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Electric vehicle's electricity consumption on a road with different slope

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HIGHLIGHTS

- An extended car-following model is proposed.
- An electricity consumption model is proposed.
- The electric vehicle's electricity consumption is explored on uphill.
- The electric vehicle's electricity consumption is studied on downhill.

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ABSTRACT

In this paper, we propose an extended car-following model and an electricity consumption model to study the effects of the road's slope on the electric vehicle's electricity consumption. The numerical results show that each electric vehicle's electricity consumption increases with the uphill's tilt angle and decreases with the downhill's tilt angle. In addition, each electric vehicle's electricity consumption increases with the uphill's (downhill's) length under a certain tilt angle.

1. Introduction

To date, traffic problems (congestions, accidents, energy consumption) have turned very serious, so researchers have developed many models to explore various complex traffic phenomena [1,2]. Roughly speaking, the models can be divided into three types: the first ones are to reduce traffic accident [3,4]; the second ones are to improve the traffic flow stability or to optimize the traffic flow [5–16]; the third ones are to develop a car-following model to explore the driving behavior [17–23]. Recently, traffic pollution has been serious, so researchers have proposed many models to study the vehicle's exhaust emissions [24–29], but traffic pollution always exists in the existing traffic systems since the traditional vehicles produce exhaust emissions. To reduce the traffic pollution, electric vehicles have been used to replace the traditional vehicles and been an important traffic tool [30,31], which has attracted researchers to propose many models to study electric vehicles (including the electric vehicle's electricity consumption [32,33] and the electric vehicle's battery life [34–36]).

The models [30–36] can describe the electric vehicle's traffic, but they cannot be used to explore the influences of the road's slope on the electric vehicle's electricity consumption. In fact, each road has its slope and the road's slope often influences the driving behavior. Thus, researchers proposed some models to explore the influences of the road's slope on the driving behavior [37–40] and Zhu [41] further studied the vehicle's energy consumption under the model [38], but they

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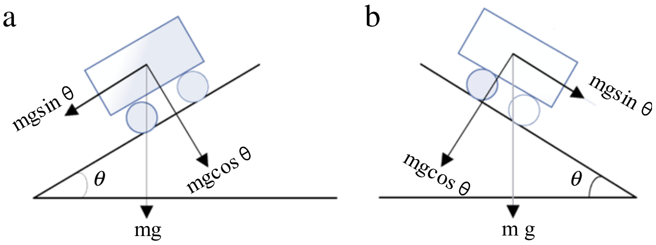

Fig. 1. Illustrations of the electric vehicle's force on uphill and downhill with (a) and (b) respectively.

do not further study the effects of the road's slope on the electric vehicle's electricity consumption. In this paper, we extend the car-following model [37] to investigate the effects of the road's slope on the electric vehicle's electricity consumption under different traffic states.

2. The relation model

In this paper, we suppose that electric vehicles move on a single lane with road slope. The gravitational force affects each vehicle in the traffic system, so the road's slope should be explicitly considered when we study the driving behavior. Fig. 1 displays the impacts of the gravitational force on the vehicle's driving behavior on the uphill/downhill road, where θ is the road tilt angle, g is the gravitational acceleration and m is the electric vehicle's mass. In fact, $mg\sin\theta$ will affect the driving behavior except its braking process, i.e., $mg\sin\theta$ does not influence the driving behavior during the braking process because this term is offset by the braking force [37]. To study the driving behavior on the road with different slopes, Zhu and Yu [37] extended the OV (optimal velocity) model [42] and proposed a new car-following model.

$$\frac{d^2x_n(t)}{dt^2} = a\left\{V(\Delta x_n) - \frac{dx_n(t)}{dt}\right\}, \tag{1}$$

where x_n is the nth vehicle's position, Δx_n is the nth vehicle's headway, a is the driver's reaction coefficient, $V(\Delta x_n)$ is the optimal velocity. In addition, $V(\Delta x_n)$ on the uphill can be defined as follows:

$$V(\Delta x_n) = \frac{\left(v_{f,\max} - v_{g,u,\max}\right)\left[\tanh\left(\Delta x_n - x_{c,u}\right) + \tanh\left(x_{c,u}\right)\right]}{2}, \tag{2}$$

and $V(\Delta x_n)$ on the downhill can be defined as follows:

$$V(\Delta x_n) = \frac{\left(v_{f,\max} + v_{g,d,\max}\right)\left[\tanh\left(\Delta x_n - x_{c,d}\right) + \tanh\left(x_{c,d}\right)\right]}{2}, \tag{3}$$

where $x_{c,u}$, $x_{c,d}$ are respectively the vehicle's safety distances on the uphill and downhill, $v_{g,u,\max}$, $v_{g,d,\max}$ are respectively the adjustment terms resulted by the uphill and downhill, $v_{f,\max}$ is the maximal speed without the road's slope.

$v_{g,u,\max} = v_{g,d,\max} = mg \cdot \sin\theta$ in the model [37], but they are unreasonable since the dimension of mg is Newton and the dimension of speed is m/s. Therefore, we should here redefine $v_{g,u,\max}$, $v_{g,d,\max}$. For simplicity, we define them as follows:

$$v_{g,u,\max} = v_{g,d,\max} = v_{\text{slope}} \cdot \sin\theta, \tag{4}$$

where v_{slope} is the adjustment term resulted by the road's slope.

Eq. (4) shows that the terms $v_{g,u,\max}$, $v_{g,d,\max}$ are proportional to the road slope, i.e., $v_{g,u,\max}$, $v_{g,d,\max}$ increase with the slope. For simplicity, we define the related parameters as follows:

$$v_{f,\max} = 10, \qquad v_{\text{slope}} = 1, \qquad v_{g,u,\max} = v_{g,d,\max} = \sin\theta. \tag{5}$$

To emphasize the impacts of the road's slope on the vehicle's driving behavior, we should study the effects of the road's slope on the vehicle's safe distance. In fact, the vehicle's safe distance decreases with the slope of uphill and increases with the slope of downhill. For simplicity, we here define the safe distance as follows [37]:

$$x_{c,u} = x_c\left(1 - \alpha\sin\theta\right), \qquad x_{c,d} = x_c\left(1 + \beta\sin\theta\right), \tag{6}$$

where x_c is the safety distance on the road without slope, in this paper we define $x_c = 20$ m. For simplicity, we set $\alpha = \beta = 1$ and define $V_0(\Delta x_n)$ as follows [37]:

$$V_0(\Delta x_n) = \tanh\left(\Delta x_n - x(\theta)\right) + \tanh\left(x(\theta)\right), \tag{7}$$

where $x(\theta)$ is defined by $x_{c,u}$ or $x_{c,d}$ that is defined in Eq. (6).