Study on the influence of acceleration curve on electric vehicle energy consumption and battery life

Lifu Li and Qin Liu*
School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, 510641, China
*Corresponding author’s e-mail: liuqin_16@126.com

Abstract. At present, much research on acceleration curve mainly focuses on reducing electric vehicle energy consumption, but there has been less consideration given to the impact on battery life, which will result in a decrease in battery life, and in turn leads to a short driving range for electric vehicle. Aiming at the problem, the relationship among acceleration curve and electric vehicle energy consumption and battery life is studied, and when electric vehicle accelerates with a single, two and three accelerations under neighborhood, urban and highway conditions, the difference between electric vehicle energy consumption per kilometer (ECPM) and percentage of battery capacity loss per kilometer (PBCLPM) is studied. Research results show that the variation trend of electric vehicle ECPM with acceleration and acceleration time under different working conditions is basically contrary to the variation trend of PBCLPM. The two are mutually contradictory, therefore, when optimizing the acceleration curve, you should not only consider energy consumption, but also consider the effect of acceleration curve on battery life.

1. Introduction
Due to its high efficiency, zero emissions and low noise, electric vehicle is considered to be one of the best solutions to solve fossil energy shortage and environmental pollution problems. However, due to limited vehicle energy, the development of electric vehicles has been restricted by the driving range. Therefore, in electric vehicle research, priority should be given to use the limited energy to maximize the energy utilization rate, reduce the energy consumption, and then improve the driving range. The results of [1] show that the acceleration values can affect the electric vehicle energy consumption greatly. The results of [2] show that the electric vehicle energy consumption with multiple acceleration values is less than a single acceleration value. And the energy consumption differences under different acceleration conditions (low velocity, medium velocity, high velocity) are studied in the reference [3]. The results show that the energy consumption under high velocity is higher than that under low velocity.

And for the study of power battery life, relevant scholars mainly focus on the study of the influence factors of battery life and the prediction model of remaining life. For example, the effect of charging current and charging voltage on lithium ion battery cycle life is studied in [4]. The effect of temperature and state of charge on the aging of lithium-ion battery has also been investigated in [5]. A capacity fading model based on temperature and depth of discharge is established in reference [6]. And in reference [7], a semi-empirical prediction model for the Li-ion battery cycle life based on actual driving conditions is proposed for HEV.
In summary, the existing research on electric vehicles mainly focuses on the single angle of energy consumption or battery life. The two are not comprehensively analyzed, and not from the point of view of acceleration curve to analyze the effect of different acceleration curves on electric vehicle energy consumption and battery life. Therefore, taking an electric vehicle as the research object, the influence of different acceleration curves on electric vehicle energy consumption and battery life is studied, and the effect of acceleration number and changing trend on electric vehicle energy consumption and battery life is also considered. It can provide a theoretical basis for the optimization of the subsequent acceleration curve.

2. The model to analyze the relationship among acceleration curve and electric vehicle energy consumption and battery life

2.1 The model of electric vehicle energy consumption

On the basis of automobile theory[8], when electric vehicle accelerates on good road, assuming the road has no gradient, the traction force \( F_t(t) \) (N) can be calculated as:

\[
F_t(t) = mgf + \frac{C_D Au(t)^2}{21.15} + \delta ma(t)
\]

(1)

Where \( m \) (kg) is electric vehicle mass; \( C_D \) is drag coefficient; \( A \) (m\(^2\)) is electric vehicle frontal area; \( u(t) \) (km/h) is electric vehicle velocity; \( f \) is rolling friction coefficient; \( \delta \) is electric vehicle rotating mass conversion factor; \( a(t) \) (m/s\(^2\)) is acceleration.

Based on equation (1), the battery output power \( P_b(t) \) (w) can be expressed as:

\[
P_b(t) = u(t) \left[ mgf + \frac{C_D Au(t)^2}{21.15} + \delta ma(t) \right]^{3.6/\eta_T \eta_V \eta_m}
\]

(2)

Where \( \eta_T \) is transmission system efficiency; \( \eta_V \) is inverter efficiency; \( \eta_m \) is electric motor efficiency.

According to equation (1) (2), the electric vehicle energy consumption per kilometer (ECPM) \( E_{a+j}(t) \) (Wh/km) can be rewritten as:

\[
E_{a+j}(t) = \frac{\int_0^t [k_f u(t) + k_{c_o} u^3(t) + k_s a(t) \cdot u(t)] \, dt}{\int_0^t u(t) \, dt}
\]

(3)

Where, \( k_f \) \( (k_f = mgf/3.6 \eta_T \eta_V \eta_m) \) is rolling resistance factor, \( k_{c_o} \) \( (k_{c_o} = C_D A/76.14 \cdot \eta_T \eta_V \eta_m) \) is air resistance impact factor, \( k_s \) \( (k_s = \delta m/3.6 \eta_T \eta_V \eta_m) \) is accelerate resistance factor. According to Equation (3), it can be found that, when the working conditions and road load are certain, \( k_f \), \( k_{c_o} \), and \( k_s \) can be considered as fixed values, \( E_{a+j}(t) \) mainly depends on \( u(t) \) and \( a(t) \), \( u(t) \) and \( a(t) \) mainly depend on acceleration curves. Consequently, it is important that study different acceleration curves.

The main parameters of electric vehicle are listed in table 1.

| Parameter                   | Value | Parameter                  | Value |
|-----------------------------|-------|----------------------------|-------|
| Vehicle mass, \( m \) (kg)  | 2295  | Vehicle rotating mass conversion factor, \( \delta \) | 1.04  |
| Drag coefficient, \( C_D \)    | 0.28  | Efficiency of the inverter, \( \eta_V \) | 0.92  |
| Frontal area, \( A \) (m\(^2\)) | 2.67  | Efficiency of the transmission system, \( \eta_T \) | 0.9   |
| Rolling friction coefficient, \( f \) | 0.01  | Efficiency of the electric motor, \( \eta_m \) | 0.9   |
2.2 The model of battery life

For the lithium-ion power battery life, the most typical model is proposed by John Wang of US HRL laboratory [9]. The model takes into account Ah throughput (time), charge/discharge rate, and temperature, and the model can be expressed as:

$$Q_{loss} = B \cdot \exp \left( -\frac{31700 + 370.3 \times n}{RT} \right) \times (A_h)^{0.55}$$  (4)

Where $Q_{loss}$ (%) is percentage of battery capacity loss (PBCL) under a constant current charge/discharge condition; $B$ is pre-exponential factor; $A_h (A \cdot h)$ is cumulative ampere-hours, which can be calculated by $A_h = I \times t / 3600$, $I$ is single cell current; $n$ is discharge rate; $T$ is temperature; $R$ is gas constant, $R = 8.314J / (mol \cdot K)$.

On the basis of experimental data in reference [9], the relationship between $B$ and $n$ can be fitted by the following Equation:

$$23 = 36042 + 9419n - 1215n^2$$  (5)

For the purpose of predicting battery capacity loss under actual working condition, the capacity loss model is modified using the method in reference [10]. $Q_{loss}$ is the PBCL under $1C$, $Q_{lossn}$ is the PBCL under $nC$. And when $Q_{loss1} = Q_{lossn}$, the PBCL $Q_{lossn}$ (%) at $nC$ can be derived as:

$$Q_{lossn} = B_h \cdot \exp \left( -\frac{31329.7}{RT} \right) \times \left[ \frac{B_h}{B_1} \cdot \exp \left( \frac{370.3 \cdot n - 370.3}{RT} \right) \right]^{0.55} \cdot A_h^{0.55}$$  (6)

Where $B_h = 27790$; $Q_{lossn}$ is calculated PBCL at $nC$ on the basis of the calculation method at $1C$.

In this research, due to only study the acceleration process of electric vehicle, then the battery discharge process is only considered, so the PBCL in an acceleration process $Q_{loss1}$ can be calculated as:

$$Q_{loss1} = B_h \cdot \exp \left( -\frac{31329.7}{RT} \right) \times \left[ \frac{B_h}{B_1} \cdot \exp \left( \frac{370.3 \cdot n(t) - 370.3}{RT} \right) \right]^{0.55} \cdot n(t) \times I(t) \cdot \frac{3600}{3600} \cdot dt^{0.55}$$  (7)

Where $I(t)$ is discharge current for $1C$; $n(t)$ is discharge rate at $t$, $n(t) = I(t)/C_r$; $C_r (A \cdot h)$ is rated capacity of single cell; $I(t)$ is single cell discharge current during driving; $I(t) = I_{pack}(t)/Num$, $I_{pack}(t) = P(t)/U$, $U$ (V) is the total voltage of the battery pack, $Num$ is parallel number of battery pack. Based on equation (2) (3) (7), the PBCL under an acceleration working process can be calculated as:

$$Q_{loss1} = B_h \cdot \exp \left( -\frac{31329.7}{RT} \right) \times \left[ \frac{B_h}{B_1} \cdot \exp \left( \frac{370.3 \cdot n(t) - 370.3}{RT} \right) \right]^{0.55} \cdot \frac{\int_{t_i}^{t_f} [k_1 u(t) + k_{n1} u'(t) + k_2 a(t) \cdot u(t)] \cdot \frac{n(t)}{3600} \cdot dt}{3600 \cdot U \cdot Num}$$  (8)

For the purpose of comparing and analyzing the PBCL under different acceleration conditions, we use percentage of battery capacity loss per kilometer (PBCLPM) to measure it. The PBCLPM $q_{loss}$ (%/km) can be calculated as:

$$q_{loss} = \frac{Q_{loss}}{S} = \frac{Q_{loss}}{\int_{t_i}^{t_f} u(t) dt}$$  (9)

Based on equation (8), (9), it can be found that, when electric vehicle accelerates on good road, the PBCLPM $q_{loss}$ also mainly depends on $u(t)$ and $a(t)$. Consequently, researching acceleration curves is also a momentous method to prolong battery life.

The main parameters of battery are listed in table 2.
Table 2 Key parameters of battery

| Parameter                              | Value       |
|----------------------------------------|-------------|
| Nominal voltage of single cell (V)     | 3.2         |
| Nominal capacity of single cell, $C_r$ (Ah) | 10         |
| The number cells in parallel, $Num$    | 18          |
| Total battery voltage, $U$ (V)         | 316.8       |
| Total battery capacity (Ah)            | 180         |
| Type                                   | Lithium-ion |

3. The difference of electric vehicle energy consumption and battery life under different acceleration curves

Based on the analysis in [11, 12], for a given acceleration condition which the initial velocity is zero, compared to concave acceleration curve with multiple accelerations, the convex curves with multiple accelerations are more effective in reducing the electric vehicle energy consumption. Therefore, taking the convex acceleration curves in figure 1 as an example, the influence of the number of accelerations on electric vehicle energy consumption and battery life under different working conditions is analyzed.

In figure 1, the curve $OA$ is a linear curve with a single acceleration value, the curve $OBA$ is a convex curve with two acceleration values, the curve $OCCA$ is a convex curve with three acceleration values, the curve $OD_1D_2...D_nA$ is a convex curve with $n$ acceleration values.

Figure 1. The vehicle velocity change under different acceleration curves

The influence of different acceleration numbers on $E_i$ and $q_{loss}$ is analyzed under three acceleration conditions, namely, neighborhood $(<40km/h)$, urban $(40–80km/h)$, highway $(>80km/h)$ conditions. The regulation of the magnitude of the acceleration in reference [2] is used to determine the minimum and maximum acceleration times for different acceleration conditions, and on the basis of actual driving condition and NEDC, FTP75, JAP1015 standard conditions, and the acceleration time and the number of accelerations of the three operating conditions are set as shown in table 3.

Table 3 The setting of different acceleration conditions

| Velocity change (km/h) | Acceleration range (m/s²) | Acceleration time range (s) | Acceleration time setting(s) | The number of acceleration |
|------------------------|----------------------------|-----------------------------|------------------------------|---------------------------|
| 0–40                   | [0.1 3.0]                  | [3.7 111]                   | 10–30                        | ≤ 6                       |
| 0–80                   | [0.1 3.0]                  | [7.4 222]                   | 10–60                        | ≤ 6                       |
| 0–120                  | [0.1 3.0]                  | [11.1 333]                  | 10–90                        | ≤ 6                       |

3.1 Analysis of electric vehicle energy consumption and battery life with a single acceleration value

When the electric vehicle accelerates with a single acceleration under different acceleration conditions, the variation trend of $E_{n-j_i}$ and $q_{loss}$ is shown in figure 2 and figure 3.
Figure 2. The electric vehicle energy consumption per kilometer (ECPM) change under different working conditions with a single acceleration. (a) velocity change: 0-40km/h; (b) velocity change: 0-80km/h; (c) velocity change: 0-120 km/h.

Figure 3. The percentage of battery capacity loss per kilometer (PBCLPM) change under different working conditions with a single acceleration. (a) velocity change: 0-40km/h; (b) velocity change: 0-80km/h; (c) velocity change: 0-120 km/h.

From figure 2, it is found that, when the electric vehicle accelerates with a single acceleration value, for the 0-40km/h velocity change, the $E_{b-j}^{-1}$ increases linearly as the increase of acceleration; for the 0-80km/h and 0-120km/h velocity change, the $E_{b-j}^{-1}$ increases as the increase of acceleration and acceleration time, and the higher the velocity, the greater the $E_{b-j}^{-1}$. And it can be seen from figure 3, when the electric vehicle accelerates with a single acceleration under different acceleration conditions, the $q_{loss1}$ decreases as the increase of acceleration and acceleration time. Moreover, it can be found that, the higher the velocity, the smaller the $q_{loss1}$. This is exactly opposite to the variation trend of $E_{b-j}^{-1}$.

3.2 Analysis of electric vehicle energy consumption and battery life with two acceleration values

When electric vehicle accelerates with two accelerations (as shown in figure 1), assuming that acceleration and acceleration time of first segment are respectively $a_1, t_1$, the second segment are respectively $a_2, t_2$, and $a_1 > a_2$, and final vehicle velocity and total acceleration time are respectively $u_f, t_f$. For a given vehicle velocity, $u_f, t_f$ are certain, acceleration time of second segment can be expressed as $t_2 = t_f - t_1$, and the acceleration of second segment can be expressed as $a_2 = (u_f - 3.6 \cdot a_1 \cdot t_1) / (t_f - t_1)$. That is, the acceleration and acceleration time of second segment can be obtained by first segment. Therefore, when the electric vehicle accelerates with two acceleration values, the variation of $E_{b-j2}$ and $q_{loss2}$ with $a_1$ and $t_1$ can be analyzed.

Based on the above analysis, the variation of $E_{b-j2}$ and $q_{loss2}$ with $a_1$ and $t_1$ is shown in figure 4 and figure 5.
Figure 4. The electric vehicle ECPM change under different working conditions with two accelerations. (a) velocity change: 0-40km/h; (b) velocity change: 0-80km/h; (c) velocity change: 0-120 km/h.

Figure 5. The PBCLPM change under different working conditions with two accelerations. (a) velocity change: 0-40km/h; (b) velocity change: 0-80km/h; (c) velocity change: 0-120 km/h.

In figure 4, it can be seen that when electric vehicle accelerates with two acceleration values, the variation of \( E_{n-j2} \) is different from that of a single acceleration. For the 0-40km/h velocity change, the \( E_{n-j2} \) gradually decreases as the increase of the \( a_1 \) and the \( t_1 \). However, for the 0-80km/h and 0-120km/h velocity change, the \( E_{n-j2} \) decreases first and then increases as the increase of the \( a_1 \) and the \( t_1 \), and the higher the vehicle velocity, the more obvious this variation trend. This shows that there is an optimal point where the \( E_{n-j2} \) is minimized when the electric vehicle accelerates with two acceleration values. And in figure 5, it can be seen that when electric vehicle accelerates with two acceleration values, the variation of \( q_{loss2} \) is different from that of a single acceleration. When the electric vehicle accelerates with two acceleration values under different acceleration conditions, the \( q_{loss2} \) as the increase of the \( t_1 \), and the \( q_{loss2} \) increases first and then decreases as the increase of the \( a_1 \), and the lower the velocity, the more obvious this variation trend. In addition, it is found that the longer the \( t_1 \), the smaller the \( a_1 \), and the smaller the \( q_{loss2} \), which is also different from the variation trend of \( E_{n-j2} \).

3.3 Analysis of electric vehicle energy consumption and battery life with three acceleration values

When electric vehicle accelerates with three acceleration values (as shown in figure 1), Similar to the analysis of two accelerations, assuming that the acceleration and acceleration time of the first segment are known, that is \( a_1, t_1 \), the acceleration time of the third segment can be expressed as \( t_3 = t_f - t_1 - t_2 \), the acceleration of the third segment can be expressed as \( a_1 = \left( u_f - 3.6 \cdot a_1 \cdot t_1 - 3.6 \cdot a_2 \cdot t_2 \right) / \left( t_f - t_1 - t_2 \right) \).
Therefore, when the electric vehicle accelerates with three acceleration values, the variation of $E_{p,j3}$ and $q_{loss3}$ with $a_2$ and $t_2$ can be analyzed.

When electric vehicle accelerates with three accelerations, the first acceleration time is increased when the first acceleration is constant, and the variation of $E_{p,j3}$ is shown in figure 6-8.

![Figure 6](image1)

(a) $a_1 = 0.8m/s^2$; $t_1 = 3s$; (b) $a_1 = 0.8m/s^2$; $t_1 = 5s$; (c) $a_1 = 0.8m/s^2$; $t_1 = 7s$.

![Figure 7](image2)

(a) $a_1 = 0.8m/s^2$; $t_1 = 6s$; (b) $a_1 = 0.8m/s^2$; $t_1 = 10s$; (c) $a_1 = 0.8m/s^2$; $t_1 = 14s$.

![Figure 8](image3)

(a) $a_1 = 0.8m/s^2$; $t_1 = 9s$; (b) $a_1 = 0.8m/s^2$; $t_1 = 15s$; (c) $a_1 = 0.8m/s^2$; $t_1 = 21s$.

From figure 6-8, it can be seen that when the electric vehicle accelerates with three acceleration values, the variation trend of $E_{p,j3}$ is similar to that of using two accelerations. For the 0-40km/h velocity change, the $E_{p,j3}$ gradually decreases as the increase of the $a_2$ and the $t_2$. However, for the 0-
80km/h and 0-120km/h velocity change, the $E_{w,3}$ decreases first and then increases as the increase of the $a_z$ and the $t_z$. This shows that when the electric vehicle accelerates with three acceleration values and the first working condition is certain, there is an optimal point (the best second working condition) where the $E_{w,3}$ is minimized.

The variation of the $q_{loss3}$ with the $a_z$ and the $t_z$ is shown in figure 9-11.

![Figure 9](image.png)

Figure 9. The PBCLPM change under neighborhood condition (0-40km/h) with three acceleration values. (a) $a_i = 0.8m/s^2; t_i = 3s$; (b) $a_i = 0.8m/s^2; t_i = 5s$; (c) $a_i = 0.8m/s^2; t_i = 7s$.

![Figure 10](image.png)

Figure 10. The PBCLPM change under urban condition (0-80km/h) with three acceleration values. (a) $a_i = 0.8m/s^2; t_i = 6s$; (b) $a_i = 0.8m/s^2; t_i = 10s$; (c) $a_i = 0.8m/s^2; t_i = 14s$.

![Figure 11](image.png)

Figure 11. The PBCLPM change under highway condition (0-120km/h) with three acceleration values. (a) $a_i = 0.8m/s^2; t_i = 9s$; (b) $a_i = 0.8m/s^2; t_i = 15s$; (c) $a_i = 0.8m/s^2; t_i = 21s$.

In figure 9-11, it can be seen that when electric vehicle accelerates with three acceleration values, the variation trend of $q_{loss3}$ is also similar to that of using two accelerations. Under different working conditions, the $q_{loss3}$ gradually decreases with the increase of the $t_z$, and the $q_{loss3}$ increases first and then decreases with the increase of the $a_z$. 
Based on the above analysis, it can be found that, when the electric vehicle accelerates with two or more acceleration values, the bigger the \( a_i \) and the longer the \( t_i \), the smaller the \( E_{n,i} \) \( (i = 2,3,4,...) \), besides, it can be found that the variation trend of the \( E_n \) with \( a \) and \( t \) is basically contrary to \( q_{loss} \).

4. Conclusion
In this paper, the relationship among electric vehicle energy consumption and battery life and acceleration and acceleration time is theoretically analyzed. And when electric vehicle accelerates with a single, two and three acceleration values under neighborhood, urban and highway working conditions, the variation trend of electric vehicle ECPM and PBCLPM with acceleration and acceleration time is studied. The results show that, when the electric vehicle accelerates with a single acceleration under different working conditions, electric vehicle ECPM increases as acceleration and acceleration time increase; however, the PBCLPM decreases as acceleration and acceleration time increase. When electric vehicle accelerates with two or more acceleration values, for the neighborhood condition (0-40km/h), the electric vehicle ECPM gradually decreases as acceleration and acceleration time increase, for urban and highway conditions (0-80km/h and 0-120km/h), electric vehicle ECPM decreases first and then increases as acceleration and acceleration time increase, and the higher the vehicle velocity, the more obvious this variation trend is; however, under different working conditions, PBCLPM decreases as the acceleration time increases, but increases first and then decreases as the acceleration increases, and the lower the velocity, the more obvious this variation trend is. It can be found that the variation trend of electric vehicle ECPM with acceleration and acceleration time is basically contrary to PBCLPM. The two are contradictory, therefore, the electric vehicle energy consumption should not only be considered in optimizing the acceleration curve, but also the effect of acceleration curve on battery life.

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