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自動車における安定化制御についての研究動向
––DYC および電気自動車における安定化制御

Technologies and New Trend of Vehicle Stability Control
––Direct Yaw-moment Control (DYC) and stability control in EV

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Abstract

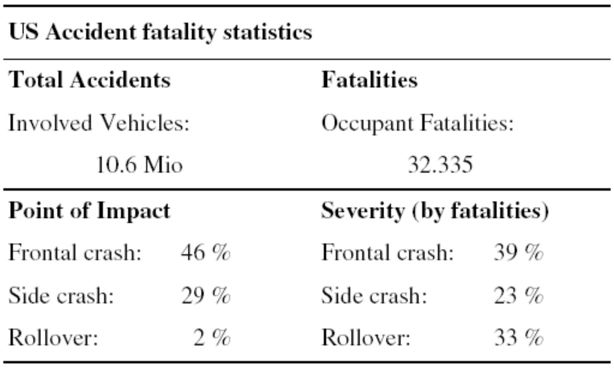
In recent years, vehicle stability control technologies are playing more and more important roles in road safety. It is to prevent accidents caused by losing control of vehicles. As a kind of active safety technologies, the system assists the driver to keep the vehicle on the intended path. In this paper, firstly, the basic concept of vehicle stability control is introduced. Secondly, vehicle stability control technologies are categorized; its history and some of technologies are also discussed. Then As a new trend of vehicle stability control, DYC (Direct yaw-moment control) is analyzed. In addition, novel approaches for stability control with the development of motor-driven electric vehicle are also presented.

1 Introduction

With the rapid growth of economy, the amount of vehicles sharply increases. Meanwhile traffic accidents lead to more and more people's injury and even losing their lives. So it requires additional efforts to improve the road safety.

In spite of improvements in passive safety and efforts to alter driver behavior, the absolute number of highway fatalities increased to the highest level since 1990. Statistics show a total of 1.3 million accidents for the year 2000 with 1.7 million injured persons.

Many of the serious accidents happen because of loss of vehicle control in critical driving situations. When the vehicle goes into a skid for loss of control, a side accident is the frequent result. Even seriously, skidding may lead to a rollover. With a reduced protection zone for the occupants compared to front crashes, these accidents show an amplified severity. The severity of rollover accidents is extremely high. Accounting for only 2% of the total crashes, they contributed in 2002 with 10,656 fatalities to one third of all occupant fatalities in the US(Fig.1).

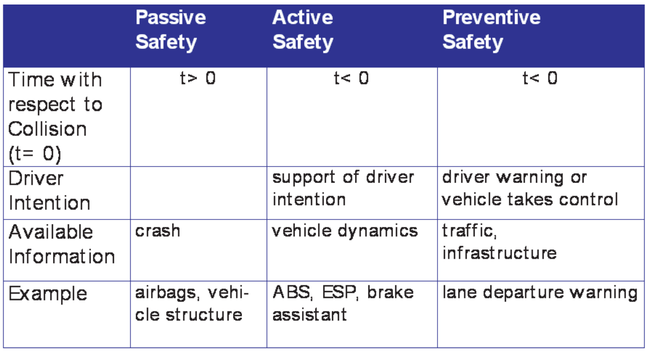


US Accident fatality statistics

Total Accidents		**Fatalities**	
Involved Vehicles:		Occupant Fatalities:	
10.6 Mio		32.335	
Point of Impact		**Severity (by fatalities)**	
Frontal crash:	46 %	Frontal crash:	39 %
Side crash:	29 %	Side crash:	23 %
Rollover:	2 %	Rollover:	33 %

Fig. 1: North America accident fatality statistics

To solve this problem which is mentioned above, technologies about vehicle active safety control have been extended from just slip control to the vehicle stability control in every direction: longitudinal, lateral, vertical and yaw. Individual control technologies are being integrated to make higher performance. Shown as Fig.2, vehicle stability control is to prevent accidents caused by losing control of vehicles. It refers to active safety technologies that assist the driver to keep the vehicle on the intended path with the use of electronic control.



	Passive Safety	Active Safety	Preventive Safety
Time with respect to Collision (t= 0)	t> 0	t< 0	t< 0
Driver Intention		support of driver intention	driver warning or vehicle takes control
Available Information	crash	vehicle dynamics	traffic, infrastructure
Example	airbags, vehicle structure	ABS, ESP, brake assistant	lane departure warning

Fig. 2: Classification of vehicle safety measures

In recent years, a new generation vehicle control system was put forward: vehicle stability control system. It is developed from several previous safety control technologies, such as ABS, TCS and EBD systems. Vehicle stability control system is especially effective in keeping the vehicle on the road and mitigating rollover accidents. This new generation vehicle stability control system has a higher level performance for the integration of previous individual safety technologies, and extends to a new function called direct yaw-moment control [1-3].

In this paper, the basic concept of vehicle stability control will be introduced. The main functions of vehicle stability control system are presented, for example, ABS and TCS. Then, the principle of DYC will be analyzed. Finally, DYC for Electric vehicle application will be discussed.

2 Basic concept and main technologies of vehicle stability control

2.1 Planar vehicle model and related forces

Considering that vehicle usually performs planar movement, vehicle dynamics can be simplified shown as Fig.3.

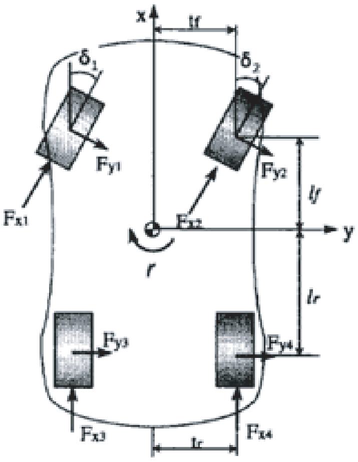


Fig. 3: Planar vehicle model and related forces

$$\begin{aligned} I\dot{\gamma} &= 2F_{yf}l_f\cos\delta_f - 2F_{yr}l_r + N \\ ma_y &= 2F_{yf}\cos\delta_f + 2F_{yr} \\ N &= \frac{d}{2}(-F_{x\_f1} + F_{x\_f2} - F_{x\_f3} + F_{x\_f4}) \end{aligned} \tag{1}$$

Where, I is the moment of intertia of the vehicle, γ is the yaw velocity, F_{x_f1}, F_{x_f2}, F_{x_f3}, F_{x_f4} are the longitudinal forces on the front left, front right, rear left, rear right tire respectively, N is the yaw moment on the vehicle generated by driving/braking tire forces, a_y is the lateral acceleration of the vehicle, d is the distance betweenleft and right wheel, m is the mass of the vehicle, and δ_f is the steering angle of the wheel.

From above equations we can get the conclusion that the trajectory of the vehicle moving is determined by the outside forces (mainly as tires friction forces) acted on it. In another words, the expected movement of vehicle must be supported by tire/road friction forces. However, Tire/road friction force has the limitation which depends on the friction coefficient of the road and the vertical load on the tire. When the requirement for friction forces is equal to or greater than a tire can provide, dangers may occur.

In most cases, when a tire or two obtain its adhesion limitation, the others still have some potential adhesive ability which can be made use of. So the purpose of vehicle stability control is to utilize all of the tire adhesive ability as much as possible, and to make the vehicle running on expect path.

2.2 Analysis on the deterioration of vehicle stability

Generally, drivers alter the tire/road force to control the vehicle motion by exerting traction/braking and steering operation through accelerating/braking pedal and steering wheel. Unfortunately, according to paper [4], the average driver can neither judge the friction coefficient of the road nor the grip reserves of the tires. Tire friction forces are apt to get their limitation in critical situations without the consciousness of divers.

In such critical driving situations，the deterioration of vehicle stability behaves as sliding. The most common types of slides are referred to as understeer and oversteer (Fig.4). In an understeer situation, the front of the car plows toward the outside of a turn without following the curve of the turn. In an oversteer situation, the rear of the car fishtails toward the outside of a turn, increasing the chance of a spin.

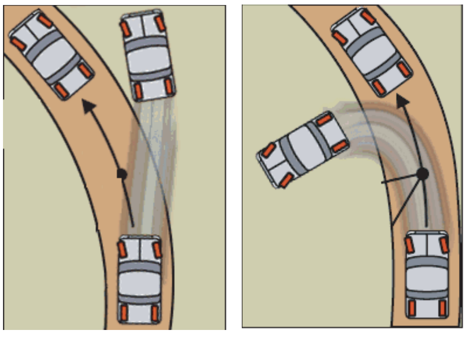


Fig. 4: Deterioration of vehicle stability for sliding

In critical driving situations (such as corning with high speed on wet road) most drivers are overburdened with the stabilizing task. The drivers are typically startled by the altered vehicle behavior in unstable driving situations; as a result, a well-considered and thought-out reaction of the driver can not be expected.

2.3 Development of vehicle stability control technologies

From above analysis, it is clear that tire/road friction force is the main factor to be controlled in the vehicle stability control system. According to the force controlled in tire, typical technologies of vehicle stability control can be classified as longitudinal force control (ABS, TCS), lateral force control (4WS:4 Wheel Steering, AFC:Active Front steer Cotrol), vertical force control (ARC:Active Roll Control) and yaw-moment control.

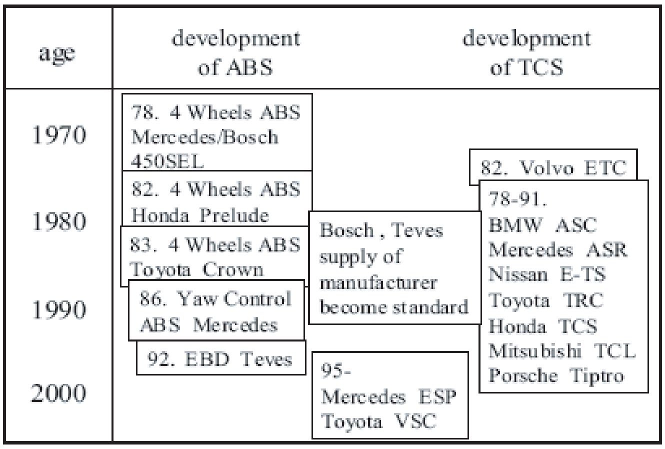


Fig. 5: Development from ABS/TCS to VSC

As shown in Fig.5, developed based on ABS and TCS, but unlike ABS and TCS which only adjust maximum longitudinal force control, vehicle stability control focus on the new generation longitudinal force control with a higher level above ABS and TCS. These systems are usually referred Vehicle Stability Control (VSC).

Yaw moment can be directly generated and actively controlled with these systems. Such technologies involve Electronic Braking Distribution (EBD), Active Four-wheel Drive (4WD) and Direct Yaw-moment Control (DYC) with differential braking control. All these systems which still have ABS and TCS functions extend their control ability from longitudinal (wheel slipping) control to lateral control of vehicle through yaw moment modulating. Researches on VSC are still being carried on for higher performance and lower price of production.

Be aware that such safety control technology is researched under different names among automakers. For example, they are called as Vehicle Stability Control (VSC), Vehicle Stability assistant (VSA), Electronic Stability Control (ESC) in Toyota Company and Vehicle Dynamics Control (VDC), Electronic Stability Program (ESP) in Bosch Company. VSC system generally integrates the following technologies and functions.

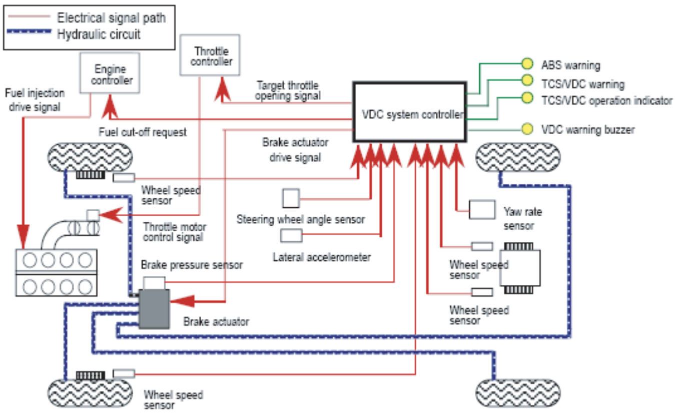


Fig. 6: Bosch VDC system

One of the main tasks of vehicle stability control is the limitation of side slip angle dependent on the actual friction coefficient. Fig.6 shows a VSC system by differential braking, which is called VDC here. The system provides a higher level of driving stability by automatically correcting a vehicle's lateral behavior based on detection of sideslip. This is accomplished by using various sensors to monitor the driver's steering and braking operations as well as the vehicle's dynamic state.

Shown as Fig.7, first, from the driver's input, measured by a steering wheel angle sensor, a throttle position sensor and a brake pressure sensor, the nominal behavior is determined. Second, from the signal values of the wheel speed sensors, the yaw velocity sensor and the lateral acceleration sensor the actual behavior of the vehicle as described by the actual values of its controlled variables are determined. The difference between the nominal and the actual behavior is then used as the set of actuating signals of vehicle dynamics controller. Even in the range of characteristic side slip angles, where the effectiveness of steering is rather limited, the system can exercise remarkable yaw moments by brake interventions.

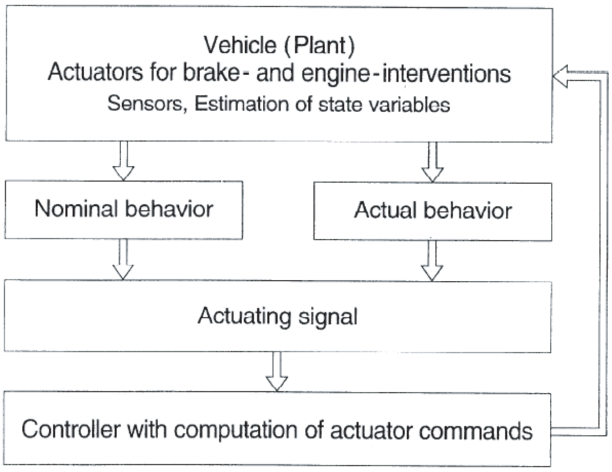


Fig. 7: Control scheme of Bosch VDC system

2.3.1 ABS and TCS

The principle of ABS and TCS

Shown as Fig.8, ABS and TCS is to control the slip ratio of wheels in an optimal range, and this enables the wheel with best braking/traction to regain grip by preventing remarkable decrease of the lateral force, maintaining directional stability and steerablilty [4].

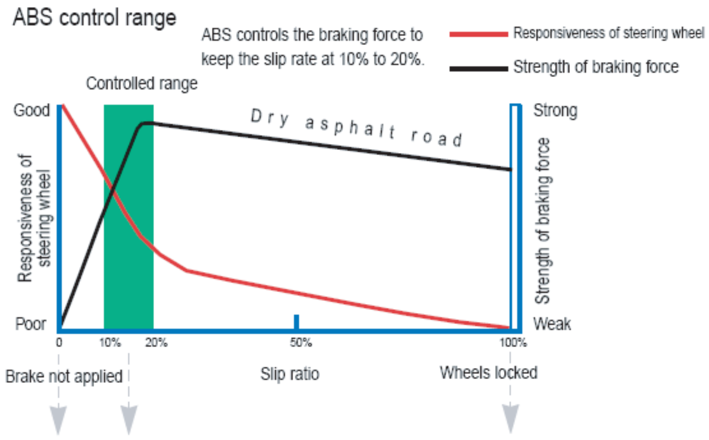


Fig. 8: Slip ratio regulating principle for ABS

The process and effect of ABS and TCS

Shown in Fig.9, ABS and TCS are developed to restrain wheel-lock at braking by modulating brake pressure or wheel-spin during accelerating phase by applying brake pressure to the spinning wheel and reducing engine output.

Fig.9 shows that while braking, turning is possible when the slip ratio up to roughly 20% but the vehicle cannot be turned when the wheels lock. The reason is that lateral friction coefficient is nearly zero when the wheels lock, and the front tires can not provide lateral forces which is necessary to cornering.

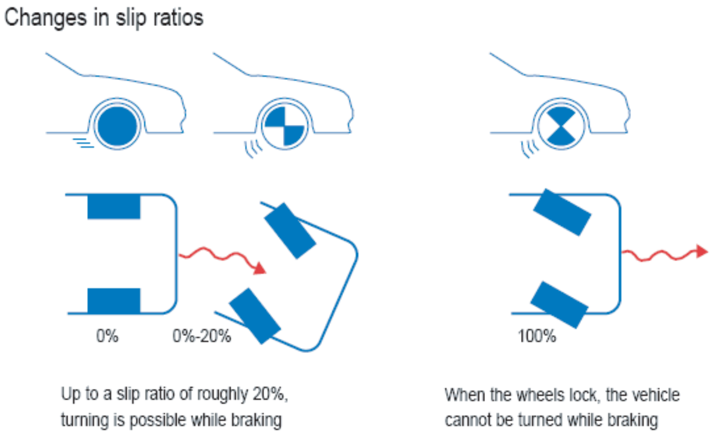


Fig. 9: Influence of slip ratio on turning

2.3.2 DYC

If the traction force and braking force are properly distributed to the right and left wheels, yaw moment in accordance with the forces distributed will be obtained and thus the vehicle lateral motion can be accurately controlled. A direct yaw moment control (DYC) controlling vehicle motion by a yaw moment which is actively generated by the intentional distribution of the tire longitudinal forces is becoming one of the most promising chassis control.

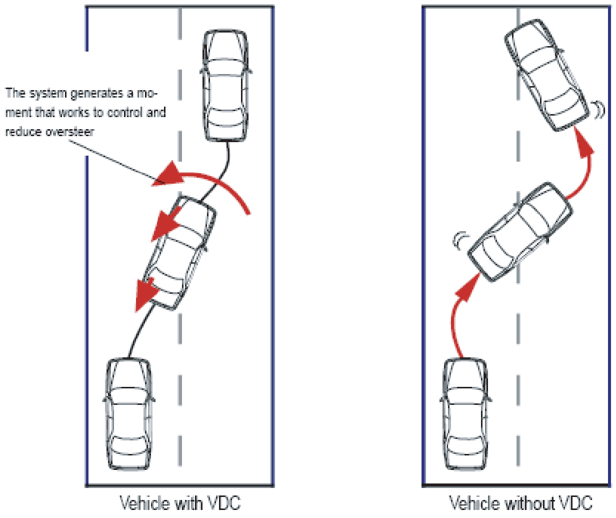


Fig. 10: A typical situation of DYC working

Shown as Fig.10, the VSC system prevents a vehicle from spinning when large incipient oversteer occurs during a lane change on a slippery road surface. It does this by acting braking force at the outer wheels to generate a direct yaw moment according to the degree of oversteer detected so as to reduce oversteer and maintain driving stability. The detail of DYC will be discussed in the next chapter.

3 Analysis of Direct Yaw-moment Control

3.1 Basic description of DYC

The reason why stabilizing a vehicle in critical situations is so challenging can be shown by considering the physical effects. Steering of a vehicle generates a yaw moment which results in a directional change. The effect of a given steering angle depends on the actual side slip angle [5, 6]. Only slight alterations of the yaw moment are possible at large side slip angles even for extensive steering interventions which can be seen in Fig.11. The characteristic side slip angles, where the steerability of the vehicle is vanishing, are dependent on the road friction coefficient. On dry asphalt it is around 12 ° as shown in Fig.11, whereas on polished ice it is in the range of 2 °. The driver experiences in all day traffic situations side slip angle values of typically not more than 2 °.

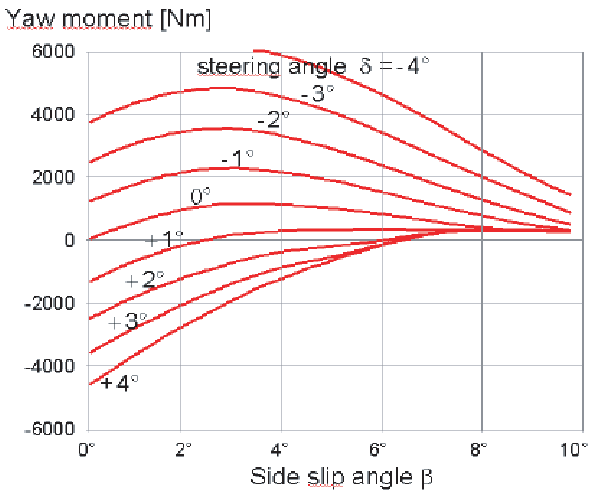


Fig. 11: Influence of side slip angle on yaw moment on dry asphalt

DYC is a system that can stabilize vehicle motion by a yaw moment actively generated as a result of the difference in tire traction or braking forces between the right and left side of the vehicle. As mentioned above, one of the main tasks of DYC is the limitation of side slip angle dependent on the actual friction coefficient. The side slip angle and yaw rate of the vehicle are controlled to desired values. Even in the range of characteristic side slip angles, where the effectiveness of steering is rather limited, DYC can exercise remarkable yaw moments.

3.2 Principle and working process of the DYC

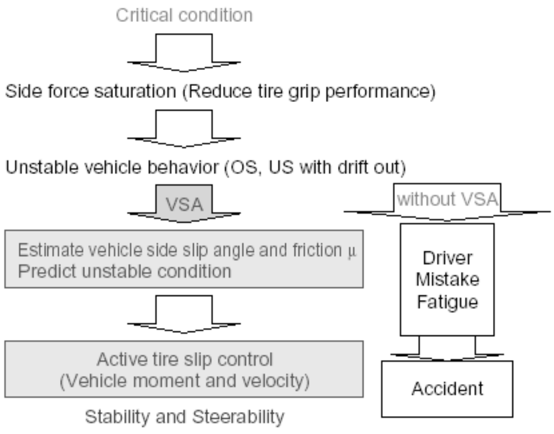


Fig. 12: Algorithm of Direct Yaw-moment Control

Fig.12 shows the working principle of DYC. The main functions included in a DYC algorithm are [5]:

- Vehicle side slip angle and tire side slip angle estimation.
- Friction coefficient between tire and road Estimation
- Tire side force estimation and stability judgments
- 4-wheel slip control to maintain stability

3.2.1 Tire slip angle α and vehicle side slip angle β estimation [6]

As shown in Fig.13, the method for estimating vehicle side slip angle β is a logic that can estimate forces on each tire by combining the conventional two tire vehicle model and tire model. Furthermore, the total of the estimated side forces for all 4 wheels is fed back, and those estimated side forces are read from the tire data map. Tire data map is expressed as three characteristics:

- Side slip angle / side force
- Slip rate / side force
- Slip rate / braking and traction force

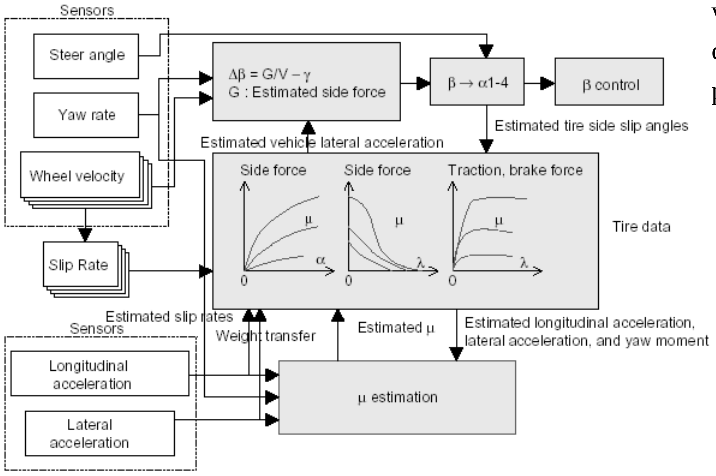


Fig. 13: Parameters estimation logic of DYC system

3.2.2 Tire and road surface μ estimation

The μ estimation logic is the most important issue. The situation that should be estimated is as follows: there is a change from constant speed straight line driving to cornering that is close to limit conditions, or when there is a sudden jump in μ, and in addition, tire slip control is implemented through such means as ABS, and it is necessary to stably maintain estimation accuracy across a wide range. In order to achieve this, the logic was created, based on the following flow:

- Separate μ estimation for each mode:straight line driving, cornering, jump μ
- Calculation of longitudinal and lateral acceleration and yaw moment from the estimated tire side slip angle β and the tire data map
- Calculation of the μ correction value from a comparison of the estimated value (longitudinal and lateral acceleration, yaw moment) and each sensor's value
- Application of the tire characteristics data map gain, based on the μ correction value

3.2.3 Tire side force estimation and stability judgments

Fig.14 shows the results of analysis of OS using estimated tire side slip angle α, vehicle side slip angle β, yaw rate, lateral acceleration and tire side forces. According to these results, we found that rear tire side forces are saturated from the onset of OS. Calculating the absolute value of ar (rear wheel side slip angle) and the differential value Dar, then comparing them with each limit (judgment value), makes it possible to make an early prediction of critical conditions.

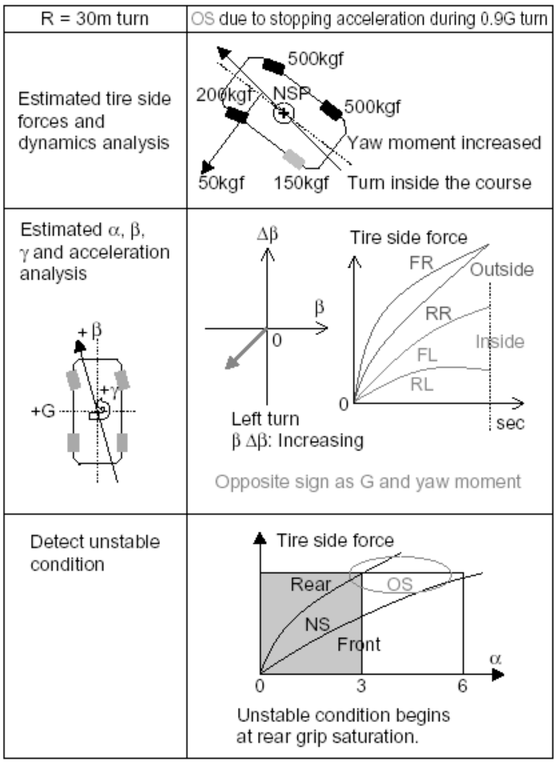


Fig. 14: Tire side force estimation and stability judgments

3.2.4 Four wheel slip control to maintain stability

Take an oversteering (OS) situation control as an example, the process for analyzing OS and spin during cornering on icy and snowy roads can be divided into four stages.

(1) Rear tire side slip angle α_r exceeds limit value

(2) Rear tire side forces are saturated

(3) Vehicle side slip angle and yaw moment increase

(4) Grip is lost and consequentially so is steerability, rendering turning impossible

As can be understood from this process, if OS can be predicted in step (1), then by repeating both counter moment control and deceleration control in steps (2) and (3), vehicle stability can be maintained, steering is effective, and it is possible to recover the motion state. That is, stability uses front outside wheel brake control, and steerability uses the brake control of the two rear wheels to return to the grip range [7-9].

3.3 Problems and difficulties in the realization of DYC [10]

For the conventional internal combustion engine vehicles (ICVs), complexity and difficulties limit the application of the optimization distribution control of driving/braking control. Therefore, in the process of developing DYC system, there are problems and difficulties which need more attention:

- First, independent adjustment of driving/braking force on each wheel needs more complicated actuating technologies.
- Second, it is difficult to accurately control the driving/braking torque with conventional traction/brake technologies. Especially, traction torque distribution between tires by differential control is still complicated and difficult to get high accuracy.
- Third, parameter estimations described above often depend on complicated algorithm, because it is difficult for the traditional vehicle control systems to measure traction/braking forces accurately.

4 Stability control in electric vehicle with independent driven motor-in-wheel

4.1 Background of control technologies for electric vehicle

Recently, electric vehicles (EVs) are intensively developed. With improvement of motors and batteries, some pure EVs (PEVs) with only secondary batteries have already achieved enough performance. Hybrid EVs (HEVs), like Toyota Prius, are going up to the commercial products. The background of this developments is energy and environmental problems, thus main concern over EVs is energy efficiency and environmental impacts. However, another important advantage exists, which is being recognized well now. It is controllability of electric motors. Advantages of motor controllability can provide more flexible and novel control ideas for vehicle safety [10-11].

4.2 Advantages of EVs for stability control

Compared with internal combustion engine vehicle’s difficulties in applying advanced stability control like DYC, from the viewpoint of electrical and control engineering, EVs have evident advantages over ICVs. The advantages and the novel control approaches accordingly are as follows:

- Torque generation of electric motor is very quick and accurate, for both accelerating and decelerating.

This should be the most essential advantage. Electric motor’s torque response is several milliseconds which is 10-100 times as fast as that of the internal combustion engine or hydraulic braking system. ”Super ABS (antilock brake system)” will be possible. Further, ABS and TCS (traction control system) can be integrated.

- Motor can be attached to each wheel.

Small but powerful electric motor installed in each wheel can generate even anti-directional torques on left and right wheels. Distributed motor location can enhance the performance of vehicle stability control such as DYC. It is not allowed for ICV (internal combustion engine vehicle) to use four engines, but it is all right to use four electric motors with small cost increase.

- Motor torque is easily comprehensible.

There exists much smaller uncertainty in driving or braking torques generated by an electric motor than that of IC engine or hydraulic brake. Motor torque can be easily known from the motor current. Therefore, simple ”driving/braking force observer” can be designed and we can easily estimate the driving and braking forces between tire and road surface in real time. This advantage will contribute a great deal to application of new control strategies based on road condition estimation, such as improved ABS and DYC [12].

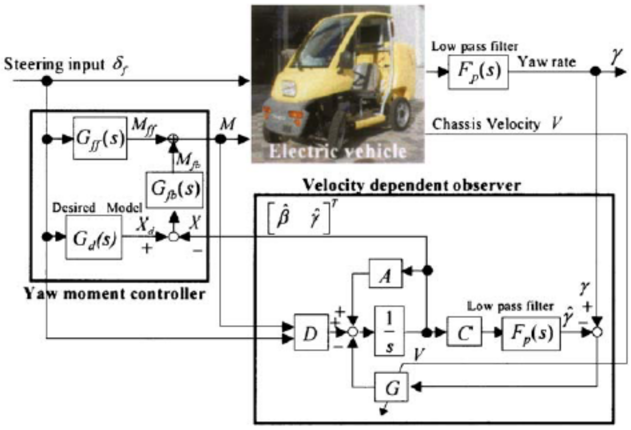


Fig. 15: Block diagram of DYC for a small-scale electric vehicle

4.3 DYC for Electric vehicle implementation

As mentioned above in 4.2, merits of EV make an easier implementation of DYC compared with that in ICV. Fig.15 is the controlling structure of a DYC system for a small-scale electric vehicle. The electric vehicle was developed to be able to generate the additional yaw moment by individual wheel torque command to each in-wheel-motor of the rear axle [13].

The direct yaw-moment generated by the traction force at the rear axle is employed as the control input to make actual response trace the desired values. With the application of model matching control technique, the control system consists of a feedforward compensator for to the steering angle, and a feedback compensator depending on state deviations of side slip angle and yaw rate.

5 Conclusion

Vehicle stability control with integrated functions becomes a new trend of vehicle safety technologies. It will take the place of the individual anti-slip systems to get higher performance.

Direct yaw-moment control is the most important function of such new vehicle stability control systems. It can effectively prevent accidents caused by losing control of vehicles with assisting the driver to keep the vehicle on the intended path.

For electric vehicles, with the merits of motor controllability, such as distinct advantage in the precise and quick torque generation, researches has been conducted concentrating on more flexible and novel control ideas for advanced vehicle stability.

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