ORIGINAL ARTICLE

A numerical simulation of vehicle dynamics behavior for a four-wheel steering vehicle with the passive control system

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ABSTRACT – The Advanced Driver Assistance System (ADAS) is a technology in the vehicle to assist drivers in mitigating road risk and improving maneuverability. The system is capable of providing warnings to drivers and even executing an action if necessary. However, these systems are limited to the sensors and capability of the vehicle. Increasing the degree of freedom of a vehicle could potentially develop new ADAS with more efficiency. Along with the X-By-Wire technology, a four-wheel drive and independent steering (4WDIS) can be produced as a part of ADAS, especially for electric vehicles. In this research, an understanding of the steering characteristic of a 4WDIS during steady-state cornering (SSC) is presented using numerical simulation in MATLAB. An actual Segment B type vehicle is used as a simulation model and a preliminary two-wheel steering SSC simulation was performed to determine the steering characteristics. The model is modified to include a rear steer angle with a passive control system and the SSC simulation was repeated. The results show that the vehicle can perform SSC by increasing the yaw rate at high speed using the opposite steering mode. Meanwhile, parallel steering mode is suitable during low-speed cornering which can increase the yaw rate while maintaining stability.

INTRODUCTION

More and more modern vehicles are equipped with advanced driver assistance systems (ADAS) [1]. ADAS is supporting many vehicle functions, such as adaptive cruise control, automatic parking, collision warning, and automatic driving mode [2]. In addition to driver comfort and assistance, these systems can also be used to prevent vehicles from colliding with other objects or other vehicles, thereby improving safety [3, 4]. For example, when ADAS gives a proximity warning, and the driver fails to deal with it immediately, the system will force the vehicle to brake urgently, thereby avoiding a collision [5]. However, these systems are limited to the vehicle's sensors and capability [6]. It requires coordination between many sensors and cameras to complete the assistance work of the vehicle. The automatic driving function will control the vehicle automatically to avoid car accidents happen when the vehicle lost control and starts to deviate from the lane, not by the driver's control [7]. Usually, most of the vehicles to have an understeer (US) or oversteer (OS) phenomenon occur was due to the driver's wrong operation US phenomenon is during the vehicle cornering [7, 8]. The steering angle cannot be achieved to the suitable cornering steering angle, also means the yaw moment is smaller than the actual needs [9]. OS is when the car steering angle more than the driver commanded, also means the value of the yaw moment is more than actual cornering needs [10]. There are many traffic accidents happen when the vehicles are lost control by the driver operation error [11]. To solve the problem of the vehicle are US and OS, by using X-by-wire technology in this research, the model vehicle is transformed into an electric vehicle model that can realize 4WDIS [12]. this is in order to increase the degree of freedom of the vehicle, thereby developing a more efficient ADAS [13]. For the 4WDIS, the opposite steering mode means the rear wheel has a different direction from the front wheel. The parallel steering mode means the rear and front-wheel turning in the same direction.

Generally, the four-wheel drive (4WD) refers to the four wheels of a modern vehicle that can provide power to the movement of the vehicle, but different types of vehicles provide power in different ways [14]. The way that the motor vehicle provides the power is that the engine transmits power to the wheels through the transmission shaft, and the electric vehicle (EV) is powered by the vehicle power supply driving the motor, and the motor powers the wheels through the transmission shaft [15]. The in-wheel motor also called a wheel hub motor, is an electric motor that is mounted in a wheel hub and can be direct drives it. In-wheel motor is usually used on EVs [16, 17]. This type of motor cuts mechanical losses, which are inherent in every component between the engine and wheel, and makes the car run more quietly. It also cuts weight which saves energy for the vehicle. All the wheels of EVs equipped with in-wheel motors can be controlled independently. It will be more able to achieve four-wheel drive independent steering (4WDIS) [18]. EVs are also a type of new energy vehicle [19], so EVs were selected for the simulation vehicle type in this paper.

The Equation of motion (EOM) has two main descriptions of motion: dynamics and kinematics [20]. This paper uses dynamic equations of motion (DEOM) to simulate the vehicle. Due to there are many assumptions for the linear equation, even it is easier to calculate manually but the calculation results often deviate from the real results. Because of this study

uses MATLAB Simulink software to do the calculations in order to calculate the results more accurately, this paper uses nonlinear DEOM for simulation.

In this study, the numerical simulation of the linear DEOM with a 4WDIS EV was performed There are eight different speed values was set by used in this study which are 10 km/h, 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h and 80 km/h. The simulation time range setting is 100s for each speed. For the steering angle, it starts with zero degrees and simulating with every single angle. The rules of the steering angle, positive means wheel turn left, negative means the wheel turn right. For the simulation, start with two-wheel steering (2WS) to find the stability velocity. Based on the results shown, the vehicle is oversteering when the vehicle speed rich to 50 km/h. So, the speed lower than 50 m/h use opposite steering mode, the speed greater or equal to 50km/h use parallel steering mode.

METHODOLOGY

Vehicle Model

Figure 1 illustrated the Malaysian car brand-Proton, a Segment B type research vehicle from the University of Malaysia Pahang under the Automotive Engineering Center. The car is a sedan type with a 1.6-liter engine capacity and a manual transmission. This test car was used in the research to provide the specification for the numerical simulation. All the basic specifications of the simulation model have been derived from this vehicle.

Figure 1. Testing vehicle of Universiti Malaysia Pahang

Vehicle Dynamics Equation

The key emphasis of vehicle dynamics analysis is on how vehicles react to driver feedback on a specific route. The dynamic equation of motion is derived from the application of Newton's law within the inertial frame of reference. For dynamic equation, longitudinal velocity, lateral velocity, and yaw rotational velocity were used in this paper [7]. In order to make the simulation result more realistic, the equation adopts a nonlinear equation, and the equations are listed below.

$$m\left(\frac{du}{dt} - v\gamma\right) = (X_{FR} + X_{FL})\cos\theta_F + (X_{RR} + X_{RL})\cos\theta_R - (Y_{FR} + Y_{FL})\sin\theta_F - (Y_{RR} + Y_{RL})\sin\theta_R \tag{1}$$

$$m\left(\frac{dv}{dt} + u\gamma\right) = (X_{FR} + X_{FL})\sin\theta_F + (X_{RR} + X_{RL})\sin\theta_R + (Y_{FR} + Y_{FL})\cos\theta_F + (Y_{RR} + Y_{RL})\cos\theta_R \tag{2}$$

$$\begin{aligned}
I\frac{d\gamma}{dt} = {} & l_F[(X_{FR} + X_{FL})\sin\theta_F + (Y_{FR} + Y_{FL})\cos\theta_F] + l_R[(X_{RR} + X_{RL})\sin\theta_R + (Y_{RR} + Y_{RL})\cos\theta_R] \\
& + \frac{d_F}{2}[(X_{FR} + X_{FL})\cos\theta_R + (Y_{FR} + Y_{FL})\sin\theta_F] \\
& + \frac{d_R}{2}[(X_{RR} + X_{RL})\cos\theta_R + (Y_{RR} + Y_{RL})\sin\theta_R]
\end{aligned} \tag{3}$$

Tire Characteristics

In this research, the wheel is an important factor because it will affect the movement of the vehicle. Furthermore, during the simulation process, the slip ratio, the side-slip angle of the tire, and the weight distribution are all taken into consideration when measuring the friction force and the side lateral force. The tire model was based on the brushless tire model and it's also a nonlinear model. The deformation of the rubber tire tread is also used to derive these non-linear equations shown below.

When $\xi s > 0$, then the equations of longitudinal force and lateral force can be written as:

$$F_x = -K_s s \xi_s^2 - 6\mu F_z \cos\theta \left(\frac{1}{6} - \frac{1}{2}\xi_s^2 + \frac{1}{3}\xi_s^3\right) \tag{4}$$

$$F_y = -K_\beta(1+s)\tan\beta\,\xi_s^2 - 6\mu F_z \sin\theta \left(\frac{1}{6} - \frac{1}{2}\xi_s^2 + \frac{1}{3}\xi_s^3\right) \tag{5}$$

And when $\xi s \leq 0$, then

$$F_x = -\mu F_z \cos\theta \tag{6}$$

$$F_y = -\mu F_z \sin\theta \tag{7}$$

Where :

$$\tan\theta = \frac{K_\beta \tan\beta (1+s)}{K_s s} \qquad\qquad \cos\theta = \frac{s}{\lambda}$$

$$\sin\theta = \frac{K_\beta \tan\beta (1+s)}{K_s \lambda}$$

During the simulation, the equation of the point at which the contact surface changes from the adhesive region to the slip region is identified as follows:

$$\xi_s = 1 - \frac{K_s}{3\mu F_z}\lambda \tag{8}$$

Where :

$$K_s = \frac{bl^2}{2}K_x \qquad\qquad K_\beta = \frac{bl^2}{2}K_y$$

$$\lambda = \sqrt{s^2 + \left(\frac{K_\beta}{K_s}\right)^2 (1+s)^2 \tan^2\beta}$$

The side-slip angle equation for each tire is given as below:

$$\beta_{FL} = \tan^{-1}\left(\frac{v + l_F\gamma}{u + d_F\frac{\gamma}{2}}\right) - \theta_F \qquad , \qquad \beta_{RL} = \tan^{-1}\left(\frac{v - l_R\gamma}{u + d_R\frac{\gamma}{2}}\right) - \theta_R \tag{9}$$

$$\beta_{FR} = \tan^{-1}\left(\frac{v + l_F\gamma}{u - d_F\frac{\gamma}{2}}\right) - \theta_F \qquad , \qquad \beta_{RR} = \tan^{-1}\left(\frac{v - l_R\gamma}{u - d_R\frac{\gamma}{2}}\right) - \theta_R$$

Tire slip ratio s is used to calculate and express the slipping behavior of the vehicle wheel. The equation is shown below:

$$s = \frac{u - r\omega}{r\omega} \tag{10}$$

The coefficient of tire friction μ can be approximated by the following equation:

$$\mu = -1.10k \times (e^{35\rho} - e^{0.35\rho}) \tag{11}$$

Passive Control System

In this study, passive control is used to observe the influence of the rear wheels on the direction of the vehicle after the vehicle has skidded. Tire rotational speed ω is one of the variable and represents the different rated speeds of the vehicle. This vehicle's velocity is determined by the constant input of the tire rotational speed. As the vehicle reaches a constant speed, the front wheel steering angle θF is adjusted to rotate at a constant speed to the defined angle (to allow the observation of the influence of different angles of the rear wheels on the vehicle state, the defined angle is set to 10 degrees, θF=10°). There is a various method to initiate the rear steer angle. In this research, the rear steer angle is proportional to the front steer angle. The gain of the proportionality is the objective which will be studied in the research.
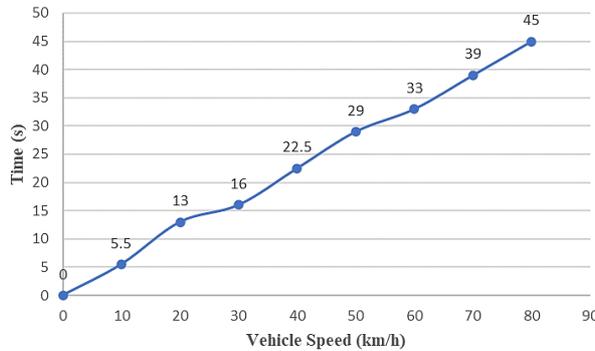

Figure 2. The front-wheel steering angle input against time

The Figure 2 is the start steering time of the steering wheel. Starting time was determined based on the time after the vehicle has achieved a constant speed. It can be seen from the Figure 2 that as the value of the required speed increases, the time for the vehicle to reach a constant speed also increases. Calculating the time when the steering wheel starts to turn is to reduce the error, The yaw value will be affected when the vehicle starts to turn before reaching a constant speed and the final yaw value will be affect too.

Simulation Producdures

This research was executed by using the software of MATLAB Simulink to do the simulation [20]. Firstly, the modeling is done in the software that includes the vehicle's specifications and parameters. Then, the simulation is divided into two stages, which is the first stage is the 2WS steady-state cornering simulation, and the second stage is the 4WDIS steady-state cornering simulation. In both simulations, the front-wheel steering angle of the vehicle was fixed θF=10°. However, in the second stage simulation, the angle of the rear wheel is set as a dependent variable regulated by the value of k. The k value is an actual independent variable that is determined according to the effects of the two-wheel steering simulation.

Steady-state Cornering with Two-Wheel Steering

For the simulation of the two-wheel steering, the k value must be set as zero and the tire rotational velocity must be set as the input variable. The vehicle can be driven with two-wheel steering when the rear-wheel steering angle is zero. After the parameter has been set, simulate with ΔF=0 ° in order to know the time it takes for the vehicle's speed reach a constant value. After the steering time has been calculated, then running the simulation with the ΔF=10 ° and start time for steering which following Table 1.

Table 1. Tire rotational speed with the front wheel steering initiate timing

Item No	Target Speed		Tire rotational speed （ω）	Theta F	Start time for steering
	km/h	m/s	rad/s	degree	s
1	10	2.7778	9.3371		5.5
2	20	5.5556	18.6741		13
3	30	8.3333	28.0112		16
4	40	11.1111	37.3483	10	22.5
5	50	13.8889	46.6853		29
6	60	16.6667	56.0224		33
7	70	19.4444	65.3595		39
8	80	22.2222	74.6965		45

Table 1 described when the vehicle had to start steering. The table shows four items. The first is the target speed which is the speed that this paper needs to be used. Second is the tire rotational speed (ω) which calculated by vehicle velocity divided by the radius of the tire. The equation is shown below:

$$\omega = \frac{V}{r} \tag{12}$$

Where: "V" is the vehicle " target speed ",

Steady-state Cornering with Four-Wheel Steering

For the 4WS simulation, the k value is a ratio between the front and rear-wheel steering angle, and it is used to control the rear-wheel steering angle. When the US phenomenon occurs in the vehicle, that is, the vehicle's yaw angle fails to reach the required yaw angle value for turning, then the vehicle needs to use the positive steering mode to increase the yaw angle. When the vehicle has an OS phenomenon, that is, the yaw angle of the vehicle is greater than the value required for turning, then the vehicle needs to use parallel steering mode to reduce the yaw angle. It can be seen from Equation 3 that different vehicles require different yaw angle values when turning. Normally, there is not necessary to find a fixed yaw angle. When the vehicle is at the same speed and the steering angle is the same, as long as the vehicle can do steady-state cornering (SSC), it can be considered that the yaw angle is normal in this case.

When starting the four-wheel steering simulation, it was found that the speed of the vehicle after steering was less than the set speed and the steering speed also changed with the change of k value. This paper uses tire rotational speed as a variable to simulate in order to intuitively distinguish the state of the rear-wheel steering at different speeds impact. And tire rotational speed can also be called the speed displayed on the car dashboard. Usually called as the speed of the vehicle. When the test speed is 10km/h, 20km/h, 30km/h, 40km/h, and 50km, the steering speed of the vehicle can reach a uniform speed. However, when the vehicle speed is lower than 30km/h, the vehicle has a US phenomenon. Meanwhile, the vehicle needs a larger steering angle to make a cornering. By applying the 4WDIS system which is decreasing the k value to increase the steering angle, the vehicle can still make a steady-state cornering even when turning at a low speed. When the set speed is 60km/h, the vehicle will slip slightly when cornering and the speed of the vehicle cannot reach a constant speed. When the vehicle speed is greater than or equal to 70km/h, the vehicle has an OS phenomenon. By applying the 4WDIS system which is increases the value of k to reduce the steering angle, so that the vehicle can make steady-state cornering at high speeds. The determination of the k value of a certain speed depends on whether the vehicle can make a steady-state cornering at this k value.

RESULTS AND DISCUSSION

Results for Steady Steady-State Corning with Two-Wheel Steering

Figure 3 shows the results of the simulation for the SSC with two-wheel steering. In this figure, the yaw rate is plotted based on the last constant value during the SSC for each constant vehicle's velocity. The yaw rate increases when the constant velocity for the SSC increases. However, after 30 km/h, the yaw rate is saturated in between the range of 0.2581 to 0.2439 rad/s. When the vehicle speed is over 60 km/h, the vehicle could not have a constant yaw rate, which means that it could not perform SSC. The dotted line in the figure does not represent the value when the vehicle reaches a constant speed. These values are taken from the value of the yaw angle that the vehicle can reach when the simulation time is 100 seconds. The changes in the yaw rate for each constant velocity during the SSC can be shown in Figure 4 to further explain the vehicle behavior.

Figure 4 shows the changes in the yaw rate with time for each constant velocity during steady-state cornering. When the constant velocity is the range of 10km/h until 50km/h, the yaw rate can maintain a constant value after a period of time. However, when the constant velocity is 60 km/h, they can no longer have a constant yaw rate and there was a slight increase in the value during the SSC. In the case of the constant velocity above 60 km/h, the increase in the yaw rate is very visible especially for velocity 80 km/h. So, we can conclude that above the 60km/h, the vehicle yaw rate could not perform the SSC. The yaw rate for the constant velocity increases which shows that the vehicle is in OS condition. Therefore, in this region, the parallel steering of the four-wheel steering should be implemented. About the steering mode selection, the speed higher than 60km/h been decided to use parallel steering mode which is the k value is positive, and the speed lower than 60km/h been decided to use opposite steering mode which is k value is negative.
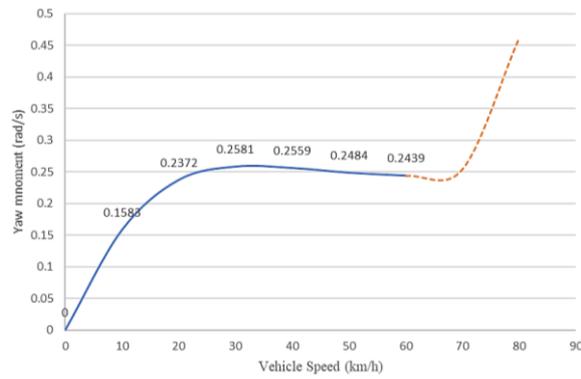
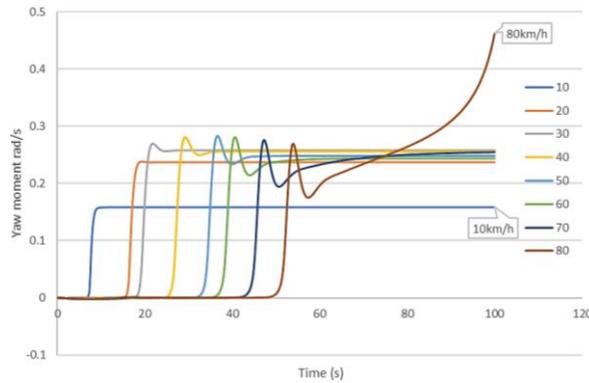**Figure 3.** The constant value of yaw at different speeds

Figure 4. The yaw moment changes with the various speed

Steady-State Cornering with Four-Wheel Steering

Figure 5 to 8 shows that how the k value effect the vehicle yaw moment for the speed from 10km/h to 40 km/h. At these speeds, the vehicle will have US phenomena occur. So, the negative k value was applied to increase the yaw moment since the yaw moment is very small. Based on the results of each figure, it is easy to find that the yaw moment can be reached to constant when the vehicle speed range between 10km/h and 40 km/h. After applied the 4WS system, the constant yaw moment value is rising almost at a constant speed. In Figure 8, the yaw moment is keeping increasing when the speed of the vehicle at 40 km/h and the k = -3. It means that the vehicle had an OS phenomenon that happened in this condition.
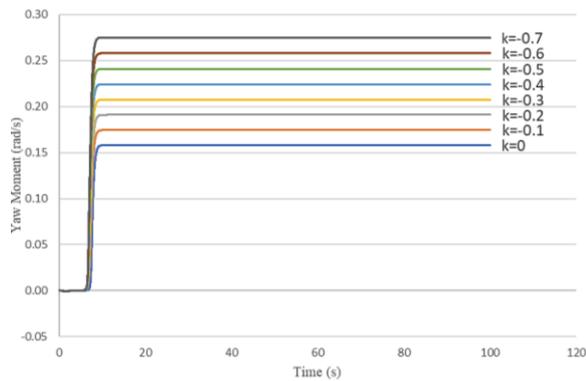

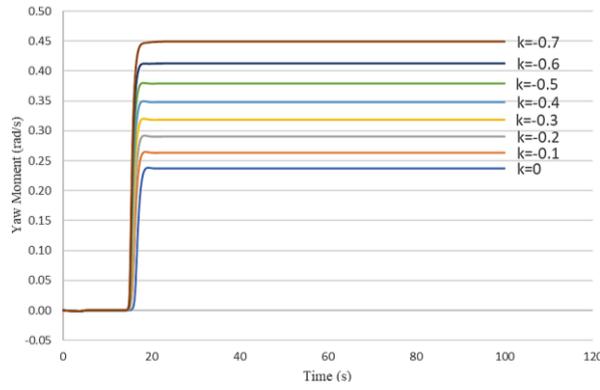**Figure 5.** The yaw moment for the vehicle speed at 10 km/h
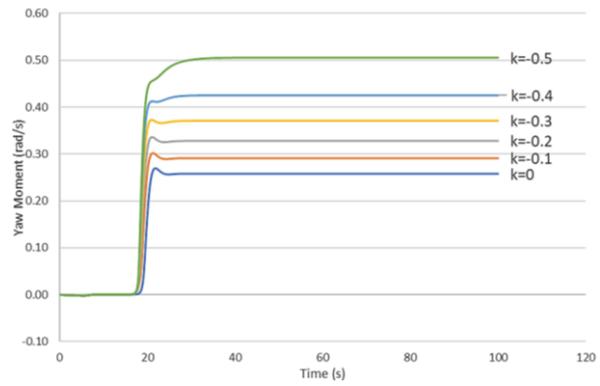
Figure 6. The yaw moment for the vehicle speed at 20 km/h

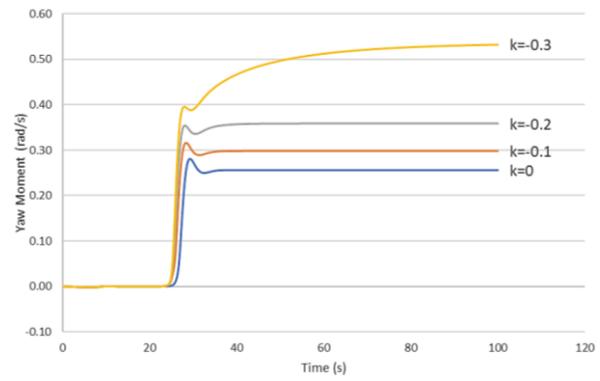**Figure 7.** The yaw moment for the vehicle speed at 30 km/h

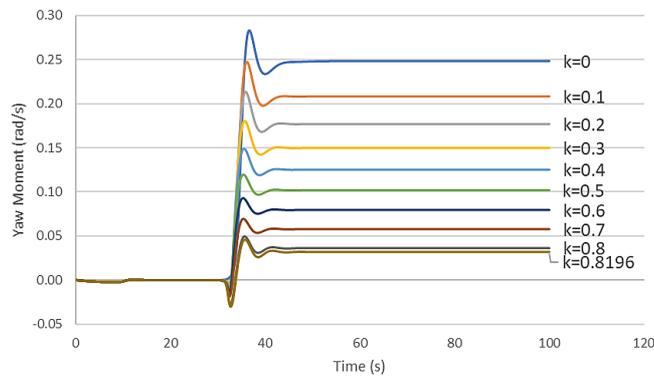**Figure 8.** The yaw moment for the vehicle speed at 40 km/h

Figure 9. The yaw moment for the vehicle speed at 50 km/h

Figure 9 is the yaw moment at different k value from 0 ~8 when the vehicle speed at 50 km/h. The top line is during the k = 0, which means that this is 2WS line, the bottom line is when k = 0.8196, this k value is getting from many times

simulation, This line with the means of the vehicle speed equals to vehicle velocity. This k value also the dividing line between OS and US for this speed.
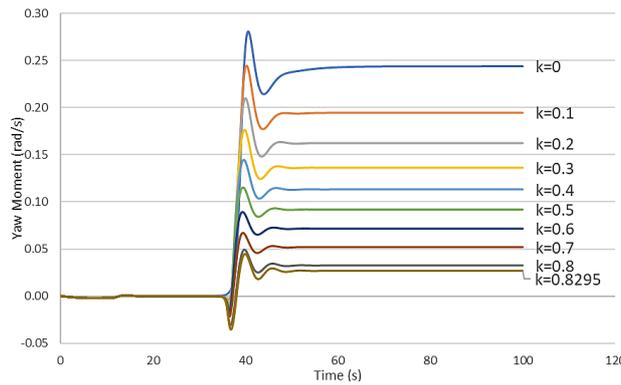

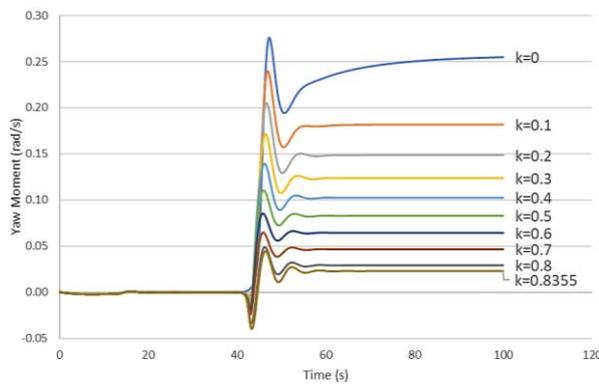**Figure 10.** The yaw moment for the vehicle speed at 60 km/h

Figure 11. The yaw moment for the vehicle speed at 70 km/h
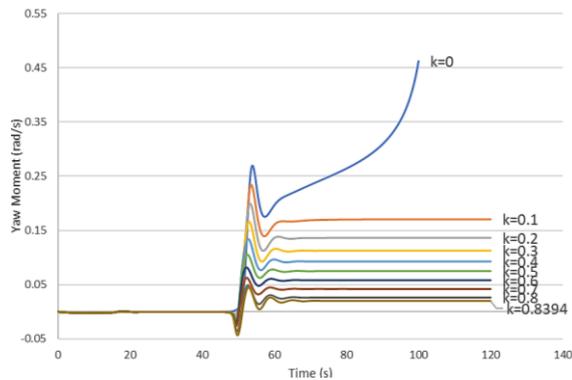

Figure 12. The yaw moment for the vehicle speed at 80 km/h

Figure 10 and Figure 12 also show when the k equals zero the yaw moment not constant but still can be seen that the yaw moment increased slower to an infinite value. From Figure 12 it is not hard to find that when the value equal to zero, the yaw moment will be increased sharply and become infinite. As the value of k increases, the value of yaw moment becomes stable and more and more become small. From Figure 9 to 12, the bottom line in each figure represents the value of the "vehicle speed" equals to the "target speed" under these k values. This can also be understood as that there is no change in the vehicle speed when vehicle turning.

Figure 13 shows how the slide-slip angle will change when the vehicle at the vehicle speed from 10km/h to 80 km/h. The line of "2WS" is meaning that the vehicle is doing cornering with two-wheel steering, rear steering angle equals to zero. The rest legend represented how the side-slip angle change based on the different vehicle speed at 4WS condition. From the "2WS" line, it is easy to see that the slide-slip angle gradually decreased according to the vehicle speed is increase. The most obvious reason for this phenomenon is the speed is increasing. The line above the "2WS" line is the 4WS which the rear wheels have the same direction as the front wheels. In contrast to this, the lines below the "2WS"

line are the vehicle has a different direction between front wheels and rear wheels. The interval between each point is k equals to ± 0.1. The point above the "2WS" line means a positive k value, the opposite side of this line means that the k value is negative. The line of "2WS" is means k equals to zero.

Figure 14 shows the relationship between the vehicle's speed and the side-slip angle. From this figure, it can be intuitively seen that the vehicle velocity is getting closer to the vehicle speed as the k's value increased. The line "poly. (SS tread)" is a polynomial trendline and is performed the steady-state trendline for the vehicle sideslip angle. The value of "k" can be determined based on the steady-state side slip angle trendline. the side-slip angle is gradually decreased when the speed of the vehicle from 10 km/h up to 40km/h. Among them, 30km/h to 40km/h has shown a very slow downward trend. The polynomial trendline on this figure is made by the selected point, and this trendline is 4 orders polynomial trendline. The reason for those points been selected is depends on the vehicle speed. when the vehicle speed is lower than 50 km/h, the vehicle does not have a spinning phenomenon happen. So, the k value of each speed is just a suggestion. Such as, when the vehicle turning at a speed of 10km/h, usually the vehicle will have an understeer phenomenon happen. So, in this situation, the vehicle needs more steering angles to increase the steering performance and it can be achieved by decreasing the value of k. when the speed of the vehicle is higher than 50km/h, the vehicle will have oversteering phenomena occur. It is proved through experiments that when the speed of the vehicle is greater than 50 km/h and less than 80 km/h, the value of k can be taken as the value below the polynomial trendline, and the minimum can be taken as the value on the polynomial trendline.
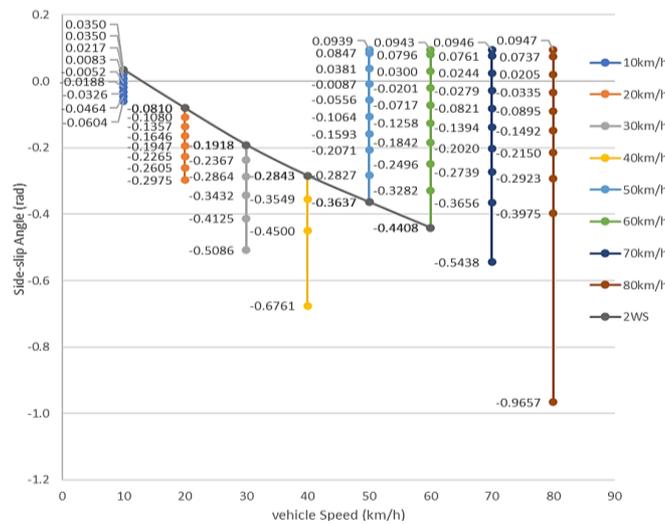

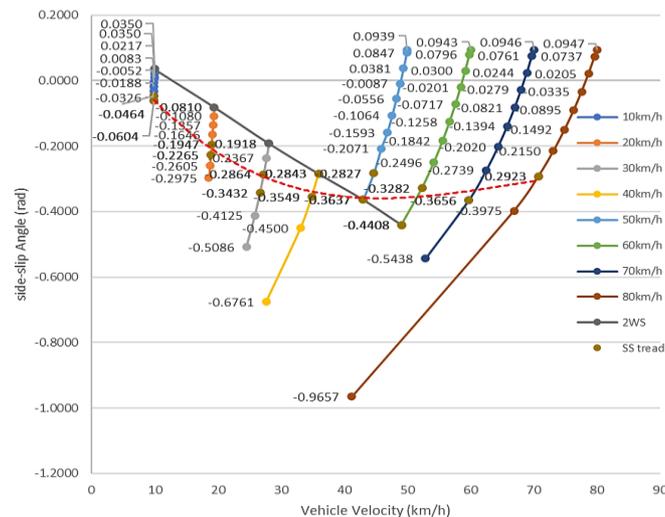**Figure 13.** The relationship between side-slip angle and vehicle speed

Figure 14. The relationship between the side-slip angle and the vehicle velocity

It can be seen from the Figure 13 and 14 that the relationship between k and the side-slip angle is proportional. The side-slip angle increases as the value of k increases and decreases as the value of k decreases. Comparing with both figures, the value side-slip angle is the same, the difference is the different types of speed. Figure 13 is the vehicle speed (dashboard shown speed) and Figure 14 is the vehicle velocity (actual speed). It can be seen from Figure 14 that the value of the side-slip angle changes with the increase and decrease of the value of k at the same vehicle speed because of the value of any speed can be selected individually from Figure 13. On the contrary, it's not easier to find the difference

between the value of the side-slip angle and the value of k at a constant speed value from Figure 14. However, in the case of the same vehicle speed, the effect of the k on the value of the vehicle speed and the side-slip angle is that as the value of k increases, the side-slip angle will increase, and the speed of the vehicle will gradually rise, and the speed of the vehicle will gradually approach the vehicle speed. Both graphs had the same point which is the 2WS line is from 0 to 60km/h and it is not connected with the speed at 70 km/h and 80 km/h. That is due to the vehicle speed is not constant after the speed at 60km/h. From Figure 13 it's can be found that when the speed at 60 km/h the vehicle velocity is very close and lower than 50km/h. For this reason, the characteristics of this car can be defined as that no drift occurs when cornering at a speed of less than 50 km/h.

Figure 15 shows the effect of the change in k on yaw at different rotational speeds. It can be seen from the figure that the whole figure is divided into 2 parts by 2WS lines. The 2WS line indicates that with only the front wheels turning, the value of yaw changes with the speed increase. The part above the 2WS line is negative k, the part below the 2WS line is positive k. The range of k values between each point is 0.1. And the 2WS line is k equal to zero. When the vehicle speed is below 30 km/h, the value of yaw is increasing as the speed increases. When the speed is from 0-20 km/h, the value of yaw is increasing rapidly, and the ascent speed slows down between 20-30 km/h. When the vehicle speed is between 30-50km / h, the value of yaw is a gentle state.

Figure 16 not only shows the effect of the k value on yaw in the case of the same vehicle speed but also shows that when the vehicle at one speed, the vehicle velocity gradually approaches vehicle actual speed with the value of k increases. The "poly. (SS Yaw)" line is a polynomial trendline for the steady-state yaw, "SS Yaw" meaning is steady-state yaw. This line has two different meanings. Before the vehicle speed reaches 50km / h, the k value passed by this line represents when the vehicle turning with this speed, this vehicle using the rear-wheel steering angle as the angle corresponding to the value of k will be suggested. If the vehicle is turning at a speed greater than 50km / h, this line represents the lowest k value for the vehicle cornering. If the value of k is lower than the value on the 2WS line (the value above the trendline line), the vehicle will drift.
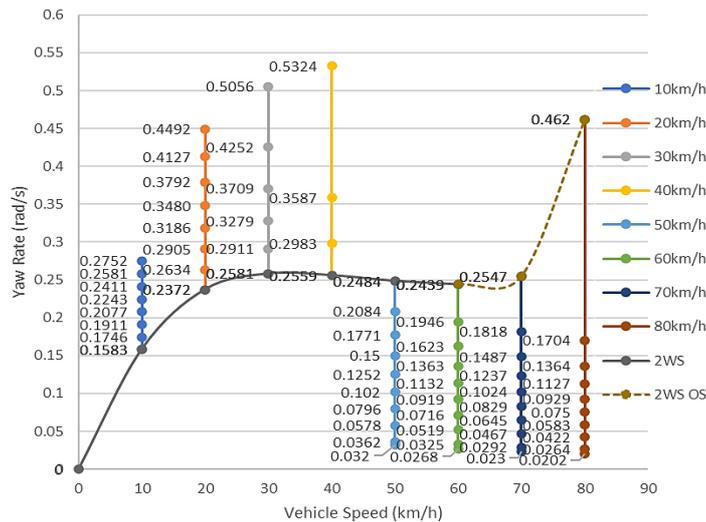

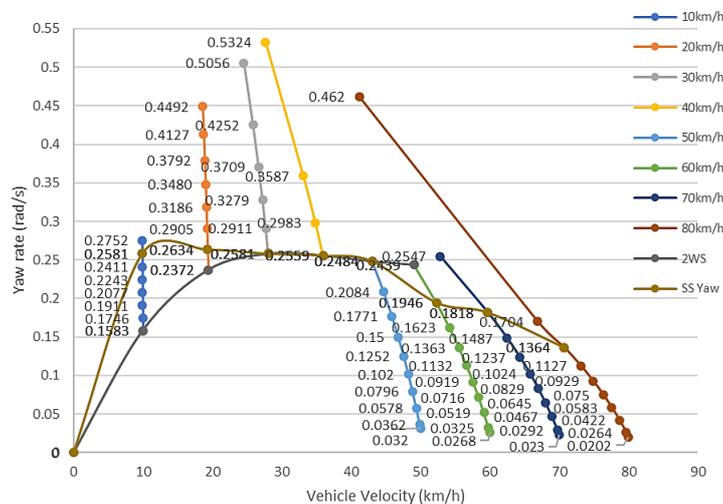**Figure 15.** The relationship between the yaw moment and the vehicle speed

Figure 16. The relationship between the yaw moment and the vehicle velocity

From Figure 15 and Figure 16, it can be seen from the data above the 2WS line that as the speed increases, the change in the value of k has a greater effect on yaw. When the vehicle speed is 10 km/h, and k decreases to 0.1, yaw increases by about 0.02 rad/s. However, at a tire speed of 10 km/h, and k decreases to 0.1, yaw increases by approximately 0.05 rad/s. And when k equal to -3, the value of yaw increases from 0.3587 rad/s to 0.5324 rad/s. When the vehicle speed exceeds 40km/h, the effect of k on yaw is only compared when k is less than 0.1 and greater than 0 When k is greater than 0.1, the effect of k on yaw is relatively average. For example, at a vehicle speed of 60km/h, k increases from 0.1 to 0.2, and yaw decreases from 0.1946 rad/s to 0.1623 rad/s, which decreases by about 0.03 rad/s. When k increases from 0.2 to 0.3, yaw changes from the reduction of 0.1623 rad/s to 0.1363 rad/s is also about 0.03 rad/s. A decrease in the yaw value means that the turning radius of the vehicle becomes larger. When the vehicle is turning in a low-speed environment, a larger yaw value means that the turning radius of the vehicle is smaller, which is more conducive to steering. When the vehicle is driving at a high speed, the turning radius does not mean that it is unfavorable for the vehicle to turn, but to prevent the vehicle from turning at a high speed, the vehicle body will slip and cause dangerous accidents.

CONCLUSION

By changing the value of k, the yaw moment of the vehicle will change accordingly. The value of the yaw moment does not mean that the vehicle can steer smoothly, it is based on whether the steering angle at a given speed can make the yaw moment have a constant value. For example, in Figure 11, when the value of k is between 0.1 and 0.8, the yaw moment still has a constant value. However, when the value of the yaw moment is very small, the vehicle does the corning request more road conditions.

This Study used the 4WS system to solve the OS and US phenomena that occur when the vehicle turns. At first, the vehicle's steering time is determined by simulating the vehicle going straight until it reaches a uniform speed. Secondly, use this steering time to simulate the two-wheel steering. The result shows that when the vehicle speed is 60km/h, the yaw angle cannot reach a constant speed. According to this situation, it can be judged that the vehicle appears a slight spin phenomenon. When the vehicle speed reaches 60km/h, the vehicle velocity is only about 50km/h, so when the vehicle speed reaches 50km/h, the author uses the parallel steering mode in 4WS to reduce the yaw moment value so that the vehicle will not spin. When the vehicle speed is lower than 50km/h, the positive steering mode in 4WS is used to increase the yaw moment value so that the vehicle will not get out of control on the road. Finally, through a large number of simulations, these results in Figures 12 to 15 are obtained. It can be seen from these four pictures that it is feasible to judge whether the US or OS phenomenon appears in the vehicle, whether by side-slip angle or yaw moment. And the figure proves that the 4WS system can be used to solve the phenomenon of US or OS in the vehicle during the steering process. Figures 12 and 14 show the changes in side-slip angle and yaw moment after applying the 4WS system. And according to the result, a polynomial trend line is made. This polynomial trend line is only used in this experiment because different front-wheel steering angles will have different speeds that can reach the OS. When the vehicle is driving under experimental conditions, turning according to the k value at the trendline, the vehicle will not have the phenomenon of the US or OS.

In real life, the phenomenon of OS occurs mainly because the driver turns the steering wheel while turning and does not reduce the speed of the car to a speed suitable for turning. The phenomenon of the US mainly occurs because the steering angle is too low and the steering angle does not reach the proper angle or the vehicle speed is too fast to turn the reassuring disk to the angle of the appropriate road. At the beginning of the design of this study, the author also considered the problem that the same steering angle cannot correspond to all road curves. However, this study is to design a solution to the problem of the US or OS phenomenon in vehicles. For the 4WS system can correspond to all road information. This research can be left to qualified people to complete.

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NOMENCLATURE

Symbol	Means Description	Value	Unit
l_F	length from the front wheel axle to gravity	1.08	m
l_R	length from the rear wheel axle to gravity	1.52	m
d_F	front tread	1.475	m
d_R	rear tread	1.47	m
r	the radius of the tire	0.2975	m
m	mass of the vehicle	1447.5	Kg
b	width of wheel interact surface	0.152	m

(Cont.)

Symbol	Means Description	Value	Unit
l	length of wheel interact surface	0.145	m
k	road coefficient	0.8	
I	yaw inertia moment at gravity point of the vehicle	274.39	kgm^2
K_X	longitudinal tread rubber stiffness	1.5x10^6	N/m^3
K_Y	lateral tread rubber stiffness	1.5x10^6	N/m^3
$\omega_{FL}, \omega_{FR}, \omega_{RL}, \omega_{RR}$	tire rotational speed of each tire		Rad/s
$X_{FR}, X_{FL}, X_{RR}, X_{RL}$	friction force for each tire		N
θ_F, θ_R	front and rear wheels steer angle		°
$\gamma:$	yaw rotational speed		Rad/s
ρ	slip ratio		
β	side slip angle		°
$\beta_{FR}, \beta_{FL}, \beta_{RR}, \beta_{RL}$	tire side slip angle		°

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