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Research Article

Effects of Exchanging Battery on the Electric Vehicle's Electricity Consumption in a Single-Lane Traffic System

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We propose a car-following model to explore the influences of exchanging battery on each vehicle's electricity consumption under three traffic situations from the numerical perspective. The numerical results show that exchanging battery will destroy the stability of traffic flow, but the effects are related to each vehicle's initial headway, the time that each electric vehicle exchanges the battery, the proportion of the electric vehicles that should exchange the battery, the number of charging stations, and the distance between two adjacent charging stations.

1. Introduction

Recently, traffic energy consumption and pollution have turned very serious and attracted researchers to develop various models to explore the vehicle's fuel consumption and emissions [1–9]. Although the models can describe some mechanisms of the vehicle's fuel consumption and exhaust emissions, the traffic pollution cannot completely be eliminated since the traditional vehicles need to consume oil and will produce exhaust emissions. To reduce the vehicle's exhaust emissions, engineers designed the electric vehicles without exhaust emissions [10–15]. With the development of the electric vehicles, researchers proposed some models to study the electric vehicle's electricity consumption under some specific conditions [16–18], but they do not study the influences of exchanging battery at the charging station on the electric vehicle's electricity consumption. In this paper, we use the car-following model [17] to explore the influences of exchanging battery at the charging station on the electric vehicle's consumption.

2. Numerical Tests

In this section, we study the influences of exchanging battery at the charging station on each electric vehicle's electricity consumption. Before studying the effects, we should give the following assumptions.

(1) There are M on-line charging stations, where their positions are, respectively, $x_{10}, x_{20}, \ldots, x_{M0}$ (see Figure 1).

(2) All N vehicles are electric vehicles, where N is the number of vehicles; the proportion that the vehicle should exchange its battery at the charging station is r.

(3) All the drivers are homogeneous.

(4) The road is a ring and its length is L.

(5) When an electric vehicle should charge electricity at the charging station, the driver will choose to exchange the battery, since the charging time is relatively long.

(6) At each charging station, only a vehicle can exchange the battery every time and there are enough batteries.

(7) Each vehicle's initial headway is Δx_0.

(8) The time that each driver exchanges the battery is T_0.

Based on the aforementioned assumptions, the nth electric vehicle's driving behavior can be decomposed as in the following five parts.

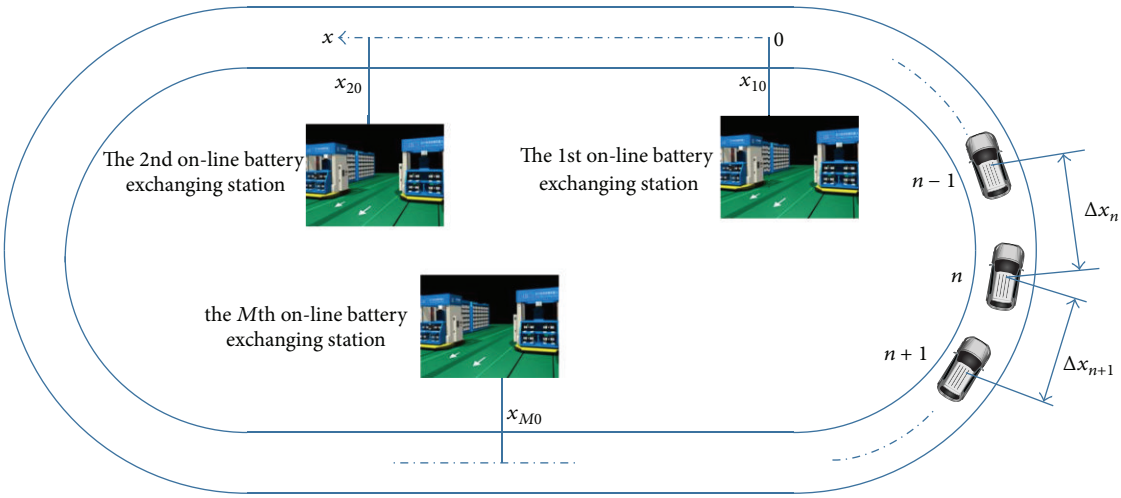

Figure 1: The car-following model for electric vehicle on a road with on-line charging stations.

(a) Before the $(n-1)$th vehicle arrives at a charging station or after the nth vehicle leaves the charging station, the nth vehicle's acceleration can be formulated as follows:

$$\frac{dv_n}{dt} = \alpha\left(V\left(\Delta x_n\right) - v_n\right) + \lambda \Delta v_n, \tag{1a}$$

where α, λ are reaction coefficients and $v_n, V\left(\Delta x_n\right), \Delta x_n$, and Δv_n are, respectively, the nth vehicle's speed, optimal speed, headway, and relative speed.

(b) When the $(n-1)$th vehicle is running forward to one charging station, the nth vehicle's acceleration can be formulated as follows:

$$\frac{dv_n}{dt} = \alpha\left(V\left(\Delta x_n\right) - v_n\right) + \lambda\left(1 - p_{n-1}\right)\Delta v_n + \mu p_{n-1}\left(-v_n\right), \tag{1b}$$

where μ is a reaction coefficient and p_{n-1} is the probability that the $(n-1)$th electric vehicle stops to exchange battery at the charging station.

(c) When the $(n-1)$th vehicle leaves a charging station and if the nth vehicle should exchange its battery at the charging station, the nth vehicle will adjust its acceleration; that is, before the nth vehicle gets to the charging station, its acceleration can be reduced formulated as follows:

$$\frac{dv_n}{dt} = \alpha\left(V\left(\Delta \overline{x}_n\right) - v_n\right) + \mu\left(-v_n\right), \tag{1c}$$

where $\Delta \overline{x}_n = x_0 - x_n$ is the spatial distance between the nth vehicle and the charging station (here x_0 is the charging station's position and x_n is the nth vehicle's position).

(d) During the whole process where the driver exchanges the battery at a charging station, the nth vehicle's motion equation can be formulated as follows:

$$v_n = 0, \qquad \frac{dv_n}{dt} = 0. \tag{1d}$$

(e) After the nth vehicle's driver exchanges the battery, this vehicle will immediately restart and its acceleration can be described by (1a).

In real traffic system, p_{n-1} is related to two factors, where one is the time that the $(n-1)$th driver gets to a charging station (at this charging state, the $(n-1)$th driver should exchange the battery) and the other is the time of exchanging battery. Thus, we can define p_{n-1} as follows:

$$p_{n-1}(t) = \begin{cases} 1, & \text{if } t_0 < t \le t_0 + T_0 \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

where t_0 is the time that the $(n-1)$th driver reaches the charging station.

Although there may be quantitative differences between the electric vehicle's optimal speed and the traditional vehicle's optimal speed, there are no qualitative differences between the two optimal speeds. Therefore, we can for simplicity define the optimal speed in (1a), (1b), (1c), and (1d) as follows [19]:

$$V\left(\Delta x_n\right) = V_1 + V_2 \tanh\left(C_1\left(\Delta x_n - l_c\right) - C_2\right), \tag{3}$$

where $V_1 = 6.75\,\text{m/s}, V_2 = 7.91\,\text{m/s}, C_1 = 0.13\,\text{m}^{-1}$, and $C_2 = 1.57$ are four parameters and $l_c = 5\,\text{m}$ is the vehicle's length.

It is difficult to use (1a), (1b), (1c), and (1d) to study the effects of exchanging battery on each vehicle's electricity consumption from the analytical perspective, so we should here apply numerical scheme to discretize (1a), (1b), (1c), and (1d). There are many numerical schemes to discretize (1a), (1b), (1c), and (1d), but the numerical schemes have no qualitative effects on the following numerical results; in addition, the main aim of this paper is to study the qualitative effects of exchanging battery on each electric vehicle's electricity consumption in a single-lane traffic system. Therefore, we can here use the Euler difference scheme in the following numerical tests; that is,

$$\begin{aligned} v_n(t + \Delta t) &= v_n(t) + \frac{dv_n(t)}{dt}\Delta t, \\ x_n(t + \Delta t) &= x_n(t) + v_n(t)\Delta t + \frac{1}{2}\frac{dv_n(t)}{dt}(\Delta t)^2, \end{aligned} \tag{4}$$

where $\Delta t = 0.05$ s is the time-step length. Other parameters are defined as follows [20]:

$$\alpha = 0.41, \qquad \lambda = 0.2, \qquad \mu = 0.3. \tag{5}$$

Before studying the influences of exchanging battery on the electric vehicle's electricity consumption, we should introduce some models that are used to study the electric vehicle's electricity consumption. Mehrdad et al. [21] proposed a model to study the output power of the electric vehicle's battery, where the output power of the nth vehicle's battery can be written as follows:

$$P_{\text{b-out}} = \frac{v_n}{\eta_{\text{te}}\eta_m}\left(\delta m\frac{\mathrm{d}v_n}{\mathrm{d}t} + mg\left(f+i\right) + \frac{\rho C_D A}{2}v_n^2\right), \tag{6}$$

where $P_{\text{b-out}}$ is the battery's output power; δ is the coefficient related to the vehicle's mass; f is the rolling resistance coefficient; i is the grade coefficient; C_D is the aerodynamic drag coefficient; ρ is the air density; g is the gravity acceleration; m, A, η_{te} are, respectively, the vehicle's mass, frontal area, and transmission efficiency; and η_m is the motor efficiency.

Since each electric vehicle can partly recover the braking energy and restore it into the battery, we obtain the nth vehicle's regenerative braking power based on (6); that is,

$$P_{\text{b-in}} = kv_n\eta_{\text{te}}\eta_m\left(\delta m\frac{\mathrm{d}v_n}{\mathrm{d}t} + mg\left(f+i\right) + \frac{\rho C_D A}{2}v_n^2\right), \tag{7}$$

where k $(0 < k < 1)$ is the percentage of the total braking energy that can be recovered by the motor. In real traffic system, k is a function of the property of the electric vehicle's braking, the battery property, and other related factors.

In this paper, we do not use (6) and (7) to study the vehicle's electricity consumption, since they consider too many factors. Since (6) shows that the vehicle's some electricity is consumed by its resistance, we should use the parameter η_e to substitute the parameter η_m, where η_e is the battery's driving efficiency and $\eta_e < \eta_m$. The electricity consumed by other accessories (e.g., the electric power steering) is not considered and the electricity consumption may be relatively higher, so we should consider the influences of the accessories on the vehicle's electricity consumption. Thus, we should here rewrite (6) as follows:

$$P_{\text{total}} = \frac{v_n}{\eta_{\text{te}}\eta_e}\left(\delta m\frac{\mathrm{d}v_n}{\mathrm{d}t} + mg\left(f+i\right) + \frac{\rho C_D A}{2}v_n^2\right) + P_{\text{accessory}}, \tag{8}$$

and (7) can be rewritten as follows:

$$P_{\text{total}} = kv_n\eta_{\text{te}}\eta_e\left(\delta m\frac{\mathrm{d}v_n}{\mathrm{d}t} + mg\left(f+i\right) + \frac{\rho C_D A}{2}v_n^2\right) + P_{\text{accessory}}, \tag{9}$$

where P_{total} is the battery's total power.

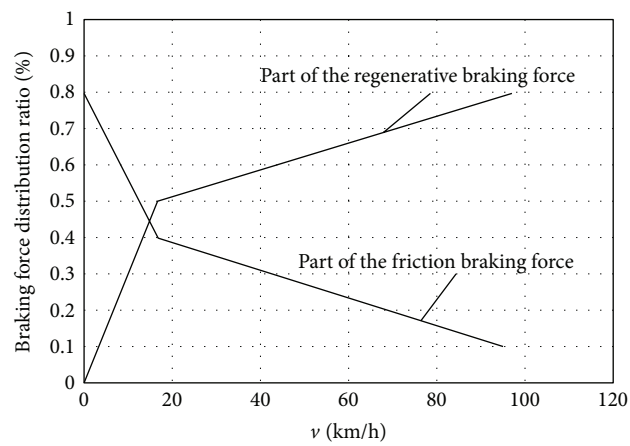

Figure 2: The distribution of the braking force in ADVISOR [22].

Table 1: The values of the vehicle's related parameters.

δ	1.1
m	1500
f	0.015
C_D	0.3
A	1.8
ρ	1.2
η_{te}	0.85
η_e	0.85
$P_{\text{accessory}}$	1000
U	300
I	100

Using the relationship between the power and energy, the vehicle's electricity consumption can be defined as follows:

$$W = P_{\text{total}} \cdot t, \tag{10}$$

where W is the electric vehicle's electricity consumption.

In real traffic system, the parameter k is very complex and is related to many factors (e.g., speed, acceleration, etc.), but it is directly related to the regenerative braking force (see Figure 2) [22]. Thus, based on Figure 2, here we define k as follows:

$$k = \begin{cases} 0.5 * \dfrac{v_n}{5} & \text{if } v_n < 5\,\text{m/s} \\ 0.5 + 0.3\dfrac{v_n - 5}{20} & \text{otherwise.} \end{cases} \tag{11}$$

And other related parameters' values are shown in Table 1.

In this paper, we use three typical situations to explore the effects of exchanging battery on the vehicle's electricity consumption (note: the main aim of this paper is to study the influences of exchanging battery on each electric vehicle's electricity in a single-lane traffic system, so we do not explore the shock wave, travelling wave, and other traffic phenomena

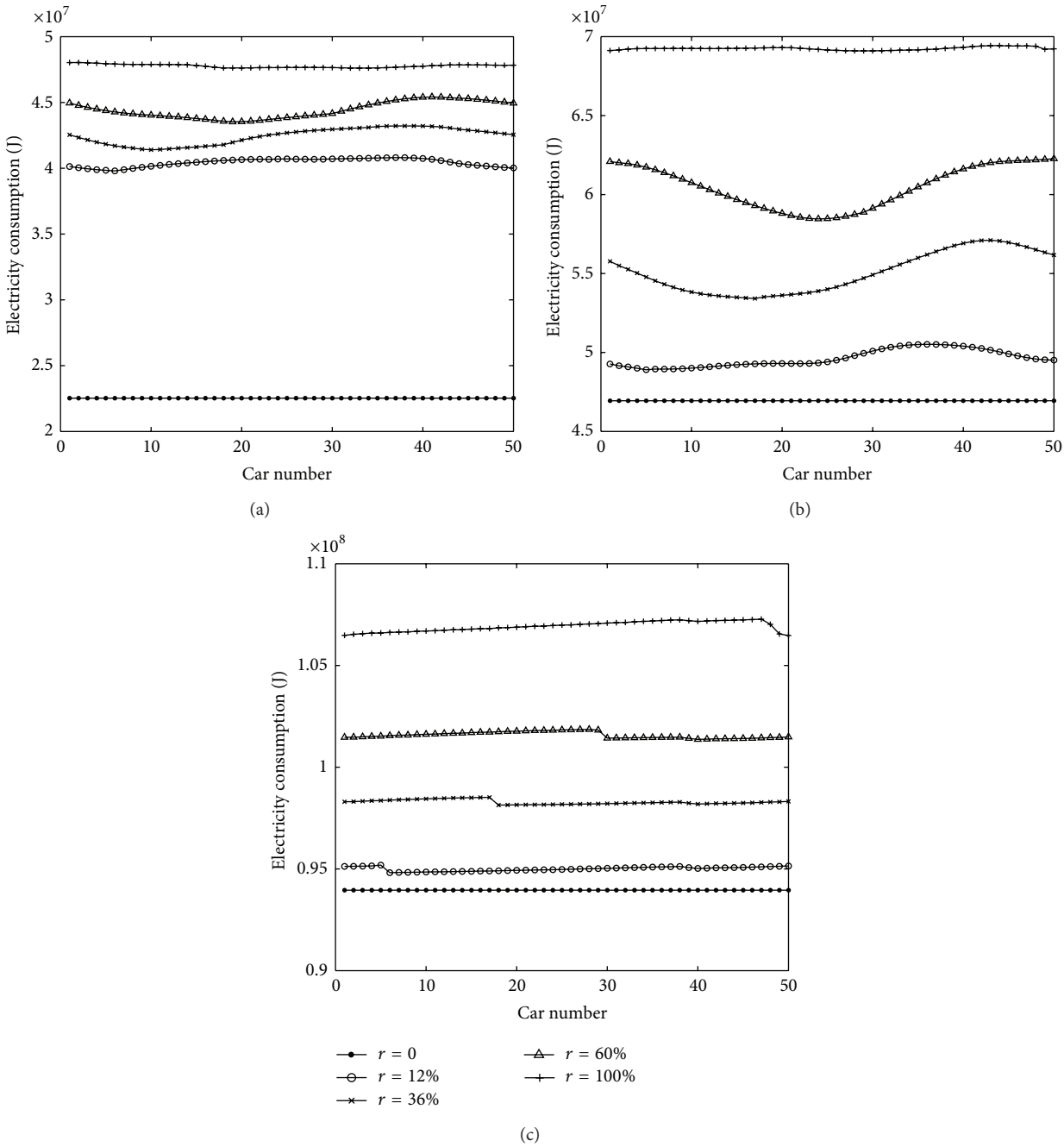

Figure 3: The total electricity consumed by each vehicle under $T_0 = 120$ s, where (a) $\Delta x_0 = 20$ m, (b) $\Delta x_0 = 40$ m, and (c) $\Delta x_0 = 80$ m.

resulted by exchanging battery in this paper); that is, consider the following.

Case I. There exists one charging station.

Case II. There exist two charging stations, where the spatial distance between the two adjacent charging stations is 300 meters.

Case III. There exist two charging stations, where the spatial distance is 500 meters.

2.1. Case I. Firstly, we study the effects of exchanging battery on each vehicle's electricity consumption under different Δx_0 (see Figure 3). From this figure, we can conclude the following results.

(1) Exchanging the battery at the charging station will enhance each vehicle's electricity consumption.

(2) Under the same Δx_0, the increments increase with r.

(3) Under the same r, the increments increase with Δx_0.

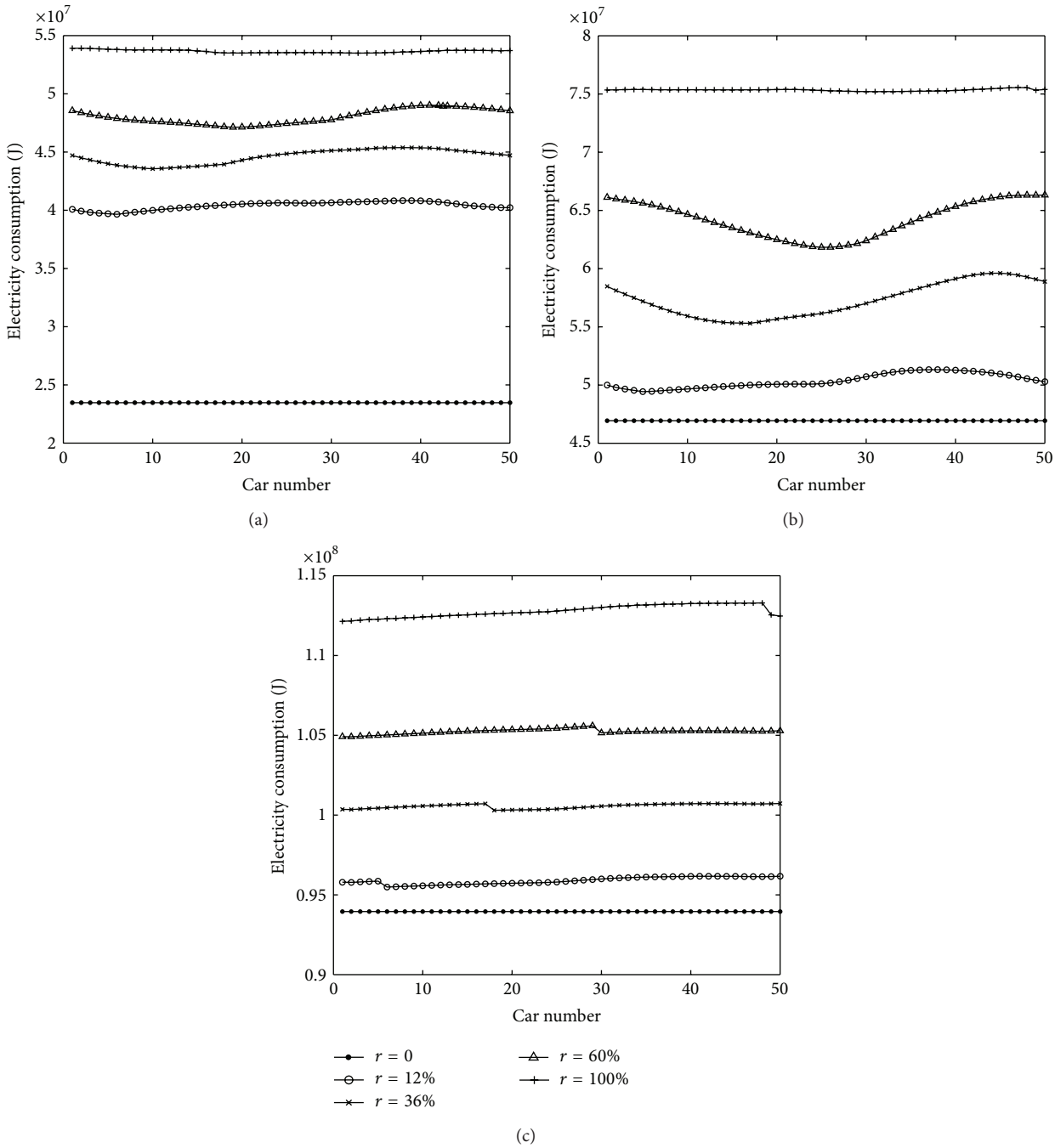

FIGURE 4: The total electricity consumed by each vehicle under $T_0 = 240$ s, where (a) $\Delta x_0 = 20$ m, (b) $\Delta x_0 = 40$ m, and (c) $\Delta x_0 = 80$ m.

Next, we study the impacts of exchanging battery on each vehicle's electricity consumption under different T_0 (see Figure 4). Combining with Figure 3, we find that under the same Δx_0, the increments increase with T_0.

Finally, we study all of the vehicles' total electricity consumption under the above two situations (see Figure 5). From this figure, we have the following.

(I) The total electricity consumption increases with r.

(II) Under the same Δx_0, the total electricity consumption increases with T_0.

(III) Under the same T_0, the total electricity consumption increases with Δx_0.

2.2. Case II. In this subsection, we explore the effects of the number of charging stations on each vehicle's electricity consumption, where other parameters are the same as those used in Case I. The numerical results are shown in Figure 6. From Figure 6, we can see the following.

(1) Figure 6 is qualitatively similar to Figure 3.

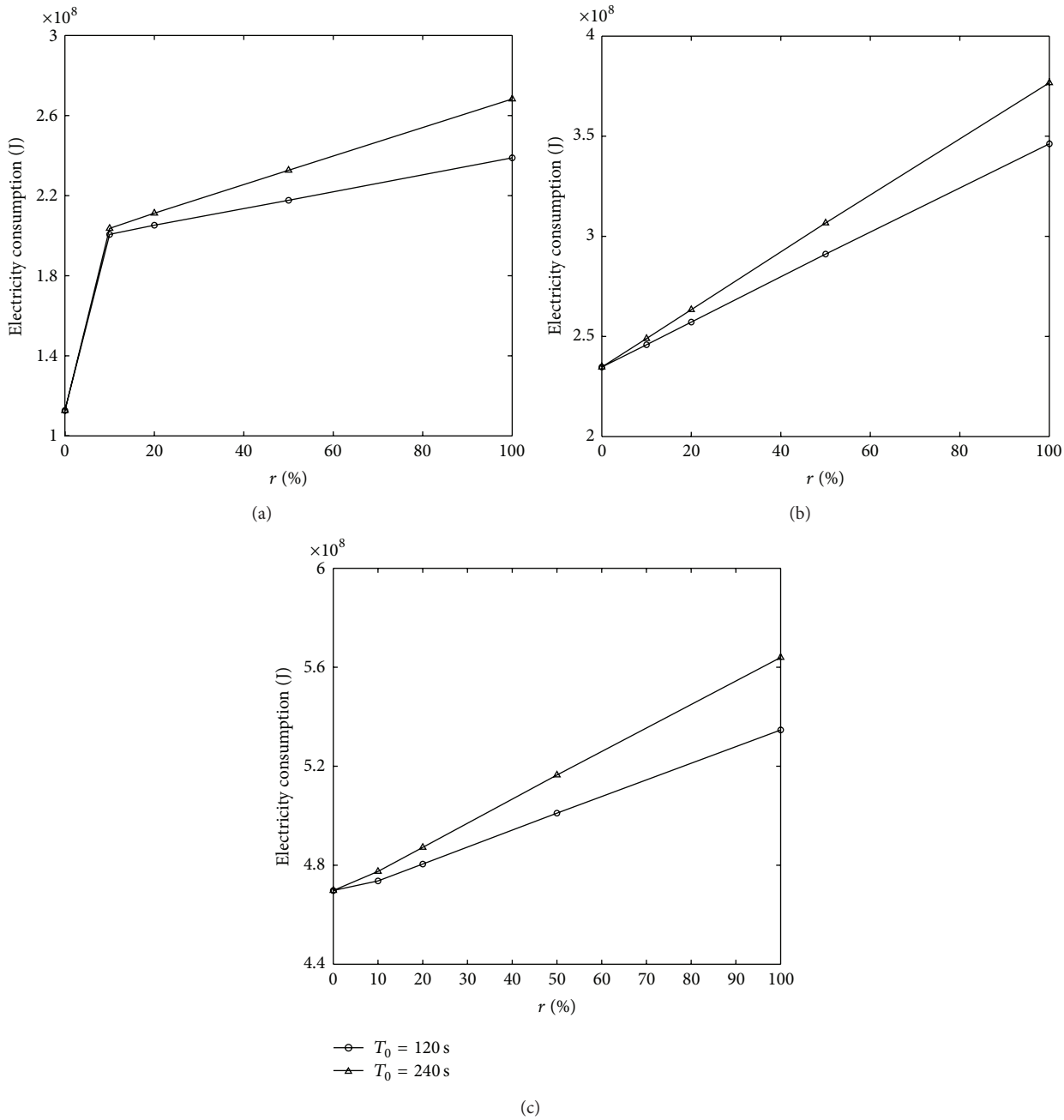

Figure 5: The total electricity consumed by all the vehicles under different conditions, where (a) $\Delta x_0 = 20$ m, (b) $\Delta x_0 = 40$ m, and (c) $\Delta x_0 = 80$ m.

(2) When the proportion of the electric vehicle that should exchange the battery is very low, the number of charging stations has little impacts on the total electricity consumed by each vehicle; when the proportion of the electric vehicle is relatively high, the number of charging stations has prominent impacts on the total electricity consumed by each vehicle; that is, the total electricity increases with r.

2.3. Case III. In this subsection, we study the impacts of the distance between the two charging stations on each vehicle's electricity consumption, where other parameters are the same as those used in Case I. The numerical results are shown in Figure 7. From this figure, we have the following.

(1) Figure 7 is qualitatively similar to Figure 6.

(2) When the proportion of the electric vehicle that should exchange the battery is very low, the distance between the two charging stations has little impacts on the total electricity consumed by each vehicle; when the proportion of the electric vehicle is relatively high, the distance between the two charging

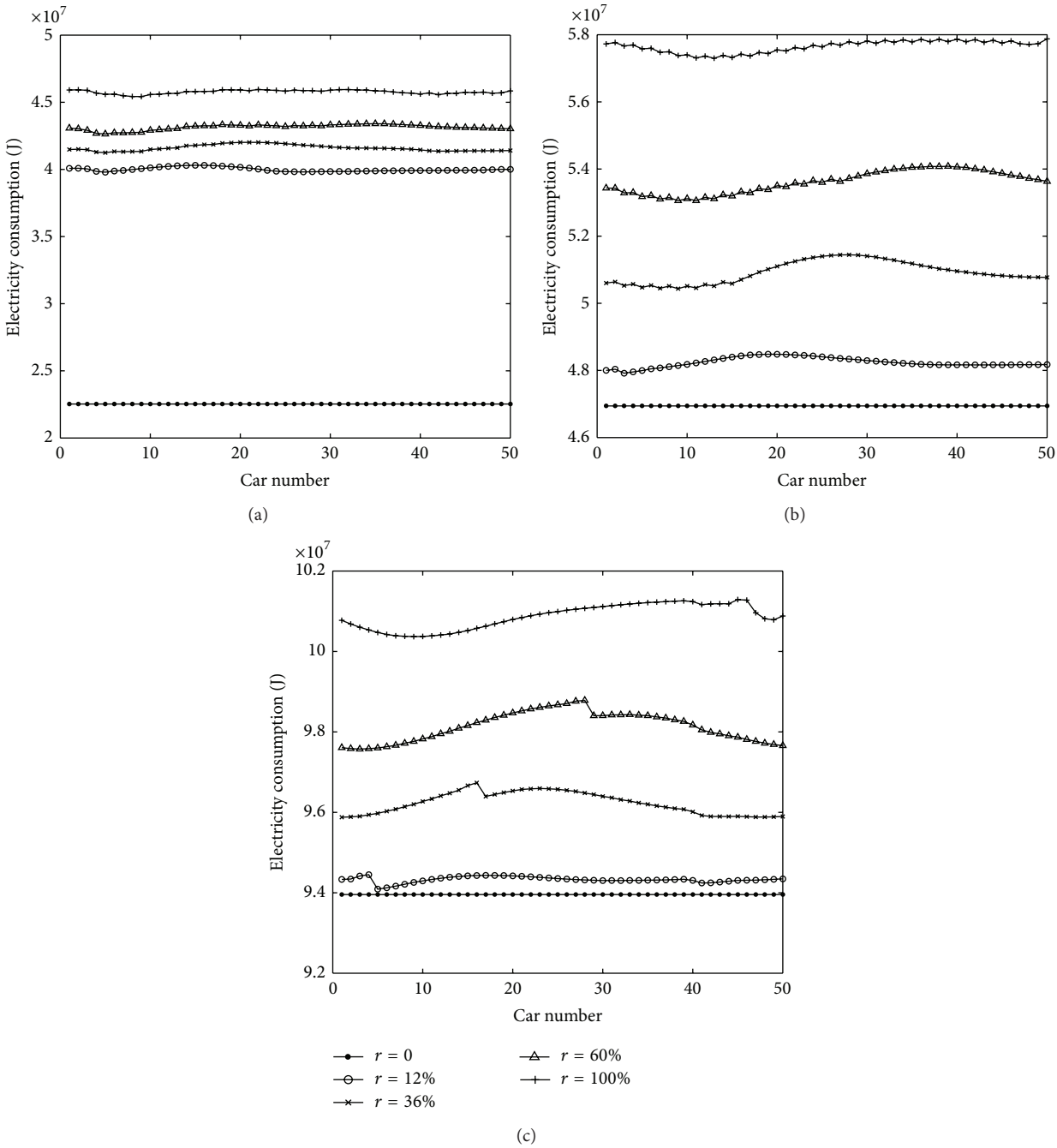

Figure 6: The total electricity consumed by each vehicle when the distance between the two charging stations is 300 m, where (a) $\Delta x_0 = 20$ m, (b) $\Delta x_0 = 40$ m, and (c) $\Delta x_0 = 80$ m.

stations has prominent impacts on the total electricity consumed by each vehicle; that is, the total electricity decreases with the increasing of the distance.

3. Conclusions

In this paper, we use the car-following model to study the effects of exchanging battery on the electric vehicle's electricity consumption from the numerical perspective. The numerical results show that each vehicle's electricity consumption is enhanced because of exchanging the battery at the on-line charging station and that the increments are relevant to many factors; that is,

(1) the increments increase with the initial headway, the number of the charging stations, the number of the vehicles that should exchange the battery, and the time that the driver exchanges the battery;

(2) the increments decrease with the distance between two charging stations.

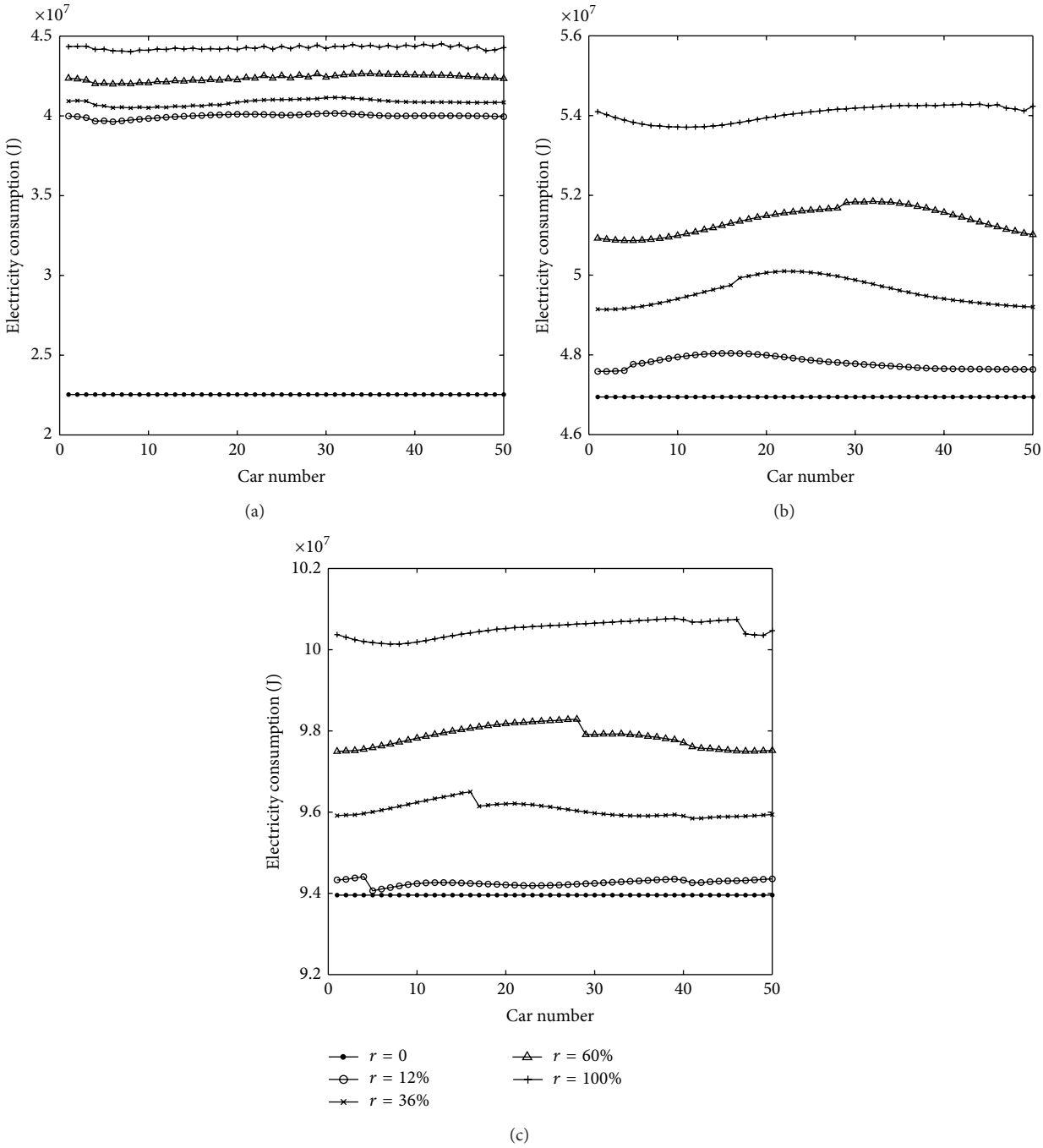

Figure 7: The total electricity consumed by each vehicle when the distance between the two charging stations is 500 m, where (a) $\Delta x_0 = 20$ m, (b) $\Delta x_0 = 40$ m, and (c) $\Delta x_0 = 80$ m.

However, this paper has the following limitations.

(a) The parameters are not calibrated by empirical data.

(b) The road is a single-lane system, which is not accordant with the reality.

(c) The mode of the charging station is on-line; that is, we do not study the impacts of exchanging battery at the off-line charging station on each vehicle's electricity consumption.

(d) We do not further study the effects of the numerical schemes on the numerical results (including the traffic phenomena, e.g., stop-and-go wave and travelling wave).

In view of the above limitations, we will use empirical data to study the effects of exchanging battery on the vehicle's electricity consumption (including the on-line charging station and off-line charging station) in the future.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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