International Journal of Scientific Advances
ISSN: 2708-7972
Volume: 5 | Issue: 1 | Jan – Feb 2024 Available Online: www.ijscia.com
DOI: 10.51542/ijscia.v5i1.3

Analysis of Braking Performance of Distributed Drive Vehicle Under Two-Wheel Hub Motor Failure

Wen Yaxin

School of Transportation and Vehicle Engineering,
Shandong University of Technology, Zibo City, Shandong Province, China 255000

*Corresponding author details: Wen Yaxin; wenyxsdut@163.com

ABSTRACT
For distributed hub-driven vehicles, under braking conditions, when the hub motor fails, it will seriously threaten the safety of the vehicle, and there will be dangerous conditions such as braking distance increase and braking deviation, while the failure of the two-wheel hub motor has a more complex impact on the braking performance of the vehicle. Based on this, this paper selected a distributed hub motor drive vehicle as the research object and simulated the braking performance of the vehicle under the failure of the ipsilateral-side two-wheel hub motor system, coaxial two-wheel hub motor system, and diagonal two-wheel hub motor system. Combined with the vehicle's driving track, yaw speed, and centroid side deflection Angle, the influence degree of the vehicle's braking and stability was analyzed. The results show that the failure of the outer two-wheel hub motor has the greatest effect on vehicle braking stability than that of the diagonal wheel failure and the coaxial wheel failure. The effect of two-wheel hub motor failure on vehicle braking is greater than that of diagonal wheel failure and ipsilateral-side wheel failure. With the increase in vehicle braking speed and the decrease in road adhesion coefficient, vehicle instability, and braking performance become worse and worse.

Keywords: distributed vehicle; wheel hub motor; double wheel failure; vehicle braking performance

INTRODUCTION
With the development of electric vehicle technology and the continuous improvement of people's requirements for vehicle safety, composite braking systems have become a new development direction of braking systems. However, the in-wheel motor is a highly centralized mechatronic product. The failure of each firmware may cause the in-wheel motor to fail and not work normally, so that the vehicle has yaw moment and lateral deviation, deviating from the original driving trajectory, affecting the driving stability of the vehicle. Therefore, the effective analysis of the stability of the in-wheel motor failure vehicle in the braking process is particularly important to improve the vehicle's handling stability and driving safety.

Zhang Lipeng [1] et al., taking a vehicle driven by hub motors as an example, established the vehicle dynamics model and hub motor model, and verified the instability characteristics of the vehicle due to feedback braking failure and the deficiency of motor torque cutoff control through simulation. The model of the electric assist hydraulic braking system is established, and the accuracy of the model is verified by the bench test of the principle prototype. Zhu Bing [2] et al. artificially improve the braking safety of intelligent vehicles. Redundant Electronic Braking Control System based on Integrated Electronic Braking Control System (IBC) and Redundant Brake Unit (RBU), The braking stability of the vehicle when the current sensor fails in the electronic control braking system is analyzed, and the failure state of the motor control system is obtained. Pang Z [3] et al. analyzed the failure of single motor of dual-motor front-drive electric vehicles, established an electromechanical braking system model, analyzed the instability mechanism of vehicles with single motor failure through bench test and vehicle test, and detected the motion state of vehicles through yaw Angle and sideway Angle during braking. X Peng [4] et al. analyzed the stability of vehicles with single-wheel brake system failure for steering-by-wire vehicles and drive-by-wire vehicles and quantitatively analyzed the deflection and rotation of the failed vehicles through the convergence of the vehicle yaw Angle.

Although the above research has carried out simulation analysis on the braking performance of vehicles under different failure conditions, the research on the braking performance of vehicles under the failure of two-wheel hub motors has not attracted much attention at present. Moreover, since vehicles are subjected to four-wheel independent braking, it is also of great significance to analyze the braking performance of vehicles under multiple conditions. In order to fully study the performance changes of vehicle braking with wheel motor failure, the braking time, yaw velocity, centroid side deflection Angle and motion tracking of vehicle braking and stability observation are helpful to improve vehicle maneuverability and safety.

DISTRIBUTED HUB DRIVE VEHICLE BASIC STRUCTURE

In this paper, a four-wheel drive vehicle with distributed hub motor is taken as the research object, and the drive system is driven directly by four-wheel hub motors of the front and rear axles. The braking system adopts electro-hydraulic composite braking mode, and the mechanical braking adopts a hydraulic disc brake. The steering system is a four-wheel steering system, the front wheel of the car is a mechanical steering system, and the rear wheel is an electric power steering system. The structure of the test sample vehicle is shown in Figure 1.

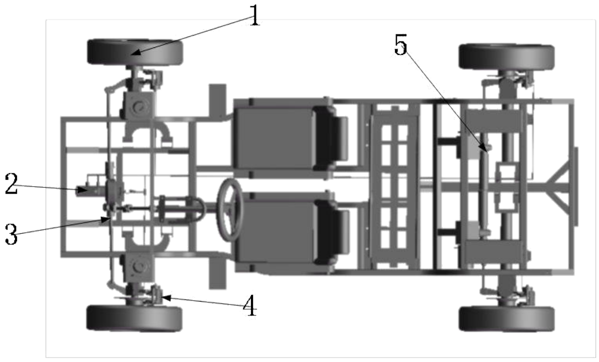


FIGURE 1: Structure diagram of the experimental sample car.

Where: 1 is the hub drive system; 2 is the brake master cylinder; 3 is the mechanical steering system; 4 is a disc brake; and 5 for the electric power steering system. The specific data of the vehicle are shown in Table 1.

TABLE 1: Basic structural parameters of the vehicle.

Parameter name	Parameter value
wheelbase (mm)	2350
Distance from front and rear wheels to center of mass (mm)	1300/1050
Front/rear wheelbase (mm)	1310/1330
Dimensions Length/width/height (mm)	2700/1550/1500
Full load/no load mass (kg)	1000/800
Height of the vehicle center of mass (mm)	500
Wheel radius (no load) (mm)	267

ESTABLISHMENT OF VEHICLE DYNAMICS MODEL

Establishment of normal vehicle dynamics equations

In order to better establish and analyze the vehicle dynamics model, this paper makes the following assumptions about the vehicle motion: (1) The suspension system of the vehicle is simplified into an equivalent spring and shock absorber that only act in the vertical direction, and there is only a relative rotation between the body and the chassis in the two directions of roll and pitch. (2) Assume that the road surface is a flat two-dimensional road surface, there is no vertical impact on the wheel, and the vertical movement of the wheel is ignored; (3) The influence of torsional vibration and pendulum vibration between transmission shafts is ignored.

Based on the above assumptions, the vehicle dynamics model with 7 degrees of freedom (DOF) as shown in Figure 2 was established, including the longitudinal motion of the vehicle along the x-axis, the lateral motion along the y-axis, the yaw motion around the z-axis and the rotation of the four wheels.

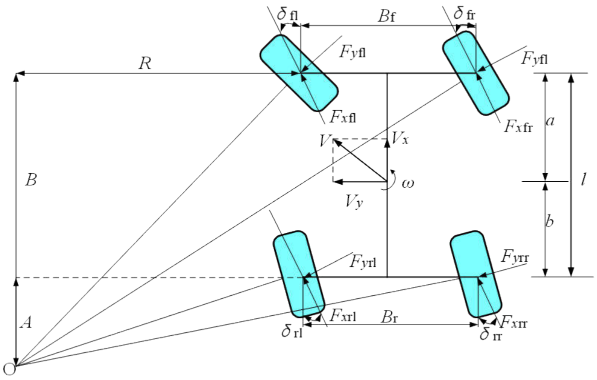


FIGURE 2: 7-degree of freedom model.

In Figure 2: m is the vehicle mass; a is the front axle wheelbase; b is the rear axle base; B_f is the front wheelbase; B_r is the rear wheelbase; v_x is the longitudinal speed of the vehicle; v_y is the lateral speed of the vehicle; δ_{ij} is the vehicle wheel Angle; F_{xij} is the tire longitudinal force; F_{yij} is tire lateral force; （*ij=fl*，*fr*，*rl*，*rr*， respectively represent the left front wheel, right front wheel, left rear wheel, right rear wheel); ω is the yaw angular speed of the vehicle.

When the vehicle is under normal braking conditions and the vehicle braking system does not fail, the vehicle braking motion equation is as follows:

$$\begin{cases} ma_x = F_{xfl}\cos\delta_{fl} + F_{xfr}\cos\delta_{fr} - F_{yfl}\sin\delta_{fl} - F_{yfr}\sin\delta_{fr} + \\ F_{xrl}\cos\delta_{rl} - F_{xrl}\sin\delta_{rl} + F_{xrr}\cos\delta_{rr} - F_{xrr}\sin\delta_{rr} \\ \\ ma_y = F_{xfl}\sin\delta_{fl} + F_{xfr}\sin\delta_{fr} + F_{yfl}\cos\delta_{fl} + F_{yfr}\cos\delta_{fr} + \\ F_{yrl}\cos\delta_{rl} + F_{yrr}\cos\delta_{rr} + F_{xrr}\sin\delta_{rr} + F_{xrl}\sin\delta_{rl} \\ \\ I_z\dot{\omega} = a(F_{xfl}\sin\delta_{fl} + F_{yfl}\cos\delta_{fl} + F_{xfr}\sin\delta_{fr} + F_{yfr}\cos\delta_{fr}) \\ -b(F_{xrl}\sin\delta_{rl} + F_{yrl}\cos\delta_{rl} + F_{xrr}\sin\delta_{rr} + F_{yrr}\cos\delta_{rr}) \\ -B_f(F_{xfl}\cos\delta_{fl} - F_{xfr}\cos\delta_{fr} + F_{yfl}\sin\delta_{fl} - F_{yfr}\sin\delta_{fr})/2 \\ +B_r(F_{xrl}\cos\delta_{rl} - F_{xrr}\cos\delta_{rr} + F_{yrl}\sin\delta_{rl} - F_{yrr}\sin\delta_{rr})/2 \end{cases} \tag{1}$$

The vehicle wheel rotation motion equation is:

$$I_{ij}\dot{\omega}_{ij} = rF_{xij} - T_{\mathrm{b}ij} \tag{2}$$

Where: a_x is the longitudinal acceleration of the vehicle; a_y is the longitudinal acceleration of the vehicle; ω_{ij} is the rotational angular speed of the wheel; T_{bij} is the motor output torque; (ij=fl, fr, rl, rr, respectively represent the left front wheel, right front wheel, left rear wheel, right rear wheel); I_z is the moment of inertia of the car body about the Z axis.

DYNAMIC ANALYSIS OF VEHICLE WITH WHEEL HUB MOTOR FAILURE

Because the distributed drive electric vehicle with a compound braking system structure can make full use of the brake energy of the wheel motor for effective braking, the wheel motor is used as the conventional braking system of the distributed drive electric vehicle. When the brake strength is high, the brake force generated by the vehicle hub motor is not enough to meet the demand of the vehicle brake force and cannot complete the normal braking of the vehicle, so the hydraulic braking system of the vehicle is supplemented by the brake force on the basis of the hub motor braking.

The vehicle dynamics analysis was carried out on the braking vehicle under the wheel hub motor failure condition. As shown in Figure 2, Where $F_{xij}=F_{m\_xij}+F_{motor\_xij}$; F_{m_xij} is the hydraulic braking force of each wheel、F_{motor_xij} is the electric mechanism power of each wheel. Therefore, when a wheel hub motor of the vehicle fails:

(1) When the braking strength is small, the wheel electric mechanism force $F_{motor\_xij}=0$, wheel braking force $F_{xij}=0$, the longitudinal braking force of the remaining wheel of the failed vehicle is equal to the longitudinal braking force of the corresponding wheel of the normal vehicle. The lateral forces acting on each wheel during initial braking are the same as in a normal vehicle. At the same time, in this working condition, because the braking force of the failure wheel is completely zero, under normal braking, according to the original braking force distribution rules, the front axle will share more braking force than the rear axle, so the failure of the front axle will lead to more serious consequences.

(2) When the braking strength is large, the wheel braking force $F_{xij}=F_{m\_xij}=F_{xij}-F_{max\_motor}$, where F_{max_motor} indicates the maximum braking force produced by the wheel hub motor. The braking force lost by the wheel is equal to the maximum braking force produced by the wheel hub motor of the normal vehicle, and the longitudinal braking force of the remaining wheel of the failed vehicle is equal to the longitudinal braking force of the corresponding wheel of the normal vehicle. The lateral forces acting on each wheel during initial braking are the same as in a normal vehicle. At the same time, under this working condition, the hub motor fails, regardless of the front wheel or the rear wheel, the hub motor will be the maximum braking force output of the motor in the state, so the position of the failed wheel has less impact.

MODEL VALIDITY VERIFICATION

After the establishment of the above vehicle dynamics model, in order to ensure the correctness of the simulation experiment results, the vehicle braking model is established by MATLAB/Simulink, and the effectiveness of the model is verified with the vehicle model established by Adams/View.

According to the requirements for braking safety in the national standard, the simulation working condition is set as follows: the vehicle is driving at a speed of 50km/h on the road surface with an adhesion coefficient of 0.7, and the braking strength Z=0.7 is taken as the simulation analysis condition. The simulation results obtained are compared with the national standard to verify whether the designed model meets the braking safety requirements. The requirements of national standards for brake system safety are shown in Table 2.

TABLE 2: National safety standards for brake systems.

Initial braking speed	Full load braking distance	Braking deceleration
50（km/h）	≤20m	≥6.2m/s^2

The simulation results of braking safety are shown in Figure 3.

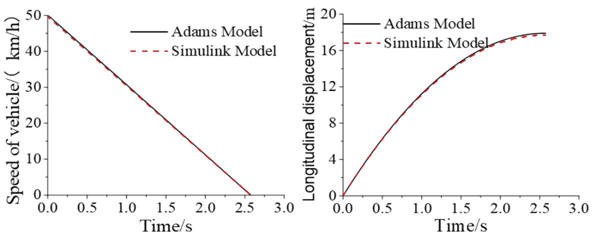


FIGURE 3: Simulation comparison diagram.

It can be seen from Figure 3 that the speed change curve and displacement change curve of the established vehicle Simulink model during braking are similar to the simulation results in the Adams model, and the vehicle model can run according to the preset working conditions. Compared with the national safety standard, under the same working conditions, the braking distance of the vehicle fully meets the national standard, and the vehicle model has good braking ability.

BRAKING ANALYSIS OF VEHICLES WITH TWO-WHEEL HUB MOTOR FAILURE

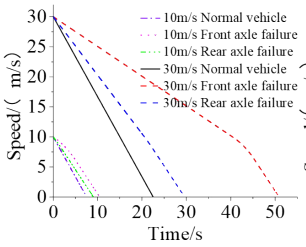
In order to study the braking performance of vehicles with two-wheel hub motor failure under braking conditions, coaxial, ipsilateral-side, and diagonal hub motor failure conditions were selected for simulation analysis under different braking intensities.

The simulation condition is that the failed vehicle performs braking with different braking intensities (Z=0.8 and Z=0.2) under high adhesion road surface and low adhesion road surface at different initial braking speeds. The braking performance of the vehicle is further analyzed by observing the braking speed and other braking evaluation indexes, as well as the stability evaluation indexes such as the side deflection Angle of the center of mass, the yaw speed, and the vehicle running track.

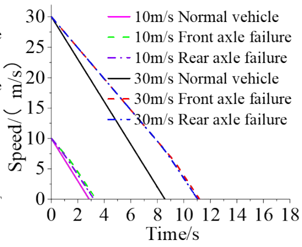
ANALYSIS OF BRAKING PERFORMANCE OF FAILED VEHICLE UNDER HIGH ADHESION ROAD SURFACE

(1) Front axle or rear axle two-wheel failure simulation condition

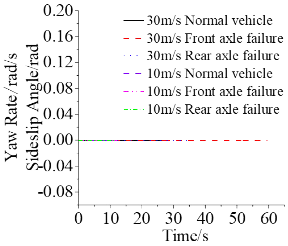
Simulation conditions were set as follows: braking strength Z=0.2 and Z=0.8, initial braking speed V=10m/s and V=30m/s, road adhesion coefficient μ=0.8, and linear braking simulation analysis was carried out by selecting the failure of front-axle and rear-axle hub motors. The simulation results are shown in Figure 4.



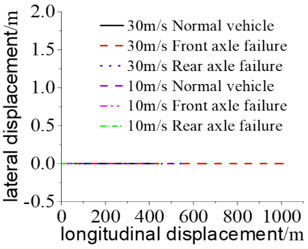
(a) Z=0.2 Brake speed diagram.



(b) Z=0.8 Brake speed diagram.



(c) Yaw rate and Sideslip angle diagram.



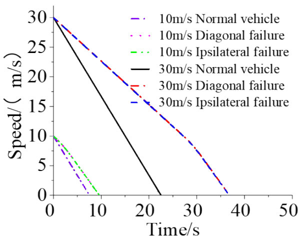
(d) Trajectory comparison.

FIGURE 4: Braking simulation results.

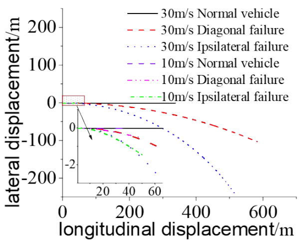
As can be seen from Figure 4, under braking conditions with high adhesion road surface, the braking force generated by the vehicle decreases due to the failure of the vehicle hub motor, and the braking performance of the vehicle is seriously damaged compared with normal vehicles. Moreover, at low braking intensity Z=0.2, the braking force of the front axle is greater than that of the rear axle. Therefore, at the initial braking speed of 30m/s, the braking time of front axle two-wheel failure increases by 21s compared with that of rear axle two-wheel failure, which is far greater than 0.3s when Z=0.8. This is because the vehicle has a larger proportion of wheel hub electric mechanism power under low braking intensity, and the vehicle loses more braking force, so the vehicle has a smaller deceleration speed and longer braking time. However, as can be seen from the comparison diagram of a driving track, yaw speed and side deflection Angle of the center of mass, due to the linear braking condition, no matter whether the front axle two wheels or the rear axle two wheels hub motor failure, under different braking intensity, the vehicle will only extend the braking time, and will not occur deviation, and the vehicle stability is good.

(2) Ipsilateral side or diagonal two-wheel failure simulation conditions

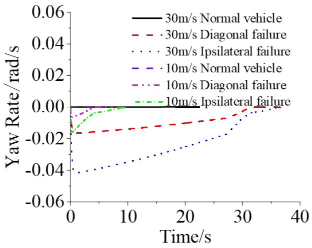
Simulation conditions were set as follows: braking strength Z=0.2 and Z=0.8, initial braking speed V=10m/s and V=30m/s, road adhesion coefficient μ=0.8, and linear braking simulation analysis was carried out by selecting the failure of ipsilateral-side two-wheel or diagonal two-wheel hub motor. The simulation results are shown in Figures 5 and 6.



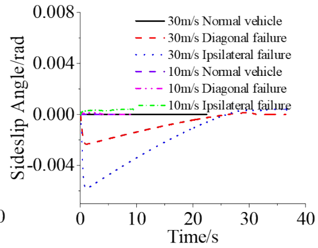
(a) Brake speed diagram.



(b) Trajectory comparison diagram.



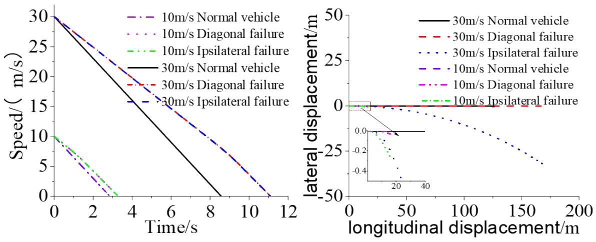
(c) Yaw rate diagram.



(d) Sideslip angle diagram.

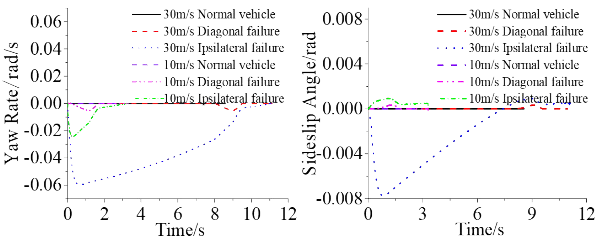
FIGURE 5: Brake simulation result of Z=0.2.

As can be seen from Figure 5, different from the failure of two-wheel hub motors of the front and rear axles, the braking force loss caused by the failure of two-wheel hub motors on the ipsilateral side of the vehicle is the same as that caused by the failure of the vehicle's diagonal two-wheel hub motors. The braking time of the vehicle after failure is also the same, and the braking time is in the middle position between the front axle and the rear axle. Different from the failure of two wheels of the front axle or the rear axle, the braking force on both sides of the vehicle appears to obvious imbalance, and the braking state of the vehicle appears to obvious deviation. From the trajectory comparison, it can be seen that the failure of the two-wheel hub motor on the ipsilateral side is larger than that of the diagonal two-wheel hub motor, and the run offset value increases by 150% when the initial braking speed is 30m/s. The yaw velocity and the side declination Angle of the center of mass have the same variation trend, and the peak value of the ipsilateral side wheel failure is greater than that of the diagonal wheel failure. With the increase of vehicle braking speed, the peak value also increases, and the vehicle stability becomes worse.



(a) Brake speed diagram.

(b) Trajectory comparison diagram.



(c) Yaw rate diagram.

(d) Sideslip angle diagram.

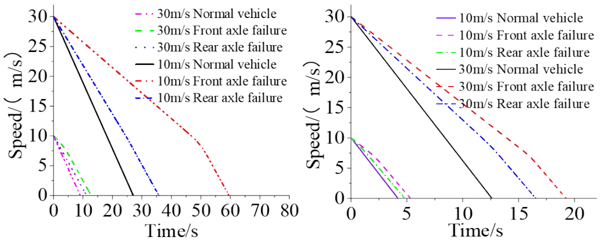
FIGURE 6: Brake simulation result of Z=0.8.

As can be seen from Figure 6, different from vehicles that fail at low braking intensity, vehicles have shorter braking time and smaller braking deviation when Z=0.8 is high braking intensity. At the same time, when the initial braking speed is 30m/s, when the diagonal two wheels of the vehicle fail, the yaw speed and the side yaw Angle of the center of mass have no great changes, and the vehicle's driving trajectory is the same as that of normal vehicles, which is because the yaw moment generated by the failure of the diagonal vehicle is the same, which can maintain the stable running of the vehicle. It can be seen from the trajectory comparison that the deviation distance of the failure of the ipsilateral-side two-wheel hub motor is much larger than the failure of the diagonal two-wheel hub motor. When the initial braking speed is 30m/s, the deviation reaches 34m, and the variation trend of the yaw speed and the side deviation Angle of the center of mass is the same, and the peak value of the two reaches 0.06rad/s and 0.0078rad respectively. It is much higher than 0.025rad/s and 0.0012rad in low-speed braking conditions.

ANALYSIS OF BRAKING PERFORMANCE OF FAILED VEHICLE UNDER LOW ADHESION ROAD SURFACE

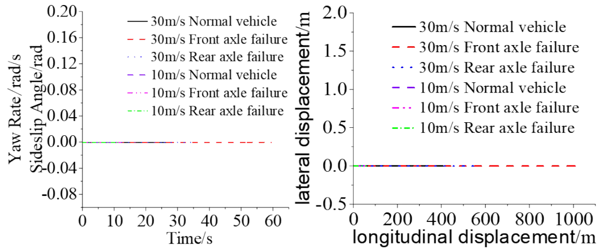
(1) Front axle or rear axle two-wheel failure simulation condition

Simulation conditions were set as follows: braking strength Z=0.2 and Z=0.8, initial braking speed V=10m/s and V=30m/s, road adhesion coefficient μ=0.2, and linear braking simulation analysis was carried out by selecting the failure of front-axle and rear-axle hub motors. The simulation results are shown in Figure 7.



(a) Z=0.2 Brake speed diagram.

(b) Z=0.8 Brake speed diagram.



(c) Yaw rate and Sideslip angle diagram.

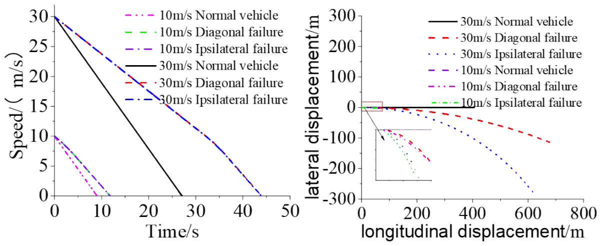
(d) Trajectory comparison diagram.

FIGURE 7: Braking simulation results.

As can be seen from Figure 7, under braking conditions of low adhesion road, due to vehicle hub motor failure, the braking force generated by the vehicle decreases. Compared with low-adhesion roads, the braking time required by the vehicle is longer and the braking performance is worse. Moreover, at low braking strength Z=0.2, the braking force of the front axle is greater than that of the rear axle, so the braking time of the failed vehicle at the initial braking speed of 30m/s is 25s longer than that of the rear axle two-wheel failure, which is far greater than 0.5s when Z=0.8, and greater than the braking time of the failed vehicle under high adhesion road surface. Due to the larger proportion of vehicle hub electric mechanism power and the more braking force lost by the vehicle, the vehicle deceleration is smaller and the braking time is longer. However, as can be seen from the comparison diagram of the driving track, yaw speed and side deflection Angle of the center of mass, due to the linear braking condition, no matter the front axle two-wheel hub motor failure or the rear axle two-wheel hub motor failure, under different braking intensity, the vehicle will only extend the braking time and the vehicle stability is good.

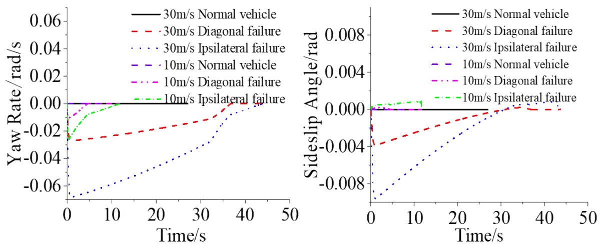
(2) Ipsilateral side or diagonal two-wheel failure simulation conditions

Simulation conditions were set as follows: braking strength Z=0.2 and Z=0.8, initial braking speed V=10m/s and V=30m/s, and road adhesion coefficient μ=0.2. The linear braking simulation analysis was carried out by selecting the ipsilateral side two-wheel or diagonal two-wheel hub motor failure, and the results are shown in Figures 8 and 9.



(a) Brake speed diagram.

(b) Trajectory comparison diagram.

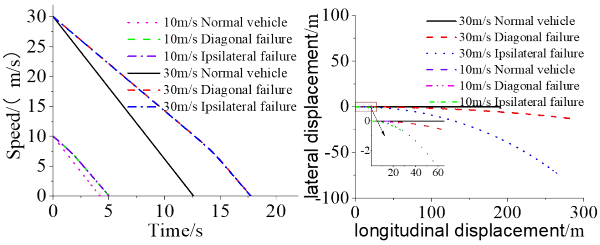


(c) Yaw rate diagram.

(d) Sideslip angle diagram.

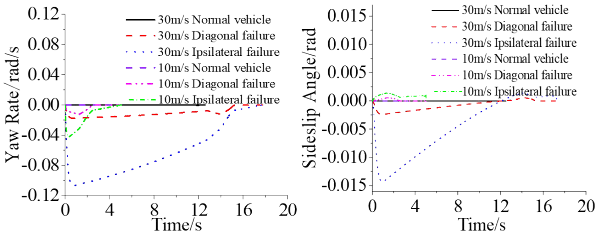
FIGURE 8: Brake simulation result of Z=0.2.

As can be seen from Figure 8, the braking force loss caused by the failure of the two-wheel hub motor on the ipsilateral side of the vehicle is the same as that caused by the failure of the diagonally two-wheel hub motor of the vehicle. The braking time of the vehicle after the failure is also the same, and the braking time is in the middle position between the front axle and the rear axle. The deviation distance of the ipsilateral side two-wheel hub motor failure is much greater than that of the diagonal two-wheel hub motor failure. When the initial braking speed is 30m/s, the deviation reaches 300m, and the deviation value increases by 180% compared with the ipsilateral side failure. The yaw velocity and the side deflection Angle of the center of mass have the same variation trend, and the peak value of the two reaches 0.069rad/s and 0.0098rad respectively, which is much higher than the 0.028rad/s and 0.0014rad in the low-speed braking condition. Compared with the high adhesion road with low braking conditions, the vehicle yaw speed and centroid side deflection Angle are also larger, at 30m/s, the two increased by 75% and 100%, and the vehicle stability becomes worse.



(a) Brake speed diagram.

(b) Trajectory comparison.



(c) Yaw rate diagram.

(d) Sideslip angle diagram.

FIGURE 9: Brake simulation result of Z=0.8.

As can be seen from Figure 9, different from vehicles that fail under low braking intensity, vehicles with high braking intensity (Z=0.8) have shorter braking time and smaller braking deviation, but with higher stability, the attached road surface becomes worse. From the trajectory comparison, it can be seen that the deviation distance of the failure of the two-wheel hub motor on the ipsilateral side is much larger than that of the diagonal two-wheel hub motor. When the initial braking speed is 30m/s, the deviation reaches 81m, and the deviation value increases by 70% compared with that of the diagonal failure. The yaw velocity and the side deflection Angle of the center of mass have the same variation trend, and their peaks reach 0.11rad/s and 0.0145rad respectively, which is much higher than 0.04rad/s and 0.0018rad in low-speed braking conditions. Moreover, compared with the high adhesion road and low braking conditions, the vehicle's yaw speed and centroid side deflection Angle are also larger. At 30m/s, the two increase by 80% and 95% respectively, and the vehicle stability becomes worse.

CONCLUSION

In this paper, the braking simulation model of the failed vehicle is established by Matlab/Simulink, and the stability parameters of the vehicle such as yaw speed, side deflection Angle of the center of mass, and slip rate are obtained. The braking performance of a distributed hub drive vehicle under the failure of a two-wheel hub motor is analyzed, and the following conclusions are obtained through research:

(1) When the vehicle brakes after the failure of the hub motor on both wheels, the failure of the twin front axle hub motor has the greatest impact on the braking time of the vehicle. When the braking strength is low on the low-adhesion road surface, the braking time of the 30m/s vehicle with the failure of the twin front axle hub motor reaches 60s, and the braking performance is the worst. The failure of the ipsilateral-side hub motor has the greatest impact on the braking stability of the vehicle. When the braking strength is high on the low-adhesion road surface, the peak values of yaw speed and side decline-angle of the center of mass of 30m/s vehicle under the failure of the ipsilateral-side hub motor reach 0.11rad/s and 0.0145rad, respectively, and the braking stability of the vehicle is the worst.

For diagonally failed vehicles, the stability of the vehicle is the best under the condition of high adhesion and high braking strength. When the initial braking speed is 30m/s, the yaw speed and the side yaw Angle of the center of mass of the vehicle have no major changes, and the vehicle's driving trajectory is basically the same as that of normal vehicles, which is because the yaw moment of the vehicle caused by the failure of the diagonally failed vehicle is basically the same. It can maintain the stable running of the vehicle.

(2) During braking, factors such as braking strength, initial braking speed, and road adhesion coefficient will all have different effects on the braking stability of the failed vehicle, and the influence range of braking strength on the stability of the vehicle is significantly greater than the influence of initial braking speed and road adhesion coefficient on the vehicle.

REFERENCES

[1] Zhang Lipeng, Yuan Xinmao, Peng Yongao, etc. Hydraulic compensation control for regenerative braking failure of distributed drive electric vehicles [J].China Journal of Highway, 2020,33 (8): 11.

[2] Zhu Bing, Dang Ruijie, Zhao Jian, et al. Fault-tolerant control of current sensor failure in redundant electric control braking system of intelligent vehicle [J]. China Journal of Highways, 2023, 36 (4): 249-260.

[3] Zhang L , Pang Z , Wang S ,et al.Electromechanical composite brake control for two in-wheel motors drive electric vehicle with single motor failure[J]. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 2019, 234(4):095440701986422.

[4] Xiaoyan P , Kaihu W .Control Strategy of Optimal Braking Force Distribution for Vehicle with Brake-by-wire System after Single Wheel Brake Failure[J].Journal of Hunan University(Natural Sciences), 2018.

[5] Cao X, Tian Y, Ji X , et al.Fault-Tolerant Controller Design for Path Following of the Autonomous Vehicle under the Faults in Braking Actuators[J].IEEE Transactions on Transportation Electrification, 2021, PP(99):1-1.

[6] Wang Weida, Peng Haonan, Huang Guoqiang, et al. Four-wheel independent drive electric vehicle driving stability analysis and joint sliding mode variable structure active control [J]. Journal of Mechanical Engineering, 2021, 57 (4): 103-112.

[7] Chen Qiping, Tian Yue, Wang Liang, et al. Analysis of factors affecting the handling stability of distributed drive electric vehicles [J]. Modern Manufacturing Engineering, 2021,000 (001): 12-16,21.

[8] Salem M, Ibrahim M, Mourad M A, et al. Sensitivity Analysis of Vehicle Parameters on Dynamic Stability and Vehicle Handling Performance[J]. International Journal of Vehicle Structures and Systems, 2021, 13(1).

[9] Silva F L, Silva L, Eckert J, et al. Parameter influence analysis in an optimized fuzzy stability control for a four-wheel independent-drive electric vehicle[J]. Control Engineering Practice, 2022, 120: 105000-.

[10] Pan Jin, Pan Hao, Pei Xiaofei, et al. Research on electro-hydraulic composite ABS control of distributed drive electric vehicles [J]. Automotive technology, 2019, (11): 10-15.