Vehicle Centroid Measurement System Based On Forward Tilt Method Error Analysis

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Abstract. This paper proposes a calculation method for accurately measuring axle weight, total weight and centroid coordinates of vehicles based on forward tilting method. The composition of the measuring device is elaborated, and the centroid calculation method is proposed.Then the vehicle's centroid height error and error influencing factors are discussed under different conditions. It is concluded that the variation of the centroid error is smaller when the inclination angle of the bearing platform is greater than 12 degrees, so the inclination angle is recommended to be 12~15 degrees. The system is calibrated by standard parts, and the position of the center of mass of the vehicle is actually measured. The repeatability error of the centroid position of the measuring system is calculated to be 0.86 mm, and the relative error when the center of mass height is maximum is 0.1%, which achieves high test accuracy.Therefore, the measuring device can be extended to the actual use field.

1. Introduction

Vehicle inertia parameter is one of the important factors of vehicle safety factor, China's national standard clearly stipulates that the maximum roll stability angle of the vehicle tilted to the left or right side under no-load or static state is not allowed to be less than 35 degrees [1], while the stability and smoothness of driving is affected by the vehicle's center of mass.

At present, the common centroid measurement methods are [2]: mass response method, roll method, cycloid method, direct identification method, platform reaction support method. Among them, the mass reaction method [3] is to measure the weight by using a gravitational meter to lift the car at a certain height, and the error during operation is large. The roll method [4] is to fix the vehicle and measure the change of the fulcrum load. An auxiliary device is needed to prevent the vehicle from tipping over, which will cause the tire to be deformed and make the measurement error large. The cycloid method [5] and the direct identification method [6] have large limitations in measurement and are not widely used; the platform reaction support method [7] is to place the car on the platform which is lifted to a certain inclination, the centroid is calculated by measuring the redistribution value of the mass. Zhong Jiang [8] measured the center of mass with a tiltable platform supported by three points, and obtained the relationship between the displacement error of the lifter and the Z-centroid measurement error. However, when the lifter tilts the platform, the load cell has a large error in data acquisition; Lu Zhihui [9] based on the unbalanced moment method, the cross-distribution sensor and the rigid blade directly support the structure to measure the centroid of the object, but the friction torque of the knife-edge pair has a large error to the center of mass, and the shaft rotation during measurement is not suitable for measuring heavy load.Wen Jingjing [10] designed the inertial parameter test system, which can convert different measurement poses of the DUT and improve the measurement efficiency, but the economic cost of the equipment is high. The electric cylinder drive has limitations on the centroid measurement of heavy-duty large vehicle equipment.Comprehensively, the analysis of domestic and international centroid measurement methods shows that the main problems to be solved are as follows: 1)to improve the accuracy of centroid measurement and reduce the error interference factor; 2)to improve measurement efficiency, the measurement devices and methods for small and medium-sized vehicles are relatively mature, but there are few studies on measurement methods for heavy-duty large vehicles; 3)to be suitable for centroid measuring devices of vehicles with different wheelbases for reducing installation and commissioning procedures.

2. Centroid measuring mechanism, principle and calculation

Based on the forward-dip method, this paper proposes a centroid measurement method for heavy-duty, multi-axle type vehicles, which can accurately measure the axle weight, total weight and centroid coordinates of the vehicle, and the measurement error is small. The main components of the measuring mechanism are: weighing device, load bearing platform and hydraulic drive system. The structure diagram is shown in Fig 1. The bottom of the hydraulic drive system is connected to the foundation by bolts, and the top of the drive cylinder supports the load platform. When weighing, the vehicle is placed horizontally on the carrying platform. The lower side of the geometric center of the carrying platform is supported by a fixed hinge, and the other side is powered by a hydraulic drive system to realize synchronous flipping movement of the carrying platform and the vehicle. When the platform is tilted forward, the weighing device can be automatically leveled to make the weighing reading accurate. Finally, the total weight and centroid coordinates of the vehicle are accurately calculated by the upper computer. In particular, for the centroid measurement of vehicles with different wheelbases, it is only necessary to adjust the longitudinal arrangement spacing of the weighing device. At the same time, the auxiliary mechanism completes the driving, passing and positioning of the vehicle.

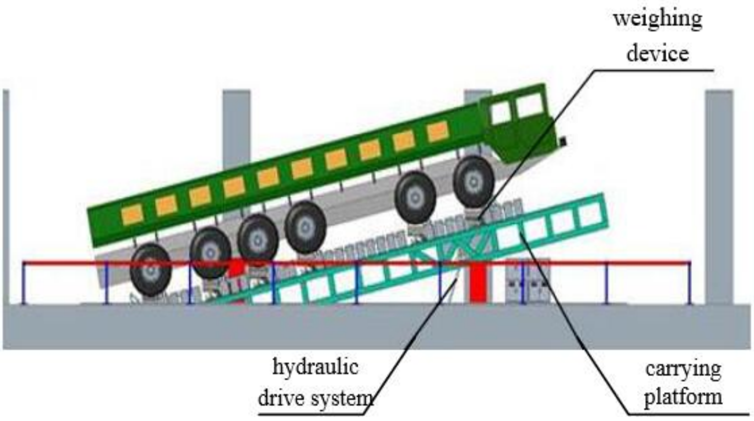

Fig 1. Working principle diagram of the centroid measuring mechanism

In this paper, the four-axle car is taken as an example for analysis and calculation, the principle is also applicable to six-axis and eight-axis vehicles. In the horizontal state, the intersection of the rear axle center line and the vehicle longitudinal center plane is the measurement coordinate origin. The longitudinal centerline of the rear axle of the vehicle is the x-axis, the horizontal centerline is the y-axis, and the vertical direction is the z-axis. The coordinate system and the measurement principle are shown in Fig 2, 3 and 4:

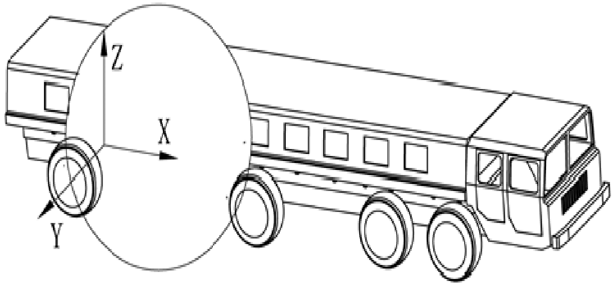

Fig 2. System coordinate system establishment

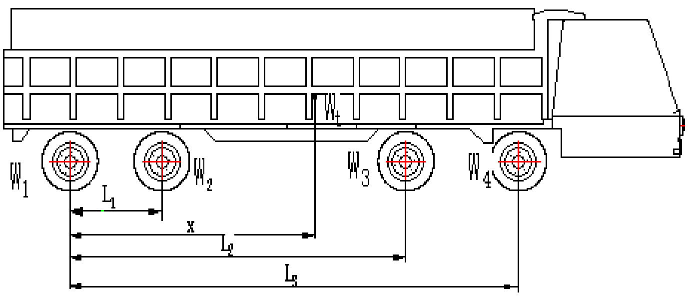

Fig 3. Schematic diagram of centroid measurement in horizontal state

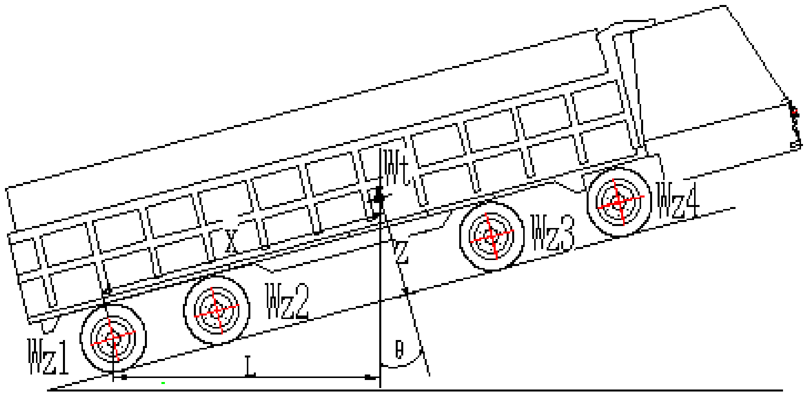

Fig 4. Schematic diagram of centroid measurement in the forward tilting state

In the picture:
Li —Wheelbase of the vehicle (m); θ—Carrying platform forward tilt angle;
W_i— Vehicle axle weight in flat state (Kg); W_{zi}—Vehicle axle weight under forward angle (Kg);
W_t—Total weight of the car (Kg); W_{li}— Each weighing device measurement (Kg);
Vehicle axle weight: $W_i = W_{l(2i-1)} + W_{l2i}, i = 1,2,3,4$
Car total weight calculation formula:

$$W_t = \sum_{i=1}^{4} W_i \tag{1}$$

When the bearing platform is in the horizontal state, the coordinates of the centroid x are obtained according to the torque balance principle.

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$$x = \frac{\sum_{i=1}^{4} W_{(i+1)} L_i}{W_t} \tag{2}$$

Similarly, the y coordinate is:

$$y = \frac{\sum_{i=1}^{4} L_{bi} (W_{l(2i-1)} - W_{l2i})}{2W_t} \tag{3}$$

Where: L_{bi} — the wheelbase of the vehicle(m);

When the load-bearing platform is tilted, the loose wheels are braked, and each wheel loader is automatically leveled to maintain the level, and the weight is again weighed to obtain the weight of each axle of the vehicle. The inclination angle θ is measured by the inclination sensor, the centroid horizontal coordinate projection distance L is calculated, and the centroid height coordinate z is calculated as follows:

$$z = h + \frac{x}{\tan\theta} - \frac{W_{z2}L_1 + W_{z3}L_2W_{z4}L_3}{W_t \tan\theta} \tag{4}$$

3. Error source analysis and derivation

3.1. Source of error analysis

The error generated by the measurement system is mainly divided into system error and random error, and the error caused by processing and installation belongs to system error, the error caused by measurement belongs to random error [11]. So the errors that need to be considered in this measurement system are mainly as follows:

1) Instrument measurement error; when using laser range finder and wheel loader, it will cause distance and mass error [12]. When measuring the tilt angle of the bearing platform with the tilt sensor, it will cause angle error. In general, the comprehensive error caused by the measuring instrument affects the centroid accuracy.

2) Repeatability error; Repeated measurements under the same conditions will cause repetitive errors, which are necessary to improve the efficiency of measuring centroid coordinates;

3.2. Derivation of error

In this paper, the error derivation and analytical calculation of the centroid height z are mainly discussed. It is easy to obtain the calculation formula of the centroid height measurement error by the system error transfer theory [13]. Wheel height h is constant, therefore, the derivative formula of z is as follows:

$$dz = \frac{\partial z}{\partial x}dx + \frac{\partial z}{\partial \theta}d\theta + \frac{\partial z}{\partial W_t}dW_t + \frac{\partial z}{\partial W_{z2}}dW_{z2} + \frac{\partial z}{\partial W_{z3}}dW_{z3} + \frac{\partial z}{\partial W_{z4}}dW_{z4} \tag{5}$$

Error transfer coefficient is:

$$\begin{cases} K_x = \frac{\partial z}{\partial x} = -\frac{1}{\sin^2\theta}, K_\theta = \frac{\partial z}{\partial \theta} = -\frac{\tan\theta(z-h)}{\sin^2\theta}, K_{W_t} = \frac{\partial z}{\partial W_t} = -\frac{x-\tan\theta(z-h)}{W_t\tan\theta} \\ K_{W_{z2}} = \frac{\partial z}{\partial W_{z2}} = -\frac{L_1}{W_t\tan\theta}, K_{W_{z3}} = \frac{\partial z}{\partial W_{z3}} = -\frac{L_2}{W_t\tan\theta}, K_{W_{z4}} = \frac{\partial z}{\partial W_{z4}} = -\frac{L_3}{W_t\tan\theta} \end{cases} \tag{6}$$

In equation (6), K_θ is the error transfer coefficient caused by the measurement error of the tilt sensor, K_{W_t} is the error transfer coefficient caused by the vehicle quality measurement error, $K_{Wz2}, K_{Wz3}, K_{Wz4}$ are the error transfer coefficient caused by the measurement error of each axle of the vehicle. K_x is the error transfer coefficient caused by the horizontal centroid x, e_θ is the error caused by the tilting angle θ of the bearing platform, e_{W_t} is the error caused by the quality of the vehicle, $e_{Wz2}, e_{Wz3}, e_{Wz4}$ are the errors caused by the axle weight of the vehicle. From the law of error transmission, the total relative error limit of the centroid height z is:

$$e_z = \pm(K_\theta e_\theta + K_{W_t} e_{W_t} + K_{W_{z2}} e_{W_{z2}} + K_{W_{z3}} e_{W_{z3}} + K_{W_{z4}} e_{W_{z4}} \tag{7}$$

3.3. Analysis of error influencing factors and case verification

3.3.1. Error influencing factor analysis. 1) Influence of the forward tilt angle of the bearing platform on the centroid error

If the tilting angle of the bearing platform is too large, the operation safety is low and the stroke of the hydraulic support system becomes larger, the relationship between the inclination angle and the centroid height of the analysis can be obtained as shown in Fig 5:

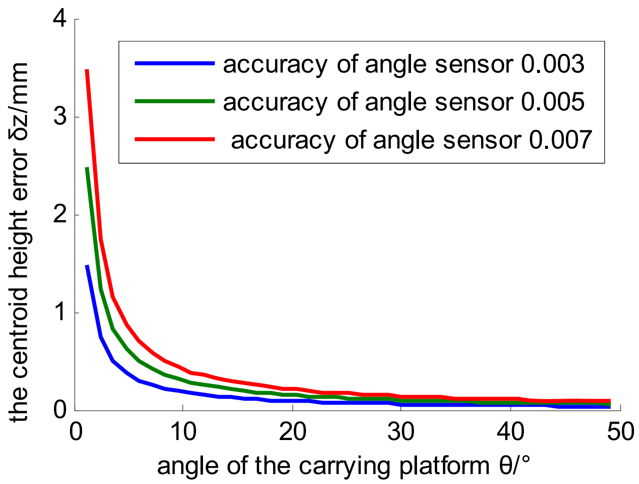

Fig 5. Relationship between centroid height error and dip

It can be seen from Fig 5 that under the same measurement condition, the centroid height error decreases as the inclination angle increases. When the inclination angle θ>12, the variation of the centroid height error is small, and the recommended inclination angle is 12-15 degrees.

2) Axle quality weighing error

According to the centroid calculation formula, the axle quality directly affects the centroid error, as shown in Fig 6(a), while the axle mass weighing error is affected by the accuracy of the wheel loader, as shown in Fig 6(b):

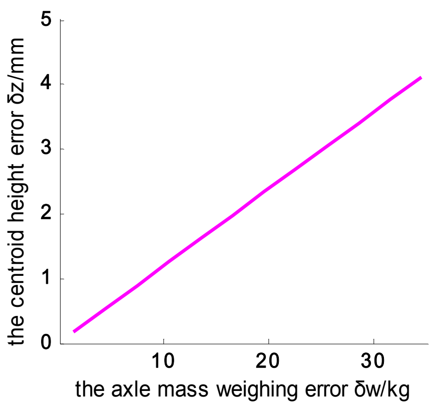

Fig 6 (a). The relationship between the axle mass Weighing error and the centroid height error

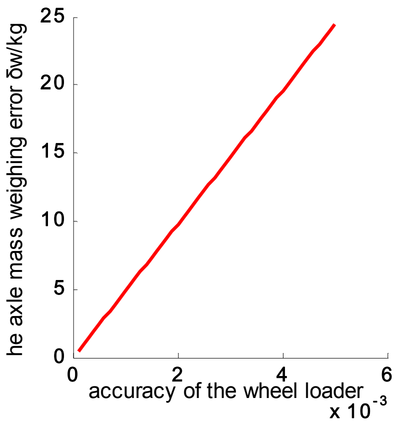

Fig 6 (b). The relationship between accuracy of the wheel loader and the axle quality weighing error

Analysis of Fig 6(a) shows that the axle mass weighing error is linear with the centroid height error, and the centroid error increases as the axle mass weighing error increases. Analysis of Fig 6(b) shows that the axle quality weighing error is linear with the accuracy of the wheel loader. The smaller the accuracy value is selected, the smaller the axle quality error is. Therefore, improving the accuracy of the wheel loader can reduce the quality measurement error and improve the z-direction centroid accuracy.

3) Influence of total vehicle mass on centroid error

As the total mass of the vehicle under test changes, the height error of the center of mass will also change, and the relationship between the total mass of the vehicle and the height of the center of mass is shown in Fig 7:

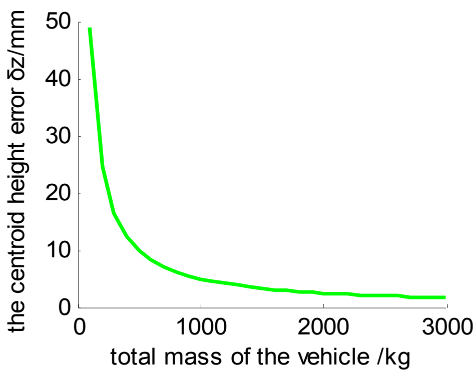

Fig7. Total vehicle mass and centroid height error relationship

Analysis of Fig 7 shows that as the total mass of the vehicle under test increases, the centroid height measurement error decreases. Especially when the vehicle mass is greater than 2500kg, the centroid error value is lower than 2mm and tends to be stable, so the centroid measurement system proposed in this paper is suitable for heavy-duty vehicles.

4) Influence of horizontal centroid x on centroid height error

The horizontal centroid x directly affects the vertical centroid error z, as shown in Fig 8 (a), while the x-direction centroid is affected by the accuracy of the laser rangefinder, as shown in Fig 8 (b):

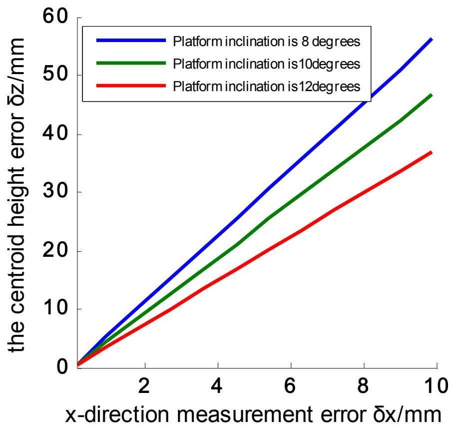

Fig 8a. Horizontal centroid x and centroid height error relationship

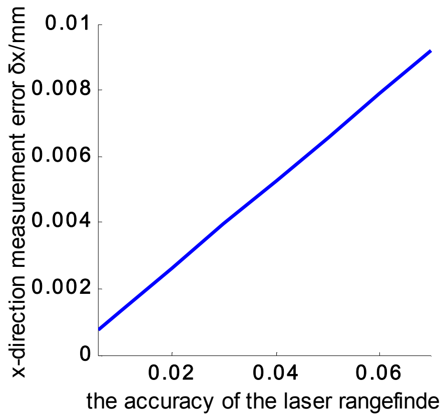

Fig 8b. Laser range finder accuracy and centroid height relationship

It can be seen from Fig 8a and Fig 8b that when the accuracy of the laser range finder is less than 0.07, the x-direction measurement error is less than 0.01 mm, so the error of the x-direction centroid error on the centroid height is negligible.

3.3.2. Standard parts calibration. On the developed vehicle centroid measurement system, the dynamic balance check calibration standard sample is taken [14]. So the average value is measured three times under the same inclination angle, the measurement results of the standard parts are shown in Table 1.

Tab 1. Standard Parts Centroid Parameter Measurement Table

Measurementnts value / Theoreticcal value		the inclination angle θ /°				average error
		12	13	14	15	
m/kg	9203	9209.15	9209.14	9208.97	9208.95	0.06%
x/mm	900	900.64	900.61	900.34	900.19	0.05%
y/mm	5	4.98	5.04	5.02	5.04	0.6%
z/mm	330	330.31	330.27	330.25	330.23	0.08%

Analysis Table 1 shows that the centroid coordinate measurement error of the standard sample is less than 1%, which meets the measurement requirements.

3.4. Instance verification

3.4.1. Repeatability error of the centroid system. Taking an actual truck as a measurement model, the parameters measured in the horizontal state are as follows:

$$L_1 = 2000mm, L_2 = 6700mm, L_3 = 8150mm,$$
$$W_1 = W_2 = 11710kg, W_3 = W_4 = 8715kg, W_t = 40850kg$$

Taking the inclination angle as $\theta = 12^{\circ}$, the measuring vehicle leaves the carrying platform every time and performs recalibration, the calculated centroid height data is shown in Table 2.

Tab 2. Centroid Height Calculation Data Sheet

frequency	1	2	3	4	5	6	7
z/mm	1596.11	1595.50	1596.09	1595.75	1595.87	1594.89	1595.67

The experimental standard deviation obtained from the Bessel formula is:

$$S(z) = \sqrt{\frac{\sum_{i=1}^{7}(z_i - \bar{z})^2}{n-1}} = 0.86,$$

Since the introduction of the repeatability of measurement error is 0.86mm less than 1mm, the measurement requirements are met.

3.4.2. Maximum relative error of the system. The errors are calculated from the parameters of each measuring instrument of the measuring system:

$$e_{\theta} = 0.005^{\circ}, e_{W_t} = 122.5kg, e_{W_{z2}} = 35.13kg, e_{W_{tz3}} = e_{W_{z4}} = 26.145kg$$

The comprehensive error limit is:

$$e_z = \pm(K_{\theta}e_{\theta} + K_{W_t}e_{W_t} + K_{W_{z2}}e_{W_{z2}} + K_{W_{z3}}e_{W_{z3}} + K_{W_{z4}}e_{W_{z4}} = \pm 1.55mm$$

The maximum relative error of the system is: $\delta = \frac{|e_z|}{z} \times 100\% = 0.1\%$

4. Conclusion

1) This paper proposes a centroid measurement system and calculation method based on forward tilt method for measuring heavy-duty, multi-axle type vehicles, and describes the system composition and measurement principle.

2) Several sources of error affecting the height of the vehicle's centroid are proposed and error analysis is performed.

3) The experimental calibration was carried out using standard samples. The calibration result is that the x/y/z centroid coordinate measurement error is less than 1%, which meets the measurement requirements.

4) The actual vehicle repeatability measurement error is 0.86 mm, less than 1 mm, the maximum centroid height relative error is 0.1%, and the measurement accuracy is high.

Acknowledgments
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