Comprehensive Evaluation and Experimental Research on Power Performance of BEV

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Abstract. This paper compares the differences between battery electric vehicles (BEV) and fuel vehicles, concludes the blind spots in the dynamic evaluation of BEV, and sets up mathematical models of the power performance of BEV, and builds a subjective evaluation system based on mathematical modeling. Test the objective evaluation data of the benchmark model, and subjectively evaluate the test results. The subjective evaluation test shows that the problem of longer acceleration time in the objective performance test of model 2 is mainly caused by the acceleration and deviation of the car in moving, which can reflect the results of the objective test and reflect the true feelings of the driver. The system can be used as the main basis for the evaluation of new BEV on the market. It is worthy of further promotion and research.

1. Introduction
A BEV is a new energy vehicle that uses a power battery as a power source for energy storage to provide power to a drive motor and drive the motor to run, thereby driving the BEV forward. The basic structure is shown in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{The basic structure of BEV.}
\end{figure}

2. Structural differences between BEV and fuel vehicle
There is no difference in appearance between BEV and fuel vehicle. From the perspective of dynamics, they all use rubber tires. When BEV run, the wheels and the ground contact and interact with each other. The suspension device and braking system are basically the same. The main difference between them is the use of different power systems. In comparison, BEV has the following advantages:
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(1) Simple structure and space saving. BEV does not use engines and are driven by electric motors. Therefore, the structure of the car becomes simpler, and the configuration including the engine, transmission, intake and exhaust system, driving axle, and exhaust muffler system is omitted, and the internal space becomes larger.

(2) Achieve zero emissions, zero pollution and low noise.

(3) High energy conversion efficiency. Energy can be recovered during braking and downhill, improving energy efficiency.

(4) The low-cost “valley power” of the power grid can be used for charging at night, which plays a role in stabilizing the peak-valley difference of the power grid.

However, for the dynamic of the car, BEV is driven by power battery and motors, and no sudden change in transmission ratio is needed. The subjective feelings such as the “push back feeling” and “roaring sound” of acceleration are often insufficient, which will reduce the subjective evaluation feelings during testing.

3. Objective evaluation indicators of BEV power performance

The dynamic of a BEV refers to the average driving speed that can be achieved by the longitudinal external force received by the vehicle when the vehicle is driving straight on a good road. For the convenience of research, the vehicle is generally restricted to drive straight in the dynamics research to avoid the influence of handling (steering) performance on the dynamics. There are three dynamic indicators of a car: maximum speed, acceleration time, and maximum grade.

(1) The maximum speed refers to the highest speed that can be achieved on a well-level pavement (asphalt or concrete) when the car runs with the specified loading quality. The unit is generally km/h.

(2) The acceleration time of a car has two meanings, namely the acceleration time at the starting place and the acceleration time for overtaking. The unit is s.

a. Acceleration time at the starting place. The on-site acceleration time refers to the time required for the car to start from gear I or gear II and gradually change to the highest gear with the maximum acceleration intensity and then reach a predetermined speed or distance.

b. Overtaking acceleration time. Overtaking acceleration time refers to the time required to accelerate at full speed from a lower speed to a certain high speed with the highest or second highest gear. When the acceleration time is difficult to calculate quantitatively, it can sometimes be used instead of acceleration. That is, given the starting and ending speeds, the greater the acceleration, the shorter the acceleration time.

(3) The maximum grade of a car is the maximum slope that the car can climb on a good road when it is fully loaded (or a certain load). "Slope” is not what we usually call "ramp angle”, but the tangent of the angle. As shown in Figure 2, the relationship is:

\[ i = \tan \alpha = \frac{h}{s} \]  

Figure 2. Schematic diagram of slope.
4. Mathematical modeling of BEV power performance

During the driving of a BEV, the power battery outputs electric energy to the motor. The output power of the motor is used to overcome the internal resistance of the EV mechanical device and the power consumed by the external resistance determined by the driving conditions. Internal resistance is often expressed by the efficiency of mechanical devices in a car. The external resistance is the running resistance of the EV.

(1) Driving force

The output torque of the motor of the EV is $M$. The torque transmitted to the driving shaft through the reduction gear is $M_i$, which causes the interaction between the driving wheel and the ground. The wheel and the ground exert a circumferential force $F_0$. At the same time, the reaction force $F_t$ is generated on the driving wheels. $F_t$ and $F_0$ are equal in size and opposite directions. The direction of $F_t$ is the same as the driving wheel’s forward direction. It is the external force that pushes the car forward and is defined as the driving force of EV. Have:

$$M_i = M_i i_g i_0 \eta$$

$$F_t = \frac{M_i i_g i_0 \eta}{r}$$

Where,
- $F_t$ --- Driving force (N),
- $M$ --- Output torque of motor (N),
- $i_g$ --- Retarder ratio or transmission ratio,
- $i_0$ --- Final driver ratio,
- $\eta$ --- Mechanical efficiency of EV (%),
- $r$ --- Driving wheel radius (m).

The mechanical transmission device of an electric vehicle refers to a mechanical device such as a reduction gear transmission, a transmission shaft, and a main reducer that are kinematically connected to the output shaft of the motor. The mechanical efficiency is:

$$\eta = \eta_y \eta_z \eta_m$$

Where,
- $\eta_y$ --- Efficiency of spur gear pairs, $\eta_y = 0.97 \sim 0.98$,
- $\eta_z$ --- Efficiency of bevel gear pairs, $\eta_z = 0.96 \sim 0.97$,
- $n$ --- Number of spur gear pairs in meshing state when transmitting torque,
- $m$ --- Number of bevel gear pairs in meshing state when transmitting torque.

The efficiency of a single-row planetary reducer is generally in the range of 0.97 to 0.98. The BEVs in this comparison all adopt this structure, so 0.98 is uniformly taken.

When the car is driving under various working conditions, the required torque and power are functions of the driving speed, which depends on the driving resistance encountered when driving at different speeds. The torque-speed characteristics of electric motors must meet this need for automobiles. Assuming that the power of the motor remains the same at different speeds, then,

$$P_M = \frac{M \cdot n}{9549}$$

Where,
Motor speed (r/min),
Motor torque (N·m),
Motor output power (kw).

In the working speed range of the motor, the torque is inversely proportional to the speed. The torque characteristic is a hyperbola in the first quadrant. Figure 3 shows the power and torque of a series-excited AC motor. When the speed is low, the torque is large. When the speed is high, the torque is small. This characteristic is relatively close to the driving conditions of the car.

Figure 3. The power and torque of a series-excited AC motor.

(2) Running resistance
When an EV accelerates uphill, the resistance and driving force acting on the EV are balanced to establish the following car driving equation:

\[ F_i = F_f + F_w + F_i + F_j \]  

Where,
\( F_i \) --- Driving force,
\( F_f \) --- Rolling resistance,
\( F_w \) --- Air resistance,
\( F_i \) --- Ramp resistance,
\( F_j \) --- Acceleration resistance.

(3) Mathematical expressions of objective evaluation indicators
During the driving process of an EV, the driving force and the running resistance always maintain a balance. This balance relationship is expressed by the EV driving equation (5) and the power performance of a BEV can be calculated [3].

The driving force on the wheels of an EV can be calculated by using formula (2), and the vehicle speed can be converted by using the speed of the motor according to formula (6).

\[ v_o = 0.377 \frac{n \cdot r}{i_d \cdot i_0} \]  

Where,
\( i_d \) --- Retarder ratio or transmission ratio,
\( i_0 \) --- Final driver ratio,
\( n \) --- Motor speed (r/min),
\( r \) --- Driving wheel radius (m).

The car is running at the same speed \( v \) on the ramp, \( F_j = 0 \), then the slope is obtained as:
When the car is accelerating on a good level hard road, $F_i = 0$, then find the acceleration time:

$$\frac{dv}{dt} = \frac{g}{\delta G} (F_i - F_f)$$

(8)

Where, $\delta$ is moment of inertia conversion factor.

5. **Objective evaluation and testing of BEV power performance**

A company researched and developed the benchmark model A on the market. According to different matching schemes of different batteries, motors, drive trains, and main reducers, three matching schemes were selected, and data calculation and experimental verification were performed for the three matching schemes. Because the highest speed of a car is often tested and evaluated in the entire vehicle evaluation (including the bench test), the motor may be scrapped after the evaluation. Testing for maximum climb requires a dedicated site. In this test verification, only acceleration time of 0-100km/h and sprint time from 0 to 400m were tested. Each item was measured three times and averaged. Calculation and test results are shown in Table 1.

| Data       | Items                      | Benchmark model A | Option 1 | Option 2 | Option 3 |
|------------|----------------------------|-------------------|----------|----------|----------|
| Calculation| Highest speed (km/h)       | 185               | 190      | 185      | 195      |
|            | Maximum grade (%)         | \                 | 50%      | 50%      | 50%      |
|            | Acceleration time of 0-100km/h (s) | 9.1       | 9.2      | 9.4      | 9.3      |
|            | Sprint time of 0-400m (s)  | 17.1              | 18       | 18.3     | 18.5     |
| Test results| Acceleration time of 0-100km/h (s) | 9.8       | 11.85    | 9.77     | 10.11    |
|            | Sprint time of 0-400m (s/km/h) | 17.43/125 | 18.32/126 | 17.33/139.2 | 17.72/131.2 |

As can be seen from Table 1, only the second option out of the three options wins the benchmark model A. Therefore, subjective evaluation tests are required for the second option and the benchmark model A.

6. **Subjective evaluation system of BEV power performance**

The subjective evaluation is different from the objective test and has strong non-repeatability. The subjective evaluation results of different evaluators are different. Even if the same evaluator performs multiple evaluations on the same car, the evaluation results are often different. One important reason is that the subjective evaluation is greatly affected by interference factors. The factors affecting subjective evaluation are shown in Figure 4.
Figure 4. The affecting factors of subjective evaluation.

(1) Determination of subjective evaluation index of BEV power performance

According to the subjective evaluation items of the power performance given in [1], as shown in Fig. 5, the acceleration includes starting acceleration, driving acceleration, acceleration of each gear, tuning acceleration, climbing performance, accelerator pedal feeling, tip-in/tip-out, accelerated deviation, accelerated pitch, accelerated jitter [8], etc..

Figure 5. Subjective evaluation index of BEV power performance.

(2) Analysis of subjective evaluation indexes of BEV power performance

The Analytic Hierarchy Process (AHP) is a systematic analysis method proposed by the famous American operations researcher Professor T.L. Satty [4]. This analysis method is suitable for
transforming intricate and ambiguous structures into quantitative analysis. Usually AHP decomposes the problem to be researched into different constituent factors, and then according to the requirements of the overall goal, according to the correlation between the various factors and the membership relationship, the factors are gathered and combined at different levels to form a multi-layered, ordered and hierarchical Hierarchy Diagram [5]. Then compare the relative importance of each factor in each level relative to the target in the previous layer, and construct a judgment matrix for pairwise comparison. The 1-9 scale method is introduced, as shown in Table 2. These judgments are then combined to determine the overall ranking of the importance of each factor relative to the overall goal.

Table 2. Judgment matrix scale and significance.

| Scale | Significance                                                                 |
|-------|-----------------------------------------------------------------------------|
| 1     | Compared with the two factors, they are both important.                      |
| 3     | Compared with the two factors, the former is slightly more important than the latter. |
| 5     | Compared with the two factors, the former is obviously more important than the latter. |
| 7     | Compared with the two factors, the former is mightily more important than the latter. |
| 9     | Compared with the two factors, the former is extremely more important than the latter. |
| 2, 4, 6, 8 | The intermediate value of the above adjacent judgment.                      |
| Reciprocal | If the ratio of the importance of factor i to factor j is \(b_{ij}\), then the ratio of factor j to factor i is \(b_{ji} = 1/b_{ij}\). |

In the judgment matrix estimation, inconsistencies are often inevitable. Therefore, Saaty introduces a consistency index to measure the difference between the maximum eigenvalue \(\max \lambda\) and the order \(n\) of the judgment matrix to measure the degree of inconsistency [7]. The relationship between RI and matrix order \(n\) is shown in Table 3.

Table 3. Value of random consistency ratio.

| n  | 1  | 2  | 3  | 4   | 5   | 6   | 7   | 8   |
|----|----|----|----|-----|-----|-----|-----|-----|
| RI | 0  | 0  | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 |
| n  | 9  | 10 | 11  | 12  | 13  | 14  | 15  |     |
| RI | 1.46 | 1.49 | 1.52 | 1.54 | 1.56 | 1.58 | 1.59 |     |

When \(n<3\), the judgment matrix is always consistent. There is:

\[
CR = CI/RI
\]

Where, \(CI\) --- Consistency index of judgment matrix,
\(RI\) --- Same-level average randomness index.

Generally, when \(CR<0.1\), the judgment matrix is considered to have satisfactory consistency. Otherwise, the judgment matrix needs to be adjusted to satisfy \(CR<0.1\), so that it has satisfactory consistency.

(3) Calculation of the subjective evaluation index weight of BEV

After calculation, the structure model of AHP as shown in Figure 6 is established [6]. After fully explaining the evaluation content and test methods of the indicators to the three subjective evaluation engineers, and introducing the two-by-two judgment matrix of AHP, according to the calculation method of AHP, write Matlab program to perform weight calculation and consistency judgment.
It can be seen from Fig. 6 that in the subjective evaluation of power performance, the acceleration indicators of starting acceleration, driving acceleration, acceleration of each gear and the climbing performance weight are the same, and the sum of the four indicators accounts for more than 66% of the overall performance. Coupled with turning acceleration, it accounts for nearly 75%. Therefore, a large part of the power performance is determined by the driving force.

7. Subjective evaluation test of BEV power performance
At a test site, three experienced subjective evaluation engineers set the score of the benchmark model A as 7 points according to the dynamic evaluation indicators and specific test methods. Engineers first tested the benchmark model A, and then tested the vehicle 2, and obtained subjective evaluation score data for each index shown in Table 4.

Table 4. Subjective evaluation score of a BEV.

| Items                      | Engineer 1 | Engineer 2 | Engineer 3 | Mean (leave one decimal place) |
|----------------------------|------------|------------|------------|-------------------------------|
| Starting acceleration      | 7          | 7.2        | 7.8        | 7.3                           |
| Driving acceleration       | 7.1        | 7.3        | 7          | 7.1                           |
| Acceleration of each gear  | 7.6        | 8          | 7.7        | 7.8                           |
| Tuning acceleration        | 7.6        | 7.5        | 7          | 7.4                           |
| Climbing performance       | 8          | 8.1        | 8.1        | 8.1                           |
| Accelerator pedal feeling  | 7.5        | 7.5        | 7          | 7.3                           |
| Tip-in / Tip-out           | 7          | 7.5        | 7.2        | 7.2                           |
| Accelerated deviation      | 6          | 5          | 6.5        | 5.8                           |
| Accelerated pitch          | 7          | 7.5        | 7          | 7.2                           |
| Accelerated jitter         | 7          | 7.5        | 7.3        | 7.3                           |
| Total score                | 71.8       | 73.1       | 72.6       | 72.5                           |

It can be seen from Table 4 that different evaluation engineers have relatively consistent scores on individual indicators of dynamics. Draw the spider diagram of the subjective evaluation after averaging the individual indicators, as shown in Figure 7.
Figure 7. Spider diagram for subjective evaluation of power performance.

8. Conclusion
(1) Compared with vehicle A, the vehicle 2 has better starting acceleration performance in the vehicle dynamic performance test, and the acceleration deviation under the influence of driving force has a lower score.
(2) The car can be put on the market for mass production, but a detailed analysis of deviation cause must be made.
(3) Subjective evaluation based on objective evaluation data is a model to improve the evaluation efficiency of BEV, and further research is recommended.

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