Chapter 2

Motion Dynamics Control of Electric Vehicles

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Additional information is available at the end of the chapter

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Abstract

In this chapter, I will explain the dynamics of electric vehicle and the support systems of drivers in detail, considering both structure and the function of the vehicle. Furthermore, the reliability is discussed. In car development and design that I have, car dynamic control system, turn ability, comfort, and safety must all be considered simultaneously. The safety and the comfort for the driver which are connected with various road surfaces and as well as the speed depend on the physical performance of the vehicle. In this chapter, we will explain the dynamics of the vehicle and the support system of the driver in detail, considering both the structure and function of the vehicle. In the design and development of car dynamic control system, turn ability, comfort, and safety must all be considered simultaneously. The safeness and comfort during a drive on various road surfaces and speed depend on the performance of these basic abilities of the vehicle.

Keywords: ABS, TRS, ESC, acceleration, understeer, oversteer, electric motor control

1. Introduction

Several of the greatest advances in automotive technology in the past 20 years are in the area of safety management. Due to the speed of microprocessors, downsizing, and the advances in software development, automobiles continue to evolve. In this chapter I will explain in detail for the dynamics of the vehicle and the driver's support system, considering both the structure and function of the vehicle. In recent years, science and technology competition in the automobile industry has been intensifying. The basic ability of a vehicle is "running," "turning," and "stopping." Currently, in-vehicle equipment is equipped with countless electric and electronic subsystems.

Some electric vehicles can control four wheels independently. It is necessary for the electric car to make a safe, reliable, and robust control system. Also, the four independent wheels of an electric car give the driver greater control and more freedom of movement. More than 100 times per second, the on-board computer can sample the input data from the steering wheel, acceleration pedal, brake, etc. and calculate how each wheel should respond. Because the wheels are independent, one or more wheels brakes and other wheels accelerate, which can enhance traction and motion control. That is, it is very difficult to drive without a controller.

Many of these subsystems include well-known standard systems such as antilock braking system (ABS), electronic stability control (ESC), traction control system (TCS), and so on. Besides that, I will also explain torque vectoring and active roll control. The EVs may have regenerative cooperative brake, which is equipped with the conventional friction hydraulic brake and the function to recover to the battery. The regenerative brake is recovered as electrical energy by rotating the motor with kinetic energy of the vehicle during braking. However, only regenerative brake does not provide sufficient braking force, and controllability is not good enough. Therefore, the controller of regenerative cooperative brake is configured to cooperate the braking force by the conventional hydraulic brake and the braking force by regeneration and thereby obtain the necessary braking force. The controller determines how much braking force is required. The maximum regenerative brake is applied within the range of the braking force. Then, the brake will compensate for the insufficient amount of brake.

First, I will explain the operating principles of each system. Next I will describe the components necessary to support the systems such as sensors, actuators, mechatronic subsystems, control elements, and so on. The stability and maneuverability of automobiles are essential for the drivers. The stability of the vehicle is the ability of the vehicle to return to a stable state during driving when faced with an irregular road surface condition. The maneuverability of a vehicle is the ability of the vehicle to quickly change direction during driving based on the steering of the driver. The stability and maneuverability of the vehicle can also be defined as the driving stability of the vehicle. Another major focus of automotive engineering is vehicle safety performance. As the safety performance of the vehicle improves, all drivers will be more confident than every day. In order to improve the reliability of the systems, two acceleration sensors may be used. The reason is that when one sensor breaks down, the failure can be easily detected by the other sensor. When estimating the vehicle slip angle, the vehicle lateral acceleration value is time-integrated and used for calculation. Therefore, if there is an error in the acceleration, the error is also time-integrated, and the error becomes very large.

As a whole, packaged together with ABS, ESC, and TSC, driving the vehicle equipped with these will greatly reduce the risk of fatal crash. Regardless of what kind of safety function is equipped on the vehicle, it is always important to pay attention and focus on driving tasks. The effects for sports utility vehicles (SUVs) are more substantial than the effects for ordinary passenger cars. This is the result of the SUVs' center of gravity being higher than that of other passenger cars. A high center of gravity is disadvantageous for the stability of the vehicle. ABS, ESC, and TSC are brake control systems that use pressure sensors, a yaw sensor, an acceleration sensor, wheel speed sensors, solenoids, a motor, and a microcontroller to electronically modulate individual wheel torque to improve vehicle stability. These systems must have high reliability, in addition to the desired performance. There are stringent government

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regulations on such systems. The more tests they conduct, the more they can say about the reliability of the system. Reliability is defined as the probability that a device will perform its intended function during a specified period under stated conditions. The vehicle lateral motion control of four-wheel-independent-drive electric vehicles (4WID-EVs) and direct yaw moment control (DYC) through in-vehicle networks is studied [1]. Fault-tolerant control strategies for electric vehicles with wheel hub motors are presented in order to maintain the directional stability of the vehicle in case of a component failure during high-speed maneuvers [2].

Several of the greatest advances in automotive technology in the past 20 years are in the area of safety. Due to the speed of microprocessors, downsizing, and advances in software development, automobiles continue to evolve. In this chapter we will explain in detail the dynamics of the vehicle and the driver's support system, considering both the structure and function of the vehicle. In recent years, science and technology competition in the automobile industry has been intensifying. The basic ability of a vehicle is "running," "turning," and "stopping." Currently, in-vehicle equipment is equipped with countless electric and electronic subsystems. Many of these subsystems include well-known standard systems such as antilock braking system (ABS), electronic stability control (ESC), traction control (TRC), and so on. Besides that, we will also explain torque vectoring and active roll control.

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As a whole, packaged together with ABS, traction control, and electronic stability control (ESC), driving the vehicle equipped with these will greatly reduce the risk of fatal crash to 50%. Regardless of what kind of safety function is equipped on the vehicle, it is important to always pay attention and focus on driving tasks. The estimates of reduction of fatal vehicle crashes vary from 17 to 62%. The effects for sports utility vehicles (SUVs) are more substantial than the effects for ordinary passenger cars. This is the result of the SUVs' center of gravity being higher than that of other passenger cars. A high center of gravity is disadvantageous for the stability of the vehicle.

2. Kinds of dynamics control for electric vehicles

The vehicle dynamics control system provides a means to enhance positive and integrated safety. In order to maximize the contribution to overall road safety, improvement of penetration is necessary. This can be achieved by increasing the awareness or by regulating in law [3]. To fully exploit the possibilities of the dynamics control of vehicles, emphasis should be placed on driver groups such as beginners and the elderly. Adapting to such drivers will help reduce traffic disasters.

One of the first active assistance systems based on proprioceptive sensors was the antilock braking system (ABS) since 1978 (Bosch). A traction control system (TCS) later augmented the system. Thus, electronic stability control (ESC) is adapted to the market by combination with ABS and TCS. An optimal torque distribution scheme for the stability improvement of a distributed-driven electric vehicle is presented [4].

2.1. Antilock brake systems

The first mechanical antilock braking system (ABS) was developed for aerospace industry in 1930 [5, 6]. In 1945, the first set of ABS brakes was put on a Boeing B-47 to prevent spin out and tires from blowing. In the 1960's, rear-only ABS was adopted only for high-end automobiles, and with the rapid progress of microcomputers and electronics technology, it was widely spread in the 1980's. Today, the all-wheel ABS can be found on the majority of latest model vehicles. The ABS system aims at minimizing the braking distance while retaining steering ability during braking. The shortest braking distance can be reached when the wheels operate at the slip of maximum adhesion coefficient.

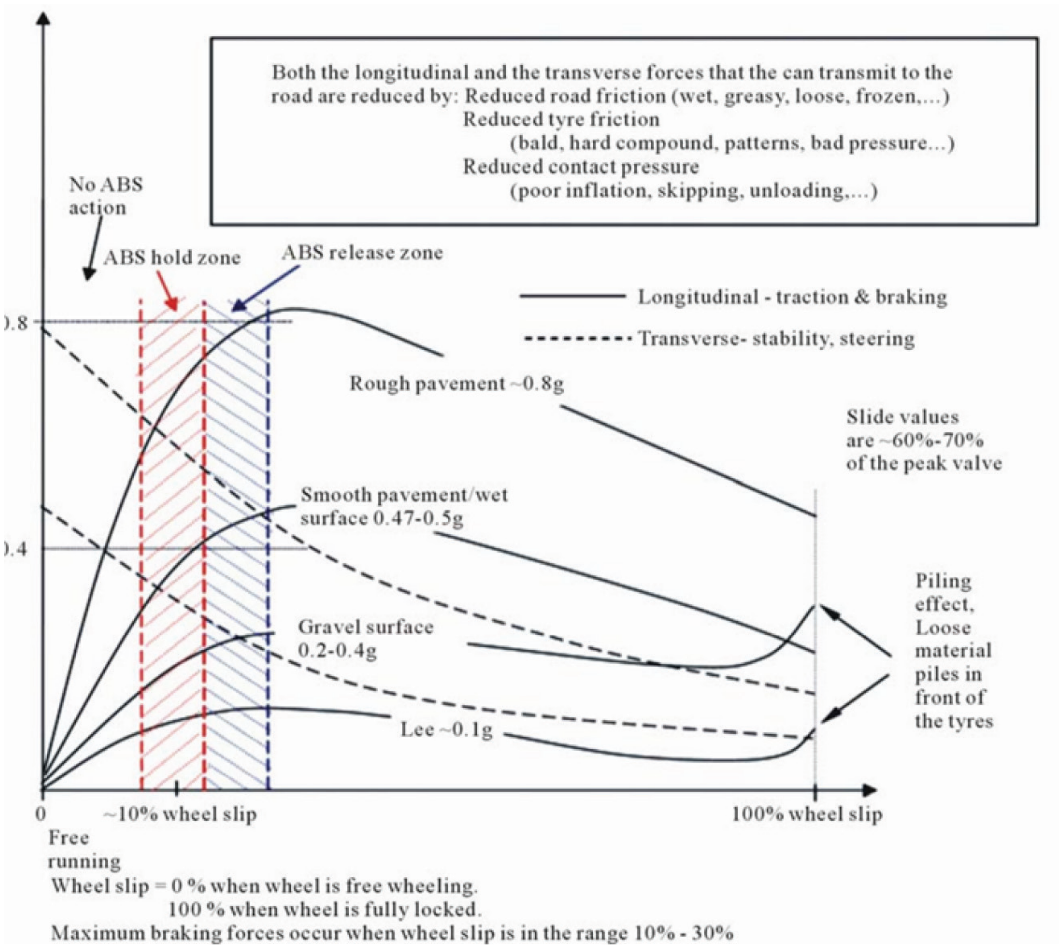

Figure 1. Relationship between braking coefficient and wheel slip [5].

The relationship between the friction coefficient and the wheel slip is shown in **Figure 1**. This figure shows that the slide value of the stop or traction force is higher in proportion to the slide value of the cornering or steering force. On applying the braking pressure, the brake torque increases. The difference between friction torque and brake torque is negative, resulting in a wheel deceleration. The wheel rotational equivalent velocity starts to decrease, and the slip starts to increase. At first, the friction coefficient increases as well as the friction torque, which narrows the torque difference. After passing the maximum friction coefficient, the friction curve changes to decrease. In order for the friction torque curve to become unstable, it might be uncontrollable in extremely high rotational wheel decelerations.

ABS is operating by monitoring the movement of each wheel using a wheel speed sensor. When ECU detects the lock of a wheel based on the speed of each wheel, by using the hydraulic pressure modulator, ECU adjusts the braking force to the desired wheel. The benefits of ABS are (1) shortening of the stopping distance, (2) improvement of stability, and (3) steering ability.

A typical antilock brake system is shown in **Figure 2**. The typical ABS components include vehicle's physical brakes, wheel speed sensors, an electronic control unit (ECU) with acceleration sensor, brake master cylinder, and a hydraulic modulator unit with pump and valves.

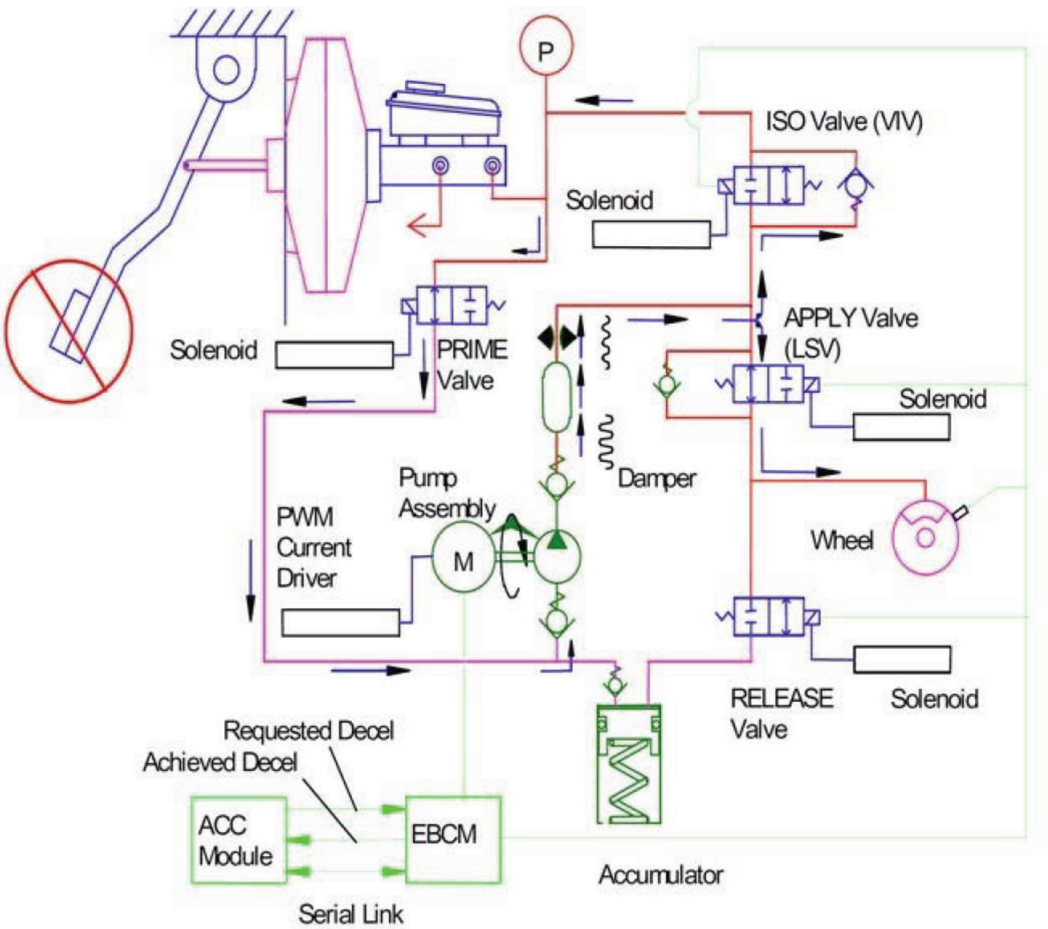

Figure 2. Antilock braking system [6].

Locked wheels provide low maneuvering force and minimum maneuvering power. As a result, the main advantage of ABS operation is to maintain directional control of the vehicle during excessive braking. In rare cases, it is possible to increase the stopping distance, but the direction control of the vehicle will be significantly bigger than if the wheels are locked up.

2.2. Control system of the ABS

ABS brake controllers pose unique challenges for designers: (a) for optimum performance, the controller must operate at an unstable equilibrium point; (b) depending on road conditions, the maximum braking torque may change over in a wide range; (c) on rough roads, the slip rate of the tire changes drastically with the bounce of the tire; (d) the change in the friction coefficient of the brake pad; and (e) the change in the braking system.

As mentioned in the previous section of this paper, the ABS consists of a conventional hydraulic brake system, in addition to an antilock component that affects the control characteristics of the ABS. ABS control has a strong nonlinearity due to the complicated relationship between the friction torque and slip rate. Another difficulty for this control problem is that the velocity of the vehicle is not directly measurable and must be estimated. The friction between road and wheel cannot be measured easily in real time or may require complex sensors.

ABS control is a very nonlinear control problem due to the complicated relationship between friction and slip. Another obstacle to this control problem is that the linear velocity of the wheel is not directly measurable and must be estimated. The friction between the road and tires cannot be easily measured, or it may require a complicated sensor.

The driver increases the braking pressure during braking. Rotational equivalent wheel speed is measured and differentiated to give wheel acceleration. The maximum friction point is passed when the wheel speed derivative falls below a predetermined threshold. In the first control cycle, even lower thresholds are applied. The braking pressure is held between a higher threshold and a lower threshold. The introduction of additional thresholds helps to suppress the effect of the final noise. When the braking pressure decreases, the wheels get speed again. When the threshold drops again, the pressure drop stops. When the wheel speed derivative exceeds the braking pressure, the pressure is increased to prevent the wheels from returning to slip values that are too small. The pressure is kept constant and rises slowly below it. When the wheel speed derivative falls again, the second control cycle begins. The brake pressure now decreases immediately without waiting for the threshold to be reached. When such a cycle is executed, the wheel rotation speed is maintained in the region where the wheel slip is close to the maximum coefficient of friction. Therefore, the braking distance can be minimized.

If the moment of inertia of the wheel is large, the wheel may lock without reaching the deceleration threshold if the coefficient of the friction is small or the brake pressure increases slowly in case of a careful braking (e.g., ice). Such a situation puts the driving ability of a vehicle at risk. Regardless of the above control cycle, therefore, the braking pressure decreases as the rotational equivalent wheel speed falls. In either condition, the maximum slip is not surpassed even when the maximum friction coefficient cannot be reached. The front wheels of

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the vehicle are independently controlled, and the rear wheels collectively receive lower brake pressures. This ensures operational stability. The main difficulty in designing ABS control is due to strong nonlinearity and problem uncertainty. Using the classical linear, frequency domain method, it is difficult to solve this problem and in many cases impossible. ABS system is designed around hydraulic system of system, sensor, and control electronics. These systems are dependent on each other, and different system components are compatible with minor changes in the controller software. Estimation of the coefficient of friction is necessary when maximum friction is used. It is necessary to evaluate the maximum brake in various kinds of road surface condition such as dry, ice, and snow cover. In the case of vehicles equipped with ABS, the panic braking state is ABS controlled. That is, when an ABS control cycle occurs, maximum friction is used. On the other hand, the operation of the ABS must generally be evaluated to evaluate whether the failure of the ABS system has affected the investigated accident. The prediction method employs the wheel speed measurements, in order to detect an ABS-cycle. Detecting the ABS-activity, the past two measurements of the wheel speed are utilized to extrapolate linearly a value of the current wheel speed.

2.3. Traction control system (TCS)

This section presents a scheme to enhance vehicle lateral stability with a traction control system. Traction control systems are used to prevent wheel slippage and to maximize traction forces. The control is an active vehicle safety feature designed to help vehicles make effective use of all the traction available on the road when accelerating on low-friction road surfaces. These conditions include cases where the road is wet, ice-caking, non-uniform, loose, or poorly maintained. When a vehicle without traction control tries to accelerate on a slippery road like ice, snow, gravel, the wheel becomes slippery. As a result of the wheel slipping, the tire rotates the surface of the road without grip, and the vehicle cannot accelerate. Traction control works when it detects that a wheel may slip and helps the driver to make the most of the traction available on the road. Traction control cannot produce force exceeding the maximum frictional force. In a state with little friction such as on ice, the performance with the traction control vehicle is hardly changed with the vehicle without traction control.

2.4. Control system of the TCS

The traction control system works at the opposite end of the scale from the ABS—dealing with acceleration rather than deceleration. Traction control works similarly to ABS and is often considered as a supplement to the existing ABS setups. Since many of the same principles apply to both systems, it might be best to visualize it as sort of ABS in reverse. In fact, traction control uses the same components as ABS: a wheel speed sensor that monitors the rotation speed of the front wheel or all four of the wheels, a hydraulic modulator that pumps the brake, information from the wheel speed sensor, and an electronic control unit (ECU) instructing the hydraulic modulator to pump the brake. ABS senses the slippage of the wheels at the time of braking and continuously adjusts the brake pressure to ensure maximum contact between the tire and the road surface. Some basic ABS systems require some modifications. First, older accelerator cables are usually replaced by electronic drive-by-wire connections. That is, the mechanical connections between the accelerator pedal and the throttle is unnecessary. Instead, the sensor converts the position to the accelerator pedal to an electrical signal, and a control unit similar to that used in the ABS is used. Standard ABS hydraulic modulators are also expanded to include traction control components. All these parts work together to operate the traction control system. Therefore, modern ABS and traction control systems are physically one unit, while functions are different because the ECU and the hydraulic modulator are mounted together. The ECU continuously checks whether some wheels are turning faster than other wheels. It is an indicator that the wheel is losing traction. Traction control monitors the wheels of the vehicle for potential "wheel slip." When the wheel of the vehicle slides down, the tire seems to be "rotating," but the grip on the road cannot be grasped. There is little chance of controlled acceleration when the wheels are spinning. When the traction control system senses that one or more of wheels are about to slip, it corrects the problem by applying the appropriate amount of the brake to that wheel. When a possible wheel slip is detected, the ECU instructs the hydraulic modulator to immediately brake the wheel in question quickly and reduce the rotational speed. Depending on the traction control system, there are things that reduce motor output to slipping wheels. When the wheels recover the traction, the system returns to monitoring the wheel speed and comparing the wheel speed of rotation. In vehicles with reduced motor power to control the rotation of slipping wheels, the driver may experience gas pedal pulsation while the traction control is in operation. This pulsation is normal and does not indicate that there is a problem with the traction control system.

The traction control system is often considered as a supplement existing in ABS settings. Both systems work to solve the opposite problem associated with wheel slip or wheel lock. The same components as ABS, such as wheel speed sensors (sensors measuring wheel rotation speed), hydraulic modulators (brakes if necessary), ECUs, etc., are used. To add traction control to the ABS, the control unit that calculate the best traction of each wheel and other valves to the hydraulic brake modulator are necessary. Thus, it is a relatively easy way to install traction controls on vehicles already equipped with ABS. The traction control system uses the individual wheel speed sensors to measure the difference in rotational speed of each wheel. These sensors are located on each wheel. The ECU sends a system to the hydraulic brake modulator, which is attached to the ECU upon detecting that one wheel is rotating faster than the other wheel indicating that the wheels are losing traction. Traction control systems have various ways to reduce the rotating speed of each wheel. The other systems combine wheel brakes with decelerated motor power, but some "pump" the brakes to the wheels in question. In vehicles with reduced motor power to control the rotation of slipping wheels, the driver may experience gas pedal pulsation while the traction control is in operation. This feeling is similar to the experience of pulsating the brake pedal when ABS is running. When the wheels recover the traction, the traction control system monitors the wheel speed and returns to comparing the wheel speed of rotation. The test shows that traction control is effective for reducing wheel slip when accelerating with low-friction condition, but this effect is more effective than four-wheel drive. It is remarkable in the car.

However, there is a risk that the driver performs traction control to respond to the safety system. First, the driver may not be sure of the sounds and sensations associated with the proper functioning of the TCS. When it is operating, the traction control system generates a crushing sound, and the gas pedal may pulsate. If the driver is not familiar with the traction control mechanism, there is a possibility that the driver may misunderstand that there is a possibility that the traction control may be canceled due to some defects in the traction control. Secondly, the traction control helps to maintain the steering force by preventing rotation of the wheels, so the driver must be careful not to exaggerate the steering command under the condition that the traction control is working. Traction control works just by preventing the tires from slipping, allowing the wheels to fully utilize the traction available on the road. Traction control cannot increase the total amount of available traction. In order to explain this point, if the road is completely freezing and there is no traction on the road, nobody has the traction power. Traction control can be useless in case of no friction. The traction control hinders the rotation of the wheel, so the driver with traction control may accelerate normally under low traction situations. Furthermore, since the wheels of the vehicle are not rotating, the driver can maintain the steering control. However, it cannot be exaggerated that a driver with traction control does not experience more traction. If slight traction is available, better handling is possible. Therefore, the driver is advised to limit or avoid driving under slippery low-friction conditions with or without traction control.

The traction control system can allow the vehicle to reach a higher speed in low-grip conditions. It is necessary to monitor the vehicle speed and to be careful not to exceed safety speed limit that depends on the situation. Regardless of the safety system installed in the vehicle, it is important to concentrate on driving always without hesitation. By selectively applying the brakes to the slipping wheel, TCS will be able to increase the traction of the wheels. This is especially important when the wheels are on surfaces with varying levels of friction. In addition to using a brake to control the tractive force during acceleration, TCS also controls the vehicle by using the motor management. TCS system, by communicating with the motor power controller, may control the amount of torque transmitted to the wheels. If the wheel is almost no traction with the road and was simply detected by the system, TCS system will be able to significantly reduce the torque supplied to the wheels. The motor power management system adjusts significantly the amount of torque supplied to each wheels. Due to this control system, the stability of the vehicle is greatly improved.

2.5. Electronic stability control

One of the biggest technological advances that enabled in a system, such as the ESC, is a wide availability of automotive electronics. Such an electronic steering angle sensor, a wheel sensor, a lateral acceleration sensor, a yaw rate sensor, and a power controller made it possible to develop a vehicle stability system. In addition, the ability to connect these electronic components to a high-speed network helped to develop these vehicle systems.

Electronic components stabilize the vehicle in a crisis situation, preventing the control from steering. System operates through a series of high-speed digital messages sent to the control unit from the sensors which is sent finally to the actuator. At a few milliseconds, these components begin their remedial action by evaluating the condition of the vehicle, determining the necessary remedial actions, braking, and controlling the torque [7]. The basic control algorithm is to evaluate the behavior of the vehicle, determine whether it is necessary to make any changes to the vehicle, and control the components responsible for changing the behavior of the vehicle, the entire electronic component using the data. Basic ESC control algorithm for four-wheel drive vehicle is shown in **Figure 3**. The main purpose of the control algorithm is to compare the actual behavior of the vehicle and desired behavior and to determine what needs to be done in order to equalize the behavior.

The electronic system has greatly improved the safety and the performance of the vehicle. In such a system, there are some inherent limitations and problems, such as the increased risk that system designers must deal with. Because these systems are important for safety, special procedures must be performed to ensure system reliability and fault tolerance.

Finally, there are many advantages of the system, such as ESC. With the introduction of many electronic controls there are significant improvements and benefits to the vehicle system, but with this development risks and problems also arise. When the vehicle electronic systems such as ESC have been developed, there is a need to solve the problems related to the reduction of the driver's control and consumer awareness.

2.6. Control system of the ESC

ESC consists of ECU and sensors such as wheel speed sensor, steering angle sensor, yaw rate sensor, lateral acceleration sensor, motor power controller, transmission controller, accelerator pedal sensor, and brake pressure sensor. The ECU collects data from the sensors and uses that data to calculate the necessary adjustments for the brake pressure or motor torque. ESC requires many different sensor data to determine the actual state of the vehicle and the desired state of the vehicle based on driver input. To determine the speed of the vehicle and the necessary torque to each wheel, the system uses a wheel that requires speed sensors. Information from wheel speed sensors is used to calculate the actual vehicle speed and the amount of slippage each wheel is experiencing. The amount of longitudinal tire slip is calculated by comparing the wheel speed and the actual vehicle speed. The actual vehicle speed can be determined by the evaluation of the speed of non-driven wheels. In the case of all-wheel-driven vehicles,

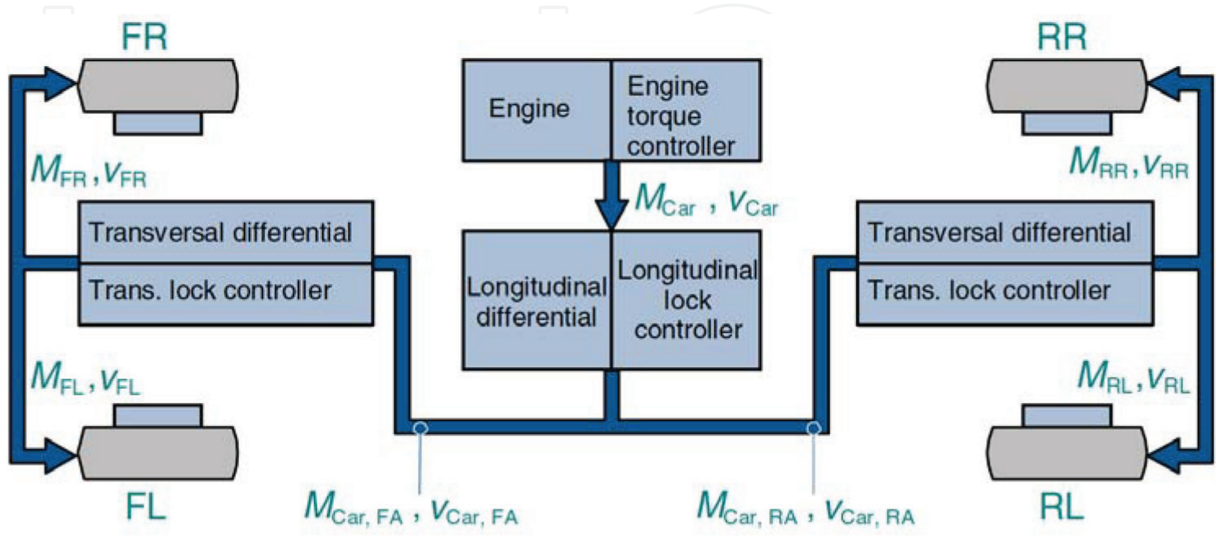

Figure 3. Basic ESC control algorithm for four-wheel drive vehicle [7].

the actual vehicle speed cannot be measured. Therefore, among the four-wheel speed, the fastest one is selected, and a pseudo-vehicle speed signal is created based on this. It is called "the principle of the select high."

The system also needs to be able to monitor the desired movement of the vehicle from the driver's input. A steering angle sensor and an accelerator pedal sensor are used to measure the input of the driver. The steering angle sensor is often mounted behind the steering wheel on the top of the steering column and measures the position of the steering wheel. The gas pedal sensor is used for the desired speed acceleration of the vehicle. Also ESC system requires the measurement of vehicle rotational acceleration around the vertical axis, which is called yaw rate. The rotational velocity is the yaw rate of the vehicle. By using the data from the yaw rate sensor, ECU determines whether the vehicle is overspeed, that is, in the oversteered state or understeered state when the vehicle is not rotating enough. The yaw rate sensor is based on a vibrating cylinder gyrometer. The metal cylinder vibrates at a constant frequency. The node is displaced according to the amount of rotation of the vehicle due to the Coriolis effect. In addition to the aforementioned sensors, vehicle stability system also uses the lateral acceleration sensor and the brake pressure sensor. ECU evaluates where the driver is steering the vehicle and where the vehicle is actually.

When the vehicle becomes unstable due to oversteer or understeer, the ESC system individually adjusts the power to the wheel. The ESC can stabilize the vehicle and control the vehicle in dangerous situations according to the slippage and torque of each wheel. When the system detects an oversteer condition while turning clockwise, braking is applied to the left front wheel. When the system detects an understeer condition, braking is applied to the right rear wheel. A schematic diagram of the control is shown in **Figure 4**. This action will help the driver avoid serious accidents caused by slippage and shaking. In addition to

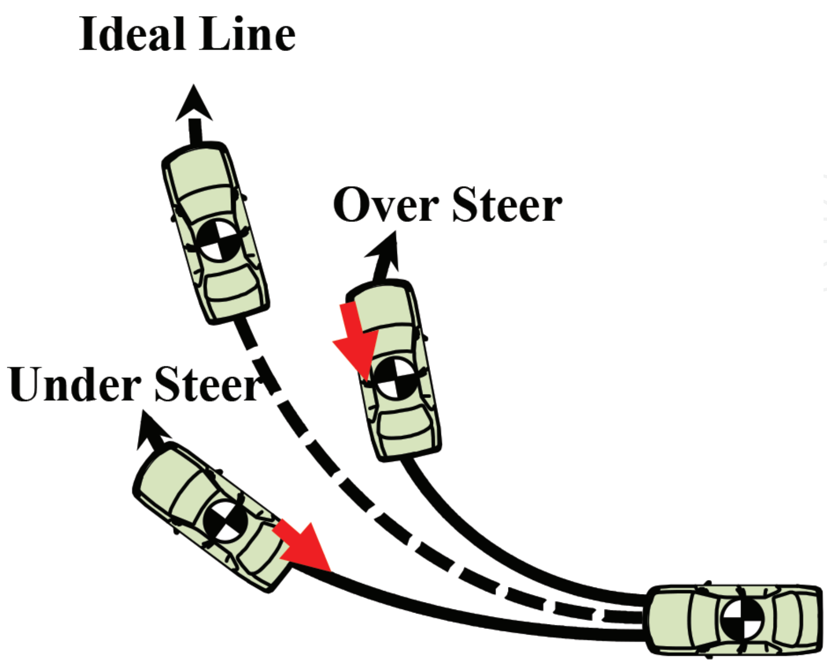

Figure 4. Schematic view of ESC method.

controlling the vehicle by applying brake, the system also interacts with the power management system by communicating with the power control unit. The motor power controller is also an embedded system that handles tasks such as fuel injection, spark timing, throttle control, air-fuel ratio, and so on. By sending a signal to the motor power control unit, the system controls the torque of the wheels. Even when the driver steps on the accelerator, the system may decide that it is necessary to reduce the torque of the wheels in order to stabilize the vehicle.

The system samples the input signal, and it is necessary to determine the current state of the vehicle. When the system detects a serious condition, the driver starts responding before the driver recognizes that the vehicle is out of control. Control time is the most important, as delays in the response of the system can have disastrous consequences for the driver. When traveling on an expressway in a frozen or damp condition, a time of one tenth of a second means the difference between striking the guardrail and safely staying in the lane. Thus, ESC must meet stringent timing requirements during operation. The main value of ESC is the ability to react and stabilize to the vehicle faster than humans. This is far superior to the fastest human response of 300 ms. Failure to meet the response time requirement of the system can result in disastrous results for both the driver of the vehicle and the other drivers on the road. In some cases, if the deadline of timing is not kept, the occupant may be killed or seriously injured. Therefore, ESC is hard real-time system that requires special precautions on systems that are designed to ensure the ability of the system to meet response time requirements.

The flow of control of ESC begins from the inputs and the current state of the vehicle driver. Steering angle, yaw rate, wheel speed, lateral acceleration, accelerator pedal pressure, the brake pedal pressure, the brake fluid pressure, and motor power management information are collected from sensors and sent to ECUs. From this information, ECUs will calculate the actual operation of the vehicle. In addition to calculating the actual movement of the vehicle, ECU must also determine the nominal or desired movement of the vehicle. The nominal motion mainly input information of the driver of the vehicle, i.e., a steering angle sensor, a throttle position sensor, is calculated based on the brake pedal sensor. The ESP design aims primarily at inducing the nominal movement of the vehicle, i.e., dynamic behavior obtained when neither front nor rear tires are saturated in the condition like a slippery road surface. The ESC controller compares the nominal value of the vehicle motion with the actual value of the vehicle motion. Once the difference between these two values is determined, the ESC controller determines the correction of the tire slip value necessary to achieve the nominal value of the vehicle motion. The overall control of the vehicle is based on the slip values of all four wheels. Tire slip is the difference between the actual speed and the vehicle tire. If the tire is rotating faster than the moving vehicle, the tire slips. The controller determines control signals that need to be sent to actuators (valves, pumps, etc.) of the system to achieve the desired tire slip value. The slip controller sends these control signals to the various actuators to change the movement of the tires.

There are several important safety issues that play an important role in the design and evaluation in hard real-time systems. One of the most important problems is the integration and verification of sensors, ECUs, and mechanical and hydraulic components. In many cases, components are manufactured by various suppliers and may have internal software that must adapt to interface with their own interfaces or other components. It is necessary to confirm the operation of integrating them. In addition, some electronic modules are general-purpose products, not designed exclusively for applications.

Their operation must be verified, and their interface must be adapted to this system. For this reason, in order to meet the stringent safety and timing requirements of the system, you must have a test and verification of each component. Another challenge facing the system suppliers is variations of vehicles. Since the driving characteristics and other components can vary greatly depending on the vehicle, the system must be reconfigured and verified for each vehicle. In addition, because system failures can cause such disastrous consequences, measures are taken to ensure partial system function and even if a failure occurs. Instead of completely off the system in the event of failure, certain important elements, such as ABS, continue to function. It is called a recovery condition. For example, if the system finds a failure in the power management interface, the portion of the system would be interrupted, and then the system will operate only during the brakes. Such steps have been done to enhance the robustness and fault tolerance of the system. One of the important functions found in ESC software is model-based sensor monitoring. This type of sensor monitoring can detect failures that are slightly out of specification. Model-based sensor monitoring operates by comparing the actual output of the sensor with the predicted output calculated by the software model. The software tracks the history of sensor output and determines the possibility of the current reading based on the model. If the controller detects a sensor operating outside the specification, the controller can reduce its own level of sensitivity to that sensor. In other words, when the sensor is under suspicion of failure, the magnitude of the system's response to that sensor can decrease dramatically.

ESC improves the ability of a car to steer on a frozen or slippery road significantly, also prevents vehicles from uncontrollable spin during critical situations, and provides many benefits to vehicle performance and safety. Furthermore, it is possible to minimize the adverse effects when there is a possibility on slippery roads that are presumed recognized beforehand—but when the drivers cannot safely control the vehicle, stabilization will be difficult. In case driver is losing control of the car, ESC can react quickly with brake and motor power intervention at speeds more than ten times faster than humans. ESC, when viewed as a mechanism for the driver's support in a crisis situation, is highly profitable and greatly improves vehicle safety. There are several important safety issues that play an important role in the design and evaluation in hard real-time systems. One of the most important problems is the integration and verification of sensors, ECUs, hydraulic components, etc. In many cases, the components are manufactured by various suppliers and may have internal software that must adapt to interface with their own interfaces or other components. The carmakers need to integrate them and check the operation. These were not intended to replace the driver's functionality. The control of the vehicle is ultimately the responsibility of the driver before the autonomous driving advent. In order to avoid potentially fatal incidents, it is important for consumers to be notified of system that functions and has restrictions like ESC.

2.7. Torque vectoring control (TVC)

Directing the yaw moment control by acceleration and by the brake is an effective technique to positively prevent accidents, which is widely spread today. The world's first straight-ahead yaw moment control system on the right and left torque vectoring type was developed and announced in 1996. This system directly controls the yaw moment when acting on the vehicle regardless of whether the vehicle is accelerating or decelerating by transmitting torque between the left and right wheels. It is an operation essentially blending braking, steering, and accelerating to provide drivers and passengers with a more accurate and stable feel. In order to uniformly control these forces and to optimize the vertical load of each tire to realize a smooth and efficient vehicle, the motor torque and the braking force are adjusted according to the steering input. Increase the vertical load of the front tire by causing a slight deceleration to achieve the natural cornering attitude of the car. Basically, it monitors three parameters of vehicle speed, throttle position, and steering wheel speed. In a system that uses the difference between the left and right torques, the torque distribution of all of the four wheels are controlled [8]. A schematic of this control is shown in **Figure 5**.

This system showed that the movement of the steering wheel was reduced, the first turning moment of each maneuver was more accurate, and fewer modifications were made in the middle. The steering performance under almost all conditions at almost all speeds has been improved. Also, on a slippery surface, the difference becomes more prominent. TVS closely monitors the speed of the steering wheel input, and it gives a signal to the motor to slightly lower the torque. This function improves cornering performance at all stages, from normal operations to critical operations.

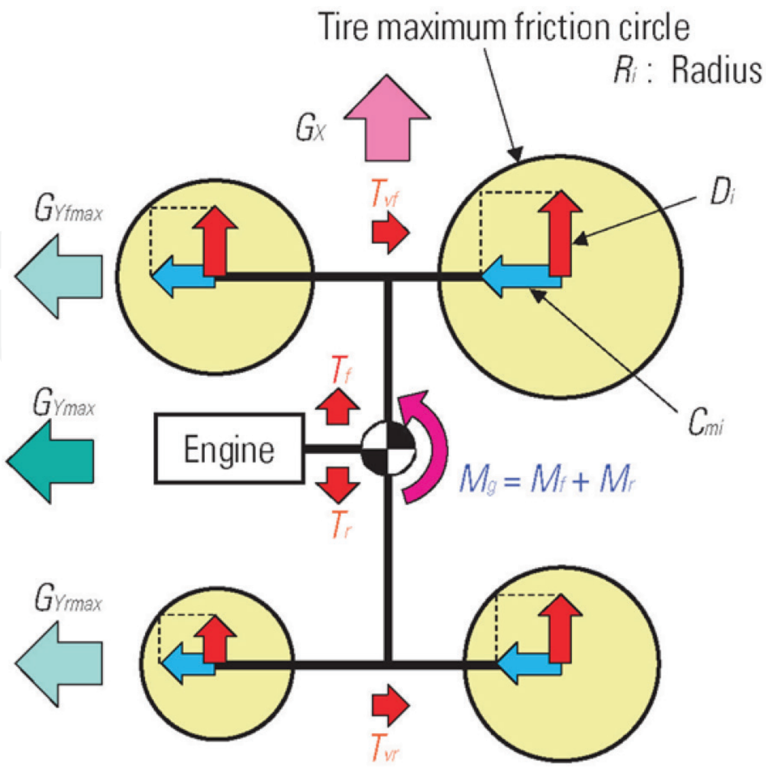

Figure 5. Effect of torque vectoring for four-wheel vehicle [8].

2.8. Active roll control system (ARC)

Active roll control (ARC) is one of the most promising active systems to improve vehicle comfort and operability. When the vehicle is cornering, the vehicle body tilts outward due to centrifugal force, which reduces driving comfort felt by passengers. If the movement of the roll becomes excessive, a fatal rollover may occur. Most passenger cars today are equipped with torsion bars called stabilizers attached to the front and rear axles to reduce roll movement. However, the roll deceleration using the torsion bar also functions as a bridge where the tire vibration on one side is transmitted to the other side. Although the hard stabilizer is good for reducing the roll motion during cornering, it cannot separate vibrations between the left and right tires, which may reduce the comfort during straight driving.

The active roll control system includes a control module, an accelerometer, a speed sensor, a fluid reservoir, an electrohydraulic pump, a pressure control valve, a direction control valve, and a hydraulic actuator on both the front and rear stabilizer bars. Accelerometers and speed sensors may be common to systems other than an active roll control [9]. The configuration of this active roll control system is shown in **Figure 6**. The active roll control system may be referred to as a roll stability control (RSC) system or a dynamic handling system (DHS). Some active roll control systems have gyro sensors that provide voltage signals to the control module in relation to the speed and angle of the vehicle roll. Active roll control can be adopted to improve handling by changing the distribution between the anti-roll torques generated at the front stabilizer bar and the rear stabilizer bar.

When the vehicle is driven straight, the active roll control system does not supply hydraulic pressure to the linear actuator of the stabilizer bar. In this state, both stabilizer bars are free to move until the linear actuator is fully compressed. This action provides improved individual wheel bump performance and better ride comfort. When the chassis begins to tilt during

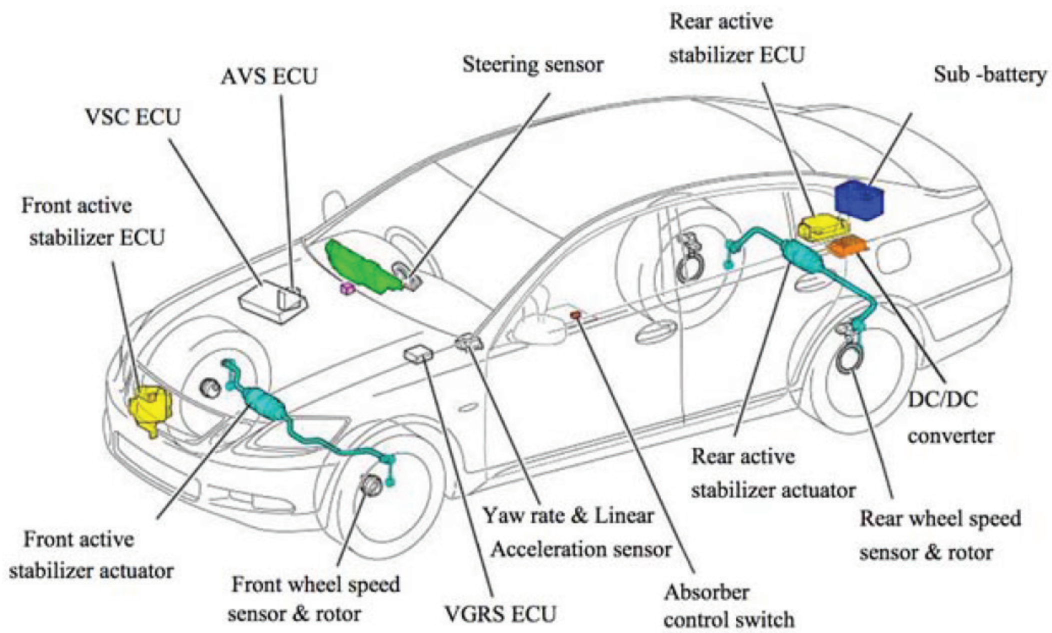

Figure 6. System configuration of active roll control system [9].

cornering, the module operates the directional valve to supply fluid pressure to the linear actuator of the stabilizer bar. This action strengthens the stabilizer bar and reduces the tilt of the body. The active roll control system reduces body lean, enhances safety, and reduces the possibility of rollover of the vehicle.

2.9. Future trends of ABS, TCS, ESC, etc.

As long as the number of built-in system of automotive applications continues to increase, it spreads the possibility of stability of vehicles. Two of the most important advancements affecting the future of ESC are the development of steer-by-wire and brake-by-wire systems. Removal of the mechanical elements from steering and brakes will allow ESC to fully control brake and steering during critical situations. True brake-by-wire is also called EMB or an electromechanical brake. Another form of brake-by-wire is an electrohydraulic brake, but this system uses a conventional method of applying pressure to the brake via a fluid. Full EMB eliminates brake fluid and completely the hydraulic line. The braking force is generated directly on each wheel by a high-performance electric motor. These motors are controlled by the central ECU and are activated by the electrical signals transmitted from the ECU in response to the electronic pedal module. There are not physical connections between the brake pedal and the brake. This mechanical connection is replaced by an electrical signal sent via the bus. Since there is no physical connection to the brake, it is necessary to install an electronic actuator on the brake pedal in order to simulate mechanical feedback to the driver. This is available since several years; ESC in the European Union is mandatory for homologation. The driver cannot control the brake power without braking feedback. Furthermore, since braking is an important safety-related system, in this type of brake-by-wire system, it is necessary to build a fault-tolerant bus or fail-safe system.

A true brake-by-wire vehicle will allow even greater control of the vehicle during system operation. The system will no longer be constrained by the physical limits of the hydraulic brake. There will be little time lag waiting for fluid pressure to build when the system is running. This shortened response time is very precious for hard real-time systems. The second fraction that traditional brakes need to start working means the difference between staying on a frozen road and ending with a groove.

It eliminates the mechanical connection between the steer-by-wire driver and the front tire of the vehicle. Conventional steering elements are replaced by two actuators located at the front corner of the vehicle. These actuators receive input from the control module and turn the front wheels according to the instructions of the control module. The system also uses the electric motor to provide road feedback to the steering wheel.

A true steer-by-wire system offers many advantages over traditional mechanical steering systems. The steer-by-wire has fewer mechanical elements that reduce the vehicle's mass and improve fuel economy in this way. Reducing the number of hardware components can also improve packaging flexibility and system reliability due to the simplification of the vehicle assembly, because system failures are due to component failures. Steer-by-wire also improves the front wheel steering ability which brings a closer turning radius. Steer-by-wire is an

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embedded system with access to a vehicle network that allows easy integration with other vehicle systems such as ESC. Hand wheel subsystem (steering wheel) includes a torque sensor and a position sensor that measures the force rotating the wheel and the angle that the driver turns the wheels. In addition, there is a motor mechanism that provides feedback to the driver to simulate the traditional "feel" of mechanical steering. The driver needs a torque feedback system to accept the steer-by-wire system. If there is mechanical feedback coming from the steering wheel, the driver might believe that the car will not function properly. The torque feedback device must be steer-by-wire a commercially viable automotive system. It can be categorized as a steer-by-wire hard real-time system. The ability to meet the response time requirements is important for systems such as steer-by-wire. The system must be designed to be fault tolerant because either type of system delay or failure will have disastrous results for the driver.

Steer-by-wire brings many advantages to the vehicle stability system. Steering control eliminates driver interference in critical situations. In a critical situation, the driver may panic and put the vehicle in an uncontrollable state. Although this system is very effective, there is a limit to the ability to stabilize the vehicle. Ultimately, it cannot completely ignore the intention of the driver. Steer-by-wire can further strengthen the control of the vehicle stability system. The ESC has the additional advantage of controlling the orientation and position of the wheel. In the case of steer-by-wire, there is also the possibility to steer each wheel independently as necessary. Steer-by-wire may add other elements to vehicle control, greatly improving ESC performance. On the other hand, for steer-by-wire system manufacturers and vehicle manufacturers, there is a possibility that problems may arise if the car encounters trouble, and then it can result in an accident. When designing and mounting a system like a steer-by-wire, careful consideration must be made so that accidents by the system do not occur.

2.10. Vehicle dynamics computer simulation

The development of automobiles is a very time-consuming and complicated process before being sold to customers after being subjected to various stages of design, development, testing, verification, and improvement. Even using vehicles scaled for testing and development, it takes a lot of time to set up and test the system for each change of vehicle or software. Today, the latest automobiles are equipped with many advanced technological solutions. This, along with strict regulatory requirements for safety and environmental standards, leads to a major challenge in design complexity, cost, and quality. To develop software and hardware used in vehicles, computer simulation is an essential tool for developing and using collision mitigation algorithms in a safe environment, without the capital cost of designing, developing, and setting up test rigs. Testing and verification are very important to ensure the correctness of the function. Simulation is an effective means to reduce time-consuming debugging in the field, allowing more iterations in the design process. Simulation allows you to run thousands of different test scenarios in just a moment of a time to run a full-scale system test. The simulation not only makes it possible to reduce the cost of capital but also visualizes the results from these tests when using graphical simulation and can qualitatively and quantitatively determine the degree of performance of the controller. In addition, it is better to adjust the algorithm parameters as well as to observe the impact of the overall system performance with increments in time and cost and further improve quality.

There are many dynamic car simulators, and it is a very realistic model in terms of vehicle dynamics and driving experience. These simulators and the models have enormous effects to capture the very complex nonlinear situations that affect the dynamic behavior of the vehicle. These simulators can interface with custom vehicle controllers in order to observe the impact on vehicle performance with outstanding reality. Many of these simulators are dedicated to automobile development. Examples include ADAMS/Car, CarSim, CarMaker, and others. Using these simulators, the engineering team can quickly build and test functional virtual prototypes of vehicles and vehicle subsystems, increase productivity, reduce time to market, reduce costs, and improve efficiency. Vehicle dynamics can be investigated due to the simulation of the dynamic behavior of many vehicles including passenger cars, racing cars, light trucks, and utility cars. However, the precision, agility, robustness, efficiency, and intelligence of the motion control system are important for the simulation system. Difficult points for engineers lie in various factors such as nonlinearity, friction, complex internal dynamics, time-varying parameters of system dynamics, working environment disturbances, and complex task tasks. To use advanced control algorithms and schemes, time/frequency domain modeling, system identification, observation of unmeasured state, estimation of important parameters, and corresponding analysis are often necessary [10]. The simulation tools provide a reliable environment in which the tests can be repeated accurately. In addition, simulation and support tools provide an atmosphere to develop a necessary environment because there are test scenarios before installing a driving assistance system on actual vehicles. A simulation tool that performs the hardware in the loop test is used to test and calibrate hardware components such as ECUs by integrating the components in a run test. Since the tool produces very accurate results, the functions of hardware components can be rigorously tested before using them in real vehicles.

3. Conclusion

In this chapter, the means of enhance active and comprehensive safety policy on the automobile dynamics control system is described. The vehicle dynamics control has evolved due to the progress of electronics, miniaturization, and software development and is growing quickly in the future. Moreover, systems of ABS, TCS, ESC, TVC, and ARC are described.

Sensor fusion and connectivity might be more important. Sensor fusion is a technique that combines in multiple physical sensors and generates that combine accurate data even if each sensor alone cannot be trusted. Not only the number and type of sensors but also how to use sensors is important. Software synthesizing results from multiple sources provides more sophisticated analysis with more rapid insight than when data from each sensor must be processed separately. By combining input from various sensors to complement the limits and errors of each sensor, the function can be assured. Automotive suppliers continue to find new ways to replace existing mechanical systems, and it is estimated that in the future, development such fusing and connecting sensors will continue for automatic operations. Electronic vehicle control has been attracting more attention with the attraction of the self-driving vehicles and advanced driver assistance systems.

Today ‘s vehicle network is transforming automobile parts, which are in the areas of mechanical or hydraulic systems or into electronic systems. Replacing mechanical parts with electronic parts will cause an integration of the level of the overall system. As a result, the cost of advanced systems should drop sharply. Sophisticated features such as chassis control and smart sensors are becoming mainstream. The X-by-wire system does not rely on conventional mechanical or hydraulic mechanisms. They make lightweight, cheap, safe, and more fuel-efficient vehicles. Such a system can eliminate a hydraulic brake and pump. The X-by-wire steering system might replace the steering column shaft with an angle sensor and a feedback motor. It will also simplify the production of models for the left hand and the right hand. It is natural to add advanced functions to such electronic systems. In a mechanical steering system, the driver actually feels that the vehicle loses control in an unstable state and can respond appropriately. To accommodate this, the X-by-wire system may include a motor on the steering wheel that provides an artificial feedback to the driver.

Technologies for collecting information with sensors mounted on vehicles have evolved with automatic driving vehicles and advanced driving support systems (ADAS). A system that collects information by various sensors such as cameras that recognize objects and people around vehicles and radars (LIDAR) that detect distant obstacles and oncoming vehicles is being put to practical use. After the surrounding environment can be accurately grasped, a technique is required that accurately utilizes the obtained information for autonomous control of accelerator, brake, and steering wheel. The technology of ABS, TRC, and ESC is applied to the operation of this accelerator, brake, steering wheel.

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