# Vehicle Dynamics

## 1 Introduction

In 2013, several reports discussed early initiatives by companies in the U.S. and Europe to develop autonomous driving technologies. Staring with the International CES 2013, three major Japanese automakers also announced test vehicles equipped with autonomous driving technology. The New Energy and Industrial Technology Development Organization (NEDO) reported the results from its Development of Energy-saving ITS Technologies project, which was carried out over the course of a five-year plan starting in 2008. NEDO released videos of autonomous platoon driving of trucks on a test course at the National Institute of Advanced Industrial Science and Technology. Automakers and suppliers in the U.S. and Europe have also released footage demonstrating autonomous and platoon driving on video posting websites. The development of technologies related to autonomous driving and sophisticated driver support is clearly advancing. In addition to automakers, control component suppliers and software manufacturers are also entering this field, and competition to develop autonomous driving technologies is likely to continue to intensify.

In the field of vehicle operating systems, mass-production vehicles equipped with steer-by-wire (SBW) systems are now on sale and technology is available for the mass-production of vehicles with drive-by-wire (DBW) capabilities, in which all of the basic driving, turning, and stopping functions are performed by-wire (XBW). Fly-by-wire (FBW) technology was the result of research into aircraft that were control configured vehicles (CCV). The movement to apply this technology to vehicles began after World War II and is expected to spur on new vehicle developments as aviation engineering helps automotive engineering to evolve.

The integration of DBW with advanced driver support systems (DSS) will help to achieve higher levels of vehicle dynamic, safety, and environmental performance. However, it is also expected to generate new issues, such as how to construct systems that will never lose operating system functionality while driving, the increasing complexity of control system operations, and interference with driver operations.

Technological developments in this field should help to improve safety and security, while reducing environmental impact and contributing to greater convenience, enjoyment, and comfort in people's lives. Through these technologies, vehicles should retain their appeal in the future by accommodating the changing values of the next generation.

## 2 Tires

Vehicle motion is determined by the forces and moments around the vehicle's center of gravity. The main components are the tire force and the force of inertia. Since driver operations change the forces generated by the tires to control the motion of the vehicle, tire characteristics are an extremely important element.

The tire models that are used in vehicle dynamics simulations have very precise tire characteristics, and empirical models are widely used. The Magic Formula is a representative empirical model that combines trigonometric functions. Since an empirical model is a method for identifying the coefficients that are the best suited to the experiment data, it is difficult to take advantage of the tire characteristics in the structural design of the tire. In the past, there were issues with the precision of the classical physical model that correlates the tire characteristics with the structural characteristics. However, research has advanced in recent years and one suggested model has improved precision up to the level of an empirical model. This model has been expanded to the transient region, resulting in the proposed transient Neo-Fiala model. The tire characteristics in this model can be correlated with the tire structure, including the response delay characteristics of the tire, by introducing a time constant expressed by the structural characteristics of the tire. Research that used the Fiala model for motorcycles was also reported and research into tire models that use tire structural characteristics is likely to continue to advance in the future.

In the field of measurement of tire characteristics, it was reported that a flat belt-type suspension tire tester was used to measure tire characteristics during vehicle assembly. In addition, technology that measures and visualizes the distribution of shear force within the tire tread was also developed. A next-generation fuel-efficient tire has also been proposed using this technology to achieve both good environmental and dynamic performance through the adoption of an innovative tire size and high air pressure. Another report investigated the changes in tire tread temperature and tire characteristics under actual driving environments. This report described the quantitative relationships between temperature and tire air pressure, and the rolling resistance coefficient (RRC) and cornering characteristics.

There are also efforts underway to turn the tire itself into a sensor. Research into a tire system that directly measures the tire force and then uses this for electronic stability control (ESC) was reported, as well as research into using the steel belt of the tire as a capacitor to constantly monitor tire damage via changes in belt capacitance.

From the standpoint of environmental conservation, automakers are still facing strong demands to improve the rolling resistance of tires since this has a large effect on vehicle fuel efficiency. In addition to conventional efforts to reduce the RRC, more focus is now being placed on the flow of air around the tires and wheels, and research into methods of reducing running resistance is also making progress.

The challenge now is to achieve high levels of very different performance aspects, including environmental and dynamic performance, as well as noise, vibration, and harshness (NVH), while also developing increasingly complicated intelligent controls with high efficiency. To accomplish these goals, it will be necessary to fully master all aspects of vehicle development from the initial stages of the development process to simulation technology. This explains the increased demand for tire models that can be used to examine tire characteristics, while also ascertaining the feasibility of other performance aspects and structures. There are growing expectations for the development of a single physical model for computer-aided engineering (CAE) that integrates models of both ride comfort and handling.

## 3 Braking and Driving Characteristics

Research into braking and driving characteristics started from basic theoretical research into stability when the vehicle is being driven at its limits, and the effects on cornering performance during normal driving. The former started from research into vehicle behavior under excess braking and then evolved to encompass anti-lock braking systems (ABS), traction control systems (TCS), and ESC, which all use control technology. The latter started from research into how different drive systems affect cornering characteristics and evolved to cover cornering characteristics during braking and driving. This eventually led to the development of direct yaw moment control (DYC), which uses four-wheel torque control to improve cornering performance. All of these technologies were then integrated with active safety technologies and further evolved into DSS.

Electric vehicles (EVs) and hybrid vehicles (HEVs) that have become very popular in Japan are now increasingly being sold by automakers in the U.S. and Europe. The motors used to power EVs and other vehicles perform drive and regenerative braking. Compared to an internal combustion engine, these motors realize far more responsive and precise braking and driving force control. Reports have examined changes to driving force distribution controls to improve vehicle dynamics and the regeneration controls that affect driving range. Other reports investigated the relationship between cornering performance and power consumption. In addition, there is research into in-wheel motor (IWM) type EVs that have a motor installed in each driving wheel. Research into DYC has also increased because IWM technology allows the independent control of each wheel with a high level of responsiveness. This also includes research into automatic steering, in which the steering torque is generated only around the king pin via braking and driving control without using any steering assistance mechanism. This is a very interesting method that utilizes the special features of IWM.

Other research proposed using the ESC unit, which is increasingly becoming standard equipment, to help coordinate DYC by braking force and deceleration control to achieve natural feeling steering. It is now being confirmed whether this improves maneuverability and stability on roads covered in compacted snow.

In this field, research is likely to continue advancing so that performance can be enhanced simply by changing software, while using DYC, driver support technologies, and existing hardware in conjunction with motors and system electrification.

## 4 Directional Stability and Steering Responsiveness

Theories for vehicle stability and maneuverability were developed based on vehicle motion dynamics that became systematized after World War II. In recent years, there has been less and less research into the basic theories from new points of view that would lead to further development of vehicle motion dynamics. However, the basic research that was reported in 2013 shows that the systematized theories are being considered, and there was an increase in examinations of mathematical models to construct control laws. This demonstrates that the development of technologies to improve vehicle dynamics is based on the foundation of vehicle motion dynamics and also reconfirms the importance of the basic theories.

This field includes active development of technologies related to steering, the suspension, DYC, intelligent controls, and weight reduction. The following sections introduce the trends in technological development, excluding those concerning DYC and intelligent controls that are covered elsewhere.

Related to steering systems, SBW technology for mass-produced vehicles was introduced above. If the rotation of the steering shaft is replaced with an electronic signal, then the steering angle, steering torque, and actual steering angle of the tires can be independently controlled. Through this, automakers are aiming to accomplish the following: a balance between agile response and straight-line stability, characteristics that do not transmit uncomfortable road surface disturbances and vibrations to the driver through the steering wheel, and characteristics that provide feedback to the driver from the reaction force of the road surface in accordance with the steering, but without any sensations of discomfort.

Related to the suspension, a comparatively large number of reports in 2013 described active suspension technology. Automakers are aiming to balance the speed of steering response, improve the vehicle limits, and ensure stability at a high level. Another report described replacing a portion of the suspension linkage with an actuator to achieve active rear-wheel steering (ARS) that can independently control the left and right alignments of the rear wheels. In recent years, four-wheel steering (4WS) has been improved in an effort to address sensations of discomfort related to vehicle response often felt with previous 4WS systems. This was achieved by advances in research into intelligent controls combining front-wheel active steering, electric power steering (EPS), and ESC.

In light of efforts to improve vehicle fuel efficiency, the effects of body stiffness and aerodynamics to enable vehicle weight reduction are being researched. The effects of making an extremely stiff body are well known through past experience, but new cases were analyzed and reported focusing on the dynamic characteristics of the body and tire slip angle. Differences in vehicle characteristics due to changes in body specifications are extremely small and it is very difficult to detect any significant difference through actual measurements. Consequently, CAE-based research is likely to continue growing in importance in the future. Furthermore, it is thought that aerodynamics will have a greater effect on changes in the vehicle's turning attitude as vehicle weight is reduced. Research has been carried out using a towing-type water tank test to measure the forces and moments acting on the vehicle. In addition, other research was reported in which the body attitude was forcibly displaced and aerodynamic analysis was carried out using a time-series implicit method to clarify the relationship between unsteady aerodynamic forces and changes in the vehicle attitude. Research into unsteady air flows has advanced even further and it is now possible to identify aerodynamic coefficients from the body attitude once the attitude has been converted into variables. This has the potential to be developed into a technology that can incorporate equations of motion and vehicle motion analysis.

The relationship between vehicle behavior, such as roll and pitch, and steering response is continuing to be examined as part of the consideration of basic theories, which indicate that this is an important vehicle behavior. The further development of basic research, such as into transient regions, may help to identify the effects of body stiffness and aerodynamic parts.

## 5 Limit Performance

One trend in Japanese domestic legislation in 2013 was the decision to make the installation of ESC on trucks, buses, and trailers mandatory. This is one part of an expanding movement to mandate the adoption of ESC on vehicles in many countries around the world. ABS is required to be standard equipment on new model vehicles registered from 2014, and on every new vehicle registered from 2017. Some large vehicles must also be installed with electronic vehicle stability control systems (EVSC) starting in 2015. There are also plans to expand the applicable scope of the EVSC requirements to all trucks and most buses and trailers, with only a few exceptions.

Since large vehicles have a large maximum loading capacity and cargo space, the vehicle mass, center of gravity position, and moment of inertia varies greatly depending on the loading conditions. There is a concern that if the control parameters are determined based on the most severe load conditions, the controls will become excessive when the vehicle is carrying no cargo and become an annoyance to some drivers. Consequently, methods were proposed that estimate the center of gravity position and other stability factors during driving and provide control parameters suitable to the load conditions at that time.

In September 2013 a new standard was established in North America to help prevent the ejection of vehicle occupants in the event of a crash (FMVSS 226). Research into rollover crashes in which tires leave the paved surface of the road and sink into an unpaved dirt surface (soil trip rollovers) was also reported. Another report compared different vehicle behavior that occurs when a tire is damaged, such as tread separation, a puncture, or tire burst, since these are also possible causes that may lead to an accident.

It is assumed that investigations and research into areas such as this, which have not been looked at carefully in the past, will continue in the future based on research and statistics provided by the National Highway Traffic Safety Administration (NHTSA) in the U.S. and other agencies. The development of technologies for helping to reduce the number of traffic accidents, such as emergency avoidance support and improved vehicle limit performance that uses intelligent controls, is also likely to continue around the world.

## 6 The Human-Vehicle-Environment System

The U.S. and Europe have led the way in the development of platoon and autonomous driving technologies. However, a driver model is still necessary to incorporate aspects such as the proper following distance, risk judgment, judgment of the surrounding situation, and collision avoidance maneuvers into the system. Therefore, efforts have been made to use mechanical engineering to capture and incorporate the human system into steering response. In addition, efforts to incorporate ergonomics have also increased because this allows for analysis of the driver's cognitive and judgment behavior, psychological state, and driving behavior characteristics.

The development of autonomous driving technologies is expected to contribute to DSS that will help to enhance active safety and reduce traffic congestion. To function properly, DSS must be realized in a way that feels natural without generating discomfort or annoyance. Possible functions of DSS include alerting the driver to careless driving, reducing driver burden, and helping to avoid collisions. Discomfort leads to driver fatigue and annoyances worsen the psychological state of the driver. Factors such as these may indirectly lead to an accident. The one major difference between a vehicle and other forms of transportation is that anyone, both young and old alike, can drive one. Consequently, several recent reports have described efforts to develop DSS that readily adapt to variety of individual driving skill levels, from beginners to experts. Since a high percentage of traffic accidents occur at intersections, many reports describe research using driving simulators (DS) to investigate the cognitive behavior of drivers at intersections. The goal is to apply DSS to help drivers at intersections and such research is likely to continue to increase in the future.

Efforts are also underway to utilize DS to link driver evaluations and vehicle behavior to evaluate increasing sophisticated and flexible intelligent controls. This includes research into stable sprung behavior and research into steering response sensations during both low speed and high speed cornering focusing on yaw rate and body slip angle characteristics.

The close relationship between steering torque when cornering slowly over a small angular range with driver evaluations is well known from past experience. Research that evaluated the effect of rear wheel cornering power (CP) on steering torque, including the damping and friction of the steering system, separately from the vehicle behavior was also carried out using DS.

It is likely that vehicles without DSS will continue as the main types of vehicles sold in expanding emerging markets. It is hoped that the development and advancement of technologies related to DSS in developed nations can also be adopted in conventional models to prevent the predicted increase in traffic accidents in emerging nations.

## 7 Intelligent Controls

Many demonstration tests of autonomous driving vehicles have been performed on public roads in the U.S. and Europe. In Japan, NEDO has also reported the results from its Development of Energy-saving ITS Technologies project. Research has studied self-tuning of the automatic steering control gain that is necessary for large vehicles to perform route-following autonomous driving. This research found that a distance of 4 meters between vehicles in a platoon was required to improve the fuel efficiency via lower drag. Other research has examined cooperative adaptive cruise control (CACC) that prevents the propagation of acceleration and deceleration from a preceding vehicle to help alleviate traffic congestion and promote better fuel efficiency. CACC utilizes the vehicle-to-vehicle distance to attenuate the acceleration and deceleration of the preceding vehicle so that these changes in speed are not passed on to vehicles following behind. This method is now being tested to confirm that it can successfully maintain the stability of vehicle groups, even in the case of large vehicles with slow acceleration response. Passenger vehicle manufacturers and the Ministry of Land, Infrastructure, Transport and Tourism cooperated in an evaluation of vehicle group stability on the Shin-Tomei Expressway before it opened to the public using adaptive cruise control (ACC), which is already widely available on mass-production vehicles. The results of this evaluation were then used in other research to predict the effectiveness of ACC in reducing congestion at sag portions of roads (i.e., where a downslope turns into an upslope), depending on the characteristics and adoption rate of the ACC system. In addition to active safety technology applications, autonomous driving technology also has the potential to facilitate safe driving by elderly drivers and the disabled.

In the field of enhanced vehicle dynamics, the standardization of ESC is already advancing in many countries. In a related development, a report described improved ride comfort control using friction increases in the suspension stroke direction through the application of braking force control via the ESC control unit. Steering characteristics in tune with driver perception are increasingly being utilized to create more sophisticated vehicle control systems. Future activities will likely use control software to further improve performance without the need for additional components.

If all four wheels of a vehicle are equipped with IWM, the reaction force of these motors can be used to achieve control in four-degrees-of-freedom (DOF). Research into 3D moment control, which controls the yaw, roll, pitch, and vertical movement of the vehicle, was reported. Since the installation of IWM in the wheels increases the unsprung mass, there is some concern that this will deteriorate the ride comfort. It was confirmed that the addition of 3D moment control improved low-frequency ride comfort and made driving on a rough asphalt road surface easier.

The development of driver support technologies and the electrification of systems should continue to advance in the future as a part of efforts to further reduce traffic accidents and environmental impact. This makes the control systems that support these technologies extremely important. Model-based vehicle development that is firmly grounded in vehicle motion dynamics from the initial stages of development to specification studies will likely become very important to help prevent malfunctions and other problems that require program modifications.

It is expected that research in this field will contribute to better safety for pedestrians and cyclists, lower environmental impact, and the construction of transportation systems that are friendly to both the environment and people, as well as helping to lead the way to a society free from traffic accidents.