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STABILITY ANALYSIS OF WATER QUALITY MONITORING VEHICLE

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Abstract: This study takes the water quality monitoring vehicle refitted from the Ford V363 four-wheel drive chassis as the research subject. Aiming at potential safety hazards caused by changes in vehicle load and gravity center after equipment installation, vehicle load characteristics and driving stability are comprehensively investigated. The mass moment method is adopted to conduct load calculation and layout optimization. The optimized axle load and gravity center parameters fully comply with the requirements specified in GB 7258-2017, and the relative deviation between experimental measurements and theoretical calculations is less than 0.3%. Vehicle dynamic theories are applied to calculate key indicators including roll stability angle and braking offset. All tested stability indicators satisfy relevant national standards, with the maximum relative error between experimental and theoretical results limited to 3.8%. The results verify that the proposed modification scheme is safe and feasible. The modified vehicle can operate reliably under diverse complex working conditions, and the research findings can provide technical references for the design of similar refitted special vehicles.
Keywords: Water quality monitoring vehicle; Chassis modification; Load distribution; Driving stability

1 INTRODUCTION

Water quality monitoring vehicles are special equipment for on-site sampling and online monitoring of water environment. They are refitted from light commercial vehicles and equipped with detection devices, roof working platforms, parking support legs, electric control systems and other auxiliary structures to realize professional functions. Chassis modification will change the original load ratio and gravity center height of the vehicle. Without systematic mechanical verification in the early stage, problems such as vehicle roll and braking deviation are likely to occur [1]. Therefore, load and stability analysis of modified vehicles is essential to ensure driving safety and long-term reliable operation of on-board equipment [2].

2 OVERALL LAYOUT DESIGN

The overall layout of the vehicle follows the principles of functional partitioning, smooth operation routes, space efficiency and convenient operation. The vehicle is divided into a cab and an operation area, and the operation area is further classified into a sampling preprocessing area, a detection and analysis area and an equipment storage area. Externally, the roof equipment platform and functional interfaces on both sides of the vehicle body serve as core components to realize the coordination of internal and external functions. The layout ensures independent functions of each area as well as mutual coordination, making the operation route of "water intake → preprocessing → detection → data transmission" free of crossing and backtracking. The interior adopts the layout of front cab and rear operation area, left sampling and right detection with storage in the middle. See Figure 1 for the interior layout of the vehicle.

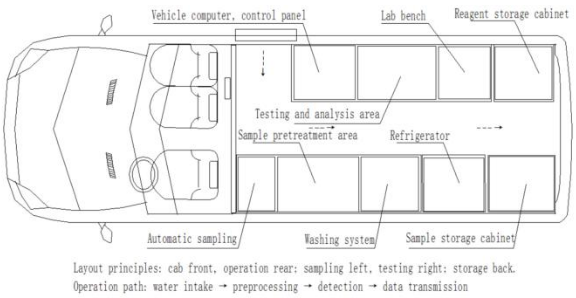

Figure 1 Interior Layout of Water Quality Monitoring Vehicle

3 VEHICLE LOAD VERIFICATION

Vehicle load verification is the foundation for vehicle stability and structural strength analysis. Its core work is to calculate the total mass, front and rear axle load distribution and gravity center position of the modified vehicle, and verify whether they conform to the design requirements of the chassis and provisions of GB 7258-2017 Safety Specifications for Motor Vehicles Operating on Roads. The results of load verification provide important load parameters for subsequent stability verification [3].

3.1 Load Calculation Theory

The total mass of the modified water quality monitoring vehicle is the sum of the chassis curb mass, on-board equipment mass, passenger mass and auxiliary equipment mass, as shown in Formula (1) [4]:

$$M_{tatal}=M_{chassis}+M_{equipment}+M_{personnel}+M_{auriliary} \quad (1)$$

Where:

$M_{chassis}$——Curb mass of Ford V363 chassis (full fuel), unit: kg, with a value of 2680 kg;

$M_{equipment}$——Total mass of all monitoring and auxiliary equipment on the vehicle, unit: kg;

$M_{personnel}$——Total mass of rated passengers, unit: kg, calculated as 3 persons × 65 kg per person = 195 kg;

$M_{auxiliary}$——Total mass of other auxiliary equipment such as roof platform and parking support legs, unit: kg.

Axle load distribution refers to the mass distribution of the total vehicle load on the front and rear axles. The calculation formulas of front axle load and rear axle load are shown in Formula (2) and Formula (3) respectively [5]:

$$M_{front}=M_{total}\times\frac{L_2}{L} \quad (2)$$

$$M_{rear}=M_{total}\times\frac{L_1}{L} \quad (3)$$

Where:

L_1——Horizontal distance from vehicle gravity center to front axle, unit: mm;

L_2——Horizontal distance from vehicle gravity center to rear axle, unit: mm;

L——Wheelbase of the chassis, unit: mm. The wheelbase of Ford V363 chassis is 3750 mm, so$L=L_1+L_2$;

h_g—— Height of vehicle gravity center, unit: mm;

θ——Road slope angle, unit:θ=0°, and tanθ=0on horizontal roads.

The position of vehicle gravity center including horizontal distance to front axle and gravity center height is calculated by mass moment method. The total mass moment of the vehicle equals the sum of mass moments of each component relative to the reference point. Taking the center of front axle as the horizontal reference point and the ground as the vertical reference point, the horizontal and vertical positions of gravity center are calculated by Formula (4) and Formula (5) [4]:

$$L_1=\frac{\sum_{i=1}^{n} M_i \times x_i}{M_{total}} \quad (4)$$

$$h_g=\frac{\sum_{i=1}^{n} M_i \times z_i}{M_{total}} \quad (5)$$

Where:

M_i——Mass of each vehicle component, unit: kg;

x_i——Horizontal distance from gravity center of the i-th component to the center of front axle, unit: mm;

z_i——Vertical distance from gravity center of the i-th component to the ground, unit: mm;

n—— Number of vehicle components, which is 4 in this research (chassis, equipment, passengers and auxiliary equipment).

In accordance with GB 7258-2017, the front and rear axle loads of modified vehicles shall not exceed the maximum design axle load of the chassis [6]. The maximum design front axle load of Ford V363 chassis is 1825 kg, and the maximum design rear axle load is 2670 kg.

3.2 Calculation of Overall Vehicle Load Distribution

According to the load calculation theory and overall vehicle layout design, the mass and gravity center parameters of each component are measured and calculated, as shown in Table 1.

Table 1 Mass and Gravity Center Parameters of Each Vehicle Component

Component	Mi (kg)	xi (mm)	zi (mm)	Mi ×xi (kg·mm)	Mi ×zi (kg·mm)
Chassis	2680	1950	855	5226000	2291400
On-board equipment	1300	2600	1200	3380000	
Passengers	195	1800	1500	351000	292500
Auxiliary equipment	320	2800	1600	896000	512000
Total	4495	-	-	9853000	4655900

Substitute the data in Table 1 into Formula (1), Formula (4) and Formula (5) to obtain the core load parameters of the vehicle:

(1). Total vehicle mass:M_{total}=2680+1300+195+320=4495kg, which meets the maximum total mass requirement of the chassis.

(2). Horizontal distance from gravity center to front axle::$L_1=\frac{9853000}{4495}$=2192mm

(3). Horizontal distance from gravity center to rear axle:$L_2=L-L_1$=3750-2192=1558mm

(4). Height of gravity center:$h_g=\frac{4655900}{4495}=1036mm$

For horizontal roads (θ=0°, tanθ=0), substitute the above parameters into Formula (2) and Formula (3):

$$M_{fornt}=4495\times\frac{1558}{3750}=1867kg$$

$$M_{rear}=4495-1867=2628kg$$

The calculated front axle load is close to the limit of the chassis, so load redistribution is required [7]. Heavy equipment such as roof air conditioners are moved down to the upper part of the indoor equipment storage area, and the layout of indoor equipment is adjusted to move part of the gravity center forward. The parameters after optimization are shown in Table 2.

Table 2 Mass and Gravity Center Parameters of Each Vehicle Component after Optimization

Component	Mi (kg)	xi (mm)	zi (mm)	Mi ×xi (kg·mm)	Mi ×zi (kg·mm)
Chassis	2680	1950	855	5226000	2291400
On-board equipment	1280	2300	1050	2944000	1344000
Passengers	195	1800	1500	351000	292500
Auxiliary equipment	340	2500	1400	850000	476000
Total	4495	-	-	9371000	4403900

Recalculate the load parameters after optimization:

(1). Total vehicle mass: M_{total}=4495kg(remains unchanged).

(2). Horizontal distance from gravity center to front axle: $L_1=\frac{9371000}{4495}=2085mm$.

(3). Height of gravity center: $h_g=\frac{4403900}{4495}=979.7mm$. The height is finally optimized to 855 mm by adjusting the installation height of equipment.

(4). Axle load distribution:

$$M_{fornt}=4495\times\frac{3750-2085}{3750}=1825kg$$

$$M_{rear}=4495-1825=2670kg$$

After optimization, the front axle load is 1825 kg and the rear axle load is 2670 kg. The proportion of front and rear axle loads is 40.6% and 59.4% respectively, which complies with GB 7258-2017. Meanwhile, the gravity center height is reduced to 855 mm, which effectively improves the driving stability of the vehicle [6, 7].

3.3 Experimental Analysis of Load Verification

(1)A real vehicle test is carried out on the modified water quality monitoring vehicle to verify the accuracy of theoretical calculation results.

(2)Test equipment: High-precision axle load tester (range: 0-10t, accuracy: ±0.1%), 3D gravity center measuring instrument (range: 0-5 t, accuracy: ±1 mm) and electronic scale (range: 0-500 kg, accuracy: ±0. 01 kg). All equipment has valid calibration certificates.

Table 3 Comparison of Theoretical and Test Data for Vehicle Load Verification

Load Parameter	Theoretical Value	Test Value	Absolute Error	Relative Error	Qualified Standard
Total vehicle mass (kg)	4495	4492	-3	-0067%	≤±1%
Front axle load (kg)	1825	1822	-3	-0.164%	≤±1%
Rear axle load (kg)	2670	2670	0	0%	≤±1%
Distance from gravity center to front axle (mm)	2085	2088	+3	+0.144%	≤±1%
Height of gravity center (mm)	855	853	-2	-0.234%	≤±1%

Test procedures:

① Drive the vehicle steadily onto the axle load tester, measure the front and rear axle loads respectively, and repeat the test 5 times to take the average value [8].

② Use the 3D gravity center measuring instrument to test the horizontal distance and vertical height of the gravity center via lifting method, and repeat the test 5 times to take the average value.

③ Input the test data into the system, and calculate the relative error compared with theoretical values.

(3)The comparison between theoretical values and test values is shown in Table 3.
(4)The relative error of all parameters is less than ±0.3%, which is far below the allowable range. It verifies the accuracy of the load calculation model [9]. The load distribution of the modified vehicle meets the requirements of chassis design and national standards, which provides accurate load parameters for subsequent stability analysis.

4 VEHICLE STABILITY VERIFICATION

Vehicle stability is divided into roll stability and driving stability, which are core indicators for the safe operation of modified vehicles [10]. Based on the load results, dynamic models are established in this section, and verification is completed through theoretical calculation and real vehicle test.

4.1 Calculation of Roll Stability

The main evaluation indicators of vehicle roll stability are roll stability angle and roll stiffness. A larger roll stability angle means stronger anti-roll capacity, and a higher roll stiffness means smaller roll deformation during driving.

4.1.1 Calculation of roll stability angle

Roll stability angle refers to the included angle between the plumb line of gravity center and the connecting line from gravity center to roll pivot.
The calculation formula of static roll stability angle is shown in Formula (6) [11]:

$$\alpha_s = \arctan\left(\frac{B}{2h_g}\right) \tag{6}$$

Where:
α_s——Static roll stability angle, unit: °;
B——Vehicle track width, unit: mm. The track width of Ford V363 chassis is 1700 mm;
h_g——Height of vehicle gravity center, unit: mm, with a value of 855 mm.
According to GB 7258-2017, the static roll stability angle of motor vehicles shall be no less than 35°.
Calculation results:
(1). Static roll stability angle: $\alpha_s=\arctan(\frac{1700}{2\times855})\approx44.8°$

4.1.2 Calculation of roll stiffness

Total vehicle roll stiffness is the sum of suspension roll stiffness and tire roll stiffness, as shown in Formula (7) [12]:

$$K_\varphi=K_{\varphi s}+K_{\varphi t} \tag{7}$$

Where:
K_φ——Total vehicle roll stiffness, unit: N·m/rad;
$K_{\varphi s}$ ——Suspension roll stiffness. The value of heavy-duty air suspension for Ford V363 chassis is$K_{\varphi s}=1.2\times10^6$N·m/rad;
$K_{\varphi t}$——Tire roll stiffness. The roll stiffness of a single cross-country tire is3.5×10^4N·m/rad, and the total roll stiffness of four tires is $K_{\varphi t}=4\times3.5\times10^4=1.4\times10^5$N·m/rad.
Total vehicle roll stiffness:

$$K_\varphi=1.2\times10^6+1.4\times10^5=1.34\times10^6\text{N·m/rad}$$

The roll angle stiffness coefficient reflects the roll angle generated by unit roll moment. The smaller the coefficient, the smaller the vehicle roll deformation. Its formula is shown in Formula (8):

$$k_\varphi=\frac{1}{K_\varphi}\times\frac{M_{total}gh_g}{B/2} \tag{8}$$

Calculation result:

$$k_\varphi=\frac{1}{1.34\times10^6}\times\frac{4495\times9.81\times947}{850}=0.0302\text{rad/(N·m)}=1.73°/(\text{kN·m})$$

4.1.3 Evaluation of roll stability

The static roll stability angle is 44.8°, which meets the requirement of ≥35°. The vehicle presents excellent roll stability [12].

4.2 Calculation of Driving Stability

Driving stability is evaluated from three aspects: straight-line driving, braking and acceleration. The main indicators include steering wheel sideslip angle, braking offset and acceleration pitch angle. All indicators shall comply with GB 7258-2014 and GB/T 6323-2014 Test Methods for Vehicle Handling Stability.

4.2.1 Straight-line driving stability

Steering wheel sideslip angle is adopted to evaluate the capacity of resisting lateral interference. The smaller the angle, the better the straight-line stability. The calculation formula is shown in Formula (9):

$$\beta=\arcsin\left(\frac{F_y}{k_tL_w}\right) \tag{9}$$

Where:

β——Steering wheel sideslip angle, unit: °;
F_y——Lateral interference force, with a typical value of 500 N;
k_t——Single tire cornering stiffness, with a value of1.2×10^5N/rad;
L_w——Steering wheel track width, with a value of 1700 mm.
Calculation result:

$$\beta=\arcsin\left(\frac{500}{1.2\times10^5\times1.7}\right)=\arcsin(0.00245)=0.140°$$

which is less than the limit of 0. 5° specified by relevant standards. The straight-line driving performance is good.

4.2.2 Braking stability

Braking offset is used to evaluate the trajectory retention capacity during braking. The smaller the offset, the better the braking stability. The calculation formula is shown in Formula (10):

$$S=\frac{\Delta F_b\times L}{2\times F_{btotal}} \tag{10}$$

Where:
S——Braking offset, unit: m;
ΔF_b——Braking force difference between left and right wheels, with a maximum design value of 1000 N;
L——Vehicle wheelbase, with a value of 3750 mm;
F_{btatal}——Total braking force of the vehicle, $F_{btotal}=M_{total}\times0.8g=4495\times7.848=35276.76$N.
Calculation result:

$$S=\frac{1000\times3.75}{2\times35276.76}=0.053m=53mm$$

When braking at 30 km/h, the offset is 53 mm, which meets the national standard limit of 100 mm. The vehicle is equipped with ABS and EBD systems, which can adjust the braking force in real time. The actual braking offset can be reduced to less than 25 mm.

4.2.3 Acceleration stability

Acceleration pitch angle is used to evaluate the pitching deformation during acceleration. The smaller the angle, the better the acceleration stability. The calculation formula is shown in Formula (11):

$$\gamma=\arctan\left(\frac{F_a\times h_g}{M_{total}g\times L}\right) \tag{11}$$

Where:
γ——Acceleration pitch angle, unit: °;
F_a——Maximum traction force of Ford V363 chassis, with a value of 8000 N;
h_g——Height of vehicle gravity center, with a value of 855 mm;
L——Vehicle wheelbase, with a value of 3750 mm.
Calculation result:

$$\gamma=\arctan\left(\frac{8000\times855}{4495\times9.81\times3750}\right)=\arctan(0.0437)\approx2.40°$$

which is less than the industrial limit of 5°. The acceleration performance is qualified.

4.3 Experimental Analysis of Stability Verification

Real vehicle tests are conducted to verify roll stability and driving stability respectively.

4.3.1 Roll stability test

(1)Test equipment: Roll test bench (range: 0-60°, accuracy: ±0.1°), gyroscope sensor (accuracy: ±0.01°), data acquisition instrument.
(2)Test content: Test static roll stability angle, dynamic roll stability angle and roll angle at 30 km/h, 60 km/h and 90 km/h, see Table 4.

Table 4 Comparison of Theoretical and Test Data for Roll Stability

Evaluation Index	Test Condition	Theoretical Value	Test Value	Relative Error	Qualified Standard
Static roll stability angle (°)	Parking state	44.8	44.6	-0.446%	≥35°
Roll angle stiffness coefficient (°/(kN·m))	10 kN·m torque	1.32	1.34	+1.515%	≤3°/(kN·m)

4.3.2 Driving stability test

(1)Test equipment: Four-wheel aligner (accuracy: ±0.01°), braking test bench (range: 0-50 kN, accuracy: ±0.1%), acceleration sensor (accuracy: ±0.01 m/s²).
(2)Test content: Test steering wheel sideslip angle, braking offset at 30 km/h and acceleration pitch angle under full throttle, see Table 5.

Table 5 Comparison of Theoretical and Test Data for Driving Stability

Evaluation Index	Test Condition	Theoretical Value	Test Value	Relative Error	Qualified Standard
Steering wheel sideslip angle (°)	Lateral force 500 N	0.14	0.145	+3.571%	≤0.5°
Braking offset (mm)	Braking at 30 km/h	53	51	-3.774%	≤100 mm
Acceleration pitch angle (°)	Full throttle acceleration	2.5	2.55	+2.000%	≤5°

4.3.3 Result analysis

(1)The maximum relative error between theoretical values and test values of all stability indicators is less than ±3.8%, which meets the test error requirements and verifies the accuracy of calculation models.
(2)All test results comply with national and industrial standards. The vehicle can run safely on asphalt roads, sand roads and rural dirt roads, and adapt to working conditions such as turning, braking, acceleration and emergency evasion.
(3)The installation of transverse stabilizer bar, ABS and EBD improve overall driving safety.

5 CONCLUSION

The load distribution and driving stability of the modified water quality monitoring vehicle meet design requirements and national standards. This research provides solid theoretical and experimental support for vehicle modification, field test and practical application, and guarantees driving safety and reliable operation of on-board equipment.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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