World Electric Vehicle Journal

MDPI

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Study on Control Strategy of Electric Power Steering for Commercial Vehicle Based on Multi-Map

Yaohua Li *, Zhengyan Yang, Dengwang Zhai, Jie He and Jikang Fan

School of Automobile, Chang'an University, Xi'an 710064, China
* Correspondence: yaohua.li@chd.edu.cn

Abstract: In order to solve the problem where the traditional electric power steering system (EPS) provides too much assist torque under low load and low adhesion coefficient, which damages the driver's road feeling and affects driving safety, this paper designs a multi-map EPS control strategy. First, based on the change of steering resistance torque under different front axle loads and adhesion coefficients, EPS power characteristics considering the front axle load and adhesion coefficient were designed. In addition, the BP (Back Propagation, BP) neural network is used to determine steering resistance torque under different front axle loads and adhesion coefficients. Furthermore, the EPS control strategy based on multi-map is proposed. The proposed control strategy is evaluated through the co-simulation of Trucksim and Simulink. Simulation results show that the proposed EPS control strategy gives the vehicle good steering portability, with the handling torque meeting the ideal handling torque for a commercial vehicle. Under light load and low adhesion coefficient conditions, the lateral acceleration and yaw rate with traditional EPS are 0.1674 g and 5.641 deg/s, and with multi-map EPS are 0.1399 g and 4.715 deg/s. Therefore, the vehicle's handliitung stability is improved. The steering wheel torque gradient is also increased, and the driver's road feeling is improved.

Keywords: electric power steering; road adhesion coefficient; front axle load; multi-map; commercial vehicle

Citation: Li, Y.; Yang, Z.; Zhai, D.; He, J.; Fan, J. Study on Control Strategy of Electric Power Steering for Commercial Vehicle Based on Multi-Map. *World Electr. Veh. J.* **2023**, *14*, 33. https://doi.org/10.3390/wevj14020033

Academic Editor: Gianmario Pellegrino

Received: 5 December 2022
Revised: 17 January 2023
Accepted: 18 January 2023
Published: 30 January 2023

1. Introduction

Compared with the hydraulic power steering system (HPS), the electric power steering system (EPS) has the advantages of reducing fuel consumption and having a simple structure, adjustable power characteristics, and high reliability, and has gained much interest [1–6]. As the core of the electric power steering system, the EPS control strategy directly determines the handling stability of the vehicle. The EPS control strategy requires vehicle to have good steering portability at low speed, and requires the driver to have an obvious road feeling at high speed.

The assist characteristic of the traditional EPS only considers the speed and the driver's hand torque on steering resistance torque, but not other factors. Research shows that the change of the front axle load and road adhesion coefficient will have an impact on steering resistance torque, thereby affecting the assist effect of the EPS and the driver's road feeling. Li uses the front axle load as the reference factor for the assist characteristic, and established the assist characteristic curve while considering the change of load [7]. Zhao uses sliding mode variable structure control to correct the assist current by estimating the road adhesion coefficient [8]. Li uses fuzzy control to compensate for the assist current while considering the adhesion coefficient [9]. Zhou uses an extended Kalman filter to estimate the lateral force of the front axle under a low adhesion road, and compensates for the assist current through feedback control of the ideal front axle lateral force obtained from the reference model under the normal adhesion coefficient [10]. The above control strategies can overcome the influence of front axle load or road adhesion coefficient change to a certain extent, and improve the driver's road feeling, but they improve the assist characteristic only from a single front axle load change or from a single adhesion coefficient change. Commercial vehicles' load and adhesion coefficient change drastically, so the design of the EPS control strategy should comprehensively consider the front axle load and adhesion coefficient change, and establish a multi-map assist characteristic curve to overcome the influence of load and road adhesion coefficient change.

This paper analyzes the influence of front axle load change and full adhesion coefficient on steering resistance torque, studies the change of steering resistance torque under different front axle loads and different road adhesion coefficients, and adds front axle load and adhesion coefficient when designing the assist characteristic curve. The BP (Back Propagation, BP) neural network is used to obtain the steering resistance torque under different front axle load and adhesion coefficient conditions, and an EPS control strategy based on multiple-MAP is proposed. The performance of the multiple-MAP EPS control strategy, traditional EPS control strategy, and the EPS control strategy that only considers the front axle load and only considers the adhesion coefficient is compared through co-simulation. The simulation results show that the EPS control strategy based on multiple-MAP meets the requirements of the national standard for steering portability, and the steering hand torque characteristic is in line with the ideal steering wheel torque characteristic of commercial vehicles, which can better overcome the influence of front axle load and road adhesion coefficient change, and improve the handling stability of the vehicle, increase the driver's road feeling under a light load and low adhesion coefficient condition, and improve driving safety.

The contributions of the paper are as follows.

- When the front axle load decreases or the road adhesion coefficient becomes smaller, the steering resistance torque will decrease. However, the traditional EPS does not take them into account and gives too much assist torque, which will reduce the driver's road sense and affect the safety of driving. Thus, the EPS control strategy needs to consider them comprehensively.
- BP (Back Propagation, BP) neural network is used to determine the resistance torque under different front axle load and adhesion coefficient conditions, and an EPS control strategy based on multiple-MAP is proposed.
- Simulation results show that the EPS control strategy based on multiple-MAP meets the requirements of the national standard for steering portability and improves the handling stability of vehicle, increases the driver's road feeling under a light load and low adhesion coefficient condition, and improves driving safety.

2. Influence of Front Axle Load and Road Adhesion Coefficient

When a vehicle equipped with an EPS system is steering, the relationship between the steering resistance torque and the assist torque of the EPS is shown in Equation (1).

$$T_r = T_d + T_a \tag{1}$$

where T_r represents the steering resistance torque fed back to the steering wheel; T_d is the hand torque applied by the driver on the steering wheel, that is, the steering wheel torque; and T_a is the assist torque provided by the power assist system.

Ignoring the influence of steering inertia, the steering resistance moment of the vehicle is composed of friction between the road surface and the wheel and internal friction of steering system. The interaction between the road and the wheel includes the gravity aligning torque and the tire self-aligning torque caused by lateral force and the friction moment between the wheel and the road.

In the steering resistance torque of the vehicle, the gravity aligning torque is as shown in Equation (2).

$$T_g = GD_n\beta\delta_f \tag{2}$$

where G is the gravity of the vehicle front axle, and δ_f is the front wheel angle.

It can be seen from Equation (2) that the gravity-aligning torque is mainly affected by the front axle load, and it has a positive correlation with the front axle load. Therefore, when the current axle load changes, the steering resistance torque will change.

The self-aligning torque is mainly produced by tire lateral force and tire offset, as shown in Equation (3) [11,12].

$$T_z = F_Y e = F_Y(e_m + e_p) \quad (3)$$

where F_Y is the tire lateral force, and e is the tire offset, including mechanical offset e_m and pneumatic tire offset e_p. The mechanical offset can be regarded as constant value. The pneumatic tire offset is affected by many factors, as shown in Equation (4).

$$e_p = e_{p0} - sgn(\alpha)\frac{e_{p0}k_\alpha}{3\mu W}tan\,\alpha \quad (4)$$

where e_{p0} is the initial value of the pneumatic tire offset, k_α represents the tire lateral stiffness, α represents the tire slip angle, and μ represents the adhesion coefficient.

It can be seen from Equation (4) that the pneumatic tire offset is positively correlated with the road adhesion coefficient. Combined with Formula (3), the self-aligning torque is also positively correlated with the adhesion coefficient. When the vehicle turns, the road adhesion coefficient also directly affects the friction torque between the wheel and the road. Therefore, the road adhesion condition will affect the resistance torque during turning. When the vehicle is driving under the condition of low adhesion coefficient, the steering resistance torque will be reduced. If the EPS applies an assist torque on the vehicle according to the original road adhesion coefficient, the assist torque is too large, which will reduce the driver's road feeling and threaten driving safety. It can be seen that road adhesion coefficient is also an important factor affecting vehicle steering resistance torque.

In order to verify the influence of road adhesion coefficient and front axle load change on steering resistance torque, a commercial vehicle dynamics model is established based on Trucksim. The vehicle parameters are shown as follows: curb weight 12 t, total mass 16 t, front axle load 5.33 t, length 12 m, width 2.5 m, height 3.5 m, wheelbase 6 m, centroid height 1.35 m, steering gear ratio 25, centroid-to-front-axle distance 4 m, maximum speed 70 km/h, steering wheel diameter 0.5 m, and steering shaft torsional stiffness 700 N·m/rad.

The steering system of the vehicle in the model is set to pure mechanical steering, the vehicle speed to 50 km/h, and the steering wheel angle is slope input. After turning the steering wheel at a constant speed to the maximum angle of 90°, the steering angle remains unchanged, and uses the final steady-state value of the steering wheel torque as the steering resistance torque. The road adhesion coefficient is set at 0.8, and the front axle load is set to 4 t, 4.67 t, and 5.33 t, respectively; the simulation results are shown in Figure 1. When the front axle load is 5.33 t, the road adhesion coefficient is set to 0.2, 0.4, 0.6, and 0.8; the simulation results are shown in Figure 2.

According to simulation results, steady-state values of steering wheel torque under different front axle loads and adhesion coefficients are shown as follows: 25.1 N·m at 4 t and μ = 0.2, 30.3 N·m at 4 t and μ = 0.8, 34.0 N·m at 4.67 t and μ = 0.4, 35.4 N·m at 4.67 t and μ = 0.8, 34.5 N·m at 5.33 t and μ = 0.2, 39.2 N·m at 5.33 t and μ = 0.4, 40.0 N·m at 5.33 t and μ = 0.6, and 40.7 N·m at 5.33 t and μ = 0.8. In addition, simulation results show that the steering resistance torque is positively correlated with the front axle load and road adhesion coefficient. The greater the front axle load is, the greater the road adhesion coefficient is, and the greater the steering resistance torque will be. In order to meet the requirement of steering portability, the traditional EPS system designs the assist characteristic based on the maximum front axle load and high adhesion coefficient (μ = 0.8). When the front axle load decreases or the road adhesion coefficient becomes smaller, the steering resistance torque will also decrease. However, the traditional EPS assist characteristic does not consider the influence of the change of front axle load and road adhesion coefficient, and still outputs an assist torque corresponding to the maximum front axle load and high adhesion coefficient, so that there is too much assistance, which reduces the driver's road feeling and affects driving safety. When the road adhesion coefficient and the front axle load decrease at the same time, the steering wheel torque decreases even more due to the dual influence of the adhesion coefficient and the front axle load reduction. Since the front axle load and road adhesion coefficient are important factors that affect the steering resistance torque, the EPS control strategy needs to consider them comprehensively. The EPS control strategy that only considers the front axle load or road adhesion coefficient ignores another important influencing factor and cannot completely solve the above problems. Therefore, it is necessary to establish an EPS control strategy based on multiple-MAP to overcome the influence of the front axle load and road adhesion coefficient.

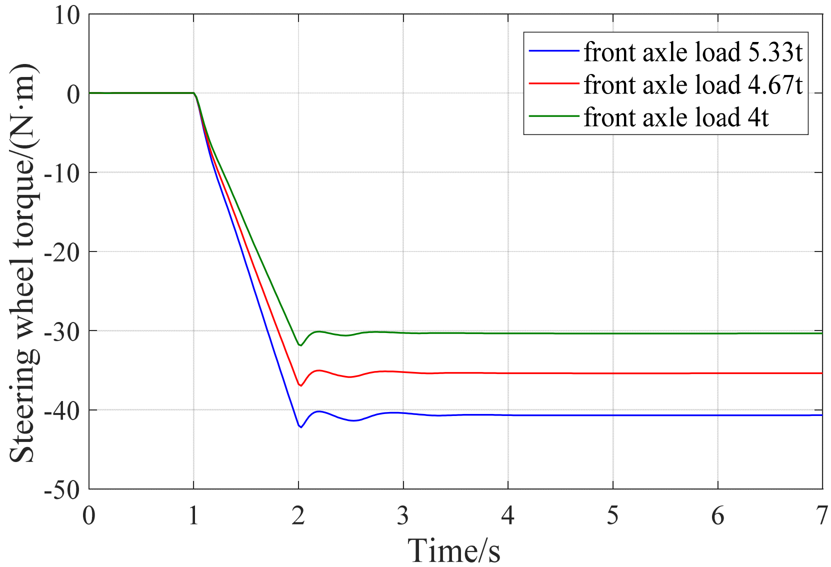

Figure 1. Steering wheel torque under different front axle loads at μ = 0.8.

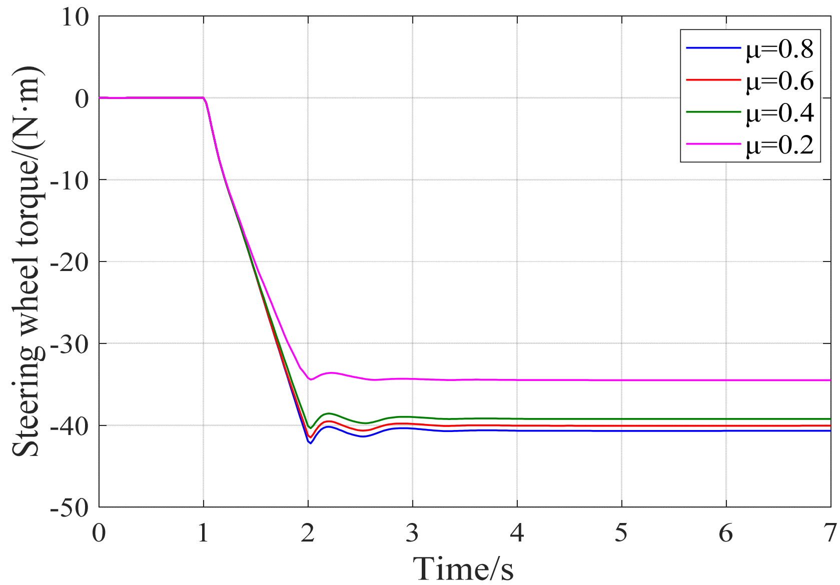

Figure 2. Steering wheel torque under different adhesion coefficients at front axle load 5.33 t.

3. EPS Control Strategy Based on Multi-Map

3.1. Determination of Steering Resistance Torque under Different Front Axle Loads and Road Adhesion Coefficients

When the vehicle is turning on the spot, the resistance torque is the largest, and the empirical formula can be used to obtain the resistance torque of the steering wheel when turning on the spot as shown in Equation (5).

$$T \frac{f}{3000i \cdot \eta}\sqrt{\frac{G^3}{p}}_{rmax} \quad (5)$$

where $T_{r\max}$ is the maximum steering resistance torque; f is the friction coefficient between the tire and the road; G is the front axle load of the vehicle; p is the tire pressure, which is 0.7 MPa; i is the steering gear ratio; and η is the transfer efficiency of the steering gear, which is 0.8.

In order to determine the steering resistance torque at other speeds, we set the adhesion coefficient to 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, and 0.2 in Trucksim, and we set the front axle load to 5.33 t, 5 t, 4.67 t, 4.33 t, and 4 t. Steering angle step tests are carried out at characteristic vehicle speeds of 20, 30, 40, 50, 60, and 70 km/h, and the steady-state value of the steering wheel torque is taken as the steering resistance torque, so the steering resistance torque corresponding to different front axle loads, adhesion coefficients, and characteristic vehicle speeds is obtained. The in situ steering resistance torque is added to obtain a total of $7 \times 5 \times 7 = 245$ groups of data, as shown in Table 1. When the adhesion coefficient is 0.8 to 0.5, we turn the steering wheel to stabilize the lateral acceleration of the vehicle to 0.3 g. Due to the high center of gravity of commercial vehicles, in order to prevent sideslip, when the adhesion coefficient is 0.4 and 0.3, the lateral acceleration can reach 0.2 g. When the adhesion coefficient is 0.2, the lateral acceleration can reach 0.15 g. Table 1 shows that the steering resistance torque is positively correlated with front axle load and road adhesion coefficient, and negatively correlated with vehicle speed.

The data in Table 1 are only the steering resistance torque data under limited conditions. If we want to get the resistance torque data under other conditions, it must be determined by fitting. Since the factors that affect the resistance torque are vehicle speed, front axle load, and adhesion coefficient, traditional polynomial curve fitting cannot be used, and spatial surface fitting is required. Spatial surface fitting methods including the B-spline method, parametric spline method, and non-uniform rational B-spline method, but the implementations are all relatively complicated. The neural network learns the mapping relationship between input and output offline, which can fully approximate complex nonlinear mapping and can be used to replace complex nonlinear law. The back propagation (BP) neural network has the advantages of a simple structure and accurate output, which can be used to simulate the output of nonlinear systems [13–15]. The following is based on the data in Table 1 to train the BP neural network to predict the steering resistance torque under different conditions.

The input of BP neural network is three parameters, including adhesion coefficient, front axle load, and vehicle speed, and the output is steering resistance torque. The number of neurons in the input layer and output layer of the BP neural network are three and one, respectively. The double hidden layer network with the number of neurons [5,5] is used, and the network topology is [3,5,5,1]. The activation functions between the layers of the network are the logsig function, the logsig function and the purelin function in turn, and the training function is the trainlm function. The network learning rate is set to 0.0001, the number of iterations is 1000. We set that if the loss value does not decrease for 50 consecutive times, the training ends. We divide the 245 groups of data in Table 1 into 217 groups for neural network training, and 28 groups for performance testing of a mature neural network. From 217 sets of training data, 174 sets of training data and 43 sets of verification data are randomly selected at 8:2. During the neural network training process, the normalized Mean Squared Error (MSE) loss graph is shown in Figure 3.

Table 1. Steering resistance torque at different front axle loads, adhesion coefficients, and vehicle speeds/(N·m).

Adhesion Coefficient	Front Axle Load/t	Speed/km·h^{-1}						
		0	20	30	40	50	60	70
0.8	5.33	190.4	113.5	97.18	92.89	91.12	90.11	89.42
	5	172.9	103.34	88.48	84.5	82.86	81.9	81.23
	4.67	155.9	93.39	79.87	76.2	74.67	73.81	73.17
	4.33	139.4	83.53	71.36	68.02	66.61	65.79	65.2
	4	123.7	73.98	63.26	60.29	59.02	58.3	57.79
				⋮				
0.2	5.33	47.6	42.07	37.82	36.19	35.42	34.97	34.66
	5	43.2	38.57	34.55	33.04	32.32	31.9	31.61
	4.67	39	35.25	31.45	30.04	29.38	28.99	28.72
	4.33	34.9	32.27	28.7	27.39	26.77	26.41	26.16
	4	30.9	29.3	25.96	24.76	24.18	23.84	23.61

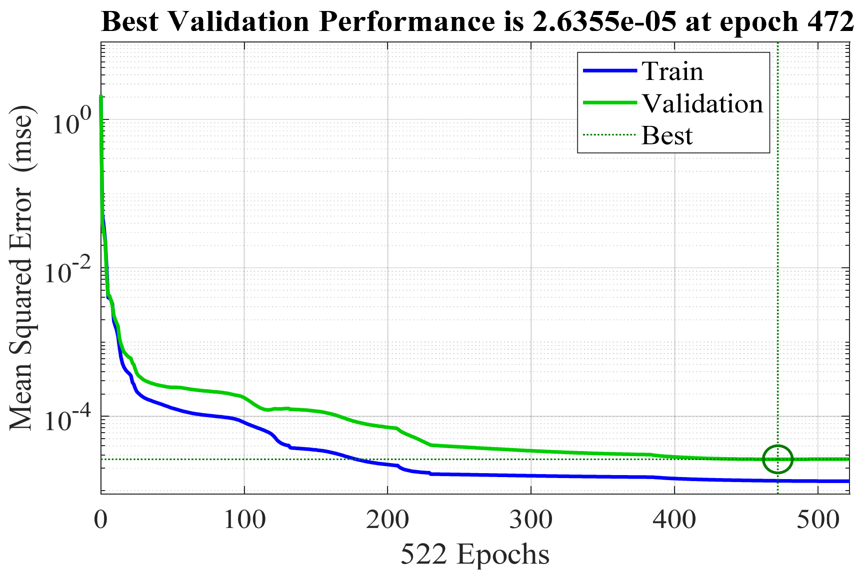

Figure 3. BP neural network mean square error loss graph.

It can be seen from Figure 3 that the loss value of the validation set is the smallest after 472 training. At this time, the normalized MSE is 2.6355 × 10^{-5}, and the anti-normalized calculation is 0.184 (N·m)^2. After 50 consecutive iterative learning, the loss value no longer drops; then, the training is terminated, and the network training ends. The BP neural network can be used to predict steering resistance torque. The parameters corresponding to the 28 sets of test data are input to the trained mature BP neural network and compared with the test set data. At this time, the prediction performance of the test set is shown in Table 2.

Table 2. Test set prediction results.

Evaluation Index		Value
Absolute error	minimum of absolute value/(N·m)	0.016
	average of absolute value/(N·m)	0.334
	maximum of absolute value/(N·m)	1.719
Relative error	minimum of absolute value/%	0.026
	average of absolute value/%	0.511
	maximum of absolute value/%	1.759
MSE/(N·m)^2		0.260

It can be seen from Table 2 that in the test data set, the average absolute value of the absolute error is 0.334 N·m, and the maximum value is 1.719 N·m. The average absolute value of the relative error is 0.511%, the maximum value is 1.759%, and the mean square error (MSE) is 0.2598 (N·m)^2, which are all within the acceptable range, indicating that the trained BP neural network can be used to predict the steering resistance torque under different conditions.

3.2. EPS Control Strategy Based on Multiple-MAP

According to the industry standard "QC/T 480-1999 Vehicle Handling Stability Index Limits and Evaluation Methods", for commercial vehicles with a total mass greater than 15 t, the maximum steering force of the steering wheel applied by the driver cannot exceed 220 N, and the average steering force cannot exceed 140 N. Combining with the diameter of the steering wheel of the commercial vehicle and considering reducing the possibility of the assist motor overload, it is set that when the driver's hand torque is greater than 23 N·m, the EPS system outputs the maximum assist torque at the corresponding vehicle speed and no longer changes. Therefore, the maximum assist torque required to be provided by the EPS system under different working conditions is shown in Equation (6).

$$T_{amax} = T_{rmax} - T_{dmax} \tag{6}$$

where T_{amax} is the maximum assist torque of the assist system; T_r is the steering resistance torque under different conditions, that is, the steering resistance torque output by the neural network; and T_{dmax} is the upper limit of the assist interval, which is 23 N·m. In order to avoid too-sensitive steering, if the driver's hand torque is less than 2 N·m, the assist motor does not provide assist torque.

From this, the initial assist point (2, 0) and the starting point of the maximum assist torque zone (23, T_{amax}) of the EPS can be obtained. The linear assist characteristic curve is simple in design and easy to implement. Therefore, this paper chooses the linear assist characteristic curve as shown in Figure 4 [16]. It can be seen from Figure 4 that the EPS assist characteristic curve can be determined from the initial assist point and the starting point of the maximum assist torque zone of the EPS system.

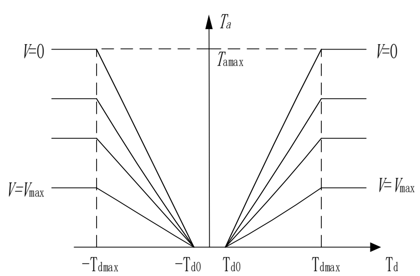

Figure 4. Linear assist characteristic curve.

It can be seen from Figure 4 that the function expression of the EPS assist characteristic curve is shown in Equation (7).

$$T_a = \begin{cases} 0\ 0 \leq |T_d| \leq 2N \cdot m \\ \frac{T_{amax}(v,m)}{21}(T_d - 2)\ 2N \cdot m \leq T_d \leq 23N \cdot m \\ -\frac{T_{amax}(v,m)}{21}(T_d + 2) - 23N \cdot m \leq T_d \leq -2N \cdot m \\ T_{amax}(v,m)\ |T_d| \geq 23N \cdot m \end{cases} \quad (7)$$

The EPS control strategy based on multiple-MAP is shown in Figure 5. As shown in the figure, the road adhesion coefficient, front axle load, and vehicle speed are input into the BP neural network to obtain the steering resistance torque, T_{rmax}. When the steering resistance torque and steering wheel torque are known, the EPS target assist torque can be obtained by Equations (6) and (7). Then, the current flowing through the motor is calculated according to the multi-map EPS control strategy. Finally, the PID controller is used to adjust the assist current and obtain the target assist torque. At this point, the assist steering is realized.

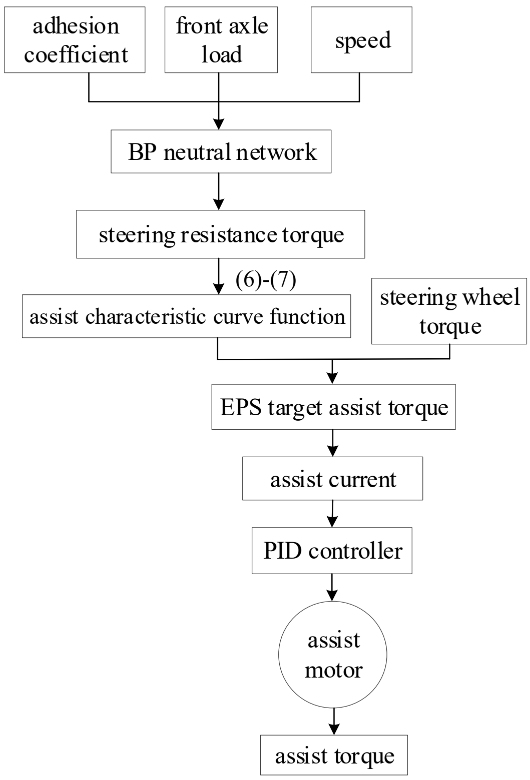

Figure 5. EPS control strategy based on multiple-MAP.

4. Simulation Verification

The EPS control strategy based on multiple-MAP is established based on Simulink, and it is verified by co-simulation with the commercial vehicle dynamics model built in Trucksim. In order to compare with the multiple-map EPS assist characteristic, based on the results of the steering resistance torque under the conditions of 0.8 for the adhesion coefficient and 5.33 t for the front axle load, the EPS control strategy is designed without considering the adhesion coefficient and the front axle load, and the EPS control strategy only considering the front axle load and control strategy only considering the adhesion coefficient.

4.1. Steering Portability Test

According to the regulation in GB/T 6323-2014, the lemniscate test is used to evaluate the steering portability. The vehicle speed is set to 10 km/h. The lemniscate test is carried out on the commercial vehicle under the conditions of front axle load 5.33 t, adhesion coefficient 0.8; front axle load 4.67 t, adhesion coefficient 0.4; and front axle load 4 t, adhesion coefficient 0.2. The test result is shown in Figure 6.

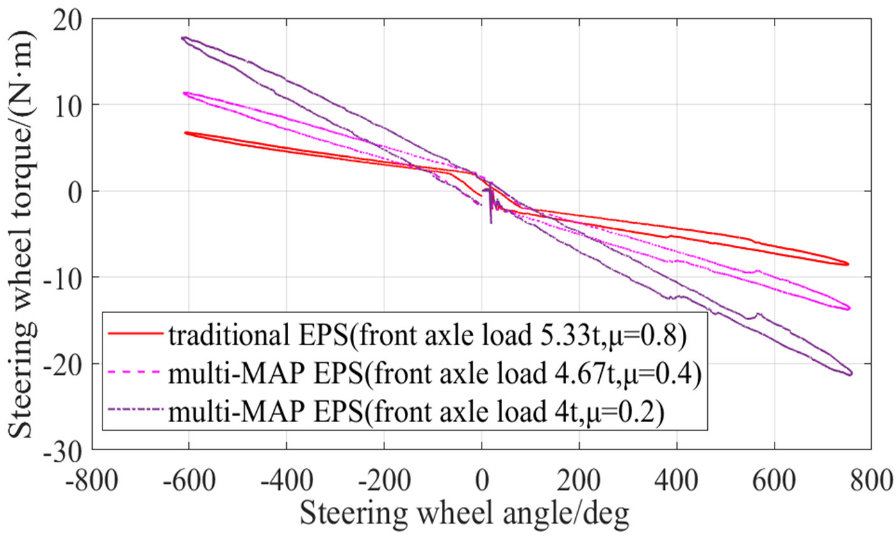

Figure 6. Steering wheel torque versus steering wheel angle.

According to Figure 6, the maximum streeing torque of the multi-map EPS at different conditions are shown as follows: 8.60 N·m at 5.33 t and μ = 0.8, 13.51 N·m at 4.67 t and μ = 0.4, and 20.32 N·m at 4 t and μ = 0.2. Lemniscate test results show that when the load is light or the adhesion coefficient is low, the EPS control strategy based on multiple-MAP increases the steering wheel torque. Under the condition of a front axle load of 4 t and adhesion coefficient of 0.2, the steering wheel torque based on the multi-map EPS is the largest, reaching 20.32 N·m. At this time, the maximum tangential force exerted on the steering wheel is 81.28 N. According to the requirement of the industry standard QC/T 480-1999 for steering portability, the maximum steering force of the steering wheel is used to evaluate the steering portability, and the evaluation formula is shown in Formula (8).

$$N_{Fm} = 60 + \frac{40}{F_{m60} - F_{m100}} \times (F_{m60} - F_m) \tag{8}$$

After calculation, the maximum steering force evaluation score N_{Fm} at this time is 110.4 points. According to the standard, when N_{Fm} is greater than 100, it is counted as 100 points. Therefore, the steering portability of the EPS system based on multiple-MAP meets the standard requirement, and at the same time improves the driving safety under a light load and low adhesion coefficient condition.

4.2. Steering Hand Torque Characteristic Verification

We refer to the regulation in GB/T 6323-2014 and ISO 13674-1 to test the steering wheel hand torque. In the low-speed zone, steering wheel hand torque is greatly affected by vehicle speed and steering wheel angle. The vehicle speed is set to 5 km/h, 10 km/h, and 15 km/h, and the steering wheel angle is 100°, 200°, 300°, 400°, 500°, 600°, and 700°. The angle step test is conducted under the condition of front axle load 5.33 t, adhesion coefficient 0.8; front axle load 4.67 t, adhesion coefficient 0.4; and front axle load 4 t, adhesion coefficient 0.2. At this time, the relationship between steady-state steering wheel torque and vehicle speed, and the steering wheel angle are shown in Figure 7. In the middle- and high-speed zone, the steering wheel hand torque is greatly affected by vehicle speed and lateral acceleration. The vehicle speed is set to 30 km/h, 40 km/h, 50 km/h, and 60 km/h. With a front axle load of 5.33 t and adhesion coefficient of 0.8, the lateral acceleration is set to 0.1 g, 0.2 g, and 0.3 g. With a front axle load of 4.67 t and adhesion coefficient of 0.4, the lateral acceleration is set to 0.05 g, 0.1 g, 0.15 g, and 0.2 g. With a front axle load of 4 t and adhesion coefficient of 0.2, the lateral acceleration is set to 0.05 g, 0.1 g, and 0.15 g. At this time, the relationship between steady-state steering wheel torque and vehicle speed, and the lateral acceleration are shown in Figure 8.

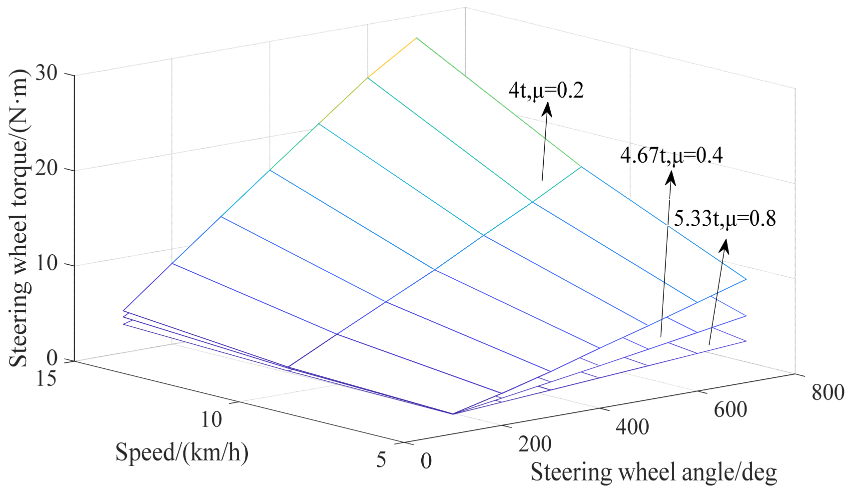

Figure 7. The relationship curve between steering wheel torque and vehicle speed and steering wheel at low speed.

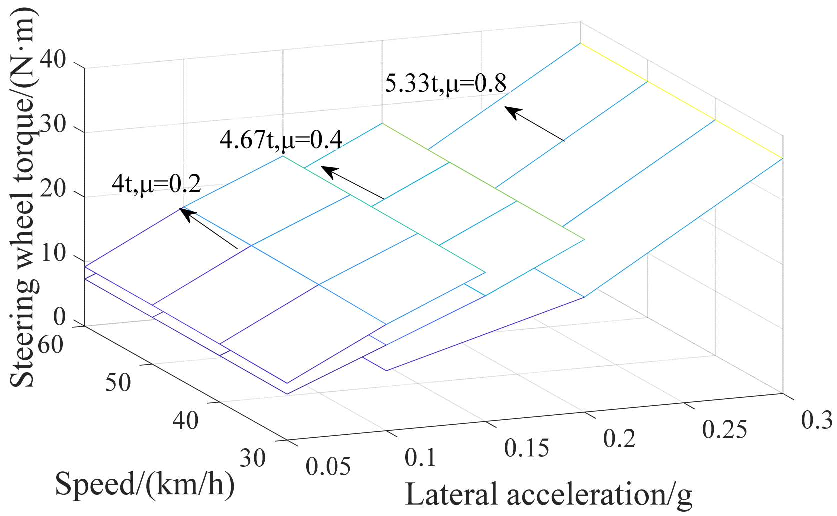

Figure 8. The relationship between steering wheel torque and vehicle speed and lateral acceleration at medium and high speed.

It can be seen from Figures 8 and 9 that the hand torque under the control strategy of the EPS system based on multi-map has the following characteristics:

(1) The steering hand torque increases with the increase of vehicle speed.
(2) The steering hand torque increases with the increase of steering wheel angle.
(3) The steering hand torque increases with the increase of lateral acceleration.
(4) When front axle load decreases and adhesion coefficient decreases, the driver's hand torque increases and the steering wheel becomes "heavier", which improves the ability of the steering system to resist road interference, effectively serving as a reminder to the driver.

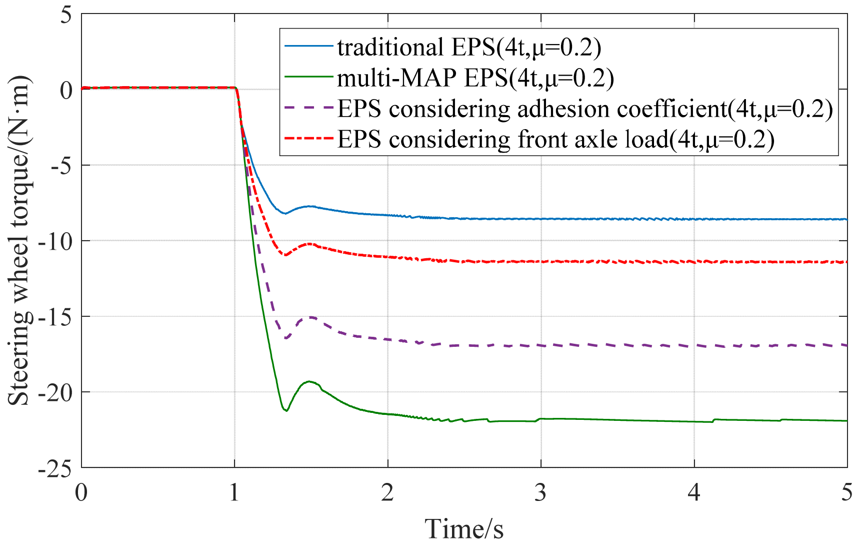

Figure 9. Comparison of steering wheel torque of different EPS system.

From the steering wheel hand torque test results, it can be seen that the hand torque characteristics based on the multi-map EPS system control strategy are in line with the ideal steering wheel torque characteristics of commercial vehicles [17–19].

4.3. Steering Wheel Angle Step Test

The steering wheel angle step test is used to determine the vehicle's transient response to the steering wheel angle input. We set the vehicle speed to 60 km/h, quickly turn the steering wheel to 60 at 1 s, and record the steering wheel torque. For the traditional EPS, the EPS based on multiple-MAP, and the EPS system only considering front axle load, and the EPS system only considering adhesion coefficient, the steering wheel angle step test is carried out under different front axle load and adhesion coefficient conditions. When the front axle load is 4 t and adhesion coefficient is 0.2, the torque of different EPS steering wheels is shown in Figure 9.

According to Figure 9, steady values of steering wheel torque of different EPS at the angle step test are shown as follows: at 5.33 t and $\mu = 0.8$, traditional EPS: 13.99 N·m, EPS only considering front axle load: 14.06 N·m, EPS only considering adhesion coefficient: 13.90 N·m, Multi-map EPS: 14.00 N·m; at 5.33 t and $\mu = 0.2$, traditional EPS: 11.51 N·m, EPS only considering front axle load: 11.57 N·m, EPS only considering adhesion coefficient: 23.13 N·m, Multi-map EPS: 22.89 N·m; at 4 t and $\mu = 0.8$, traditional EPS: 10.37 N·m, EPS only considering front axle load: 13.75 N·m, EPS only considering adhesion coefficient: 10.27 N·m, Multi-map EPS: 14.05 N·m; at 4 t and $\mu = 0.2$, traditional EPS: 8.59 N·m, EPS only considering front axle load: 11.42 N·m, EPS only considering adhesion coefficient: 16.94 N·m, Multi-map EPS: 21.91 N·m. Therefore, simulation results show that under the same angle input, in the traditional EPS system, when the front axle load and road adhesion coefficient become smaller, the steering wheel torque is significantly reduced, which makes the driver's road feeling worse, and it is not conducive to driving safety. At this time, the EPS system based on multiple-MAP and EPS only considering front axle load and EPS only considering adhesion coefficient all increase the steering wheel torque, and the EPS based on multiple-MAP can more fully consider the effects of front axle load and adhesion coefficient, and improve the driver's road feeling better.

The lateral acceleration and yaw rate in the steering wheel angle step test are selected to evaluate the handling stability of the vehicle. When the front axle load is 4 t and the adhesion coefficient is 0.2, the lateral acceleration and yaw rate of the vehicle equipped with different EPS systems are shown in Figures 10 and 11.

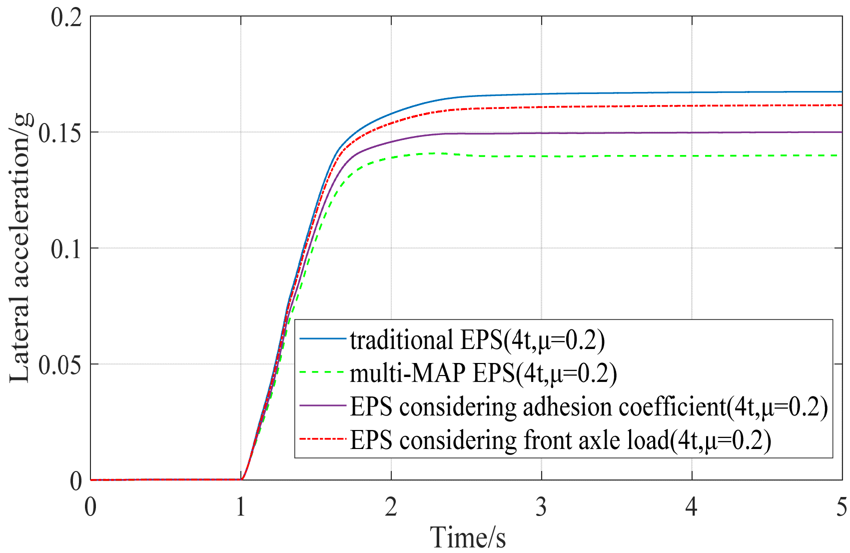

Figure 10. Comparison of lateral acceleration of different EPS.

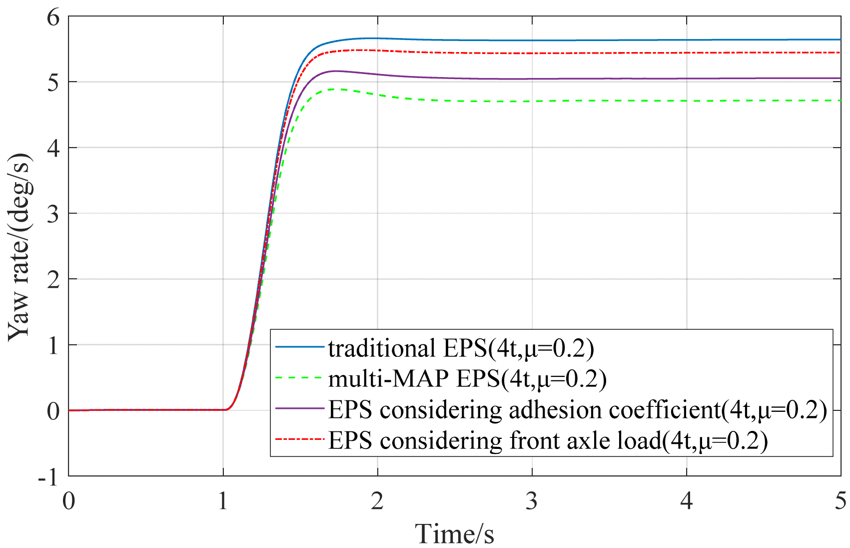

Figure 11. Comparison of yaw rate of different EPS.

According to Figures 10 and 11, the steady-state values of lateral acceleration and yaw rate of different EPS under different front axle loads and adhesion coefficients are shown as follows: at 5.33 t and μ = 0.8, traditional EPS: 0.1532 g and 5.160 deg/s, EPS only considering front axle load: 0.1530 g and 5.156 deg/s, EPS only considering adhesion coefficient: 0.1534 g and 5.168 deg/s, Multi-map EPS: 0.1532 g and 5.163 deg/s; at 5.33 t and μ = 0.2, traditional EPS: 0.1566 g and 5.279 deg/s, EPS only considering front axle load: 0.1565 g and 5.275 deg/s, EPS only considering adhesion coefficient: 0.1344 g and 4.527 deg/s, Multi-map EPS: 0.1346 g and 4.539 deg/s; at 4 t and μ = 0.8, traditional EPS: 0.1652 g and 5.568 deg/s, EPS only considering front axle load: 0.1584 g and 5.344 deg/s, EPS only considering adhesion coefficient: 0.1654 g and 5.574 deg/s, Multi-map EPS: 0.1579 and 5.320 deg/s; at 4 t and μ = 0.2, traditional EPS: 0.1674 g and 5.641 deg/s, EPS only considering front axle load: 0.1614 g and 5.442 deg/s, EPS only considering adhesion coefficient: 0.1500 g and 5.055 deg/s, multi-map EPS: 0.1399 g and 4.715 deg/s. Therefore, simulation results show that compared with traditional EPS, the steady-state values of the vehicle lateral acceleration and yaw rate are reduced after adopting the EPS based on multiple-MAP, indicating that the vehicle's handling stability has been improved. The lateral acceleration and yaw rate of the vehicle using the multi-map EPS are smaller than the EPS only considering front axle load and EPS only considering adhesion coefficient, indicating that the EPS based on multiple-MAP makes the vehicle more stable.

4.4. On-Center Road Feeling Test

The road feeling study in the central area uses the index of the torque gradient in the range of small lateral acceleration, that is, the change rate of steering wheel torque relative to the lateral acceleration. The larger the torque gradient is, the better the road feeling of the driver will be [20,21]. According to the provisions of the handling stability test of the steering wheel center area in the GB/T 6313-2014, the test vehicle speed is set to 60 km/h, and the steering wheel input sine wave with frequency of 0.2 Hz. In order to prevent the vehicle from sideslip and instability, the peak value of the lateral acceleration of the vehicle is kept at about 0.15 g. For the traditional EPS system, the EPS system based on multiple-MAP, and the EPS only considering front axle load and EPS only considering adhesion coefficient, the road feeling test in the central area is carried out under the condition of different front axle loads and adhesion coefficients. When the front axle load is 4 t and adhesion coefficient is 0.2, on-center road feeling test results of the EPS with different control strategies are shown in Figure 12. Table 3 shows the steering wheel torque gradient at 0 g and ±0.1 g under different front axle loads and adhesion coefficients.

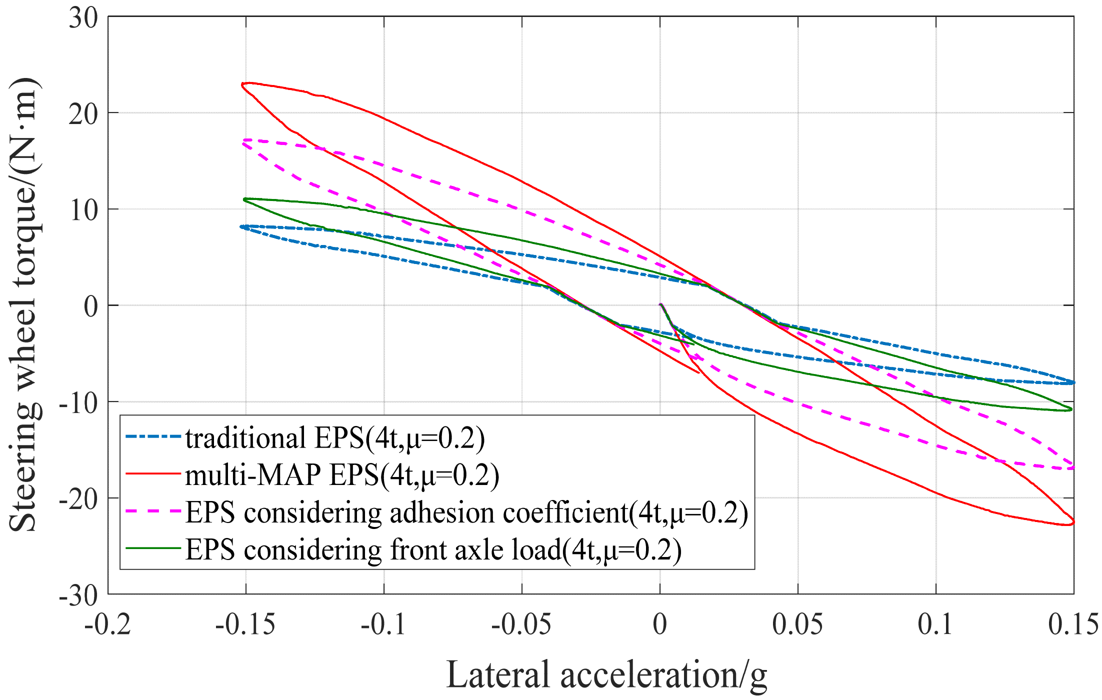

Figure 12. Results of on-center road feeling test under different EPS control strategies.

Table 3. Steering wheel torque gradient at front axle load 4 t and μ = 0.2/(N·m/g).

Simulation Condition	0.1 g		0 g		−0.1 g	
	On	Below	On	Below	On	Below
Traditional EPS	55	34	53	59	42	55
Multiple-MAP EPS	175	120	164	167	130	174
EPS only considering front axle load	81	52	75	79	59	77
EPS only considering adhesion coefficient	129	86	123	124	95	128

Simulation results show that when the front axle load is 4 t and the adhesion coefficient is 0.2, the steering wheel torque gradient with the lateral acceleration of 0 and ± 0.1 g of the multi-map EPS vehicle is larger than that of the traditional EPS and EPS only considering front axle load and EPS only considering adhesion coefficient, which indicates that the EPS based on multiple-MAP makes the driver's road feeling in the central area clearer, more effectively improves the road feeling of the driver under low adhesion coefficient and light load conditions, and makes the driver's judgment of the road condition more accurate.

5. Conclusions

The front axle load and road adhesion coefficient are important factors that affect steering resistance torque. In order to ensure portability steering, the traditional EPS design assist characteristic is based on full load and high adhesion coefficient working condition. When the front axle load and road adhesion coefficient become smaller, the traditional EPS will generate too much assist, reduce the driver's road feeling, and affect driving safety. On the basis of the traditional EPS, road adhesion coefficient and front axle load are added as consideration factors in the design of assist characteristic. Based on a BP (Back Propagation) neural network, the resistance torque under different front axle load and adhesion coefficient conditions is determined, and an EPS control strategy based on multiple-MAP is designed. Through steering portability, steering hand torque verification, steering wheel angle step input, and on-central area road feeling test, it is shown that the EPS control strategy based on multiple-MAP meets the requirement of the national standard for steering portability, and the steering torque characteristic is in line with the ideal steering wheel torque characteristic for commercial vehicles. Compared with the traditional EPS and EPS only considering front axle load and EPS only considering adhesion coefficient, the EPS based on multiple-MAP can better overcome the influence of front axle load and road adhesion coefficient change, improving vehicle handling stability. It increases the driver's road feeling under a light load and low adhesion coefficient condition, and improves driving safety. The proposed EPS control strategy will be verified by experiments in future.

Author Contributions: Methodology, Y.L.; Software, Z.Y.; Validation, D.Z. and J.F.; Formal analysis, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Xi'an Beilin District Science and Technology Project (Grant NO. GX2252).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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