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A COMPARISON OF SOME HYBRID ELECTRIC VEHICLE BATTERIES

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Abstract. Hybrid electric vehicles (HEV) use different batteries with various properties. A comparison of four HEV battery types (lead-acid, nickel-cadmium, nickel-metal-hybrid, and lithium-ion) is made in order to choose the proper one according to some criteria: fuel consumption, DC-DC temperature and environmental impact. Combining these criteria and making a decision is usually a difficult task. The Analytic Hierarchy Process (AHP) is an efficient tool used for an objective decision making process. The comparison of four vehicle battery types is made and the best choice is deduced in two cases.

Key words: analytic hierarchy process; battery; environmental impact; hybrid electric vehicle.

1. Introduction

Nowadays, hybrid electric vehicles (HEV) tend to become more and more popular amongst users. It is important to consider the environmental impact of hybrid car battery. Generally studies shows that hybrid electric vehicles (HEV) have lower gas emissions due to the reduced fuel consumption and due to functioning in electric-only mode for at least half of distance driven. For example, Toyota Plug-in Prius has CO_2 emissions of under 75 g/km officially classing it as 'ultra-low carbon vehicle' (Thomas, 2015).

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Hybrid or full electric vehicles can reduce the CO_2 emissions near to zero. Using cleaner fuels environmentally helps too.

The European Parliament, Council and European Commission has reached an agreement which is aimed to reduce the average CO_2 passenger car emissions to 95 g/km by 2020, while the mandatory 2015 target is about 130 g/km.

For example, in 2015, one vehicle, running 20,000 kilometers per year, produces $20 \times 10^3 \times 0.130 = 2{,}600$ kg CO_2/year/vehicle while in 2020, the emissions will be about $20 \times 10^3 \times 0.095 = 1{,}900$ kg CO_2/year/vehicle, which means 700 kg CO_2/year/vehicle less.

It is also important to monitor the number of vehicles around the world. In 1900, America has only 4,192 cars according to G. Elert (1978). In 2012, the worldwide vehicle population was already about 1.1 billion. If all of them are traditional cars, then, in 2015, the CO_2 emission of 1.5 billion vehicles is 3.9 trillion kilograms. In 2020, for an estimation of 2 billion cars, the total CO_2 emission will be about 3.8 trillion kilograms. This analysis shows that the CO_2 emissions can be maintained even if the number of cars grows but new standards for pollution are imposed.

It is estimated that at least 1 trillion trees exists on Earth today. A tree absorbs approximately 6 kg CO_2/year, depending on variety and age. In fact, trees sequestrate the carbon in the biomass. It seems that the tropical forest is the most efficient one in carbon sequestration, as NASA published in 2014 (Rasmussen, 2014).

We cannot afford to have a higher CO_2 global emission than the maximum quantity of CO_2 which can be sequestrated by the entire world forest which can be estimated to 6 trillion kilograms CO_2/year.

If more hybrid electric vehicles (HEV) or full-electric ones are in use, while many old cars are scrapped, then the overall CO_2 emission of vehicles can be considerably reduced.

2. About Vehicle Batteries

There are many types of batteries used by HEVs, some more toxic than others.

Today most hybrid car batteries are one of two types: (1) nickel metal hydride, or (2) lithium ion. Both are regarded as more environmentally friendly than lead-based batteries (which constitute the bulk of car batteries today). But in the future, nickel and cobalt, commonly used in many of today’s batteries, will be substituted by manganese because of the much lower price, and better availability.

It is important to know that not only driving HEV produces gas emissions but the manufacturing industries of car batteries and the recharging energy generating process are also responsible for environmental damage.

So we have to consider all these aspects when analyzing the HEV batteries impact on the environment.

According to International Standard Organization (ISO), Life Cycle Assessment (LCA) is the method primarily designed for accounting for and assessing the potential environmental impacts caused by products, processes, or activities (ISO14040, 2006).

The environmental impacts are expressed as global warming potential (GWP) applying for 100 years (IPCC, 2007), the cumulative energy demand (CED) of which only the nonrenewable (fossil fuel and nuclear) are disclosed (Hischier *et al*., 2009) and the **Ecoindicator 99** which uses an hierarchic perspective and an average weighting (EI99 H/A) (Goedkoop *et al*., 2000). EI99 H/A is more eloquent than GWP and CED because it also express the toxicity for human bodies and ecosystems.

Vehicle batteries can be compared based on many criteria:

a) environmental impact;
b) fuel consumption;
c) DC-DC temperature;
d) number of cycles of one battery pack;
e) energy efficiency;
f) fire risk;
g) price.

We consider four types of vehicle batteries for comparison:

a) Lead-acid (Pb-Ac);
b) Nickel-Cadmium (NiCd);
c) Nickel-Metal-Hybrid (NiMH);
d) Lithium-ion (Li-ion).

These four types of vehicle batteries are compared below based on the first three criteria.

2.1. Environmental Impact

This criterion includes the human health damage but also the impact of battery production over the ecosystem quality.

A comparison of the environmental impact (EI99) points of considered electric vehicle battery technologies is given below (Matheys, 2009):

a) Pb-Ac: 503.37 points;
b) NiCd: 543.52 points;
c) NiMH: 491.56 points;
d) Li-ion: 278 points.

As we can see from Fig. 1, Ni-Cd batteries are the worst from the environmental burden point of view while Li-ion is the most environmental-friendly battery technology.

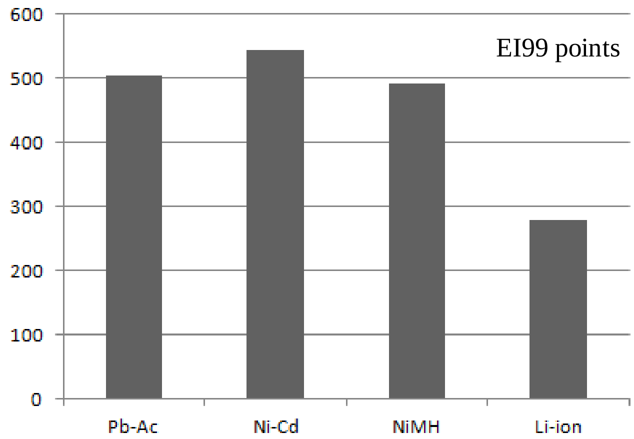

Fig. 1 – Column Chart of EI99 points for four battery types.

2.2. Fuel Consumption

Fuel consumption is another important criterion used to compare the four types of batteries. According to Nicolaica (Nicolaica, 2014), who simulated nine different driving cycles, as Barlow suggests (Barlow *et al.*, 2009), the overall average fuel consumption for each battery type is given below as liters per 100 kilometers (see Fig. 2):

a) Pb-Ac: 5.095 l/100km;
b) NiCd: 4.961 l/100km;
c) NiMH: 4.976 l/100km;
d) Li-ion: 4.968 l/100km.

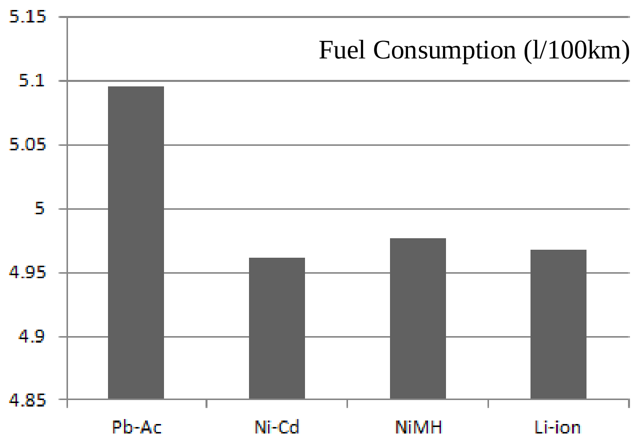

Fig. 2 – Column Chart of fuel consumption points for four battery types.

In this case, the NiCd battery seems to be the most recommended, having the lowest fuel consumption while Pb-Ac is the biggest “fuel consumer”.

2.3. DC-DC Temperature

The overall average DC-DC temperature (as Celsius degrees) of the considered four types of vehicle batteries is given below (Nicolaica, 2014):

a) Pb-Ac: 32.492ºC;
b) NiCd: 32.175ºC;
c) NiMH: 32.398ºC;
d) Li-ion: 32.377ºC.

The corresponding column chart is given in Fig. 3.

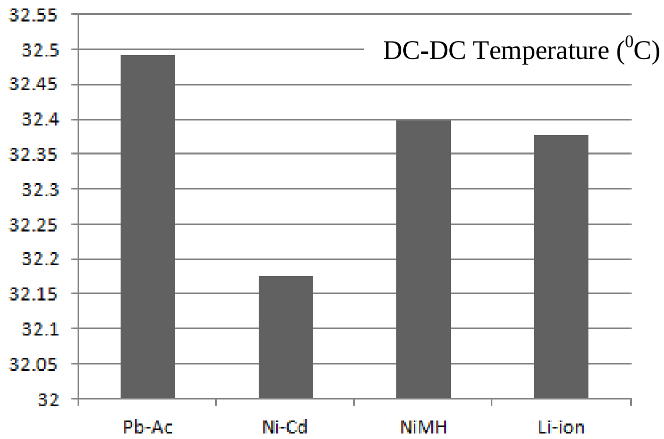

Fig. 3 – Column Chart of DC-DC battery temperature.

The differences between the temperature of these types of vehicle batteries under analysis are small (under one Celsius degree), but this fact makes a big difference in fuel efficiency. The minimum DC-DC temperature is obtained with a Nickel-Cadmium battery, while the maximum value occurs for the Lead-Acid battery.

3. AHP Based Comparison of Some Battery Types

The Analytic Hierarchy Process (AHP) is an efficient mathematic tool for strategic decision (Brunelli, 2015). AHP is recommended for multi-criteria decision making (MCDM) processes.

It is important to decide which type of battery is more convenient according to three comparison criteria: fuel consumption, DC-DC temperature and EI99 points.

The following set of alternatives is considered:

$$X = \{\text{Lead-Acid, NiCd, NiMH, Li-ion}\}.$$

Using the EI99 points for the four types of batteries, the following weight vector results:

e = [503.37, 543.52, 491.56, 278].

For the overall average fuel consumption, another vector is obtained:

c= [5.095, 4.961, 4.976, 4.968].

The overall average DC-DC temperature values of the considered battery types are very close. But these tiny differences between the temperature values are important so we will discard an offset value of 32 degrees and we will work only with the decimals to write the weight vector of temperatures:

t = [0.492, 0.175, 0.398, 0.377].

Using these weight-vectors (e, c and t), the 4-by-4 pairwise comparison matrices are deduced: A^e, A^c and A^t:

$$A^e = \begin{pmatrix} 1.0000 & 0.9261 & 1.0240 & 1.8107 \\ 1.0798 & 1.0000 & 1.1057 & 1.9551 \\ 0.9765 & 0.9044 & 1.0000 & 1.7682 \\ 0.5523 & 0.5115 & 0.5655 & 1.0000 \end{pmatrix}$$

$$A^c = \begin{pmatrix} 1.0000 & 1.0270 & 1.0239 & 1.0256 \\ 0.9737 & 1.0000 & 0.9970 & 0.9986 \\ 0.9766 & 1.0030 & 1.0000 & 1.0016 \\ 0.9751 & 1.0014 & 0.9984 & 1.0000 \end{pmatrix}$$

$$A^t = \begin{pmatrix} 1.0000 & 2.8114 & 1.2362 & 1.3050 \\ 0.3557 & 1.0000 & 0.4397 & 0.4642 \\ 0.8089 & 2.2743 & 1.0000 & 1.0557 \\ 0.7663 & 2.1543 & 0.9472 & 1.0000 \end{pmatrix}$$

Based on the geometric mean method, the following three weight vectors result:

$$w_e = \begin{pmatrix} 0.2771 & 0.2992 & 0.2706 & 0.1530 \end{pmatrix},$$

$$w_c = \begin{pmatrix} 0.2548 & 0.2481 & 0.2488 & 0.2484 \end{pmatrix},$$

$$w_t = \begin{pmatrix} 0.3412 & 0.1214 & 0.2760 & 0.2614 \end{pmatrix}.$$

A priority vector should be used by the decision maker to combine these weight vectors.

All these criteria are intended to be low enough in order to reduce the fuel consumption, the gas emission and the EI99 indicator.

But which one is the most important? Or is one of them more important than another? These are two questions that are difficult to answer if no systematic decision method is used. In fact, the answer depends on the policy of each company.

Changing the set of preferences related to the analysis criteria, the final decision can be different.

We will analyze two cases:

Case 1

Equal preferences are considered for all comparison criteria:

$$p = \begin{pmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix}.$$

The global weight vector is deduced:

$$w_1 = \begin{pmatrix} 0.2910 & 0.2229 & 0.2651 & 0.2210 \end{pmatrix}.$$

According to this vector, we decide that the fourth alternative (Lithium-ion battery) is the best choice, followed closely by the second one (Nickel-Cadmium battery).

Case 2:

EI99 indicator is considered the most important for decision and the fuel consumption is the least one. The following preference vector is used:

$$p = \begin{pmatrix} 0.2 & 0.3 & 0.5 \end{pmatrix}.$$

The global weight vector results:

$$w_2 = \begin{pmatrix} 0.3024 & 0.1949 & 0.2668 & 0.2359 \end{pmatrix}.$$

The second alternative (Nickel-Cadmium) is the best choice for a “green” decision case. Lithium-ion battery is the second choice, followed by the Nickel-Metal-Hybrid battery. Lead-Acid batteries seem to be the worst choice for a minimum environmental impact.

As a conclusion of this analysis based on three decision criteria, NiCd and Li-ion are the most recommended types of HEV batteries.

4. Conclusions

Hybrid electric vehicles use many types of batteries which have a different environmental impact, DC-DC temperature and fuel consumption. Some vehicle battery types are compared based on these criteria: Pb-Ac, NiCd, NiMH and Li-ion. The analysis is made using AHP, an efficient decision making tool. The NiCd battery technology seems to be the best choice for an environmental friendly decision followed by the Li-ion battery. It is important to develop new battery technologies for hybrid electric vehicles in order to reduce the environmental burden.

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O COMPARAȚIE A UNOR BATERII FOLOSITE DE VEHICULELE ELECTRICE HIBRIDE

(Rezumat)

Sunt analizate, prin metoda AHP, patru tipuri de baterii folosite în vehiculele hibride (Li-ion, Pb-Ac, Ni-MH, Ni-Cd), pe baza a trei criterii de comparație: impact asupra mediului, consum de combustibil şi temperatură DC-DC. În baza analizei efectuate, bateriile Ni-Cd au rezultat a fi cele mai bune, urmate de cele de tip Litiu-ion.