A Comparison of the Life Cycle Energy Consumption and Emissions of BEV and HEV

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Abstract. There is an ongoing debate over whether battery electric vehicles (BEV) contribute to reducing energy consumption and emissions compared with hybrid electric vehicles (HEV). By following the theory of life cycle assessment (LCA), a calculation model for comparing the life cycle energy consumption and emissions of BEV and HEV is built. Typical BEV and HEV are selected as the empirical objects, whose main parameters of powertrain system (including engine, battery, motor, electric control, etc.) are obtained. By using VS and Mat Lab software programming, the life cycle differences of energy-consumption and emissions between BEV and HEV are calculated and analyzed. The results reveal that the HEV is more energy-saving and environmentally friendly than BEV. This result is mainly attributed to the increase of energy consumption of BEV due to high working intensity in assembly manufacturing process. At the same time, the manufacturing process of battery, as the core component of BEV, is not as mature as internal combustion engines, which leads to higher energy consumption and emissions.

1. Introduction

In recent years, with a high-speed growth of vehicle production, which has already imposed more and more loads on the resources, energy and environment. In order to ensure the sustainable development of automobile products and promote the ecological civilization construction in China, the Chinese government has frequently issued a number of policies to urge the auto industry to carry out the green manufacture and encourage consumers to green consumption [1]. However, the predominant impacts on resource, energy and environmental of hybrid electric vehicles and battery electric vehicles were unclear, which could be fully perceived through a life cycle assessment [2-3].

Scholars both at home and abroad have carried out some researches on this issue, for example, Hackney, Van Mierlo, Aatterson and Wang have established life cycle energy consumption, emissions and cost comparison model for various kinds of fuels for vehicles, and focused on the differences between the fuel production chain and vehicles using process of various alternative fuel vehicles in the whole life cycle environmental damage rating system [4-7]. Haller estimated the environmental benefits and economic costs of a fleet of more than 180 cars from the traditional models to alternative energy vehicles in ten years, including a certain amount of infrastructure investment [8]. Kliucininkas calculated the value of life cycle weighted environmental damage through the use of a variety of alternative energy sources for the city bus and tram of Kanas, Lithuania [9]. In the field of electric vehicle research, Stefano and Oscar conducted in-depth researches on the use of efficiency, fuel
consumption, greenhouse gas emissions, cost and so on in life cycle of electric vehicles [10, 11]. In recent years, many researches have been carried out by domestic scholars of electric vehicles with a high degree of attention, for example, Tsinghua University developed a life cycle assessment model Tinghua-CA3EM, taking coal power as the scenario to carry out the simulation, compared the entire energy consumption and emissions between the new energy vehicles and traditional automobile in designing, manufacturing and using, and gave an in-depth analysis of one hundred kilometers of electric vehicles traveling LCA energy consumption and GWP situation [12, 13]. Huang from Tongji University established the model of life cycle assessment of automobile fuel, calculated and compared the life cycle of hydrogen fuel and the life cycle of the gasoline fuel, whose results showed that the hydrogen production plan was the key factor to the life cycle assessment of fuel cell vehicles [14]. Ren from Chongqing University took economic, energy, environment into consideration, through the assessment of the influence of electric vehicles on the 3E system and based on multi objective optimization method, and proposed measures and policy suggestions for development of electric vehicles from the perspective of 3E in order to maximize the overall efficiency of the goal and the boundary [15]. Xing cited a large number of actual operating parameters, and used SPSS and other statistical methods to analyze and compare the different influence degrees in the ecological environment between the electric vehicles and traditional automobiles [16].

In summary, this field of study in China starts late, but in recent years the researches on automobile life cycle assessment have gradually increased, however, the system integrity and rationality of the study are still insufficient, and this field of study in China especially lacks a complete evaluation system for energy saving for new energy vehicle’s life cycle stages including manufacturing, distribution, maintenance and scrap treatment.

2. Establishment of the assessment model

The assessment model for differences of energy consumption describes the life cycle energy consumption of HEV and BEV was established, which takes all stages in life cycle into consideration, from energies acquisition and materials preparation to components production, manufacturing, vehicle assembly, and finally to use phases and recycle phases. Based on relevant literature [17, 18], this paper puts forward a final measure for energy consumption calculation. The final method is expressed in formulae (1).

$$ET_{ij} = \begin{bmatrix} e_{w_{d11}} & e_{w_{d12}} & \ldots & e_{w_{d1y}} & \ldots & e_{w_{d1}} \\ e_{w_{d21}} & e_{w_{d22}} & \ldots & e_{w_{d2y}} & \ldots & e_{w_{d2}} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ e_{w_{d11}} & e_{w_{d12}} & \ldots & e_{w_{d1y}} & \ldots & e_{w_{d1}} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ e_{w_{d11}} & e_{w_{d12}} & \ldots & e_{w_{d1y}} & \ldots & e_{w_{d1}} \\ e_{w_{d21}} & e_{w_{d22}} & \ldots & e_{w_{d2y}} & \ldots & e_{w_{d2}} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ e_{w_{d11}} & e_{w_{d12}} & \ldots & e_{w_{d1y}} & \ldots & e_{w_{d1}} \end{bmatrix}_{q \times y}$$

In which $q$ represents the number of types of components and $y$ is the number of types of consuming resources during its processing.

So, $e_{w_{ij}}$ represents the amount (kg) of the $j$th resource consumed of $i$th component produced. Where $e_{w_{dij}}$ represents the different amount (kg) of the $j$th resource consumed between HEV and BEV.
To estimate non-renewable resource (mainly includes mineral resource: copper, iron, aluminum and etc.; fossil resource: raw coal, crude oil, natural gas and etc.) that brings inflection to the environment, the characterization factor in GaBi were used, and its specific number was expressed in Table 1.

| Impact type                  | Impact material | Characterization factor | Unit         |
|------------------------------|-----------------|-------------------------|--------------|
| Mineral resource consumption | Fe              | 3.41E-08                | kg Sb-eq     |
|                              | Al              | 3.79E-10                |              |
|                              | Mn              | 1.14E-06                |              |
|                              | Cu              | 1.37E-03                |              |
|                              | Zn              | 5.38E-04                |              |
| Fossil resource consumption  | Raw coal        | 1.80E+01                | MJ           |
|                              | Crude oil       | 4.28E+01                |              |
|                              | Natural gas     | 4.62E+01                |              |

Above table indicate that the unit of fossil resource consumption is MJ.

To unify the unit of mineral resource consumption and fossil resource consumption and compare the degree of scarcity of relate miner and resource clearly, the unit of fossil resource consumption was transformed to unified unit: kg antimony equivalent. In this paper, the resource depletion CML method proposed by the Environmental Science Research Centre of Leiden University was adopted to transform the unit of fossil resource consumption into kg antimony equivalent. The computing method is expressed in formulae (2).

$$ADP_{i,eng} = \frac{D_{i,eng} \cdot \varepsilon}{R_{i,eng} \cdot \varepsilon^2} \frac{D_{ref}}{R_{ref}}$$

where $ADP_{i,eng}$ represents characterization factor of fossil resource $i$, Unit: kg antimony equivalent) $D_{i,eng}$ represents annual production of fossil resource $i$; $\varepsilon$ represents standard coal coefficient of fossil resource $i$, $R_{i,eng}$ represents the deposits of fossil resource $i$, $D_{ref}$ represents current production of reference resource (antimony) unit: kg·yr$^{-1}$; $R_{ref}$ represents the deposits of reference resource (antimony), unit: kg.

When calculating related characteristic value of all kinds of pollutants, we will make related pollutants mass multiplied by related characterization factor and then plus them. The computing method is expressed in formulae (3).

$$T_k = \sum (M_i \cdot C_i)$$

Where $T_k$ represents characteristic value of the $k$th evaluating indicator influenced; $M_i$ represents the mass of the $i$th pollutant; $C_i$ represents characterization factor of the $i$th pollutant.

3. Development of the assessment system

The assessment system took automobiles as the study object, and the previous models were embedded in the background computer engine. Through powerful tools such as Mat Lab and VS, simple, friendly and accurate software of HEV and BEV life cycle assessment were developed. The software development route is expressed in the Fig. 1.
According to the assessment model, the basic data of the energy production and materials production and the inventory data of BEV and HEV can be obtained from relevant literature [1]. Meanwhile, reference-based data will be delivered with a one-to-one correspondence into the assessment system. The results include energy consumption and emissions of life cycle stages of raw material production, manufacturing, and use phases, but the recovery.

4. Assessment calculation

4.1. Inventory data acquisition

This study selected a representative Chinese enterprise as the example to carry out assessment calculation from relevant literature [19]. According to data requirements of the model, we went into the R&D centre, the Production and Assembly workshops and the testing centre to collect the inventory data such as BOM chart, manufacturing energy. In addition, the materials of the motor, motor control device, LiFeO2 battery, transmission, retarder, engine and Ni-MH battery were collected.

4.2. Calculation Results

In order to verify and improve the assessment system, firstly, we input its inventory such as BOM (bill of materials) table, manufacturing assembly process energy and emission table, usage stage energy consumption table, scrapping and recycling table and logistics table and so on into the system through the interactive interface. Then we called the basic data from SQL and conducted the analytical calculation with the background calculation engine out of the MATLAB work environment. The calculation results are shown in Table 2-4.

**Table 2.** Energy consumption of HEV and BEV (Unit: MJ)

| Phase of life cycle     | HEV         | BEV         |
|-------------------------|-------------|-------------|
|                         | Raw coal    | Crude oil   | Natural gas | Raw coal    | Crude oil   | Natural gas |
| Raw material production | 11315       | 154.18      | 3123.2      | 13511       | 252.23      | 3754.6      |
| Manufacturing           | 1318.1      | 11.240      | 7.3450      | 1553.1      | 12.112      | 8.0890      |
| Use                     | 8512.1      | 79509.3     | 2153.6      | 71984       | 1019.08     | 3009.1      |
Table 3. Emissions of HEV (Unit: kg)

| Phase of life cycle   | HEV   |
|-----------------------|-------|
|                       | CH₄   | SOₓ   | NOₓ   | CO    | PM    | NMVOC |
| Raw material production phase | 4.191 | 5.232 | 3.010 | 9.702 | 11.02 | 0.008 |
| Manufacturing phase    | 0.011 | 0.651 | 0.423 | 0.171 | 0.034 | 0.005 |
| Use phase              | 2813  | 100.1 | 214.2 | 3.091 | 2.002 | 3.034 |

Table 4. Emissions of BEV (Unit: kg)

| Phase of life cycle   | BEV   |
|-----------------------|-------|
|                       | CH₄   | SOₓ   | NOₓ   | CO    | PM    | NMVOC |
| Raw material production phase | 4.323 | 6.212 | 4.005 | 15.808| 14.03 | 0.141 |
| Manufacturing phase    | 0.023 | 0.751 | 0.513 | 0.189 | 0.041 | 0.006 |
| Use phase              | 5934  | 253.3 | 98.76 | 16.38 | 1.081 | 2.541 |

(1) Raw material production phase

According to formulae (1) and (3), we can calculate the energy consumption and emissions in Figure 2. and Figure 3. According to the figure, the emissions and energy consumption in all kinds of pollutants of BEV are higher than HEV, especially the emission of CO exceeding 60%. Analysis can be obtained, this reason is that the amount and weight of raw materials of BEV is higher than HEV, and high energy consumption of the battery processing, so the above data is reasonable.

Figure 2. Energy consumption differences of Raw material production phase
(2) Manufacturing phase

According to formulae (1) and (3), we can calculate the energy consumption and emissions in Figure 4. and Figure 5. According to the figures, energy consumption and emissions of BEV in material production phase and manufacturing phase present the trend of correlation, in both phases, which of BEV is higher than HEV. The reason would be the difficulty of the assembly and the complexity of the manufacturing process of BEV. Meanwhile the BEV is relatively a kind of new product so that its manufacturing proficiency cannot be compared with HEV, so the energy consumption and emissions in manufacturing phase of BEV is higher than the HEV.

Figure 4. Energy consumption differences of manufacturing phase
(3) Using phase

According to formulae (1) and (3), we can calculate the energy consumption and emissions in Figure 6 and Figure 7. According to the Figure 7, in use phase, the pollutant emissions of BEV is higher than HEV, which is due to the restrictions of China’s electricity supply, in detail, the thermal power being the main power source, and meanwhile the low power generation efficiency deeply limits the emission levels of BEV. Compared to the direct combustion of gasoline into the traction energy of HEV, the efficiency is reduced once again because of the transformation from electricity power to traction energy, at the same time the emission of BEV are still higher than HEV. In the comparison of the primary energy consumption, both BEV and HEV represent obvious differences in energy structure, HEV mainly consumes crude oil resources, and BEV is mainly dependent on coal resources, which is closely related to the power structure in China.
5. Conclusion

(1) As a result of China’s current electric power composition, which implies the electricity is relatively “dirty”, the HEV is more energy-saving and environment-friendly than BEV. If the proportion of renewable energies such as nuclear power in the power structure of China increases, the related environmental impacts of BEV will be greatly reduced.

(2) Through the comparison of energy consumption and emissions at each stage of HEV and BEV, it is found that energy consumption in use phase of BEV is lower than HEV, but in the production of the material and manufacturing process, the situation is the opposite. This is closely related to the increase of energy consumption due to high working intensity in assembly manufacturing process of BEV. At the same time, the battery is the core component of BEV, whose manufacturing process is not as mature as inner combustion engines, which leads to higher energy consumption and emissions.

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