



Araştırma Makalesi / Research Article

Evaluation of Alternative Fuel Characteristics for Internal Combustion Engines with Analytical Hierarchy Process

Analitik Hiyerarşi Prosesiyle İçten Yanmalı Motorlar İçin Alternatif Yakıt Özelliklerinin Değerlendirilmesi

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ABSTRACT

For a long time, the diesel and gasoline have been utilized as fuel for internal combustion engines. But the diminishing oil supplies along with the variable oil prices drive people to obtain alternative sources for fuel. The sustainable fuel options may alter power consumption that results in less pollution, less carbon and more variety of fuel supply. It is generally a challenging task for decision makers to determine the best feasible fuel for internal combustion engines among multiple choices because of the complicated task of considering various attributes of performances and the lack of information available. However, the right choice of the most feasible fuel option for internal combustion engines can efficiently mitigate serious environmental troubles and over-consumption of energy during transportation.

In this study, the diverse types of liquid fuel options for internal combustion engines are compared in terms of critical characteristics determined within the scope of this research. In this article, the quantitative evaluation model utilized provides decision makers with a tool to be utilized during important strategic decision-making processes on issues with regard to fuel policy in the near future. The applied model presents quantitative conclusions that can contribute to enhance the decision-making progression.

ÖZ

Uzun süredir içten yanmalı motorlarda benzin ve motorin yakıt olarak kullanılmaktadır. Ancak değişken yağ fiyatlarının yanısıra azalan yakıt kaynakları insanları alternatif yakıt kaynakları edinmeye itmektedir. Sürdürülebilir yakıtlar, havayı daha az kirleten, daha az karbon salınımına yol açan güç tüketimini değiştirebilen çeşitli yakıtlardır. Otoriteler yakıtların performansı ve özellikleri hakkındaki bilgi eksikliği nedeniyle içten yanmalı motorların alternatif yakıtları için karar vermekte zorlanmaktadır. Bununla birlikte, içten yanmalı motorlar için en uygun yakıt seçeneğinin doğru seçimi, nakliye sırasında ciddi çevresel sorunları ve aşırı enerji tüketimini etkili bir şekilde azaltabilir.

Bu çalışmada, değişik tipteki sıvı yakıt seçeneklerinden hangisinin içten yanmalı motorlar için uygun olduğu değerlendirilmiştir. Bu makalede, kullanılan nicel değerlendirme modeli, karar vericilere yakın gelecekte akaryakıt politikası ile ilgili konularda önemli stratejik karar alma süreçlerinde kullanılacak bir araç sunmaktadır. Uygulanan model, karar alma sürecinin ilerlemesine katkıda bulunabilecek nicel sonuçlar vermektedir.

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1. INTRODUCTION

Fossil-based energy sources have various purposes of consumption in different regions of a country such as: commercial, transport, industrial, and domestic sectors for the mechanical production of power. These sources' speedy depletion and crude oil's ever raising cost made the researchers to search for the other sources of energy. The petroleum reserves' deficiency is causing sustainable energy sources to be more appealing. In addition, the fossil-based fuel's cost is rising continuously because of the hike in raw oil cost. The increasing concerns about the unpredictability of fossil-based fuel make alternative fuels more appealing to researchers as well as the manufacturers. The environmental issues emerging from hazardous emissions and a limited fossil-based fuel source motivates the searches for option fuels from sustainable-renewable resources [1]. The most feasible way to meet this ever-growing requirement is by using option fuels [2].

The transportation sector relies heavily on fossil-based energy sources such as liquefied petroleum gas, liquefied natural gas, diesel, and gasoline fuel. Therefore, there is an extensive recent concern in learning more about acquiring fuels from biomass-based resources. The environmental laws and ever increasing demand from automotive sector has encouraged the production of renewable fuel from biomass to replace fossil-based fuels [3]. In addition to the combination of pollution and climate instability, issues of security, increasing fuel prices, and rising poverty in agricultural and rural fields are propelling countries to pass effective incentives for the utilization of these natural liquid energy sources, which is in turn brilliant investment [4]. Burning fossil-based fuels create higher amount of CO₂ and other harmful gases. Using bio-based counter-part rather than fossil-based fuel is efficient in decreasing greenhouse gas and creating financial benefits by reducing health care expenses as well. Hence, utilization of many bio-based fuel alternatives is more volatile than conventional fuel, which can contribute to the solution of ozone trouble [5].

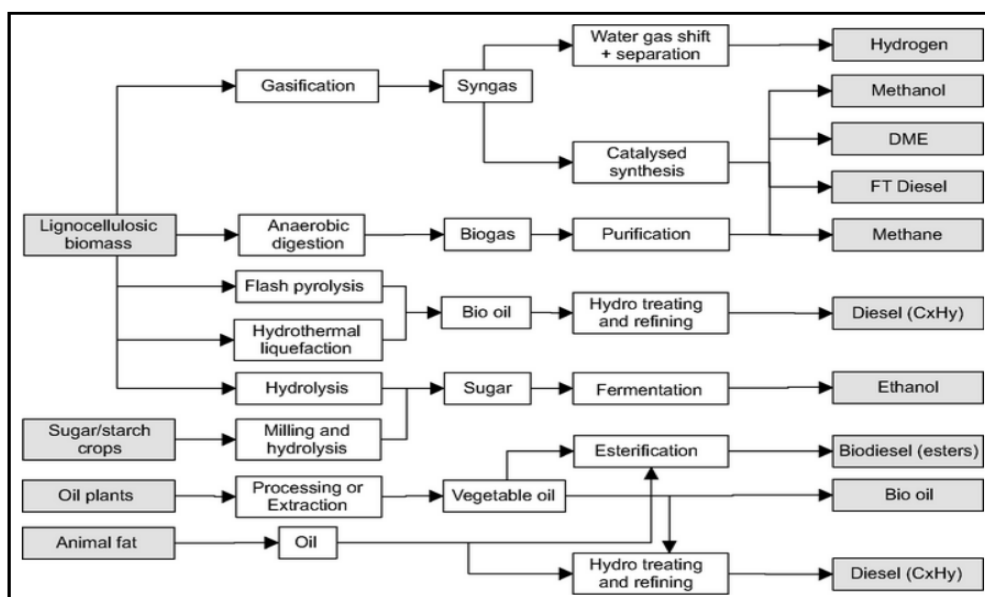


Figure 1. The primary energy resources view as automotive fuels [6].

The primary energy resources' view as automotive fuels is given in Fig. 1 [6]. Some of the alternative fuels have been utilized in reality and display a potential as future automotive fuels. Compared with fossil-based conventional fuels, biomass-based non-conventional fuels have sustainability, energy power, and superiority in environment effect. The liquefied petrol gas and liquefied natural gas are more environment friendly, acceptable running variety, and minor running costs, and hence are able to replace the traditional fossil-based fuels in the near future. In the mid-term period, the biomass-based fuels will probably develop to be more cost efficient and sustainable. In the long period, the hydrogen is predicted to replace the traditional fuels because of the trend of unsustainable generation pathway of the future and high investment costs [7-9]. But, bio-based fuels cannot be utilized directly because of high oxygen and water content, high corrosiveness, viscosity, and low heating capacity [10]. For example, bio-gasoline can be produced from wood waste, agricultural straw, animal oils, animal waste, and algae. In addition, vegetable oil can become more attractive for the generation of bio-gasoline due to the numerous bio-varieties. All of the plant-based oils are eminently viscous. Their viscosities are 9 to 17 times greater than fossil-based gasoline fuel. On the other hand, vegetable-based oil's heating capacity is lesser than half that of fossil-based gasoline. Hence these vegetable oils are proposed to be transformed into bio-gasoline by hydrothermal or pyrolysis. However, these chemical processes require high production cost [11-13].

There are articles that have evaluated a range of biofuels and fossil fuels according to structural properties. For example, Frank et al compared a plenty of algae-based pathways for manufacturing renewable-based fuels such as renewable gasoline and diesel, and bio-diesel [14], Sobrino et al. analyzed fossil-based fuels with ethanol [15], Festel et al. analyzed a plenty of biofuels containing biodiesel and ethanol [16], and Xie et al. compared a series of coal and biomass-based liquid fuel alternatives[17]. In the literature, few diverse approaches are presented to evaluate the fuel options by multi-criteria analysis. For Taiwan' urban fields, Tzeng et al. used an integrated decision making methodology for the choice of option fuel buses. A set of 11 criteria was used for evaluation and comparison purposes. They utilized buses fueled with liquid propane gas, compressed natural gas, diesel, methanol, hybrid electric buses and hydrogen fuel cell bus. Analytical Hierarchy Process (AHP) was utilized to obtain the criteria weights along with VIKOR and TOPSIS methodologies to evaluate and rank the option fuel buses [18]. To obtain the proper fuel mixture, Köne and Buke used Analytical Network Process (ANP). By Super Decisions software, the proposed analysis was applied to two different option scenarios with environmental indicators and electricity production[18]. Streimikiene et al. utilized the TOPSIS technique for comparative evaluation of power sources in transportation. The evaluation depended on economic and environmental parameters. They also considered the transportation infrastructure's impact on the emissions and energy consumption by vehicles [20]. Through a data envelopment analysis (DEA) method and Pareto optimal approach, Fazeli et al. (2011) presented a multi-criteria assessment for the selection of the light-work vehicle fleets' fuel alternatives. To determine the most desirable alternative, they considered user's approval, technology development's risk, and pollutants' emissions to the atmosphere, fuel supply availability, and transition costs as assessment criteria [21]. By using

AHP, Pilavachi and Tsita assessed 7 option fuels for transportation sector in Greece. Internal combustion engine, biofuels (1st and 2nd generation) and gasoline's blends, fuel cells, electric vehicles, hybrid vehicles, and plug-in hybrids were assessed according to policy and cost perspectives [22]. For road transportation, Mohamadabadi et al. proposed PROMETHEE Methodology application for evaluation and enrichment for ranking non-renewable and renewable fuel vehicles. The vehicles that depend on E85 ethanol, gasoline-electric (hybrid), compressed natural gas, diesel, gasoline, and B100 biodiesel were assessed in regard to fuel cost, vehicle cost, distance between refueling centers, vehicle alternatives accessible to the harmful emissions, and consumer in their article [23]. Zhou et al. presented fuels' multi-criteria evaluation to compare the traditional fuels with renewable and new fuels. Pure ethanol, compressed natural gas, blend of 85% methanol and 15% gasoline by volume, traditional diesel, and traditional gasoline were evaluated in regard to global warming potential, life cycle cost, vegetable oil, vehicle alternatives available to consumer, net energy product, and nonrenewable source depletion potency utilizing an LCA viewpoint [24]. Brey et al. used DEA method to analyze and compare the fuel-cell vehicles with hybrid and traditional internal combustion engine vehicles in terms of environmental, technical, and economic aspects. The used method entails more familiarity and computation with the linear programming concepts [25]. In Malaysia, Najib and Abdullah developed an IF-AHP (intuitionistic fuzzy analytic hierarchy process) for choosing the best power technology[26]. To resolve alternative fuel group problem, Montajabiha used PROMETHEE II methodology. By IFS, all criteria weights and ratings of each alternative were presented. To display the methodology's practicability, it was implemented to maintainable power designing problems [27]. To determine the criteria weights and to rank the option fuels, Paul et al. (2015) applied AHP, MOORA, and PROMETHEE methodologies. The determination of data in regard to the assessment signs is pre-necessity before utilizing all these methodologies for obtaining the maintainability order of the option fuels. Nevertheless, it is generally problematic or even impossible to utilize accurate data with units to characterize the alternative fuels' performances in regard to the assessment indicators [28]. To assess the biodiesel optimum blend, Sakthivel et al. performed an analysis by combining VIKOR and TOPSIS with ANP methodologies[29]. Liang and Ren utilized the fuzzy TOPSIS methodology which was then used to obtain the marine fuels' maintainability order and the fuzzy logarithmic least squares methodologies to obtain the criteria weights for marine fuels' maintainability evaluation[30]. Sehatpour et al. used the PROMETHEE methodology to study the alternative fuels utilized in light vehicles including diesel, biodiesel, liquid petroleum gas, compressed natural gas, ethanol, methanol, hydrogen, and biogas in regard to the assessment indicator[31]. For shipping, Lutzen and Ren used fuzzy AHP to obtain the criteria weights for maintainability evaluation of alternative energy resources and then rank the energy resources by unifying Dempster-Shafer theory with MADA methodology[32]. For CO₂ emissions, Nocera and Cavallaro evaluated alternative fuels by the three alternative scenario analyses[33]. In the years 2020–2030, Ang and Poh performed backward and forward AHP to assess the possible plans and transportation fuels for Singapore depending on the choice of the most proper fuel option for road transportation[34]. On the basis of multiple criteria, Lanjewar et al. employed a hybrid multi-criteria method by using graph theory, as well as AHP

methods for the nonconventional and conventional transportation fuels' efficiency evaluation[35]. Papalexandrou et al. performed AHP to assess the biofuel production's complete chain. The substitution's potential, the biofuel cost over the conventional fuels, the total cycle energy consumed and the total life cycle emissions were considered as the criteria. The best alternative was determined to be the bioethanol produced from wheat straw [36].

The aim of this paper is to investigate the most feasible liquid fuel alternative to utilize in the internal combustion engines by using many critical comparison criteria from various scientific aspects. The assessment scale points are defined for each of comparison criteria. The experts evaluated the performance of 8 fuel alternatives (gasoline, diesel, biodiesel, ethanol, methanol, liquefied petroleum gas, liquefied natural gas, and hydrogen) according to given points for each of criteria. Based on their significance, the weights for each comparison criteria are found. The most feasible liquid fuel is determined with given assessment scale points for each of fuel alternatives, and weighing for each of criteria based on their significance in internal combustion engines.

2. MATERIAL AND METHOD

2.1 The Model Structure

To obtain a framework for relations with multi criteria decision-making issues, an AHP based model is structured. Among decision levels, AHP models adopt a unidirectional hierarchical connection. AHP methodology permits the hierarchical tree building and weighing each indicator through pairwise comparison between indicators and criteria by a matrix to obtain a coherent and consistent administration of both qualitative and quantitative data. To determine weights of criteria, such a method is used in this paper.

In an AHP hierarchy for choosing an optimum fuel for internal combustion engines, the goal would be to choose the most appropriate alternative that satisfies various sets of criteria. These criteria are often subdivided into several sub-criteria. This study involves six main criteria of top level. *Composition* of the fuel involves Carbon, Hydrogen, and Oxygen. *Physical and chemical properties* of analyzed fuels are considered as the second main group of criteria. Density, molecular weight, specific gravity, freezing point, boiling temperature, and Reid vapor pressure are considered within this group. The third main criterion is the *fuel properties* which involves cetane and octane numbers, energy content, flash point, auto ignition temperature, viscosity centipoise, flammability, latent heat of vaporization, stoichiometric air/fuel ratio, and maximum practice compression. The fourth group is the *environmental criteria*. HC, NO_x, CO, PM10, CO₂, and ozone forming impact of the selected fuel types are considered as the sub-criteria under this group. The fifth group covers a set of qualitative criteria that are quantified based on expert evaluations for the purpose of this study. Energy security impacts, fuel availability, types of vehicles available, maintenance issues, and safety are evaluated. The final criterion involves *financial aspects* of the fuel types used. 8 Alternative fuel types are

compared from the perspective of each criteria mentioned. The main criteria and the hierarchy composed of these criteria are constructed as shown in Fig.2 and Table 1, respectively.

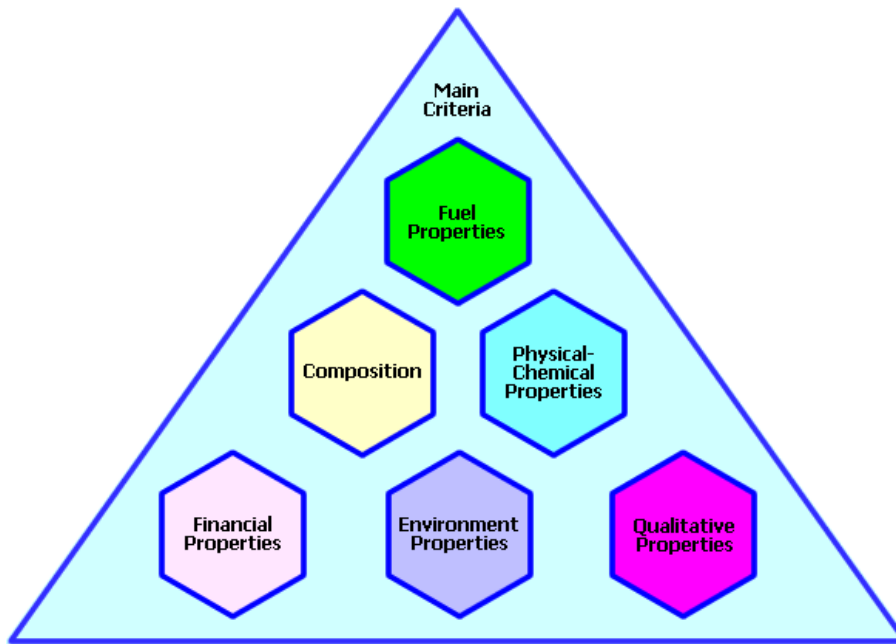


Figure 2. Main criteria

Table 1. Hierarchy of criteria

Main Criteria	Fuel Properties	Composition	Physical-Chemical P.	Environment	Qualitative	Financial
Sub-criteria	Cetane number	Carbon	Density	HC	Energy Security Impacts	Price
	Octane number	Hydrogen	Molecular Weight	NOx	Fuel Availability	Production cost
	Energy Content	Oxygen	Specific gravity	CO	Types of vehicles available	
	Flash Point		Freezing point	PM10	Maintenance Issues	
	Autoignition Temperature		Boiling temperature	CO ₂	Safety	
	Viscosity		Reid vapor pressure	Ozone-forming impacts		
	Centipoise					
	Flammability					
	Latent heat of vaporization					
	Stoichiometric air/fuel					
	Max. Practical compression					

2.2 Result and Discussion

While measurements for some criteria are readily available, some others can only be estimated with respect to other variables. As it is the case in all multi-criteria decision models, the relative priorities of such criteria need to be determined. This is accomplished by pairwise comparison of the factors, starting with the main criteria. Below are the resulting priorities of composition, physical-chemical properties, fuel properties, environmental properties, qualitative aspects, and financial properties shown in Fig. 3.

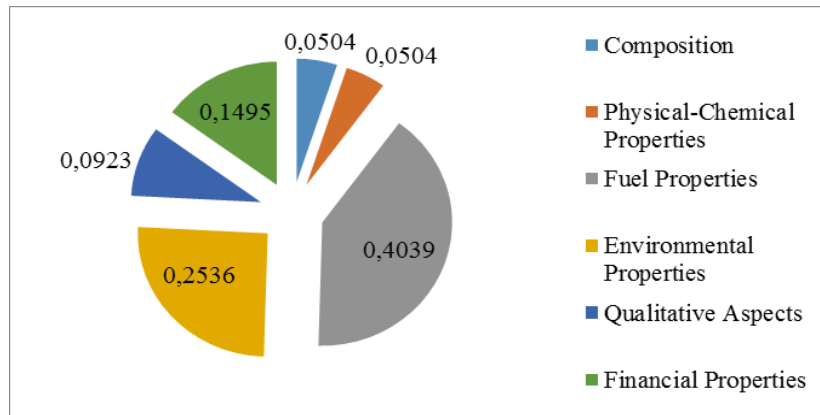


Figure 3. Priorities of main criteria

In the next step, there are groups of sub-criteria under each main criterion to be compared two by two. Each pair of sub-criteria related to the fuel property is compared based on their impact on fuel property criterion.

At this point, the comparison for fuel property criteria is made, and the method has obtained the local priorities for this group. These priorities reflect on how much it adds to the weight of its parent, thus we need to calculate the “global priority” of each sub-criterion which shows the impact of each on the overall goal of determining the best fuel for internal combustion engines. The global priorities throughout the hierarchy should add up to one. The global priorities of each sub-criterion are calculated by multiplying their local priorities with the priority of its parent criterion which results in the following values for the sub-criteria under fuel property. Fig. 4 shows the resulting global weights for these criteria based on pair wise comparisons.

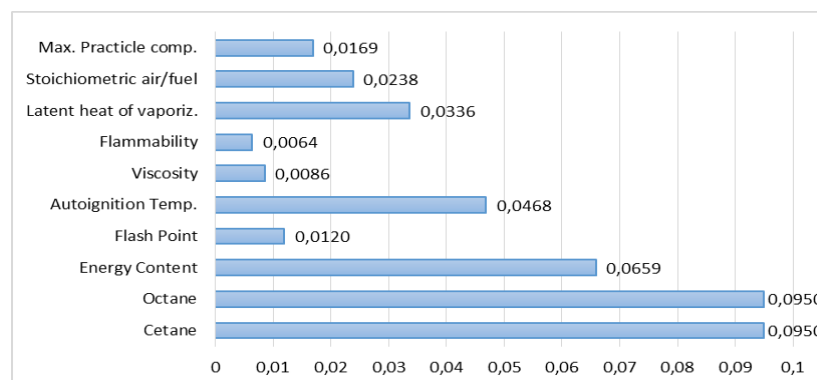


Figure 4. Global priorities of sub-criteria under fuel properties

The second group of sub-criteria involves the composition of the fuel in terms of C, H, and O. These three atoms are evaluated in terms of their impact on the quality of fuel. The factors under the fourth group

showing the physical and chemical properties of the fuel alternatives are also compared pairwise to assess their impact. Financial criterion covers the production cost of the fuel and the price. The fuel alternatives are evaluated from the environmental perspective due to its critical role on the sustainability of these energy sources. HC, NO_x, CO, PM10, CO₂ production of the fuel types along with their ozone impact are evaluated under within this group. Finally, a set of qualitative properties such as energy security, fuel availability, types of vehicles available, maintenance, and safety issues are grouped under this main criterion. All these elements are compared as to how significant impact they have on the overall goal. Fig. 5 shows the global priorities of the mentioned groups of sub-criteria.

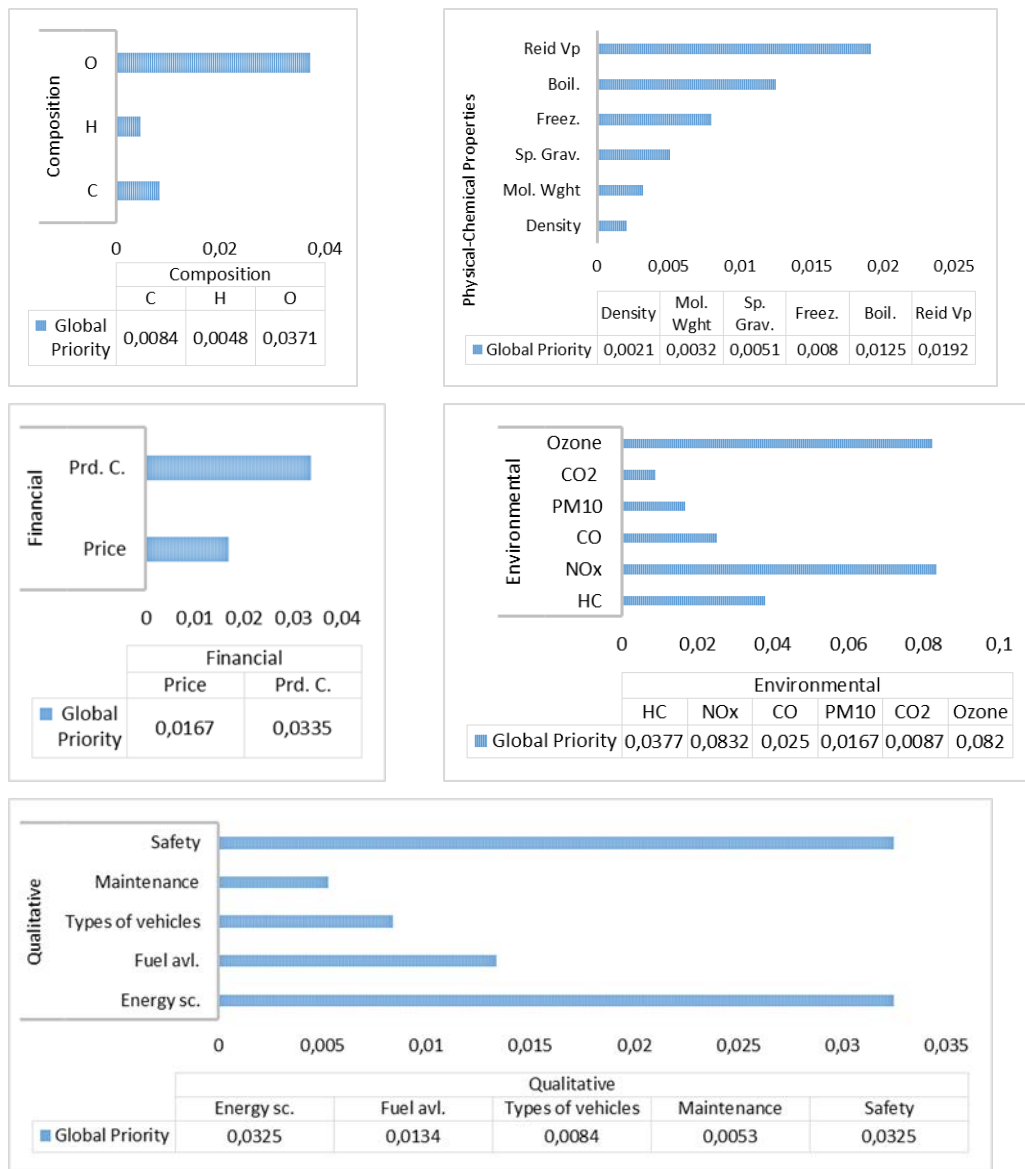


Figure 5. Sub-group priorities

After determining the priorities of the main criteria with respect to the overall goal of choosing the optimum fuel and priorities of each sub-criterion with respect to their own main criterion, the fuel alternatives

are compared two by two with respect to each sub-criterion. 8 different fuel alternatives are used for the purpose of this investigation to be evaluated.

The properties of the selected alternatives are presented in Table 5-6 below:

Table 2. Physical and chemical properties[37-56]

	Gasoline	Diesel (No. 2)	Biodiesel	Ethanol (E85)	Methanol (M85)	Liquefied Petroleum Gas (LPG)	Liquefied Natural Gas (LNG)	Hydrogen
Composition, Weight %								
Carbon	85–88	84–87	66.1	52.2	37.5	82	75	0
Hydrogen	12–15	33–16	13.7	13.1	12.6	18	25	100
Oxygen	0	0	18.2	34.7	49.9	0	0	0
Density, kg/m ³ @ 15,56 °C	718.98 – 778.95	802.861- 886.742	826.827	792.08	794.47	505.68	128.22	–
Molecular Weight	100–105	200	88.15	46.07	32.04	44.1	16.04	2.02
Specific gravity, 15,56°C	0.72–0.78	0.81–0.89	0.744	0.796	0.796	0.508	0.424	0.07
Freezing point, °C	-40	-40–30	-164	-173.2	143.5	-305.8	-296	-435
Boiling temperature, °C	26.67– 225	187.68– 343.33	55	77.78	65	-42.22	-161.67	-20.13
Reid vapor pressure, kPa	55.16– 103.4	1.4	53.8	15.86	31.72	1434.11	16547.42	–

Table 3. Fuel properties [37-56]

	Gasoline	Diesel (No. 2)	Biodiesel	Ethanol (E85)	Methanol (M85)	LPG	LNG	Hydrogen
Cetane no.	5 to 20	40 to 55	46 to 60	0-54	N/A	N/A	N/A	N/A
Octane no.	86 to 94	8 to 15	~25	110	112	104	120+	130+
Energy Content [kJ/m ³] (Lower heating value)	31246.17- 2354.28	35809.61	33318.585	21273.17	15955.58	23480.48	5919.59	14376.74
Energy Content [kJ/m ³] (Higher heating value)	33552.14- 34653.56	38597.16	35662.45	23558.51	18171.24	25478.75	6612.44	17004.32
Flash Point [°C]	- 42.78	73.89	100 -170	12.78	11.11	-87.22	-187.78	N/A
Autoignition Temperature [°C]	257.22	315.55	148.89	793	422.78	454.44- 510	-17.22	-17.19- - 17.18
ViscosityCentipoise @ 15,56 °C	0.37–0.44	2.6–4.1	0.35	1.19	0.59	–	–	–
Flammability limits, volume%	1.4-7.6	1-6	1.6-8.4	4.3-19	7.3-36	2.2-9.5	5.3-15	4.1-74
Latent heat of vaporization kJ/kg@ 15,56 °C	348.90	232.60	320.99	921.10	1176.96	449.15	509.40	446.82
Stoichiometric air/fuel, weight	14.7	14.7	11.7	9	6.45	15.7	17.2	34.3
Max. Practicle compression ratio	10:1	23:1	23:1	19:1	19:1	17:1	17:1	-

Table 4. Weighted emissions obtained (in µS/km) for vehicles using alternative fuels on basis of exposed emissions [37-56]

	Gasoline	Diesel (No. 2)	Biodiesel (soybean)	Ethanol (E85)	Methanol (M85)	LPG	LNG	Hydrogen
HC	2643	2173	2461	2005	2488	1595	454	516
NOx	10113	15581	17694	1176	576	2114	3210	787
CO	164	33	26	30	28	5	2	2
PM10	361	7716	5145	1637	175	1703	103	128
Total	13281	25502	25327	4848	3267	5417	3768	1432
*The ozone-forming impacts of burning the fuel	2	1	5	4	5	5	6	5
CO ₂ (lbs CO ₂ /gal)	20	22	19	13	3	13	10	0

Table 5. Qualitative Characteristics [52-56]

	Gasoline	Diesel (No. 2)	Biodiesel (soybean)	Ethanol (E85)	Methanol (M85)	Liquefied Petroleum Gas (LPG)	Liquefied Natural Gas (LNG)	Hydrogen
Energy Security Impacts	2	1	5	4	4	2	3	5
Fuel Availability	6	5	3	2	2	4	1	1
Types of vehicles available today	6	5	5	4	4	5	4	1
Maintenance Issues	6	6	3	4	4	5	5	5
Safety	5	4	6	6	6	3	4	4

Table 6. Financial attributes [55-56]

	Gasoline	Diesel (No. 2)	Biodiesel (soybean)	Ethanol (E85)	Methanol (M85)	Liquefied Petroleum Gas (LPG)	Liquefied Natural Gas (LNG)	Hydrogen
Price (\$ per Liter) ^a	0.597	0.652	0.850	0.525	0.436	0.750	0.665	0.317
Production cost (\$/GJ _{fuel})	9.73	8.87	21.73	10,34	11.69	7.32	14.22	5,91

^a National average price between July 1 and July 31, 2017

The final step in applying the AHP technique is pairwise comparisons of the alternatives with respect to the sub-criteria. In order to design an objective scheme for this purpose, the maximum and minimum values of the alternatives for each sub-criteria is determined. This range is divided into nine even ranges on a scale from 1 to 9. Finally each alternative is placed in one of these ranges based on their values to compare them with each other. Remainder of this section presents the priorities obtained under each sub-category using this scheme.

3. CONCLUSIONS

The biomass-derived fuel is renewable and clean energy source that is considered to be a potential to replace the traditional fuel. The multi-criteria evaluation methodology has been performed in transport projects to choose among various options considering mostly economic, environmental, technical, safety, policy, and social criteria.

This study aims to find the most appropriate plant oil based on various criteria exist in the literature. A list of criteria is evaluated and divided into five groups. Each criterion is appointed a relative weight as a result of expert evaluations. Finally, AHP method is applied to the resulting scheme. Based on the calculations above, the relative priorities corresponding to the attractiveness of each fuel about all factors are presented below:

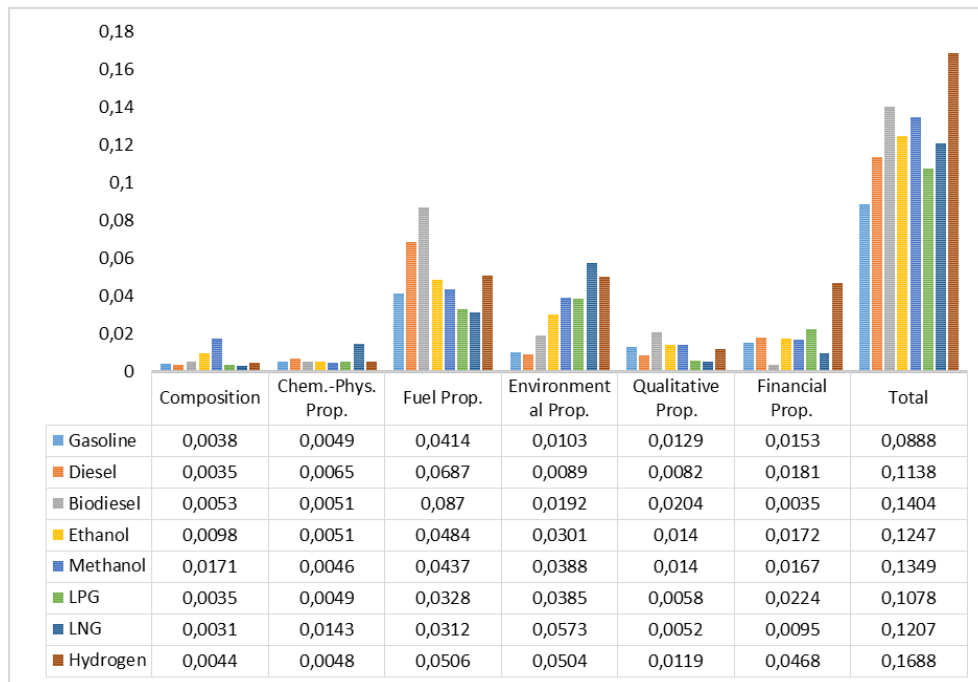


Figure 6. Fuel comparison

The obtained results indicate that the Hydrogen with a global priority of 0.1688 presents itself as the optimum source of energy that satisfies all the criteria selected. On the other hand, Gasoline obtains the lowest priority score of 0.0888. The results also indicate that LNG is the alternative that contributes the most to the environment, presenting itself as an environment-friendly energy source.

Aside from providing a quantitative method to evaluate the alternative fuels, this study brings together a wide range of properties that are grouped under a set of criteria. Various critical qualitative aspects of fuels such as energy security and safety etc. are also quantified to be added into this quantitative analysis.

The model developed within the scope of this study can further be enhanced or improved to cover different aspects of alternative energy sources for internal combustion engines and serve both the policy-makers and the industry itself.

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