Research on multi-acceleration curve optimization for electric vehicle

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Abstract. As the great differences of the electric energy consumption are generated when electric vehicle (EV) accelerates in different ways, this research studies on the difference of energy consumption per distance when accelerating in a multi-acceleration way and single-acceleration way, on the basis of the theory research, an EV is taken as the research object and the energy consumption per kilometre is used as the objective function, an optimization design method for the EV acceleration way is presented. The optimization method is used to optimize the acceleration curve of the NEDC drive cycle and the optimum acceleration curve is obtained. In order to verify the energy saving effect of the optimum acceleration curve, the EV test of optimum curve is conducted. The experiment results show that compared with the NEDC curve, the energy consumption per kilometre of the No.1-5 optimum curve is reduced by 14.6%, 13.5%, 6.2%, 6.7% and 1.9% respectively.

1. Introduction
Recent study shows that the short driving range of EV is one of the essential factors that hinder its popularization [1], while its energy consumption during the acceleration process has a significant impact on its driving range. According to the theory of EV [2], when the vehicle parameters and road conditions are unchanging, the energy consumption of EV during the accelerating process mainly depends on its speed and acceleration. Therefore, it is necessary to find out the relationship between the speed and acceleration of EV and the its electric energy consumption in different acceleration processes, thereby providing a foundation for designing an energy-saving acceleration curve for EV. Relevant scholars have done a lot of researches in this field. For example, WU X[3] and ZHANG R[4] analyzed the relationship between the output power of battery pack and the speed and acceleration of EV based on the experimental data which was obtained through the vehicle experiment in urban areas and expressways; HUANG[5] and PAN[6] studied the changes of the energy consumption of EV when it accelerated with a few constant accelerations, the results showed that the energy consumption increased with values of acceleration increasing. The influence on energy consumption of EV while taking different accelerating curves which represented different driver behavior was also researched by some scholars [7-9]. The results showed that the acceleration curve with lower demand for speed and smooth changes on acceleration consumed less energy. In summary, most of the relevant literatures analyzed the influence on energy consumption when EV accelerated with different single-acceleration curve. However, few literatures studied the effects on energy consumption with multi-acceleration curve and the optimal design method of multi-acceleration curve for EV, therefore, it is difficult to...
obtain the lowest energy consumption per kilometer curve. In order to obtain the optimal acceleration curve, the influencing factors of EV’s energy consumption are analyzed and the relationship between EV’s energy consumption per kilometer and its speed and acceleration is deduced. Finally, the lowest energy consumption curve is optimized through Genetic Algorithm and the feasibility of the optimization design method for the EV acceleration curve is verified through the EV experiment.

2. The Factors of EV’s Energy Consumption Per Kilometre

In order to eliminate the influences of different driving distances on the evaluation of energy economy when EV accelerates in different ways, the energy consumption per kilometer is defined as its economic evaluation index [10]. According to the theory of EV [2], the energy consumption per kilometer of EV in an acceleration process can be expressed as:

\[
E = \frac{W}{S} = \frac{1}{\eta} \left[ \frac{G f + G i + \frac{C_d A u(t)^2}{21.15} + \delta ma(t)u(t)}{3600 \eta \eta_m} \right] dt
\]

Where \( E \) (kWh/km) is the energy consumption per kilometer of EV; \( W \) (kWh) and \( S \) (km) are the energy consumption of EV and driving distance during the acceleration process respectively; \( t_0, t_f \) are the starting and ending moments of the acceleration process respectively; \( G \) (N) is the gravity of EV; \( f \) is the rolling friction coefficient; \( i \) is the road slope; \( C_D \) (N) is the drag coefficient; \( A \) (m²) is the frontal area of EV; \( u(t) \) (km/h) is the velocity of EV; \( \delta \) is the vehicle rotating mass conversion factor; \( m \) (kg) is the mass of EV; \( a(t) \) (m/s²) is the EV’s acceleration; \( \eta \) is the efficiency of the transmission system; \( \eta_m \) is the efficiency of the electric motor.

It can be seen that the energy consumption per kilometer of EV mainly depends on the road conditions \( (f, in) \), the EV’s parameters \( (G, CD, A, \delta, m, at) \), the efficiency of the electric motor \( (am) \) and the acceleration process parameters \( (u(t), a(t), t_0, t_f) \) through (1).

The EV energy consumption per kilometer \( E \) can be transformed through (1):

\[
E = \frac{1}{\eta} \left[ \int_{t_0}^{t_f} (k_r u(t) + k_v u(t)^3 + k_a a(t) u(t)) dt \right]
\]

Where, \( k_r = \frac{(G_0 + G_I)}{3600 \eta \eta_m} \), \( k_v = C_D A \eta / (76140 \eta \eta_m) \), \( k_i = \eta_m / (3600 \eta \eta_m) \).

If the road conditions and vehicle parameters are determined, assuming that the efficiency of the motor is unchanging, then if, \( k_v \) and \( k_i \) can be regarded as constant. When the \( t_0 \) and \( t_f \) are determined, the energy consumption per kilometer of EV during an acceleration process can be expressed as a function with speed and acceleration:

\[
E = f(u(t), a(t))
\]

Therefore, studying the influence on EV energy consumption with different acceleration curves is a significant way to reduce energy consumption.
3. The Relationship Between EV’s Energy Consumption Per Kilometre And Different Acceleration Ways

3.1. Difference in energy consumption per kilometer between two accelerations and single acceleration way

The EV’s speed of two accelerations and single acceleration curves over time are shown in Figure 1. Where, A and B represent the starting and the ending points of the acceleration curve, $u_0$ and $of$ are the starting and ending speeds of the acceleration curve, respectively. When the EV accelerates from point A to point B with a single acceleration $a_{11}$ according to the acceleration curve 2 shown by Figure 1, its instantaneous speed $u(t)$ can be represented by (4):

$$u(t) = u_0 + a_{11}(t - t_0)(t_0 \leq t \leq t_f)$$

There are two forms of two-acceleration ways for the EV to accelerate from point A to point B, the first one is the EV accelerates from point A to point O1 with the acceleration $a_{121}$ and then accelerates from point O1 to point B with the acceleration $a_{122}$, as the Figure 1 shown, convex curve $A O B$ is above the linear curve $AB$, which means $a_{121} > a_{122}$ as well as $a_{121} > a_{11}$. The EV can also accelerates from point A to point O2 with the acceleration $a_{021}$ and then accelerates from point O2 to point B with the acceleration $a_{022}$, concave curve $A O B$ is below the linear curve $AB$, which means $a_{021} < a_{022}$ and $a_{021} < a_{11}$ as well. When the EV accelerates from point A to point B according to the two-acceleration curve like curve1 or curve3 shown by Figure 1, its instantaneous speed $u(t)$ can be represented by (5)

$$u(t) = \begin{cases} 
   u_0 + a_{21}(t - t_0)(t_0 \leq t < t_1) \\
   u_0 + a_{21}(t_1 - t_0) + a_{22}(t - t_1)(t_1 \leq t \leq t_f) 
\end{cases}$$

Where, $t_1$ is the terminal moment when accelerating with acceleration $a_{21}$; in represents the acceleration way, When in=1, it represents the convex acceleration way; when in=0, it represents the concave acceleration way.

Assume that EV starts accelerating from a stationary state, where $t_0=0$, $u_0=0$. For the single acceleration way, $a_{11}=of/ft.$; for the two-acceleration way, $air_{22} = (of - air_{21} t_1)/(ft. - t_1)$.

According to (2) and (4), the EV’s energy consumption per kilometer of the linear curve $E_1$ can be expressed as:
The EV’s energy consumption per kilometer of the two-acceleration curve E2 can be deduced from (2) and (5):

\[ E_i = \frac{W_i}{S_i} = k_j \frac{1}{2} u_j^2 k_{c_i} + \frac{u_j}{t_j} k_s \]  

(6)

The difference between E2 and E1 can be expressed as:

\[ E_i - E_i = \frac{(a_{i_1} - a_{i_2})(2t_iu_i k_s - (a_{i_1}^2 t_i^2 + u_i t_i^3 a_{i_2})k_{c_v})}{2(t_i u_i + a_{i_2} t_i - t_i u_i)} \]  

(7)

Except for \( K_i \), the difference between E2 and E1 is relevant to \( a_{i_1} \) and \( a_{i_2} \). Since the EVs are mostly driven in urban conditions [11-12], taking an acceleration process of NEDC as the research object [13], where \( u_i = 0, t_0 = 0, \delta = 50 \text{km/h}, t = 26 \text{s} \); taking an EV as the study object, where \( m = 2295 \text{kg}, \delta = 1.04, \text{CD} = 0.29, A = 2.547 \text{m}^2, a_m = 0.90, a_t = 0.90, \text{so } K_i = 0.00012, K_i = 0.818. \) Analyze the difference between E2 and E1 when the EV takes different accelerating curves. As is known:

\[ a_{i_1}^2 t_i^2 + u_i t_i^3 a_{i_2} \leq u_j^2 t_j^2 + u_j t_j^3 a_{j_2} = 2u_j^2 t_j^2 \]  

(9)

\[ t_i u_i + a_{i_2} t_i - t_i u_i = a_{i_2} t_i + u_i (t_i - t_i) > 0 \]  

(10)

\[ t_i u_i > 0 \]  

(11)

\[ u_i t_i k_{c_v} - k_s < 0 \]  

(12)

When EV accelerates with the convex two-acceleration curve:

\[ E_i - E_i \leq \frac{(a_{i_1} - a_{i_2})(2u_j^2 t_j k_{c_v} - 2t_i u_i k_s)}{2(t_i u_i + a_{i_2} t_i - t_i u_i)} \]  

(13)

It can be deduced that \( E_2 - E_1 < 0 \) through (9) ~ (12).

When EV accelerates with the concave two-acceleration curve:

\[ E_i - E_i \geq \frac{(a_{i_1} - a_{i_2})(2t_i u_i k_s - 2u_j^2 t_j k_{c_v})}{2(t_i u_i + a_{i_2} t_i - t_i u_i)} \]  

(14)

It can be deduced that \( E_2 - E_1 > 0 \) through (9) ~ (12).
In conclusion, compared with the single acceleration way, the EV consumes less energy per kilometer when takes the convex two-acceleration curve while consumes more energy per kilometer when takes the concave two-acceleration curve.

3.2. Difference in energy consumption per kilometer between multiple accelerations and single acceleration way

![Figure 2. Multi-accelerations way](image)

The EV’s speed of multiple accelerations ways over time are shown in Figure 2. Where, curve 1 is the upper convex n-acceleration curve, a1 no is the acceleration of the kith acceleration segment, and a1 n1>a1 n2>…>a1 nun, a1 n1>a11; curve 2 is the concave n-acceleration curve, a0 no is the acceleration of the kith acceleration segment, and a0 n1<a0 n2<…<a0 nun, a0 n1<a11. The speed of the n-acceleration curve over time u (t) can be expressed as:

\[
 u(t) = \begin{cases} 
 u_0 + a'_1 (t - t_0) & (t_0 \leq t < t_1) \\
 u_0 + \sum_{k=1}^{n-1} a'_k (t_{k+1} - t_k) + a'_m (t - t_{n-1}) & (t_{n-1} \leq t < t_n, n \geq 2) 
\end{cases}
\]

Where, air no and to are the acceleration and acceleration termination moment of the kith acceleration segment, respectively. When in=1, it represents the convex n-acceleration way; when i=0, it represents the concave n-acceleration way.

Assume that EV accelerates from a stationary state, where t0=0, u0=0, En is the EV energy consumption per kilometer of the n-acceleration way. It can be proved through mathematical induction that: when air n1>a11, En<E1; when air n1<a11, En>E1.

While n=2, it can be known that when air 21>a11, E2<E1; when air 21<a11, E2>E1 from the section 2.1.

Assume that when n=k-1(k≥3), if air n1>a11, then En<E1; if air n1<a11, then En>E1; while n=k, the proposition is also established.
In Figure 3, assuming that n-1-acceleration blue curve \( \overline{AC}^i \) is curve D, single acceleration black curve \( \overline{AC} \) is curve G, single acceleration curve \( \overline{CB} \) is curve F n-1-acceleration green curve \( \overline{AC}^o \) is curve H, single acceleration purple curve \( \overline{AC}^o \) is curve J, single acceleration curve \( \overline{CB} \) is curve I. The EV’s energy consumption, driven distance and energy consumption per kilometer can be described as \( W_\beta, S_\beta \) and \( E_\beta \), respectively, where \( \beta = \{D, G, F, H, J, I\} \), different value of \( \beta \) means that the EV accelerates with different curve.

As the Figure 3 shown, since \( a_1 k_1 > a_1 k^{-1} \), from the assumption we can know that:

\[ E_D < E_0 \]  
(16)

WD, SD can be expressed as: WD=\( \text{Waged} \), SD=\( \text{Sq} \), where \( d>0, q>0 \).

When the EV accelerates from point A to point B according to curve D and curve F, the energy consumption per kilometer can be expressed as:

\[ E_\gamma = \frac{W_a + W_b}{S_a + S_b} = \frac{W_a + d + W_r}{S_a + q + S_r} \]  
(17)

When the EV accelerates from point A to point B according to curve G and curve F, the energy consumption per kilometer can be expressed as:

\[ E_\gamma = \frac{W_a + W_f}{S_a + S_f} \]  
(18)

From (16) ~ (18), it can be known that:

\[ E_\gamma = \frac{W_a + d + W_r}{S_a + q + S_r} < \frac{W_a + W_f + d}{S_a + S_f + q} < \frac{W_a + W_f}{S_a + S_f} = E_{\gamma'} \]  
(19)

Since \( a_1 k^{-1} > a_11 \) according to (13), it can be known that \( \text{Eke}'' < \text{E1} \), therefor \( \text{Eke} < \text{E1} \).

As the Figure 3 shown, since \( a_0 k_1 > a_0 k^{-1} \), from the assumption we can know that:

\[ E_J < E_\mu \]  
(20)

WJ, SJ can be expressed as: WJ=\( \text{Whams} \), SJ=\( \text{Shank} \), where \( m>0, n>0 \).

When the EV accelerates from point A to point B according to curve H and curve I, the energy consumption per kilometer can be expressed as:
When the EV accelerates from point A to point B according to curve J and curve I, the energy consumption per kilometer can be expressed as:

$$E_i = \frac{W_{i} + W_{j}}{S_j + S_i} \quad (21)$$

From (20) ~ (22) we can know:

$$E_i = \frac{W_{i} + m + W_{j}}{S_j + n + S_i} = E_n \quad (23)$$

Since $a_1 > a_0$, according to (14), it can be known that $E_1 < E_{ke}$, therefore $E_1 < E_{ke}$. So when $n = k$, the proposition is also established.

To sum up, when air $n_1 > a_1$, there is $E_n < E_1$; when air $n_1 < a_1$, there is $E_n > E_1$, which means compared with the single acceleration way, the EV consumes less energy per kilometer while taking the convex multiple accelerations curve and consumes more energy per kilometer while taking the concave multiple accelerations curve.

4. Multi-acceleration Curve Optimization For EV

From the above theoretical analysis, it can be seen that when the EV consumes less energy per kilometer while taking a convex multi-acceleration curve. Thus for specific acceleration conditions, the acceleration curve of the EV needs to be optimized so as to save more energy.

4.1. Objective functions and constraints

The optimization problem can be described as:

$$\min J = E_n (a_{i1}, \cdots, a_{in}, t_{i1}, \cdots, t_{in-1}); n > 1$$
$$s.t. g_i(a_{i}, t_{i}) \leq 0; \quad i = 1, 2, \cdots, n - 1$$
$$g_i(a_{i}, t_{i}) = 0; \quad i = 1, 2, \cdots, n - 1 \quad (24)$$

Where $J$ is the objective function, $g_i (animating) \leq 0$ is the inequality constraint, and $g_2 (animating) = 0$ is the equality constraint, where any (m/s$^2$) is the nth acceleration of the n-acceleration curve; $t_i (s)$ is the accelerating time of the nth acceleration segment. For an acceleration segment which the starting and ending speed, acceleration time as well as the number of accelerations are determined, the optimization goal is to find the proper an and $t_i$ of each acceleration segment for the multi-acceleration curve so that the EV can achieve the goal of lowest energy consumption per kilometer while satisfying the constraints. According to the international acceleration standard ISO2631 [14], determine the maximum value of the acceleration of EV is 0.83 m/s$^2$.

With reference to the typical urban driving cycle NEDC, five accelerating segments are selected and will be optimized in the next part. They are 0-50km/h accelerating segment with 26s, 0-70km/h accelerating segment with 41s, 15-50km/h accelerating segment with 20s, 15-70km/h accelerating segment with 33s and 35-70km/h accelerating segment with 22s, respectively. The five selected accelerating segments are defined as NO.1-5 curve, successively.

The constraints of each accelerating segments are as follows:
4.2. Optimization Algorithm

Genetic Algorithm (GA) is an adaptive and globally optimized probabilistic search algorithm which mimics the working principles of natural evolution and genetics. Genetic Algorithm operates on a population of feasible solutions by applying the principle of “survival of the fittest” to produce better approximations to a solution. At present, the genetic algorithm has been applied in many fields such as EV driving range estimating [15], energy distribution [16] and so on. Therefore, genetic algorithm is used in this paper to find out the most energy saving acceleration curve for the EV.

4.3. Optimization Results

Taking an EV as the research object, the accelerating curve is optimized by genetic algorithm based on the MATLAB platform. The main parameters of the EV are shown in Table 1:

| Parameter                        | Value | 0.28 | 2.67 | 0.01 | 1.04 | 120 | 450 |
|----------------------------------|-------|------|------|------|------|-----|-----|
| Vehicle mass, m (kg)             | 2295  |
| drag coefficient, C_d            |       |
| frontal area, A (m²)             |       |
| rolling friction coefficient, f  |       |
| vehicle rotating mass conversion factor, δ |       |
| Motor maximum power(kW)          |       |
| Motor maximum torque(NM)         |       |

The optimization results of the parameters of accelerating curve are shown in Table 2:

| Driving condition | Numbers of acceleration | Parameters of accelerating curve |
|-------------------|-------------------------|---------------------------------|
| 26s 0-50km/h      | 3                       | NEDC curve (m/s²,s)            |
|                   |                          | Optimization curve(m/s²,s)     |
|                   | a_31=0.69 t_31=6        | a_31=0.78 t_31=5.34            |
|                   | a_32=0.51 t_32=11       | a_32=0.63 t_32=8.82            |
|                   | a_33=0.46 t_33=9        | a_33=0.35 t_33=11.84           |
| 41s 0-70km/h      | 4                       |                                |
|                   | a_41=0.69 t_41=6        |                                |
|                   | a_42=0.51 t_42=11       |                                |
|                   | a_43=0.42 t_43=10       |                                |
|                   | a_44=0.40 t_44=14       |                                |
| 20s 15-50km/h     | 2                       |                                |
|                   | a_21=0.51 t_21=11       |                                |
|                   | a_22=0.46 t_22=9        |                                |
| 33s 15-70km/h     | 3                       |                                |
|                   | a_31=0.51 t_31=11       |                                |
|                   | a_32=0.46 t_32=9        |                                |
|                   | a_33=0.43 t_33=13       |                                |
| 22s 35-70km/h     | 2                       |                                |
|                   | a_21=0.46 t_21=9        |                                |
|                   | a_22=0.43 t_22=13       |                                |
5. Simulation and Experiment Analysis

5.1. Simulation Analysis
In order to verify the energy saving effect of the optimized acceleration curve, an EV simulation experiment is performed based on the AVL Cruise platform. The main technical parameters and model of the EV are shown in Table 1 and in Figure 4.

After the optimized accelerating curve files are imported into the AVL Cruise software, the accelerating simulation is performed and the simulation results are shown in Table 3.

| No. | Driving condition | Energy consumption per kilometer (kWh/km) |
|-----|-------------------|------------------------------------------|
|     |                   | NEDC curve | Optimization curve |
| 1   | 26s 0-50km/h      | 0.418      | 0.349              |
| 2   | 41s 0-70km/h      | 0.382      | 0.325              |
| 3   | 20s 15-50km/h     | 0.390      | 0.358              |
| 4   | 33s 15-70km/h     | 0.377      | 0.354              |
| 5   | 22s 35-70km/h     | 0.374      | 0.368              |

As it is shown in Table 3 that compared with the original NEDC curve, the energy consumption per kilometer of the optimized acceleration curve was reduced by 19.8%, 17.4%, 9.0%, 6.6% and 1.6% respectively, which verified the feasibility of energy saving of the optimized multi-acceleration curves.

5.2. Experiment Analysis
An EV test is conducted to validate the energy conservation of the optimal accelerating curve. The EV energy consumption test system which mainly consisted of AVL roads chassis dynamometer and DEWE tester is established, as the Figure 5 shown.

According to the GB 18386-2005, the EV accelerating experiment of different optimal multi-acceleration curve is carried on, during which the driver controlled the accelerator pedal in order to
make sure the speed of EV can follow the settled accelerating curve. And when the EV is accelerating, the voltage and current of the battery pack are tested by the DEWE energy consumption test system, so the energy consumption during the acceleration can be calculated. The AVL roads chassis dynamometer measures of speed of the EV, therefore the distance of EV during the acceleration could be obtained. The parameters of the settled curves are shown in Table 1 and the experimental energy consumption results are shown in Table 4:

| No. | Driving condition | Energy consumption per kilometer (kWh/km) |
|-----|-------------------|-----------------------------------------|
|     |                   | NEDC curve | Optimization curve |
| 1   | 26s 0-50km/h      | 0.385      | 0.336            |
| 2   | 41s 0-70km/h      | 0.369      | 0.325            |
| 3   | 20s 15-50km/h     | 0.376      | 0.354            |
| 4   | 33s 15-70km/h     | 0.382      | 0.358            |
| 5   | 22s 35-70km/h     | 0.382      | 0.375            |

From Table 4 it can be known that compared with the NEDC curve, the energy consumption per kilometer of No.1-5 optimization curve is reduced by 14.6%, 13.5%, 6.2%, 6.7% and 1.9%, therefore the energy conservation effect of the optimal accelerating curve is confirmed.

6. Conclusion
The EV consumes different electric energy per distance when accelerating in different ways. The research shows that the convex multi-acceleration way has the significant effect on energy-saving for EV.

In order to find out the optimum accelerating curve at the specific acceleration condition for the EV, the GA is applied to obtain the minimum energy consumption per kilometer acceleration curve. The EV simulation based on the AVL Cruise and the actual EV experiment is carried on so as to validate the feasibility of theoretical analysis and optimization result. The experiment result shows that compared with the NEDC curve, the energy consumption per kilometer of No.1-5 optimization curve was reduced by 14.6%, 13.5%, 6.2%, 6.7% and 1.9% respectively.

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