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An energy matching method for battery electric vehicle and hydrogen fuel cell vehicle based on source energy consumption rate

Huiyuan Xiong [a,b], Huan Liu [a], Ronghui Zhang [a,c,*], Limin Yu [a,d], Zhijian Zong [a,b], Minghui Zhang [a], Zhu Li [b]

[a] School of Intelligent Systems Engineering, Sun Yat-Sen University, Guangzhou, Guangdong 510006, China
[b] Institute of Dongguan-Sun Yat-Sen University, Dongguan, Guangdong 523808, China
[c] Guangdong Key Laboratory of Intelligent Transportation System, Sun Yat-sen University, Guangzhou, Guangdong 510275, China
[d] School of Automobile and Transportation Engineering, Guangdong Polytechnic Normal University, Guangzhou, Guangdong 510665, China

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ABSTRACT

The smart cities development requires reducing energy consumption and using as much renewable energy as possible, so the widespread use of new energy vehicles is a very important measure. In this work, for the energy system configuration and energy efficiency balance of new energy vehicles, we propose an energy matching method to study its energy efficiency from the view point for energy life cycle. Nowadays, new energy vehicles mainly include battery electric vehicles (BEV) and hydrogen fuel cell vehicles (HFCEV). Firstly, we proposed the Source to Range (STR) model. Then, based on STR model, we used energy efficiency analysis chart to visually represent the conversion, delivery and consumption of the vehicle energy life cycle. Furthermore, we proposed a Source Energy Consumption Rate (SECR), which is used to evaluate the vehicles energy efficiency. Finally, based on STR model, we obtained the dividing line of the same SECR for new energy vehicles and equivalent fuel vehicles, which provides constraints on the vehicle energy system design. The results show that STR model can provide an effective tool for energy matching and energy efficiency analysis of new energy vehicles, and has a reference for product development of new energy vehicles.

Introduction

Problem and motivation

Based on urban sustainable development demand and new generation information technology application, smart city will become people's future model [1,2]. On one hand, smart city needs convert energy-dissipating type development to energy-saving type development. On the other hand, it reduces the environmental burden, and puts higher demands on urban environmental management. Therefore, to build a smart city, we should rely on new energy vehicles to solve traffic energy and environmental problems [3]. The improvement of traditional fuel vehicles's fuel economy is limited. In

* *Corresponding author.*
E-mail address: zrh1981819@126.com (R. Zhang).
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addition, emissions from traditional fuel vehicles account for 60% of urban air pollutants. It becomes the main source of urban air pollution [4–6]. Traditional fuel vehicles, as a large oil consumption and emissions of carbon dioxide, need to be a revolutionary change. Therefore, the development of new energy electric vehicle has become the consensus of the world [7]. On this background, the article has sorted out the current state and the related development planning of new energy electric vehicles in different countries. It has predicted the vehicles ownership of the new energy electric vehicles by using elastic coefficient method and setting different path of development. The article conclude that under the consideration of energy conservation and emissions reduction factors, our country should promote the new energy vehicles to realize the maximum energy conservation [8–10]. It meets the design requirements of a smart city.

New energy vehicles should achieve the goal of energy saving, good economy and strong practicability at the same time. In the fact, the energy of new energy vehicles completely comes from the limited power battery or small energy storage devices [11]. Therefore, compared to traditional fuel vehicles, there is a contradiction between the weight and energy efficiency of new energy vehicles. Under current technical conditions, we need to strike a reasonable balance between the driving range and the energy density of new energy vehicles. We need to find a suitable method to specifically assess the energy efficiency of new energy vehicles [12,13]. Therefore, it is necessary to find a suitable method to specifically evaluate the energy efficiency of new energy vehicles. That is, in the entire life cycle, to evaluate energy from raw materials to wheels, and then from the wheel to the driving range.

Related works

The research on new energy vehicles has been carried out as early as the 1970s. After decades of development, electromotor with driving system and control system tend to be intelligent and digital [14–16]. In terms of new energy vehicle body technology, by reducing the weight and optimizing the structure, we can improve its driving range [17]. In automotive power battery technology, from the first generation of lead-acid batteries to the second generation of alkaline batteries, then to the third generation of fuel cells, the energy conversion efficiency, specific energy and specific power have been continuously improved [6,18,19]. To suppress the performance degradation of the fuel cell (FC), the newly proposed energy management method deals with main FC degradation causes, such as low humidification and frequent and rapid voltage changes [20]. The article answers the question whether for city areas, solar and wind electricity together with fuel cell electric vehicles as energy generators and distributors and hydrogen as energy carrier, analysis the energy balance and cost [21–24]. This paper will introduce the concept of 100% renewable energy and the role hydrogen can play for storage and transportation sectors. This reality confirms that hydrogen energy technologies will play an important role in reaching the 100% renewable energy target [25,26].

In the process of hydrogen production, the study provides methodologies and results of well-to-wheel greenhouse gas analysis for fuel-cell electric vehicle [27]. And the results are compared with other powertrain vehicles such as internal combustion engine vehicle (ICEV), hybrid electric vehicle and electric vehicle. It considers different current and emerging power train technologies, and provides a comparison within a techno-economic framework [28]. The model takes into account functional parameters such as the battery range as well as daily driving range segmentation statistics [29–32]. At last, a rule-based power management strategy is applied to a fuel cell hybrid vehicle. Fuel economy is evaluated based on equivalent fuel consumption and compared to optimal control results [33]. This paper examines various potential methods of hydrogen production using renewable, and increase both energy and exergy efficiencies to bring them forefront as potential options [34–36]. In this article, it will eventually provide targeted recommendations for the development of Chinese cities, public transport, and hydrogen fuel cell vehicles [37].

At present, the energy efficiency analysis of new energy vehicles is based on the WTW model, which analyzes the process of transferring vehicle energy from raw materials to wheels [38]. However, the transfer of raw energy to the wheels is not the ultimate goal. Driving the vehicle to travel a certain distance to meet the needs for people to travel is the ultimate value of vehicle energy. Based on mean values for maximizing driving range of a fuel cell bus, the article proposes an energy flow model and an optimal energy management strategy [39]. However, the article focuses on control strategies and optimal effects. There is no comparison of the energy consumption of equivalent traditional fuel vehicles, and it cannot provide constraints on the design of new energy vehicles [40]. Actually, the actual test cruising range proposed in the article is a direction for our future work.

Contribution

In this paper, based on the energy efficiency of vehicle energy from raw material to wheel phase, and the process of driving the vehicle with vehicle energy, the STR model is established. Then, we graphically expressed the STR model by means of energy efficiency analysis chart. At the same time, we proposed the SECR and based on it, we can better evaluate the energy efficiency levels of new energy vehicles and ICEV. Therefore, the energy-saving boundary line of new energy vehicles is obtained, that is, the equal consumption rate curve, which is used to evaluate whether new energy vehicles are energy-saving or not. Finally, based on the equal consumption rate curve, a balanced configuration scheme for driving range and battery capacity is determined. The main contribution of this paper is to propose an energy matching method and establish an energy efficiency evaluation model, namely STR model, and graphically describe the SECR and energy-saving standards of new energy vehicles by means of energy efficiency analysis chart.

Structure of text

This text is structured as follows: An energy and environmental sustainability new mode about new energy vehicles is put forward in Section New energy vehicles: An energy and environmental sustainability new model. Section STR model specified the vehicle STR model. Section Energy system matching method based on SECR introduces one SECR-based energy system matching method in detail. Section Practical example analysis carries on the practical example analysis. Section Conclusion and future work summarizes the conclusions and propose future work.

New energy vehicles: an energy and environmental sustainability new mode

Compared with traditional fuel vehicles, new energy vehicles have obvious effect in reducing energy consumption. As you can see from the following example: Taking a bus in Guangzhou as an example, the traveling distance is 25 km. If the bus is a traditional fuel vehicle, and the fuel consumption is generally about 0.3 L/km under the condition of uniform driving. Then, the total fuel consumption is 7.5 L. The calorific value of gasoline is 44000 kJ/kg, and the efficiency of gasoline engine is about 30%. The total mechanical energy used by the bus to overcome internal and external resistance is as follows

$$E_{ICEV} = \rho V q \tag{1}$$

$$E_m = E_{ICEV}\eta_f \tag{2}$$

In formula (1) and (2), $E_{ICEV}$is the gasoline consumption of a traditional fuel vehicle; $\rho$is the density of gasoline; Vis the volume of gasoline consumed; $q$is the calorific value of gasoline; $E_m$is the total energy consumed by 25 km; $\eta_f$is the efficiency of gasoline engine.

And new energy vehicles do the same work on the same road as traditional fuel vehicles. If a BEV, the efficiency of an electromotor is about 80%. If a HFCEV, the transformation efficiency of hydrogen and oxygen reactions is about 70%. Then the energy consumption of a new energy vehicle is

$$E = \frac{E_m}{\eta_e} \tag{3}$$

In formula (3), Eis the total energy consumed, which is electrical energy for BEV or hydrogen energy for HFCEV. $E_m$is the total energy consumed by 25 km, and $\eta_e$is the conversion efficiency of electrical energy or hydrogen energy.

According to the above calculation, under the same conditions, the energy consumption of the traditional fuel vehicle is 74250 kJ. The energy consumption of the BEV is 92813 kJ, and HFCEV's is about 106072 kJ. Then the energy consumption of the traditional fuel vehicle is about 2.7 times that of BEV, and it is about 2.3 times that of HFCEV. According to the research of China Automobile Energy Research Center, if we only rely on improving fuel economy, controlling range and limiting the total number of cars, we can reduce energy consumption by 20%. On the other hand, if the bus adopts the traditional fuel mode, there are idle, acceleration and deceleration conditions and braking conditions in the running process, so these conditions account for about 10% of the whole journey [41]. The existence of these conditions will further increase fuel consumption. And the electric or hydrogen energy form of a bus, its electric motor does not need idle running, basically no energy consumption when stopping for a short period of time. An electric motor can act as a generator when braking, that is, it converts the vehicle's kinetic energy into electricity and stores it in a battery. From this we can see the remarkable advantage of new energy vehicle in the aspect of energy consumption.

From the visual calculation, both BEV and HFCEV can reduce energy consumption and the burden of environment, so it can meet the requirements of smart cities. If the analysis ends here, it is obvious that new energy vehicles are more energy efficient. However, the situation is not so simple. Because neither hydrogen nor electricity comes out of nowhere, it takes a lot of energy. Therefore, the energy efficiency of new energy vehicles needs a new scientific evaluation method. Then, based on the energy efficiency and driving range of vehicle energy, we proposed the STR model (see Fig. 1).

STR model

STR model principle

The Well to Wheel (WTW) model [44], is a model dedicated to the full life cycle analysis and evaluation of the vehicle. It analyzes the energy efficiency, emissions and costs of vehicles by analyzing the entire process of vehicle energy from the raw material acquisition phase to the wheel phase. The vehicle energy of traditional fuel vehicles is gasoline or diesel, and raw materials are petroleum [45,46]. The vehicle energy of new energy vehicles is the power battery pack, which comes from electric energy or hydrogen energy [47], and raw materials may be coal, oil, water energy and natural gas, etc. Taking into account the diversity of raw materials corresponding to vehicle energy, and in order to further analyze the effect of vehicle energy driving the car, we added the driving range to the WTW model [48–50]. Then, the STR model is established. The framework of the STR model is shown in Fig. 2.

In this paper, new energy vehicles mainly refer to BEV and HFCEV. HFCEV belongs to fuel cell electric vehicles, which is also a kind of battery electric vehicle in essence. Their difference is the concept of batteries. BEV store electricity in batteries. However, hydrogen fuel cells aren't batteries, which is a power package stores hydrogen inside. Its energy is provided by a chemical reaction between hydrogen and oxygen [42]. Except for power battery's working principle, the main structure of BEV and HFCEV is basically the same. Therefore, both of BEV and HFCEV, their energy will eventually be converted into electricity for use by cars [43]. Their energy conversion processes are shown in Fig. 3. The STR model studies the energy efficiency of a vehicle from the perspective of the energy life cycle, rather than a model that specifically studies a certain vehicle. Therefore, the STR model is applicable to BEV, HFCEV and ICEV.

The STR model includes 3 sections: Source to Vehicle (STV) phase, Vehicle to Wheel (VTW) phase and Wheel to Range (WTR) phase. The STV phase is the process from raw material extraction to transport raising, including the acquisition, transportation, processing, transport raising of raw materials. The VTW phase is a process in which vehicle energy is transferred from a storage device to wheels, including fuel

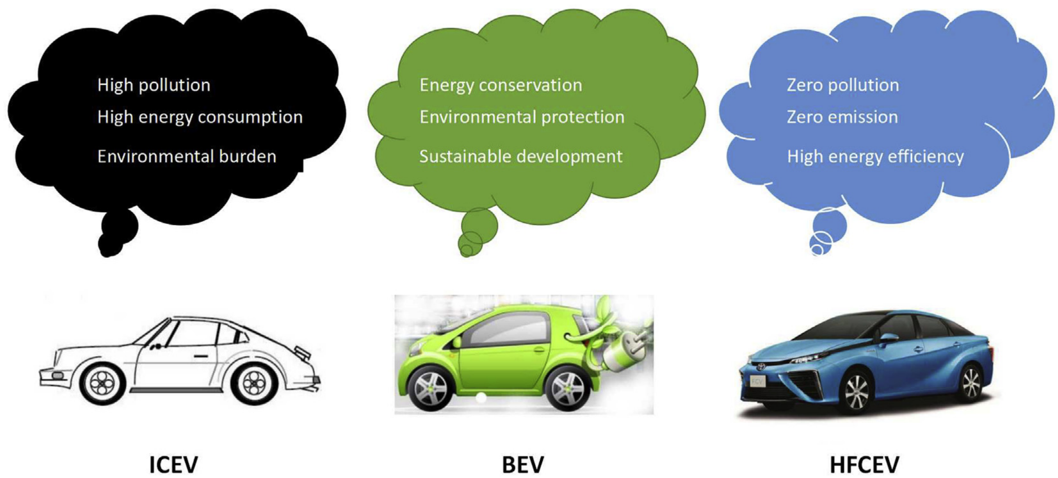


Fig. 1 – Comparison between ICEV and new energy vehicles.

combustion or chemical energy conversion, power transmission, and so on. The WTR phase is the stage in which the energy on the wheels drives the vehicle to the end of the vehicle's energy consumption.

Suppose the energy of the raw material is E_0, the efficiency at all stages is η, all stages and energy variation in the STR model are shown in Fig. 4.

The relationship between the energy $E_i$after i process and the energy E_{i-1} after the last process is as follows

$$E_i = \eta_i E_{i-1} \tag{4}$$

In formula (4), $E_i$is the energy after i process and $\eta_i$is the energy conversion efficiency in i process.

The efficiencies of the STV phase and the VTW phase are

$$\eta_{stv} = \eta_1 \eta_2 \eta_3 \eta_4 \tag{5}$$

$$\eta_{vtw} = \eta_5 \eta_6 \tag{6}$$

In formula (5) and (6), $\eta_{stv}$and $\eta_{vtw}$are the energy efficiencies of the STV phase and the VTW phase, respectively. $\eta_1$is the efficiency of mining; $\eta_2$is the efficiency of transportation; $\eta_3$is the efficiency of processing; $\eta_4$is the efficiency of transport raising; $\eta_5$is the efficiency of the engine/electric motor; η_6 is the efficiency of transmission systems.

The total efficiency of STW is

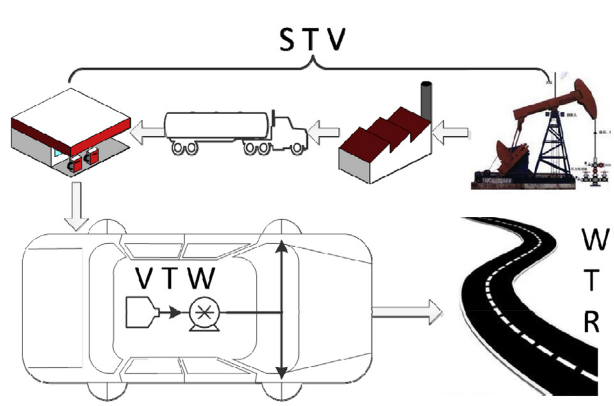


Fig. 2 – STR model framework.

$$\eta_{stw} = \eta_{stv} \eta_{vtw} \tag{7}$$

In formula (7), $\eta_{stw}$is the total efficiency of STW.

The relationship between driving mileage S in WTR stage and energy E_6 in wheel stage is:

$$E_6 = \int_0^s \left(mgf \cos\alpha + mg \sin\alpha + \frac{C_D A \rho v^2}{2} + \delta ma \right) ds \tag{8}$$

In formula (8), $E_6$is a is the energy transmitted by transmission systems to the drive wheels. m is the quality of the preparation; $g$is the coefficient of gravity; $f$is the rolling friction coefficient; α is the road ramp angle; $C_D$is the drag coefficient; A is the windward area; $\rho$is the air density; v is the speed of a vehicle; δ is the vehicle rotation mass conversion factor; $a$is the driving acceleration; $s$is the continuous driving range. It can be seen that the continuous driving range is related to whole vehicle quality, vehicle parameters, driving conditions, road conditions and energy on wheels.

Energy efficiency analysis diagram based on STR model

The STR model is represented by an energy efficiency analysis chart based on a Cartesian coordinate system, as shown in Fig. 5. The energy efficiency analysis chart can comprehensively and visually express and analyze the whole process of vehicle energy from raw materials to driving vehicles until they are exhausted. The four vertical axes in the figure record the four key nodes from the raw energy to the wheel conversion process: Source (raw energy), Vehicles, Transmission Systems and Wheels, respectively represented by the symbols S, V, TS, W.

Taking the longitudinal axis of wheels as the dividing line, the curve on the left is the energy transfer curve, and the curve on the right is the continuous driving consumption curve. Energy transfer curve includes two phases: STV phase and VTW phase. The straight line segment represents the transmission or conversion of energy at each stage, and the diagonal line of the straight line is related to the energy conversion efficiency. The intersection of the straight line and the vertical

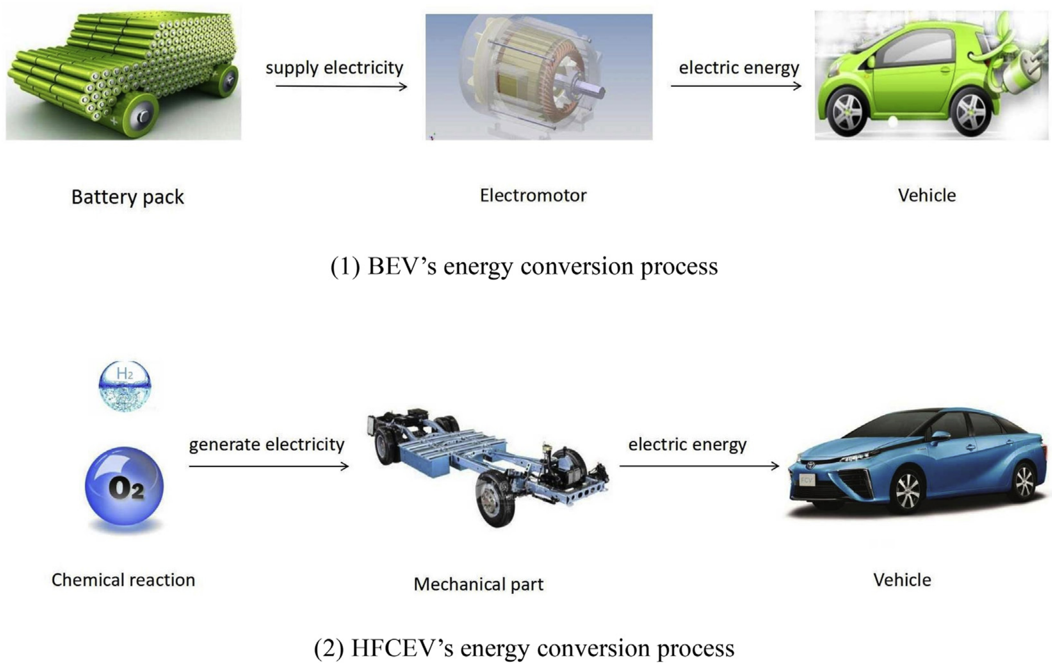


Fig. 3 – New energy vehicles' energy conversion process.

axis represents the remaining energy delivered to the node, which may be the amount of oil or electricity, in units of liters (L) and kilowatt hours (kwh). Continuous driving consumption curve represents WTR phase. The curve takes the vertical axis of the wheel as the vertical axis and the driving range as the horizontal axis. Then it used a straight line or curve to express the process, from transmitted-to-wheel energy driving a car to consuming it. When the vehicle is running at a constant speed, the continuous driving consumption curve is a straight line. The intersection of the curve and the horizontal axis is the driving range value, indicating that the vehicle energy is completely exhausted at this time, and the driving distance reaches the maximum value.

In the STR model, only one parameter is changed under the premise that other parameters are unchanged, and the energy efficiency analysis curve forms a set of maps. Assume that the model, working conditions and vehicle energy are the same. Different vehicle weights correspond to different driving ranges, which are recorded as the continuous driving consumption map, as shown in Fig. 6.

Based on the energy efficiency analysis map, it can establish the continuous driving consumption chart with different vehicle weights. Then, it is clear to analyze the energy transfer curve and the continuous driving consumption curve. In the charts, it can be seen that since the vehicle energy is the same, the starting point of each continuous consumption curve in the map is the same, the greater the vehicle weight, the shorter the mileage, the greater the energy consumption rate, and the lower the energy efficiency. Based on the continuous driving consumption map, the driving range corresponding to a certain vehicle weight or the vehicle weight corresponding to a driving range can be quickly calculated.

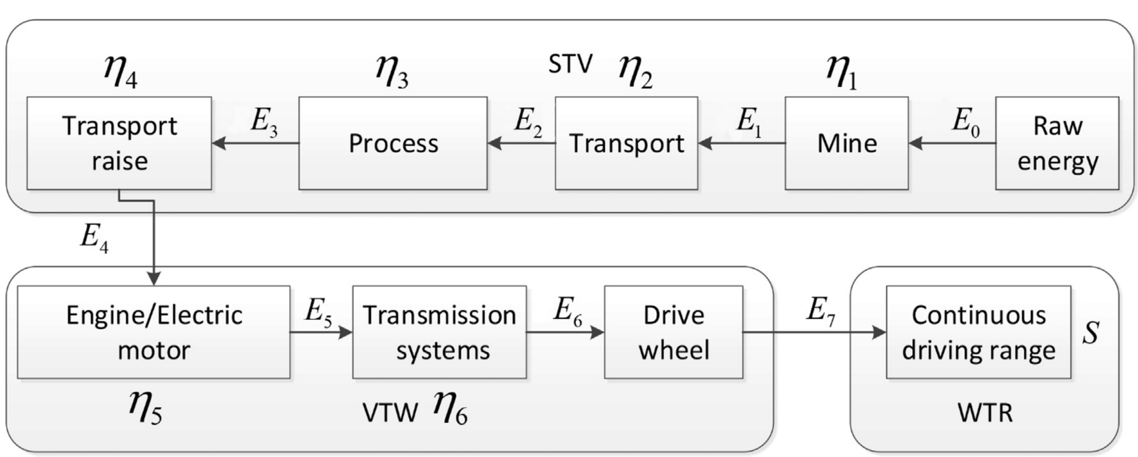


Fig. 4 – Energy variation of the STR model.

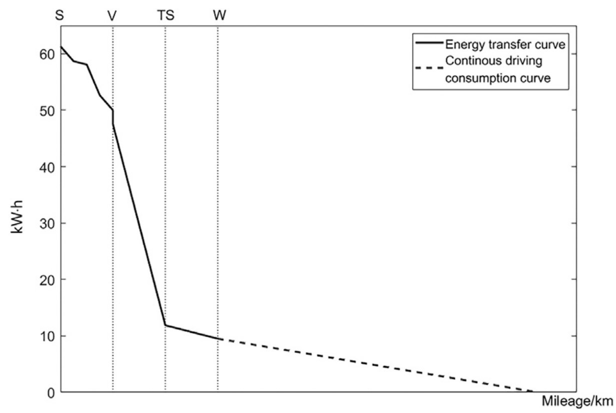


Fig. 5 – STR energy efficiency analysis chart (S: source; V: vehicles; TS: Transmission Systems; W: wheels).

Source energy consumption rate (SECR)

To characterize energy efficiency, define the vehicle's SECR as

$$SECR = E_0/S \tag{9}$$

In formula (9), E_0 is the energy of raw materials and S is the continuous driving range. Its unit is kJ/m, representing raw materials consumed by the range of the driving unit. The smaller the SECR value, the higher the energy efficiency and the greater the distance traveled by the same raw energy. The larger the SECR value, the lower the energy utilization rate and the shorter distance traveled by the same raw energy. SECR is an indicator for evaluating the energy efficiency of new energy vehicles, so it is available for both BEV and HFCEV. Then, the energy efficiency level of the vehicle can be evaluated based on the SECR.

Energy system matching method based on SECR

SECR is an index to evaluate vehicle consumption of original energy. Since energy of BEV and HFCEV must be converted into electric energy, and their main structures are basically the same. For convenience, so we select BEV as the representative, and the method obtained is also applicable to HFCEV. The SECR comparison between BEV and ICEV, is a sign to judge whether a new energy vehicle is energy efficient or not. In the energy efficiency analysis chart, the energy efficiency analysis curve, which is equal to the reference vehicle's SECR, is recorded as equal consumption rate curve.

Based on the energy efficiency analysis chart, the calculation steps for obtaining the equal consumption rate curve are as follows:

1) Get the relevant data of the ICEV: vehicle energy is E_f (L), and continuous driving range is S_f (km). Based on the STR model, ICEV's energy transfer curve Line 1 and continuous driving consumption curve Line 2 are obtained.
2) Use the same energy as the ICEV in the raw material phase, the power is first generated and then the power battery is stored once to drive the vehicle. Then energy transfer curve Line 3 and continuous driving consumption curve Line 4 are obtained.
3) Calculate continuous driving consumption charts of Line 3 under different vehicle weights.
4) Connect the starting point of Line 4 to the end of Line 2, a reference line, Line 5 is obtained. Then from the continuous consumption driving map, find a curve with the same slope as Line 5, and then the weight M_e of the whole car is obtained.
5) The battery weight M_b is calculated from M_e. According to battery energy density, the calculated energy storage capacity is E_b. Then the corresponding energy transfer curve Line 6 and continuous driving consumption curve Line 7 are obtained, which is the equal consumption rate curve.

The SECR corresponding to the equal consumption rate curve is equal to that of the fuel vehicle, representing the watershed of energy efficiency. Above the equal consumption rate curve, SECR is higher than that of the corresponding fuel vehicle, and below the equal consumption rate curve, SECR is lower than that of fuel vehicle. So the equal consumption rate curve is recorded as equal consumption rate dividing line. It is shown in Fig. 7. The continuous driving range target value and the configuration of the power battery should be in the area below the equal consumption rate dividing line.

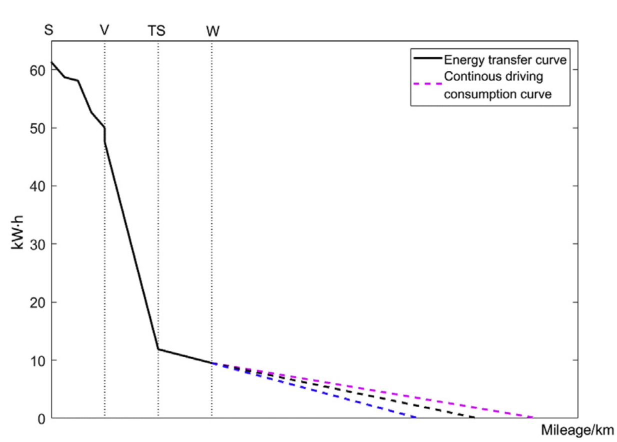


Fig. 6 – Continuous driving consumption map with different vehicle weights(S: source; V: vehicles; TS: Transmission Systems; W: wheels).

Practical example analysis

Base on the above discussion, ICEV and BEV are selected as examples. In this passage, ICEV take a gasoline vehicle as the research object, and gasoline mainly comes from crude oil. The grid power that charges the BEV is mainly generated by coal, natural gas and hydropower.

The traditional fuel vehicles in this paper is based on the ICEV, which is mainly refined and processed by crude oil. In the STV model, the efficiency of the crude oil extraction process is 95.7%, the efficiency of the crude oil transportation process is about 99%, the efficiency of processing into gasoline is 90.6%, and the efficiency of the gasoline transportation and

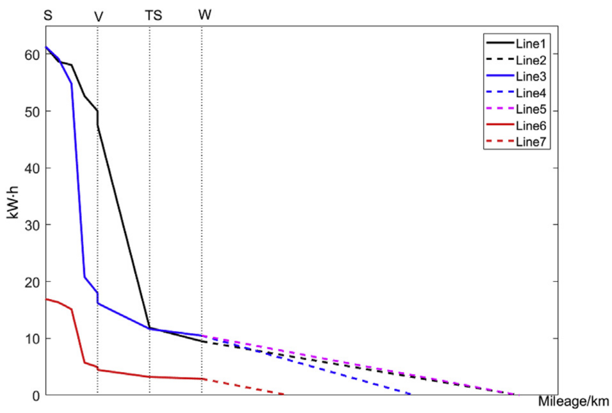


Fig. 7 – Equal consumption rate dividing line (S: source; V: vehicles; TS: Transmission Systems; W: wheels).

filling process is 95%. In the VTW model, the efficiency of the engine motor is 25%, and the efficiency of the transmission is 80%.

BEV uses vehicle battery pack as energy source. The efficiency of the energy mine and energy transportation was 96.5% and 92.6%, and the efficiency of overall average power generation was calculated to be 46.3%. The power transmission conversion efficiency is about 83.6%. In the VTW model, the efficiency of the battery output to the transmission system is 76.5%, and the transmission efficiency is 92%.

The efficiency values of ICEV and BEV in each phase of STW are shown in Table 1.

Selecting a fuel vehicle (ICEV1) in Advisor as the reference vehicle, its main parameters and power configuration are shown in Table 2.

Taking UDDS as operating condition, then simulating energy consumption of ICEV1, the speed time diagram of working condition is shown in Fig. 8(1), and instantaneous fuel consumption rate is shown in Fig. 8(2).

Under UDDS condition, 100 km fuel consumption of ICEV1 is 5.84 L. Assuming that 95% of the oil in the tank can be used in continuous driving process, the continuous driving range of ICEV1 is 813 km when it is one-time filled with oil, and the energy in raw material phase is 61.3 L. The energy efficiency analysis curve of ICEV1 is shown in Fig. 10, line 1&2, and SECR is 2.5326.

Using raw energy equal to ICEV1's to produce electricity, and driving the vehicle with a one-time storage of the vehicle battery. At this time, the battery shaft capacity is 167 kWh. Then the required battery pack mass is 1394 kg, and the whole vehicle weight is 2422 kg, which is recorded as BEV1. Under UDDS condition, the continuous driving range of BEV1 is 545 km. At this time, the energy efficiency analysis curve is shown in Fig. 10, line 3&4, and its SECR is 3.7779. Obviously, in order to store the energy equivalent to ICEV1, BEV1 is loaded with a large number of batteries, resulting in a sharp increase in the weight of the vehicle, a drastic reduction in driving range, and an increase in SECR of 49%. BEV1's total weight is between 1400 kg and 2500 kg, and its continuous driving consumption charts is shown in Fig. 9. As the weight of the vehicle increases, the continuous driving range becomes shorter.

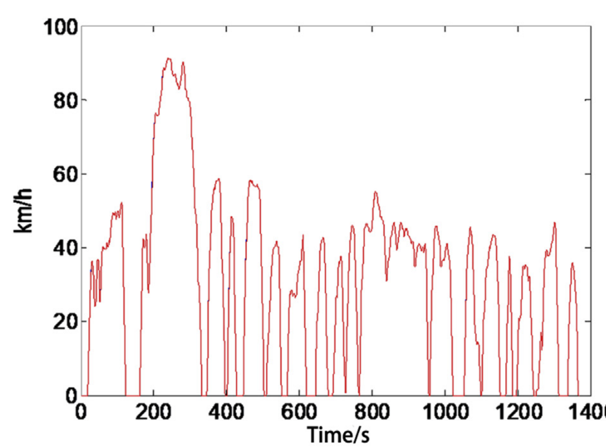
BEV1's energy in wheel shaft phase is 97.53 kwh. Connecting this point to the 813 km's point on the horizontal axis,

Table 1 – Efficiency of ICEV and BEV in all stages.

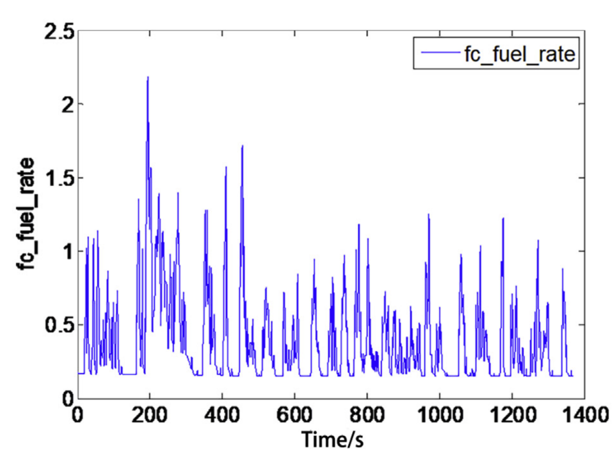
	η_1	η_2	η_3	η_4	η_5	η_6
ICEV	95.7	99	90.6	95	25	80
BEV	96.5	92.6	38	86.5	72	90

Table 2 – ICEV1 vehicle parameters.

Parameter	Numerical value
Body quality	918 kg
Curb quality	1316 kg
Frontal area	1.746 m^2
Engine capacity	1.5 L
Battery energy density	120 wh/kg
Vehicle energy	50 L
Wheel radius	0.287 m
Wind resistance coefficient	0.3
Drive Train	5-speed manual
Hydroelectric coefficient	9.3



(1) UDDS condition



(2) Instantaneous fuel consumption rate of ICEV1

Fig. 8 – UDDS condition simulation of ICEV1.

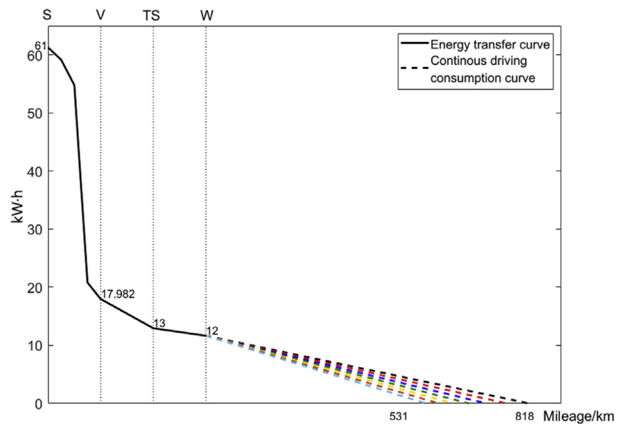


Fig. 9 – BEV1 continuous driving consumption map (S: source; V: vehicles; TS: Transmission Systems; W: wheels).

then to get the reference curve, it is shown in Fig. 10, line 5. Then find the curve with the same slope as the reference curve from the map. Therefore, the following results are obtained: The corresponding vehicle weight is 1416 kg; the corresponding battery pack weight is 388 kg; the storage quantity of battery pack is 46.56 kwh. Then, the curve is recorded as BEV2. The continuous driving range of BEV2 under UDDS condition is 223 km. The equal energy efficiency curve is shown in Fig. 10, line 6&7, and its SECR is 2.5486.

The SERC of the BEV2 is basically equal to the SECR of the ICEV1, which means that the SECR of the BEV2 reaches the level of the fuel car of the same model. Modified and designed on the basis of ICEV1, BEV can achieve a higher level of energy efficiency, when its power battery pack collocation is below the equal energy efficiency dividing line. Because HFCEV are similar to BEV, HFCEV's design can also refer to the above method. Then, based on the same method, we can get the equivalent energy efficiency boundary of HFCEV, so that the hydrogen fuel cell stack is placed in the lower area of the energy efficiency boundary to achieve a higher energy efficiency level.

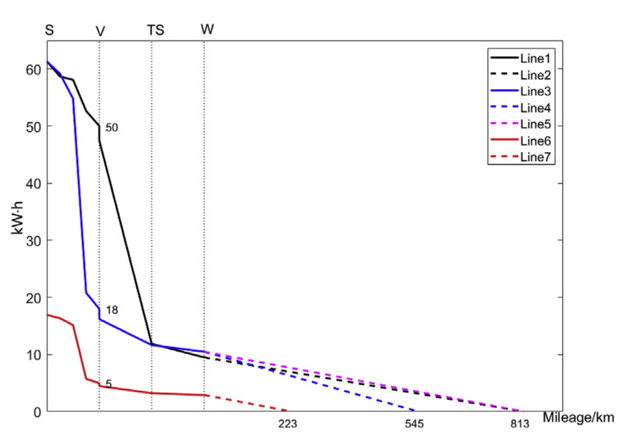


Fig. 10 – Equal consumption rate dividing Line of ICEV1 (S: source; V: vehicles; TS: Transmission Systems; W: wheels).

Conclusions and future work

Based on Well to Wheel model, this paper proposed a STR model based on the key characteristics of vehicle energy and driving range. The STR model is suitable for ICEV, BEV and HFCEV. Moreover, the energy efficiency analysis map is used to visually represent the STR model, and SECR is proposed to evaluate the energy efficiency level of the vehicle. At the same time, an equal consumption rate boundary is obtained based on the STR model and SECR. The results show that the design of the new energy vehicles must be below the equal consumption rate boundary, while balancing the relationship between battery energy and driving range. On the other hand, the results also show that STR model is not only a method of matching energy, but also a method of evaluating whether new energy vehicles are energy efficient. The research in this paper has practical application value for analyzing, evaluating and designing new energy vehicles.

The analysis of vehicle energy efficiency levels in this study is not specific enough. Therefore, the future work should mainly compare the energy efficiency levels of different vehicle types. Then, we can further analyze the relationship between the energy efficiency level and the new energy vehicles' battery configuration and driving range. Furthermore, we can use the STR model as an auxiliary design model for the vehicle parameters in the conceptual design phase, especially for BEV and HFCEV.

For new energy vehicles, the development of BEV is relatively mature. On the other hand, the future development trend of HFCEV is mainly to solve the problems of storage cost, transportation risk and hydrogenation station infrastructure. And after solving the technical and layout problems, HFCEV will develop in parallel with BEV.

Acknowledgments

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