. Each alternative fuel pathway will require further development, commercialization efforts, and user education to secure a meaningful role in a sustainable transportation ecosystem.

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