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Research Article

Impact of High-Altitude on Truck's Climbing Speed: Case study in Qinghai-Tibet Plateau Area in China

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Truck's climbing performance is an important consideration in traffic safety, efficiency, and highway geometric design. With the infrastructure development in high-altitude area in China, more attention needs to be paid on truck's climbing performance in such area. In this article, truck's climbing speed in high-altitude area was examined through field tests on different grade sections at different altitudes. Truck's speed-distance curves were built at different altitudes and the impact of altitude on truck's climbing speed was explored based on the test results. It was shown that, within the altitude range of 3000~5000m, altitude had an obvious influence on test truck's decelerating and accelerating performance. Truck's speed decreased faster on steep grades and increased slower on gentle grades with the increase of the altitude. Also, the stable speed that test truck could maintain on a certain grade was lower at a higher altitude. In addition, test truck's theoretical speed-distance curves at the sea level were estimated through truck's dynamic model. Compared with the theoretical crawl speed, a negative effect of altitude change (from 0 to the altitude above 3000 m) was found on truck's climbing performance.

1. Introduction

Trucks are an important component of highway traffic. Due to their physical and operational characteristics, they can significantly influence traffic system performance, safety, and the travel experience of other vehicles [1]. Also, truck characteristics are often a key consideration in determining the recommended values of some highway geometric design criteria [2]. For example, determination of the grade length and position of climbing lanes relies on the thorough understanding of vehicle performance. Various models were developed to study truck's speed, including statistical approach [3], regression models [4, 5], simultaneous equations approach [6], and econometric modeling approach [7].

Within the researches about truck performance, much attention was paid on truck's operating characteristics along grade sections due to its significant impact on roadway throughput, efficiency, and safety. Truck's movement alonggrade sections has long been described and different parameters were considered. Truck's speed-distance and speed-loss models were used to describe truck's movement along grade sections, and parameters including truck class, grade, speed, and road classification were considered [8]. Most of the existing researches modeled truck's speed and acceleration performance theoretically through force balance formulation based on the nominal dynamic, kinematic, and operating characteristics of trucks on grades [9–11] and truck's engine power was considered [12]. Based on these theories, software modeling approach was also applied to model truck's performance. TruckSim is the most commonly used software framework for truck motion modelling [13, 14]. Besides the dynamic based model, other assumptions about the relationship between truck speed and acceleration or other parameters were also used to estimate truck performance [15, 16]. In few researches, real measurement data were embedded to calibrate the theoretical speed-distance model [17].

Figure 1: Research area.

As most of the previous researches modeled truck's movement along grade sections through formulation-based methods or software simulation, less attention was paid on field experiments. Moreover, previous researches explored more about the influence of environmental factors such as weather-related factors or road condition on vehicle speed [18–23]. Natural regional environmental factors, such as high altitude, however, were less considered. Although some researches explored the impact of altitude on vehicle performance in recent years, they mainly focused on the effect of altitude on thermal efficiency [24], fuel consumption [25, 26], and power performance [27, 28] of vehicle engine through simulation method. The results indicated that dynamic indicators of automobiles show a downward trend with the increase of the altitude. Especially when it is over 3000 m above the sea level, vehicle's engine power deteriorated rapidly [24, 28].

China is a country with a variety of terrains and more than one quarter of the national area is above the altitude of 3000 m. With the economic and infrastructure development in recent years, the demand for highway infrastructure and freight transport in these high-altitude areas is increasing. Considering the great importance of truck performance in traffic safety and in highway geometric alignment, it is necessary to study truck's operating performance in high-altitude area. This paper reports the results of a case study on truck's performance in high-altitude area through truck's climbing test along grade sections. The possible influence of high-altitude on truck speed characteristics is explored based on the test results.

In the following sections of this paper, the research area and details about the field tests are introduced. Statistical relationship between truck speeds and altitude factor is then explored based on speed collection results. Truck's speed profile along grade sections at high-altitude area and the impact of altitude on truck's climbing performance are established based on truck's climbing test results. The results presented here lay the groundwork for future work in considering altitude factors into traffic safety management and highway geometric design in high-altitude area.

2. Experimental Method

2.1. Research Area. It is indicated from previous research that vehicle's engine power deteriorates rapidly when the altitude is over 3000 m above the sea level [28]. Therefore, high-altitude area with the altitude above 3000 m was considered as research area. In addition, considering the altitude range covered by existing highways in China, the research scope for this study is specified as high-altitude area within the altitude range of 3000~5000m. Based on these considerations, the research area selected for the field experiment was along the National Highway G214. Highway G214 is a first-class highway with the design speed of 80km/h. It was located in Qinghai-Tibet Plateau area, and the section used for experiments was from Gonghe (Station number K145+000) to Yushu (Station number K795+000) in Qinghai Province in China (as shown in Figure 1). The total length of National Highway 214 from Gonghe to Yushu is 650 km, and the altitude along the highway varies from 3000m to 5000m.

To study truck's operating characteristics in high-altitude, two types of experiment were designed for data collection. In the first experiment, trucks' spot running speed at specific sites with different altitudes was collected to examine the possible influence of altitude on the distribution characteristics of trucks' speed. In the second experiment, single truck's climbing performance in high-altitude area was explored. Details about these two experiments will be clarified in the following sections.

2.2. Truck's Climbing Tests in High-Altitude Area. The technical parameters of a vehicle have an important influence on its operating performance [2]. As truck's climbing performance is an important consideration in traffic safety and highway design [29], single truck's climbing performance tests were

Figure 2: Equipment installation and its main unit.

Table 1: Main technical parameters of test truck.

Engine model	C260 20
Rated power (kw)	191
Curb weight (kg)	11805
Rated mass (kg)	12000
Weight/power ratio (kg/kw)	120
Maximum speed (km/h)	100
Maximum torque (N∗m)	1025
Length∗width∗height (mm)	11980∗2294∗3350
Wheel base (mm)	1950+4250+1300
Tire type	Radial tire

conducted on grade sections at different altitudes to explore the possible impact of altitude on truck's dynamic characteristics. The purpose is to capture truck's deceleration driving characteristics on steep slopes (with gradient higher than 3%) and acceleration driving characteristics on gentle slopes (with gradient lower than 3%) at different altitudes. Therefore, the tests were divided into two groups. To ensure the reliability of test results, it is necessary to control the elements involved in the test process, including the test vehicle, test section, test equipment, and the driver.

2.2.1. Test Truck. Due to the large difference in dynamic performance between different truck models, truck with representative characteristics at high altitudes should be selected as the test vehicle to ensure the representativeness of the test results. As weight/power ratio is a usually key consideration in anticipating the performance of trucks [30]; the model that meets the weight/power ratio of most trucks should be considered as test truck. Considering the weight/power ratio of representative truck used in AASHTO Green Book as well as the development of truck model in the research area, Dongfeng EQ1240W (with the weight/power ratio of 120 kg/kW while being in normal full load) was selected as the test truck in the climbing performance tests. The main specific parameters of the test truck were shown in Table 1.

In practice, the real weight of the empty truck was weighed as 12520 kg. Then 10400 kg of coal was loaded to make sure that the total weight of the test truck reaches 22920 kg. With the designed engine power of 191 kW, the actual weight/power ratio of the test truck was ensured as 120 kg/kW.

2.2.2. Test Sections. To ensure that the test result is affected only by the altitude and the grade, other factors that may influence the results should be excluded. It is indicated in previous research that when the radius of the flat curve is greater than 800m, the influence of highway alignment change has a lower influence on driving safety [31]. Therefore, only straight grade sections or curved slope sections with radius of horizontal curve greater than 800m were selected as test sections to eliminate the possible influence of the horizontal alignment parameters on the truck's climbing performance. Based on these considerations, test sections for single truck's climbing performance were selected along the National Highway G214. As the maximum gradient used in this highway is 5%, upgrade sections with gradients ranging from 0 to 5% at different altitudes were selected. These test sections were classified into four groups based on the altitude range. Specific information of these selected test sections was shown in Table 2.

2.2.3. Test Equipment. The equipment used for data collection is the OES Noncontact Photoelectric Speed Sensor, which is more accurate for speed measurement than other instruments such as radar speedometer and laser speed gun. This equipment includes two parts, the speed sensor and the main unit. During the test, the speed sensor was fixed to an iron plate that was prefabricated on the bumper of the test truck in advance, as shown in Figure 2. The main unit of the equipment could display vehicle's travelling information (including driving time, distance and speed, and also the speed change curve during the driving process) in real time through LCD screen. The test data could also be stored in the sensor and transferred to data processor terminal after the test.

Table 2: Specific information of test sections.

Altitude range (m)	Entering speed (km/h)	Starting station	End station	Grade (%)	Grade length (m)	Altitude (m)	Horizontal alignment
3000-3500	40	K217+080	K218+140	0.7	1060	3250	S
		K218+140	K218+960	1.2	820	3250	S
		K207+010	K207+680	1.7	670	3250	S
		K219+920	K220+740	2.2	820	3250	S
		K221+560	K222+220	2.7	660	3300	S
	75	K201+390	K202+370	3	980	3150	S
		K199+280	K199+970	4	690	3100	C (r= 1200m)
		K184+300	K185+000	5	700	3200	S
		K212+400	K213+100	5	700	3200	C (r= 900m)
3500-4000	40	K241+730	K242+670	0.5	940	3700	S
		K244+280	K245+290	1.2	1010	3700	S
		K249+910	K250+750	2.2	840	3700	S
		K267+470	K268+210	2.8	740	3700	S
	75	K262+740	K263+810	3	1070	3700	C (r= 1000m)
		K260+880	K261+580	5	700	3750	C (r= 1000m)
		K262+030	K262+740	5	710	3700	S
4000-4500	40	K391+090	K392+070	0.4	980	4250	C (r= 6700m)
		K362+080	K363+580	1.1	1500	4250	S
		K368+510	K369+390	1.6	880	4250	S
		K394+010	K394+800	2.4	790	4250	S
		K369+190	K369+900	2.7	710	4250	S
	75	K557+300	K558+180	3	880	4400	S
		K366+200	K367+090	4	890	4250	S
		K508+730	K509+360	5	630	4250	S
		K371+530	K372+230	5	700	4250	C (r= 1500m)
4500-5000	40	K573+900	K574+760	0.7	860	4700	S
		K586+675	K587+480	1.6	805	4700	C (r= 6000m)
		K577+790	K578+670	2.2	880	4750	C (r= 4000m)
	75	K581+755	K582+665	2.3	910	4700	S
		K597+635	K598+530	4	895	4700	S
		K572+560	K571+140	5	540	4600	S

Note: in the last column, 'S' means straight line, 'C' means flat curve, and 'r' stands for the radium of the flat curve.

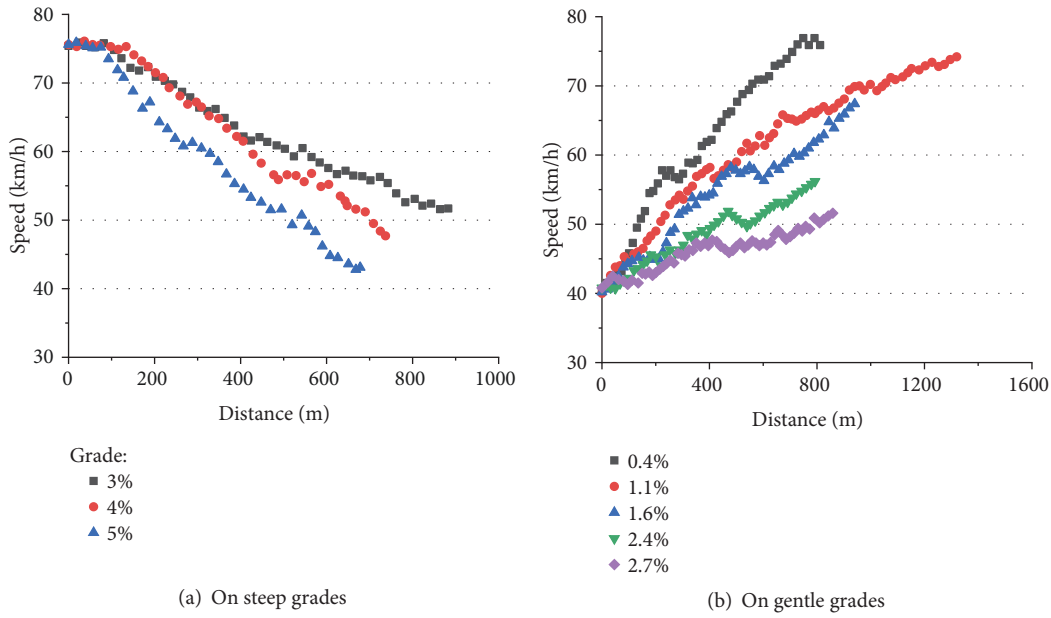
2.2.4. Driver. To exclude the possible influence of driver's individual difference on the test results, all the tests were conducted by the same driver. The driver selected for the driving tests was a 38-year-old male driver with good physical fitness. He is also very experienced in driving on Highway G214 and is familiar with the driving condition.

During the test, the driver drove the test truck into the grade section, entering the grade section with a specific initial speed. Different entering speeds were conducted in the test considering that truck's operating speed on different-class highways varies [32]. In the present work, entering speed of 75 km/h for grade sections with gradient greater than 3% and entering speed of 40 km/h for grade sections with gradient lower than 3% were considered. After driving into the test section, the driver stepped on the gas pedal to the bottom during the climbing test to ensure that the truck is travelling with its maximum climbing ability, and necessary gearshift operation should be adopted. For each test section, truck's running test with the same entering speed was conducted for three times.

During the test, truck's travel speed (km/h), travel distance (m), and travel time (s) along the grade section were recorded by the OES noncontact photoelectric speed sensor. In addition, the test was conducted under free flow condition so that truck's operation along the grade section will not be affected by other vehicles.

3. Results and Discussion

3.1. Test Truck's Speed Profile on Grade Sections Based on Field Experiment Results. After the climbing test, test truck's travelling speed and distance along grade sections were



(a) On steep grades

(b) On gentle grades

Figure 3: Trucks' speed change along grade sections at the altitude near 4250m.

exported from the sensor host. Three times' tests on each grade sections with the same entering speed were contracted with each other and sudden speed change was excluded. Scatter plot of truck's speed change along grade sections was obtained based on the recorded data.

Test results of truck's performance on steep grades with entering speed of 75 km/h and on gentle grades with entering speed of 40 km/h at the altitude of 4250m were taken as examples, as shown in Figure 3. As can be seen from Figure 3(a), after entering the steep grade section, truck's speed keeps stable for a short period (which is mainly caused by the excessive impulse of the truck when entering the grade section with a high speed) and then decreases quickly along the steep grade section with an entering speed of 75 km/h. It is also indicated that, with the increase of the gradient, truck's speed decreases in a faster speed. For instance, on grade 3%, truck's speed decreases to 59 km/h at the distance of 600m, while being on grade 4% truck's speed decreases to 56 km/h and on grade 5% truck's speed is just 48 km/h after travelling the same distance.

Test truck's speed-distance scatters along gentle grade sections at the altitude of 4250 m with an entering speed of 40 km/h were shown in Figure 3(b). It can be concluded that while being at the same altitude truck's speed increases faster with the decrease of the gradient. At the altitude of 4250m, truck's speed increases to 72 km/h at a distance of 600 m on grade 0.4%, while its speed increases to 48 km/h at the same distance on grade section of 2.7%. While in practice, for both steep grades and gentle grades, grade length of each test section is not long enough to see the final trend of truck's speed change; therefore, further steps need to be taken to explore truck's speed profile on grade sections.

Truck's speed-distance curves are usually used to describe truck's operating characteristics along grade sections. Based on previous research results about truck's speed along grade sections, truck speed on steep grade (with a high entering speed) will decrease with the increase of grade length and then become stable after a certain length [30, 33, 34]. While being on gentle grade (with a low entering speed), truck's speed will increase along the grade and reaches a stable value after a certain distance. That is to say, truck's speed along grade section is a piecewise function of grade length. In the first piece, truck's speed decreases or increases with the increase of grade length and then reaches a stable value at a certain distance. In the second piece, truck's speed would no longer change with the increase of the grade length.

In the real test, the grade length of the test sections in field experiment was not long enough (they were designed with limited grade length based on the existing design specifications) to see a complete trend of truck speed change; fitting method was used to process the speed-distance scatter data obtained from the test results. In the present work, polynomial fitting method was used to fit the scatter data and the coefficient of determination was greater than 0.97. What is more, after extending the fitted curve to longer distance, the overall trend of truck speed change was consistent with the first part of the theoretical speed-distance curve. For the data on steep grade sections, the short period of data at the beginning of the grade section where truck's speed keeps stable or slightly increases was excluded. Test truck's speed-distance curves based experimental data were shown in Figures 4 and 5.

It can be seen from Figure 4 that truck's speed deceases fast along steep grade sections, and then it becomes stable when it comes to a longer distance. What is more, there is an obvious impact of gradient on truck's stable speed and corresponding stable length on grade sections. At the altitude of 3150 m, truck's stable speed on grade 3% is about 53 km/h, and the corresponding stable length is about 1400m with the entering speed of 75 km/h. While being on grade

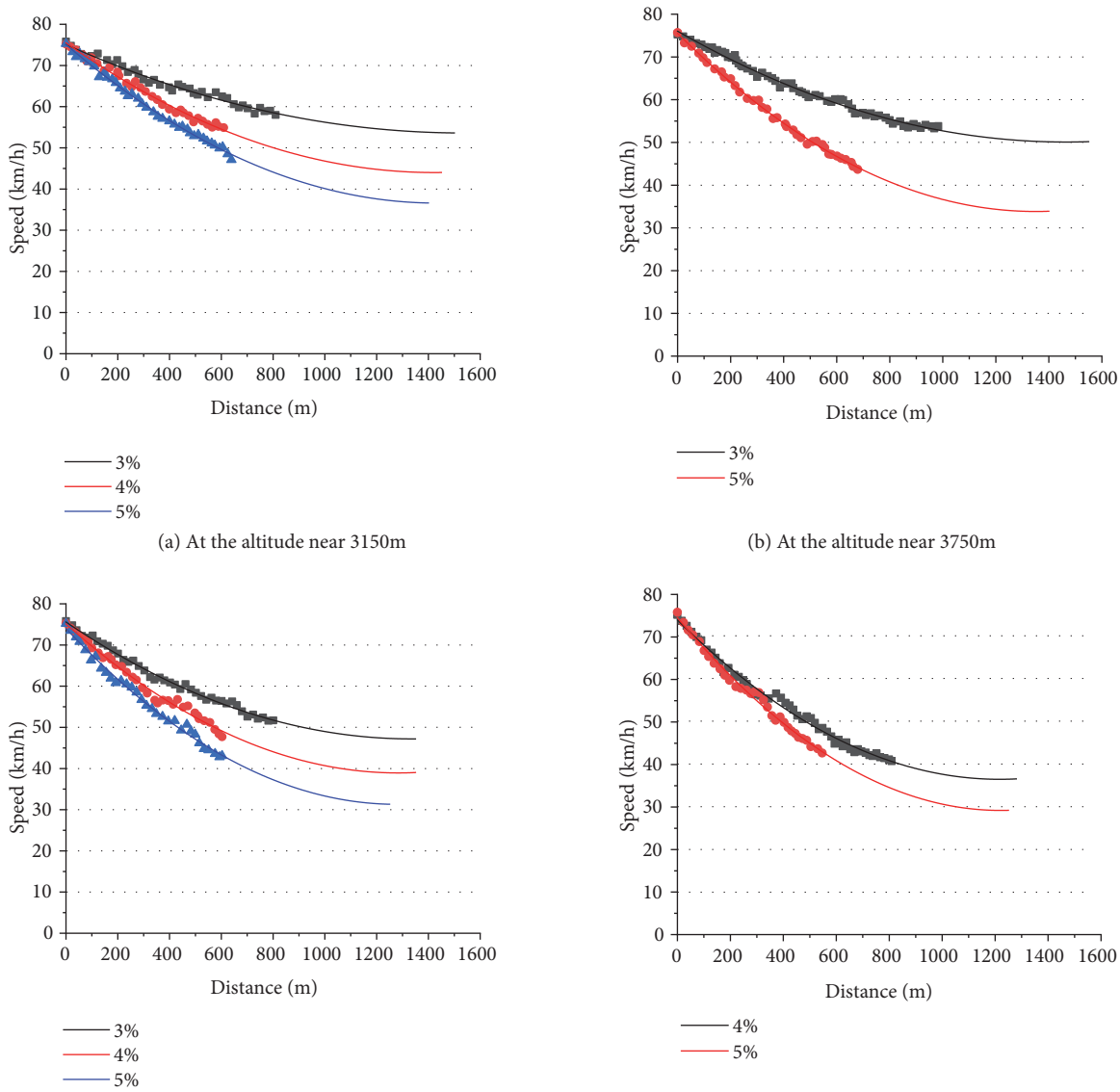


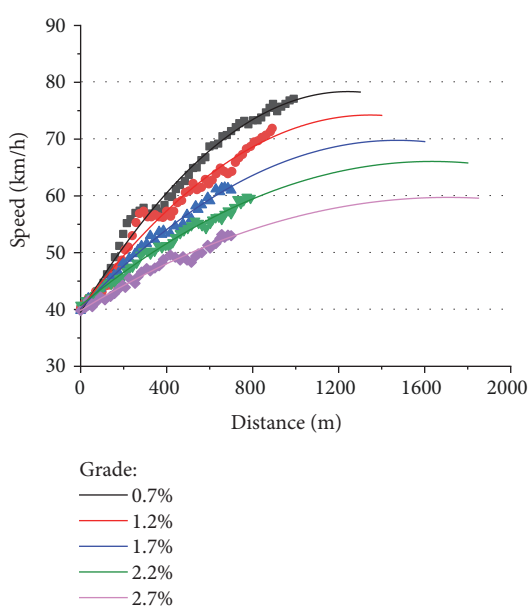
Figure 4: Truck's speed profile on steep grade sections with entering speed of 75km/h.

5%, truck's stable speed is only 37 km/h and the corresponding stable length is just 1300m. To sum up, with the increase of the gradient, truck's stable speed on grade section becomes lower and the corresponding stable length becomes shorter.

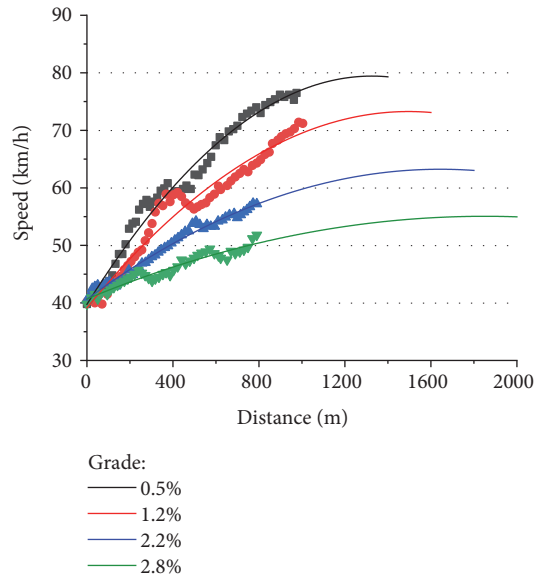
Truck's speed profile on gentle grades was shown in Figure 5. It can be seen that truck's speed increases with the increase of grade length and comes to a stable value at a certain length. It is obvious that, with the increase of the gradient, truck's speed increases slower, and the stable speed truck can maintain is lower while the corresponding stable length is longer. At the altitude near 4250m, truck's speed becomes stable at the maximum speed of 73 km/h with the stable length of 1300m on grade 1.1%. While being on grade 2.7%, truck's stable speed is just 54 km/h with the stable length of 1800m.

3.2. Impact of High-Altitude on Test Truck's Decelerating Performance. Based on the experimental results, taking test truck' speed profile on grade sections with the same gradient at different altitudes as examples, the impact of altitude on truck's deceleration performance was explored.

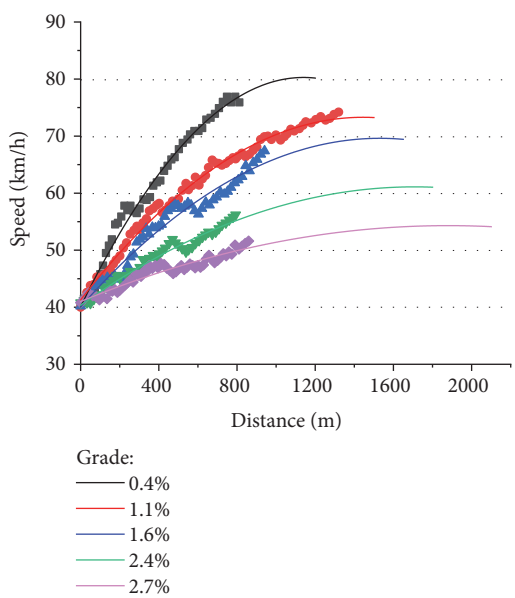
Figure 6 shows truck's speed profile on grades 3% and 5% at different altitudes. It can be concluded that altitude has a significant impact on truck's speed profile on steep grade sections. With the increase of altitude, truck's speed decreases faster, and the maximum speed it can maintain on the grade (which is called stable speed in the present work) is lower. What is more, the corresponding length when truck's speed gets stable (stable length) is longer as the altitude increases. For instance, on grade 5%, truck's stable speed at the altitude of 3250 m is 37 km/h with the corresponding stable length of 1350 m, while the stable speed at the altitude of 4600m is just



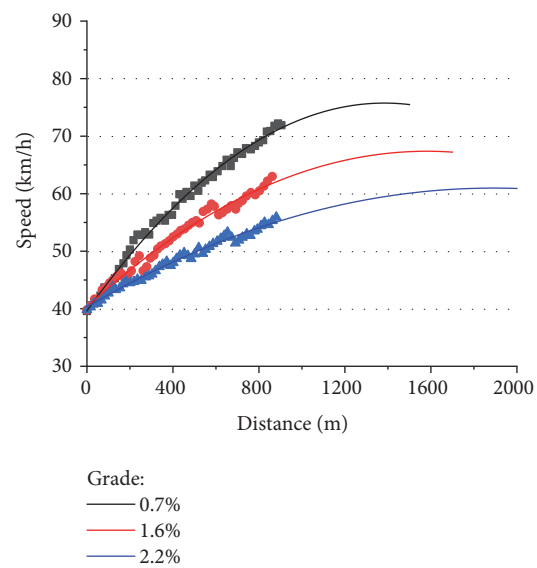
(a) At the altitude near 3250m



(b) At the altitude near 3700m



(a) At the altitude near 4250m



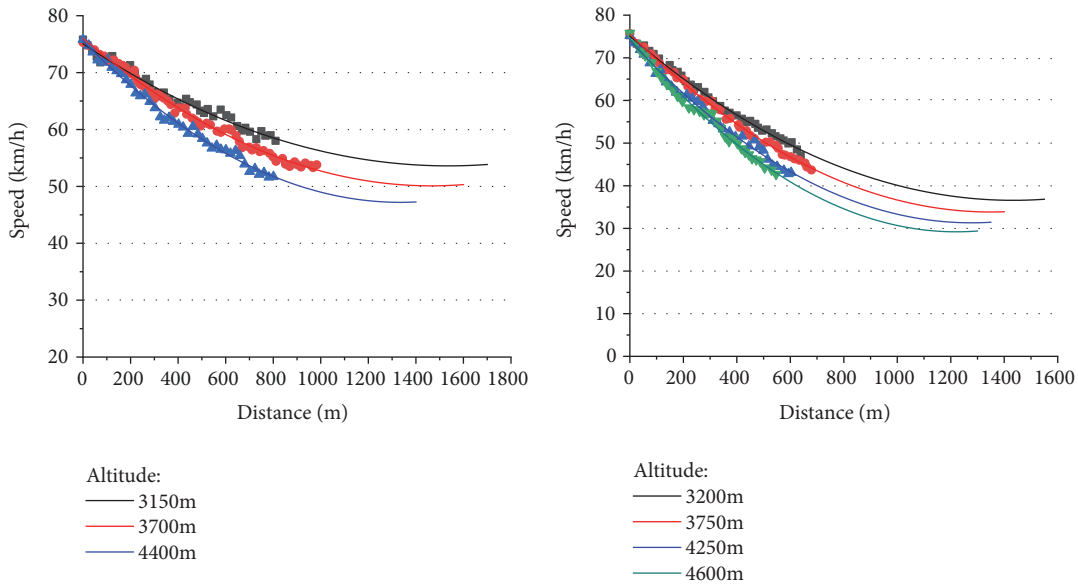
(b) At the altitude near 4700m

Figure 5: Truck's speed profile on gentle grade sections with entering speed of 40 km/h.

30 km/h with the corresponding stable length of 1150 m. It can be concluded that, within the altitude range of 3000 m to 5000 m, truck's stable speed on grade 5% decreases by about 2 km/h as the altitude increases 500 m.

To further explore the influence of high-altitude on truck's decelerating performance, detailed relationship between truck's speed loss and its corresponding travelling distance on grades was also explored. In the field test, the real length of the grade section is short; therefore the speed loss is estimated by comparing the entrance speed and the crawl speed. Test truck's traveling distance corresponding to speed loss of 5 km/h, 10 km/h, 15 km/h, and 20 km/h was listed in Figure 7.

Test truck's travel distance corresponding to a certain speed loss on different grades was shown in Figure 7. It can be seen that test truck's travelling distance corresponding to a certain speed on the same grade decreases with the increase of altitude. In Figure 7(c), truck's travels for 780 m on grade 3% when its speed loss reaches 15 km/h at the altitude of 3250 m. While being at the altitude of 4250 m, test truck's speed loss reaches the same value only after travelling for 560 m. Also, the travel distance corresponding to a certain speed loss drops heavily with the increase of gradient while taking different grades into consideration. It can be noted that, compared with the influence of high-altitude, more obvious influence of gradient is found on truck's climbing speed change. Therefore,



(a) On grade 3% (b) On grade 5%

Figure 6: Truck's speed profile at different altitudes with entering speed of 75km/h.

while considering the influence of high-altitude on truck's climbing speed, it is important that the effect of grade and grade length should also be included specifically.

Truck's speed loss is an important consideration in traffic safety and efficiency along grade sections. Also in road longitudinal geometric design, the critical length for a slope with a certain gradient is usually determined based on truck's speed loss [35]. Too much speed loss for trucks may lead to larger speed difference between trucks and other vehicles. This may lead to more frequent overtaking operation for other vehicles, resulting in negative influence on the performance the overall traffic system [36–39]. Based the results obtained here, truck's speed decreases in a faster speed at a higher altitude; this negative effect together with the effect of gradient should be taken into consideration in future traffic safety management and highway geometric design in high-altitude area.

3.3. Impact of High-Altitude on Test Truck's Accelerating Performance. A comparison about test truck's accelerating performance at different altitudes was made in Figure 8, taking its speed profiles on grade 0.7% and grade 2.2% as examples. It can be concluded that altitude change has a negative impact on truck's acceleration performance along grade sections. While being at the same entering speed, truck's speed increases faster at a lower altitude when the gradient is the same, and the stable speed it could reach is lower with a longer stable grade length. On grade 2.2%, truck's stable speed at the altitude of 3250 m is 66 km/h while it reduced to 61 km/h at the altitude of 4750m. What is more, it seems that the effect of altitude on truck's acceleration performance is more obvious when the gradient is greater. On grade 0.7%, truck's stable speed reduces by 2 km/h when the altitude increased from 3250 m to 4700 m. While being on grade 2.2%, the stable speed test truck could maintain reduces by 5 km/h from the altitude of 3250 m to 4750 m.

In addition, test truck's speed increase is estimated by comparing the entrance speed and its crawl speed. Test truck's traveling distance corresponding to speed loss of 5 km/h, 10 km/h, 15 km/h, and 20 km/h was explored, as shown in Figure 9. It is indicated that test truck's travel distance corresponding to certain speed increase value increases with the increase of altitude within 3000 m~5000 m. Also, with the increase of gradient, longer distance is needed for the test truck to reach a certain speed increase. As can be seen from Figure 9(c), on grade 2.7 %, travel distance of 1550m is needed for the test truck to reach a speed increase of 15 km/h at the altitude of 4250 m. While being at the altitude of 3250 m, only a distance of 840 m is needed. It means that, at the altitude of 4250 m, truck's speed increases very slowly on the grade of 2.7%. Moreover, it can be seen from Figure 9 that truck's travel distance corresponding to a certain speed loss increases with the increase of gradient. While considering the influence of high-altitude on truck's accelerating performance, the effect of grade should be taken into consideration.

While being in high-altitude area or mountain area, long slope sections were normally used in highway vertical alignment design to overcome the height difference and adapt to the natural terrain. In long slope sections, gentle grade sections were usually used to connect two steep grade sections to ensure that truck's speed could recover to a normal level before entering the next steep grade section [40, 41]. Therefore, truck's accelerating performance on gentle grade sections was also important for traffic safety and efficiency on long slope sections. If truck's speed increases slowly on the connecting gentle grade, longer length of the gentle grade or lower gradient should be set. Based on the results obtained in the present work, truck's speed increases slower at a higher

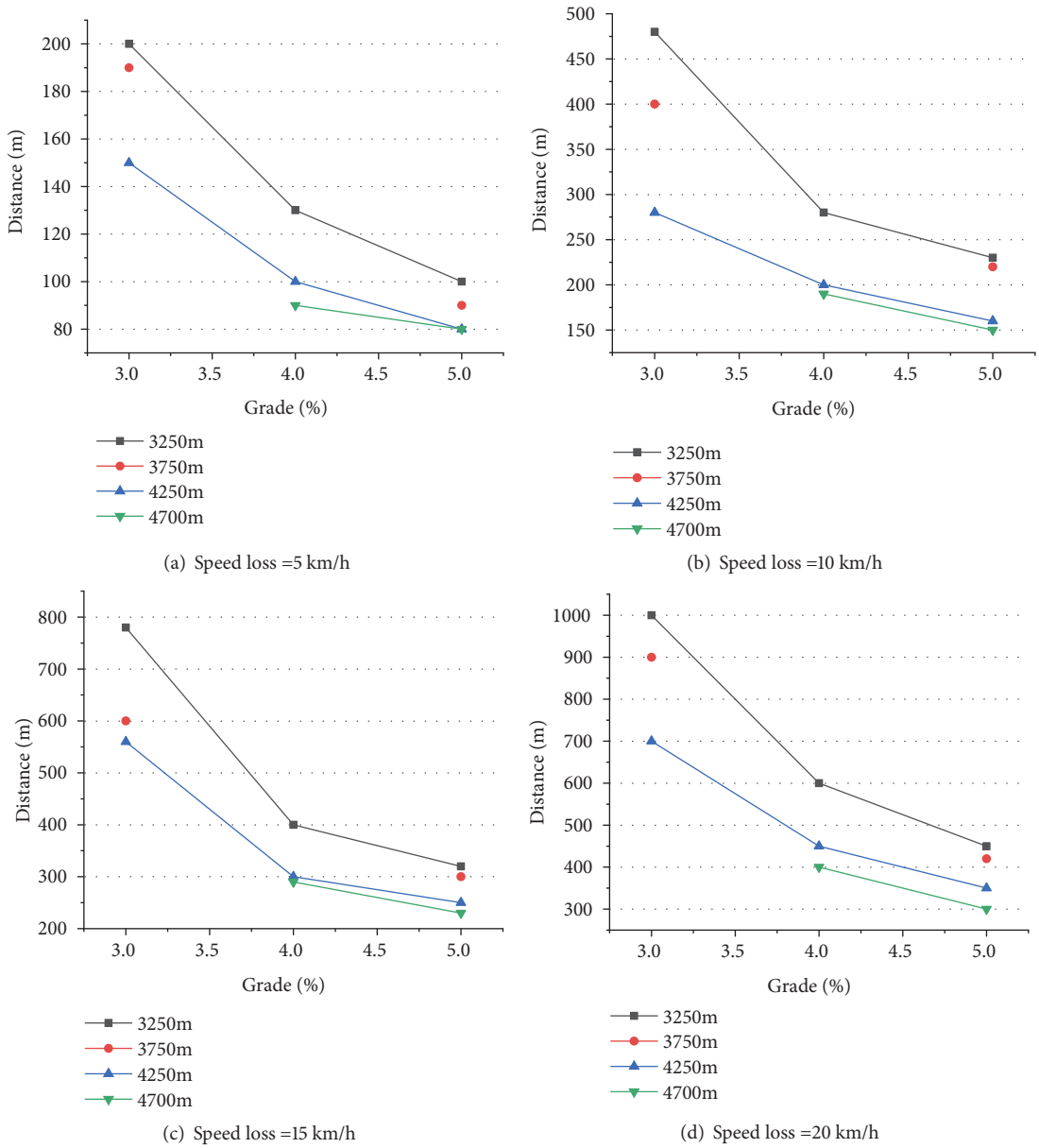


Figure 7: Test truck's speed loss and its corresponding distance at different altitudes.

altitude. The negative effect of altitude on truck's accelerating performance together with the effect of gradient should be considered in the future design of long slope sections at high-altitude area.

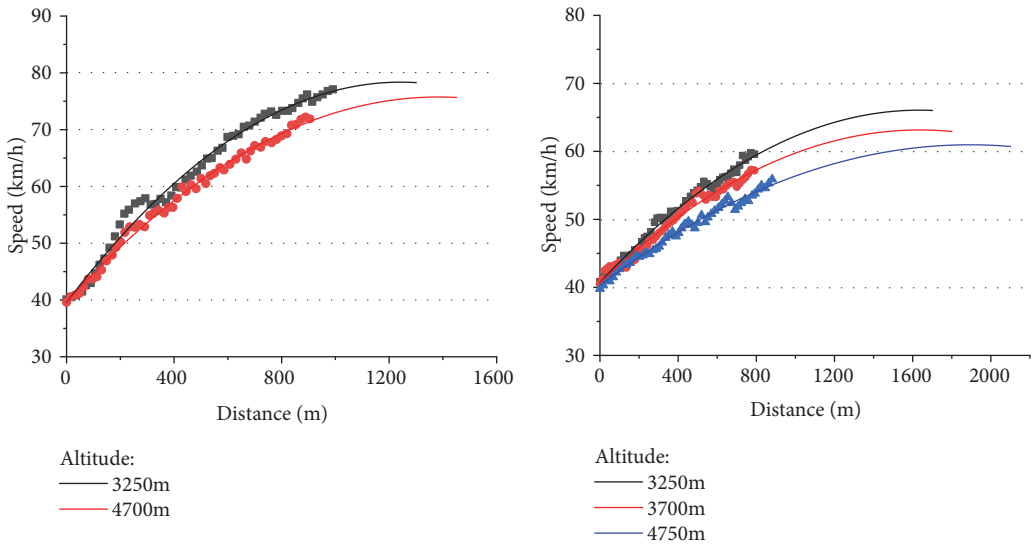
3.4. Comparison with Test Truck's Theoretical Crawl Speed. In the field experiment, the test truck was selected considering the development of truck model used in research area, where the altitude was above 3000 m. In practice, no further field test was conducted using the same test truck at low-altitude area. To further study the possible influence of altitude change (from 0 to 3000 m) on test truck's climbing performance, test truck's theoretical crawl speed is then predicted using vehicle dynamic model.

Truck's movement along grade sections depends mainly on the combined force. In vehicle dynamic model, tractive force is needed from the engine to provide enough power support for truck's running on the grade. The vehicle tractive effort is computed using

$$T = 3600\eta\frac{P}{v} \tag{1}$$

where T=tractive effort (N); P = engine power (kW); v=truck speed (km/h); η = transmission efficiency.

Three resistance forces are also considered in truck's dynamic model, namely, the aerodynamic resistance, the rolling resistance, and the grade resistance. The aerodynamic resistance is a function of the vehicle frontal area, the location



(a) On grade 0.7% (b) On grade 2.2%

FIGURE 8: Truck's speed profile at different altitudes with entering speed of 40km/h.

altitude, the truck drag coefficient, and the square of speed of the truck, as indicated in

$$R_a = c_1 C_d C_h A v^2 \tag{2}$$

where R_a= aerodynamic resistance(N); c_1 accounts for the air density at sea level at the temperature of 15°C, which equals 0.047285; C_d = truck drag coefficient; A= vehicle frontal area (m^2). $C_h = 1 - 8.5 \times 10^{-5} H$, which represents altitude coefficient, and H=altitude (m); typical values of vehicle frontal areas for different truck and bus types as well as the typical drag coefficients are provided in [10].

The rolling resistance is a linear function of the vehicle speed and mass, as indicated in (3). The grade resistance is a constant that varies as a function of the vehicle's total mass and the percent grade that the vehicle travels along, as indicated in (4). The grade resistance accounts for the proportion of the vehicle weight that resists the movement of the vehicle.

$$R_r = 9.8066 C_r \left(c_2 v + c_3\right) * \frac{M}{1000} \tag{3}$$

$$R_g = 9.8066 \mathrm{Mi} \tag{4}$$

In the above equations, R_r= rolling resistance (N); M= truck total mass (kg); C_r= rolling coefficient, and c_2, c_3 = rolling resistance coefficients. R_g= grade resistance (N); i= percent grade. Typical values for rolling coefficients (C_r, c_2, and c_3), as a function of the road surface type condition and vehicle tires, are provided in [10].

Based on Kinematics and driving conditions, the maximum vehicle acceleration levels (at the time step t_i) can be computed through the resultant force acting on a vehicle, as summarized in (5). Eq. (5) can be solved by recasting the model as a system of two first-order equations, as demonstrated in (6). Specifically, (6) can be solved by simulating the motion of the truck at small time step Δt, as shown in (7) and (8).

$$\mathrm{a}\left(t_i\right) = \frac{\mathrm{T}\left(t_i\right) - \mathrm{R}\left(t_i\right)}{M} \tag{5}$$

$$\begin{bmatrix} \dfrac{d\left(\mathrm{v}\left(t_i\right)\right)}{dt} \\ \dfrac{d\left(\mathrm{X}\left(t_i\right)\right)}{dt} \end{bmatrix} = \begin{bmatrix} \mathrm{a}\left(t_i\right) \\ \mathrm{v}\left(t_i\right) \end{bmatrix} \tag{6}$$

$$\mathrm{v}\left(t_i\right) = \mathrm{v}\left(t_{i-1}\right) + \mathrm{a}\left(t_{i-1}\right) \Delta \mathrm{t} \tag{7}$$

$$\mathrm{X}\left(t_i\right) = \mathrm{X}\left(t_{i-1}\right) + \mathrm{v}\left(t_{i-1}\right) \Delta \mathrm{t} \tag{8}$$

Based on the dynamic model, with the input of parameters aligned with the model of the test truck, the theoretical crawl speed-distance curves can be computed through MATLAB programming. The value of these variables aligned with the test truck (Dongfeng EQ1240w) was listed in Table 3. With these inputs, test truck's theoretical speed-distance curves on steep grades with entering speed of 75 km/h and on gentle grades with entering speed of 40 km/h at the sea level can be estimated, as given in Figure 10.

The difference between the theoretical curves at the sea level and the empirical results obtained at the altitude above 3000 m could indicate the impact of altitude change (from normal altitude area to area with altitude of above 3000m) on truck's operating characteristics. Based on theoretical estimation results (as shown in Figure 10), test truck could maintain a stable speed of 57 km/h on grade 3% at the sea level. While being in the real test at high-altitude area (as shown in Figure 4), test truck's stable speed on grade 3% at the altitude of 3150m is around 53 km/h, which is 4 km/h lower than that predicted at the sea level. While being on grade 5%, test truck's theoretical stable speed is 37 km/h, which is almost the same as that obtained in field test. One possible

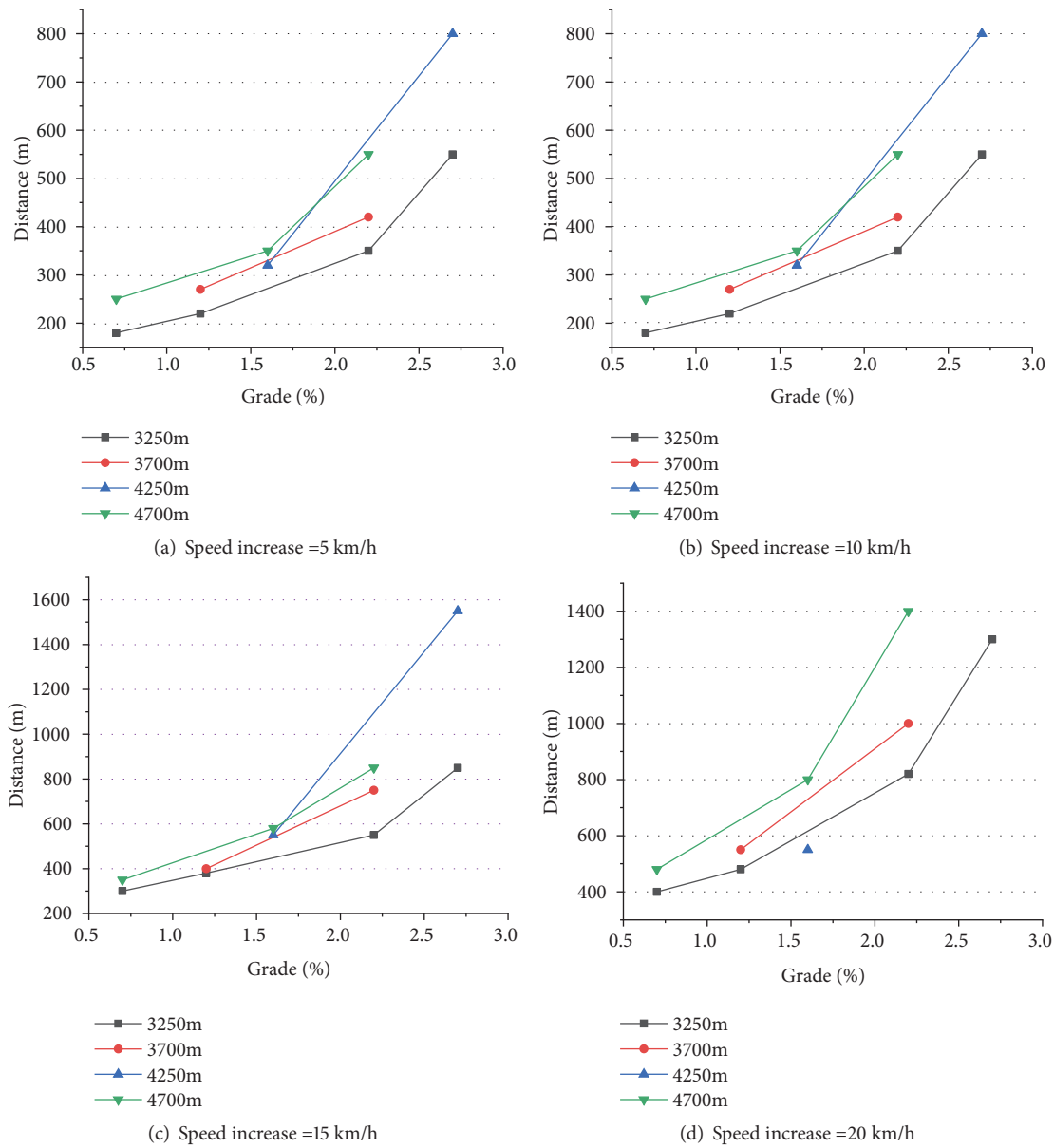


Figure 9: Test truck's speed increase and its corresponding distance at different altitudes.

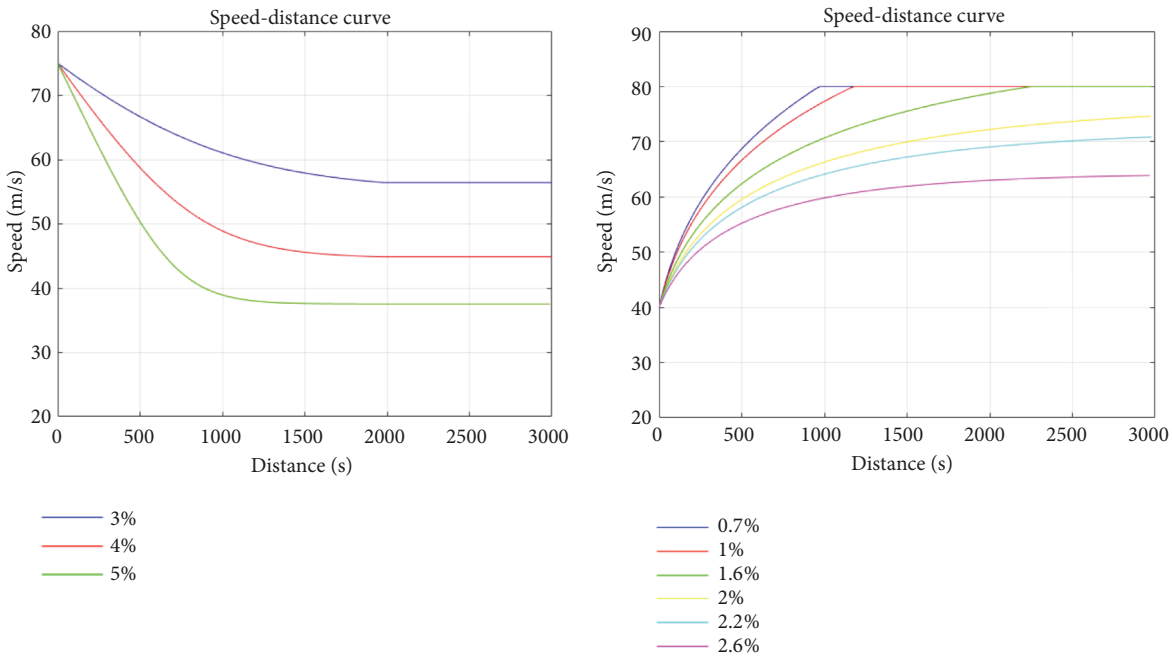
Table 3: Input values of parameters aligned with the test truck and test condition.

η	$P(kW)$	c_1	C_d	A (m^2)	C_r	c_2	c_3	M (kg)
0.8	191	0.047285	0.8	8.9	1.75	0.0328	4.575	22920

reason might be that the effect of gradient and grade length on truck's climbing performance is more obvious than the effect of altitude when a steeper grade is applied.

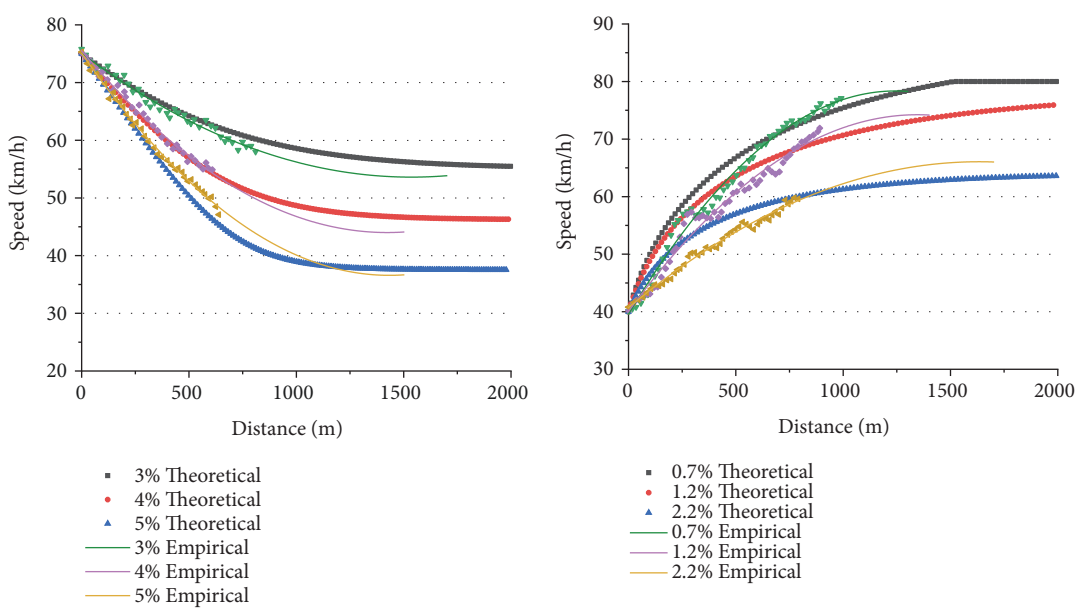
Furthermore, the theoretical curves considering the altitude were also predicted based on truck's dynamic model. With the input of H= 3250 m, truck's theoretical speed-distance curves at high-altitude can be estimated. Then test truck's theoretical speed-distance curves were compared with its empirical crawl speed at the same altitude, as shown in Figure 11.

As can be seen from Figure 11, slight difference is found between test truck's theoretical and empirical speed-distance curves on different grades. Based on Figure 11(a), test truck's speed decrease obtained in the field test within the first 500 m distance on different grade is well aligned with that predicted by the theoretical model. After that the empirical speed decreases faster and reaches a lower stable speed on grades 3% and 4% compared with the theoretical speed-distance curves. While being on grade 5%, the empirical stable speed is close to the theoretical value. From Figure 11(b), within



(a) Decelerating on steep grades (b) Accelerating on gentle grades

Figure 10: Test truck's theoretical speed-distance curves at sea level.



(a) Decelerating on steep grades (b) Accelerating on gentle grades

Figure 11: Test truck's theoretical and empirical crawl speed at the altitude 3250 m.

the first 800 m distance, test truck's speed in the field test increases slower than that predicted by the theoretical model. After that test truck's speed increases slightly faster than the theoretical speed on grades 0.7% and 1.2%. While being on grade 2.2%, test truck's speed increases to a higher stable speed than that predicted by the dynamic model. It seems that the difference between test truck's empirical climbing speed and its theoretical crawl speed at high altitude varies on different grades. While exploring the impact of high-altitude on truck's climbing performance, the effect of grade and grade length should also be considered.

4. Conclusion and Future Work

Truck's operating performance is an important parameter considered in highway design and traffic safety. Although

the American Association of State Highway and Transportation Officials (AASHTO) Geometric Design Guide provided typical truck's speed-distance curves, the influence of high altitude on truck performance is not specified. Taking the National Highway G214 from Gonghe to Yushu in Qinghai Province in China as the research area, truck's climbing performance in high-altitude area was studied through field climbing tests on grade sections within the altitude range of 3000m to 5000m.

Based on the field test results, test truck's (Dongfeng EQ1240w) speed profile along grade sections at different altitudes was established. It was shown that altitude has a negative impact on both truck's deceleration performance on steep grades and its acceleration performance on gentle grades. Within the altitude range of 3000 m to 5000 m, truck's speed along steep grades decreased faster and the stable speed it could maintain on the same grade was lower with the increase of altitude. On the same grade, truck's travel distance corresponding to a certain speed loss is lower at a higher altitude. For accelerating performance, truck's speed increased slower and the stable speed it could maintain on the same grade decreased with the increase of altitude. It should also be noted that, at high-altitude area, the effect of grade on truck's climbing speed is more obvious than the effect of altitude. While considering the influence of high-altitude on truck's climbing speed, it is important that the effect of grade and grade length should also be specified.

Moreover, test truck's speed profiles on grade sections obtained through field tests at high-altitude area were compared with its theoretical speed-distance curves estimated through truck's dynamic model. Compared with test truck's the- oretical speed at sea level, negative effect of altitude increase (from sea level to the altitude above 3000 m) on test truck's climbing performance was found. In addition, slight difference was found between test truck's empirical climbing speed obtained in the field tests and its theoretical crawl speed at the same altitude. It was noted that the influence of high-altitude on truck's climbing performance varied at different grades.

Truck performance is closely related to traffic safety and has an important influence on the performance of the traffic system. As high-altitude has a negative influence on truck's climbing performance, such negative effect on truck's climbing performance should be fully considered together with the effect of grade in future traffic safety management and highway design in high-altitude area. Future work will concentrate on the calibration of existing theoretical truck speed profile models and the establishment of more sophisticated highway geometric alignment design specifications considering truck's climbing performance in high-altitude area.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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