VEHICLE DYNAMICS

1 Introduction

Reducing traffic accidents and CO_2 emissions remained key themes in 2014, underlining the desire of the automotive industry to reduce the social costs of these problems.

In Japan, the number of new vehicles, including minivehicles, equipped with pre-crash or collision mitigation braking systems has been increasing rapidly. In addition, a large number of safety systems featuring collision prevention and safety devices have been announced and commercialized by major automakers throughout Europe, North America, and Asia. The introduction of active safety measures is progressing at an accelerated pace.

In the field of automated driving, the amount of research and demonstration tests that are being led by national governments is increasing around the world. These efforts include those of the Transport Research Laboratory in the UK, the announcement of a joint consortium between France and South Korea, and a research program announced by the Cabinet Office in Japan, called the Innovation of Automated Driving for Universal Services (SIP-adus). In addition, the 164th session of the World Forum for the Harmonization of Vehicle Regulations formally decided to establish the Automated Driving Informal Working Group. This group will examine how assisted and automated driving should be handled from a legal standpoint, as well as proposed standards for collision mitigation braking systems.

The field of vehicle dynamics provides the fundamental technologies that support all of these new innovations and proposals. A wide range of research reports were published in this field in 2014, from the study of response characteristics based on flat, two-degree-of-freedom models to proposals to evaluate driving and braking that include operation near to the vehicle's limits. Research into steering mechanisms, driving force, and braking force included reports that assumed control as a prerequisite. Many of these reports examined not only how to improve the dynamics of the vehicle itself, but also considered how to best achieve collision prevention safety as well. Research and development aimed at even higher levels of vehicle dynamics, which consider everything from near straight-line acceleration to driving near the vehicle's limits, are likely to continue increasing.

At the same time, vehicle weight reduction, which is important to help reduce CO_2 emissions, also remains a focus of attention, and the use of multiple different materials in the vehicle body has continued to expand at the major European automakers. In Japan as well, research into carbon fiber composite materials has become more active as industry, academia, and government have come together to help reduce vehicle weight and the total number of vehicle parts.

One of the most important concepts for reducing vehicle weight is to increase efficiency by improving the basic structure. However, since technologies that enable different materials to be joined together are also developing and improving, the choice of materials is likely to continue expanding from the standpoint material mechanics.

In the future, it is presumed that the social environment of vehicles will change greatly. However, the basic fact of transportation, i.e., moving a large amount of inertia (the vehicle itself) will not change, and this starts with the relationship between the tires and the road surface. Therefore, vehicle dynamics will remain one of the foundations of the social environment and it will be necessary to efficiently combine a wide range of new technologies to handle future traffic environments.

2 Tires

Vehicle motion is a physical phenomenon that first occurs because of the existence of force acting between the tires and road surface. Therefore, one of the most important elements in the field of vehicle dynamics is knowing the tire characteristics.

There is now widespread recognition that the influence of tire temperature cannot be ignored to accurately predict tire characteristics, even within the normal range. Tire temperature is also becoming an essential parameter for accurately predicting vehicle performance. This was described in a report that investigated the effect of tire temperature on fuel consumption [(1)] and a report that examined the relationship between temperature change and braking distance at a start-of-the-art indoor automatic brake analysis facility [(2)].

Research into reducing fuel consumption has continued to be pursued actively from the standpoint of helping to protect the environment. It goes without saying that the tires, as the point of contact between the vehicle and the road surface, play an extremely large role in determining fuel consumption. Many reports have focused on reducing the rolling resistance coefficient (RRC) of the tires as an approach to reducing fuel consumption. However, more recent reports have shown a shift in the focus of research toward improving the overall balance of tire performance. These reports included one that looked at decreases in drive transmission efficiency as a negative effect of low-rolling resistance tires [(3)] and one that investigated the air resistance around rotating tires [(4)].

Recently, there has been an upsurge in interest in autonomous vehicle operation and integrated vehicle control. To make these technologies into a reality, it is becoming more and more necessary to have an accurate grasp of tire performance, including in non-linear regions, especially if the applicable scope is expanded to include high-load ranges and roads with uneven surfaces. Therefore, various methods have been discussed to help identify the state of the tires with high precision and in real-time. Conventionally, the main method used to gather this kind of information has been to attach sensors to the tires and wheels. However, new measuring methods have also been proposed. These include a method for estimating the tire slip angle up to the high-load range using only information obtained from existing sensors, such as wheel speed and steering torque [(5)], and a method of estimating the state of the tires due to a wet road surface or changes in the amount of contact area with the road, by observing changes in the quasi-electrostatic field of the vehicle without having to add sensors around the tires [(6)]. All of these methods are cognizant of taking a low-cost approach to identifying tire states, are likely to be pursued actively with an eye toward eventual commercialization.

It is believed that the development of technology that can grasp the state of the tires, such as the slip angle and the state of contact with the road surface, and the improvement of overall tire performance will continue to accelerate in the future. The aim is to ensure high levels of both safety and environmental performance, regardless of the road or driving environment.

3 Braking and Driving Characteristics

Recent research into vehicle braking and driving characteristics has led to the development of advanced driving assistance systems. This was accomplished by fusing functions that improve stability when the tires reach the road surface friction limit, such as the now widely adopted anti-lock brake system (ABS) and electronic stability control (ESC) technologies, with functions that improve vehicle dynamics, such as direct yaw control (DYC) using torque vectoring systems (TVS). TVS, which control the amount of drive torque that is applied to both the front and back wheels, as well as the left and right wheels, has been the focus of a great deal of development work in recent years.

Some examples of vehicles that were sold in 2014 that employ a TVS are as follows. The electronically-controlled front differential lock on the Golf GTI performance model is called XDS+ and it is a TVS with drive torque control for the left and right wheels. The rear differential on the Lexus RC F, called TVD, also provides drive torque control for the left and right wheels [(7)]. The Honda Legend actually has independent motors at the left and right rear wheels in a system called SPORT HYBRID SH-AWD [(8)]. Active torque vectoring on the Subaru Levorg is also a form of TVS achieved via brake control using ESC. It is expected that these kinds of TVS will continue to be adopted in the future, mainly on sporty and luxury cars, as systems that will allow the driver to feel the effect of torque vectoring from the normal driving range.

Electric vehicles (EVs) have spread and become popular mainly in developed countries. EVs can be equipped with multiple motors with good control responsiveness. In the future, it may be possible to utilize the characteristics of EVs and motors to develop a TVS with four-wheel independent braking and drive torque control, which would be difficult to realize with an internal combustion engine. Therefore, research into this type of TVS technology is now being actively pursued. In addition, the use of braking and drive torque control to combine independent control of yaw, roll, and pitch [(9)] or active suspension control [(10)], will make it possible to cover an even wider range of vehicle movement. Even in the case of a two-wheel drive EV, a mechanism that provides drive to the left and right wheels independently using a simple two-motor differential structure has been proposed because it would provide excellent torque vectoring performance [(11)].

Another report examined a new control method for semi-trucks that would improve braking stability and other performance when towing a trailer by using braking control and DYC [(12)].

In the field of basic research, reports examining new control algorithms for both braking and drive systems point to promising new technological developments. These reports included an investigation of tire braking characteristics at an automatic indoor testing facility for tires and ABS [(2)], an examination of hydraulic and regenerative braking control for maximum utilization of regenerative energy [(13)], and the speeding up of EV driving force control operations [(14)].

4 Directional Stability and Steering Responsiveness

2014 saw several examples of a shift from the mainstream method of using theoretical examinations to construct control laws based on mathematical models, toward verification testing using actual vehicles. Many research reports described how the use of actual vehicles enables the construction of control laws incorporating a subjective evaluation so that the driver and passengers do not feel a sense of discomfort when the vehicle controls intervene.

Steer-by-wire (SBW) systems offer a high degree of freedom for the layout of the steering system and the controls. There have been many examinations of failsafe systems for SBW because there is no mechanical connection between the steering wheel and the tires. In addition to isolating the driver from unpleasant road surface disturbances and vibrations, some reports indicated that SBW systems greatly reduce the amount of required steering corrections by restricting vehicle deviations caused by disturbances, such as the cant of the roadway and cross winds. There were also reports that showed how the functional value of SBW systems was improved using subjective evaluations that improved the straight line stability of the vehicle [(15)(16)].

Some four-wheel steering (4WS) systems can control the toe angle of the rear wheels. In this case, left and right wheel independent toe angle control proportional to the longitudinal acceleration is carried out to counteract the unstable moment of turning. This greatly reduces the entrainment of the vehicle when the brakes are applied while turning. It was reported that this also reduced feelings of discomfort compared to conventional 4WS systems [(17)]. Another report described how driving force control could be used to improve line traceability without diminishing the steering intention of the driver [(18)]. This was accomplished by controlling the amount of steering caused by variation in the vertical load during turning based on the suspension characteristics.

Research into four-wheel independent control in vehicles with in-wheel motors (IWMs) continues despite the issues this technology faces in terms of cost and installability. A report indicated that controlling the braking and driving force distribution of each wheel using highly responsive and precise motors improved the turning performance due to torque vectoring [(19)]. It also reported that the yaw, roll, and pitch control made it possible to achieve a vibration damping effect on the vehicle that was equal to that achieved via full active suspension. This research is fully expected to make further progress as subjective evaluations are incorporated.

There is no doubt that the integrated control of multiple devices, such as SBW, 4WS, and even drive force controls using IWMs, will only continue to progress in the future. It is also expected that the synergistic effects obtained by combining research and development with verification testing that includes subjective evaluations and actual vehicles will be applied to more and more mass-production vehicles in the future.

5 Limit Performance

Research into the limits of vehicle performance made further progress to help develop vehicle motion control devices to enhance stability and to help predict and explain the mechanisms of limit performance using simulations.

As a concrete measure to improve vehicle safety, the mandatory adoption of ESC on vehicles in Japan has been expanded. In 2014, in addition to all new models of registered passenger vehicles, the mandate was expanded to include all models from previous years that were continuing to be produced. This obligation also began to be applied to all new mini-vehicle models as well. Some new large vehicle models are also obligated to be installed with electronic vehicle stability control systems (EVSC). In the future, there are plans to expand the applicable scope of the EVSC requirements in stages to other models as well.

The changes in the cargo weight in a large vehicle, such as a semi-truck, are much greater than those in a passenger vehicle. Furthermore, since a truck may be carrying a wide range of loads, it is not easy to identify the mechanisms of dynamic characteristics and develop devices to control vehicle movement. Especially in the case of a large articulated vehicle (a semi-truck with a trailer), the manufacturers of the semi-truck and trailer are often different and there are many different kinds of trailers. This creates large individual differences in dynamic characteristics. One report described actual vehicle tests and simulations used to quantitatively determine roll characteristics due to different types of trailers, cargo load conditions, and trailer torsional stiffness [(20)]. Another report analyzed the causes of semi-truck accidents using simulations re-created using detailed vehicle dynamics obtained from actual accidents involving real semi-trucks pulling trailers loaded with shipping containers from cargo ships [(21)].

There has been a lot of research into vehicle motion control devices to develop integrated control combining DYC. One report described that control combining DYC and steering through the independent application of braking force to the left and right wheels was an effective means of helping vehicles to avoid objects [(22)]. Another report described the use of four-wheel independent drive force to realize an integrated control system consisting of DYC and front-wheel steering angle control. This system was capable of controlling the planar motion of the vehicle when a large amount of body side slip occurred [(23)].

The study of the limit performance of vehicles is helping to promote the coordination of intelligent controls, such as collision avoidance support systems and automated driving, in addition to improving vehicle stability to help reduce the number of accidents. It is fully expected that research in this field will help contribute to the construction of even safer traffic systems.

6 The Human-Vehicle-Environment System

The Strategic Innovation Promotion Program (SIP) administered by the Cabinet Office in Japan started in 2014. One of the issues addressed by the SIP is automated driving systems. The aim is to commercialize a semi-autonomous driving system (Level 2) by the year 2017, a semi-autonomous driving system (Level 3) by the first half of the 2020s, and a completely autonomous driving system (Level 4) from the second half of the 2020s and on. Therefore, the entire Japanese automotive industry is rapidly promoting automated driving technologies in the run up to the summer Olympic Games that will be held in Tokyo in 2020. In the U.S., verification testing of completely autonomous driving vehicles has already begun on public roads. Consequently, a great deal of research is now being undertaken in the field of human-machine interfaces, which is critical to automated driving.

Research has found that the driver feels a mental burden when a predictive control intervenes in the driving of the vehicle, even when the intervention is mild [(24)]. When the intervention is steering related, this research also clearly shows that the driver feels a sense of discomfort with the steering operation, especially when the scale of the intervention grows larger [(25)]. Other research has confirmed that presenting the driver with appropriate information when the control intervention occurs serves to increase the driver's confidence in the system and also improves driver acceptance [(26)(27)].

Another new technology judges the driver's current status, such as alertness. This technology uses drowsiness determination logic to evaluate the driver based on heartbeat information obtained from a pulse sensor that clips onto the driver's ear. The accuracy and real-time performance of this technology has been confirmed through driving tests [(28)(29)].

Research into vehicle head-up displays (HUD) found that these devices are an effective way of presenting information to the driver. However, simulated driving tests also found that driving operations become neglected while the driver performed a task such as identifying and answering (reacting) to superimposed HUD indications. This research also confirmed that driver's reaction times tend to become longer when the amount of information increases [30][31].

The research mentioned above confirmed that some new vehicle technologies, such as intervention by predictive controls and HUD systems, can cause a mental burden on the driver, generate discomfort, and even increase reaction times. Consequently, it will be critical to enhance these technologies and examine ways to improve the level of coordination between automated driving systems and the driver.

7 Intelligent Controls

In developed countries with aging societies, the percentage of traffic accidents involving elderly drivers remains high.

In the field of active safety, research reports described driving support technologies such as emergency braking and emergency avoidance steering control systems. However, one report also identified the effects on the driver's body (especially in the case of elderly drivers), such as the arms, when these driver assistance systems suddenly intervene [24].

Another report described the harmful effects that occur when object avoidance systems intervene. Consequently, there have been proposals to improve the level of steering coordination to take into consideration the possibility that steering control intervention by driving support systems may interfere with driver operations [25].

Although autonomous driving support systems utilize collision avoidance support systems, in some situations it is difficult for conventional systems to detect risk, carry out collision avoidance support measures, and actually avoid the collision. However, one report has described the results of experiments indicating the feasibility of a system that can predict potential risks from the surrounding environment in advance like a skilled driver, and then avoid collisions by controlling the vehicle's speed and course [32]. This is drawing a great deal of attention to risk prediction technologies.

Research into new technologies to help vehicles recognize the surrounding environment is also drawing more and more attention. One report examined a method for detecting road boundaries on residential roads with no white lines using cameras and lidar that detects distances using laser light [33]. Another report examined a method to detect the position of a moving body by using the reinforcing signal of Michibiki, Japan's first Quasi-Zenith Satellite, in addition to GPS signals to make it possible to obtain even more precise positioning information [34]. Since peripheral recognition technology and improving the accuracy of vehicle positioning information are both critical to realizing autonomous driving systems, there will continue to be great interest in reports concerning these topics.

Advancing research into active safety and automated driving support systems is essential to improving safety technologies in the future to help address the challenges of an aging society. In addition there are great expectations that technological advancements such as these will also help to build traffic systems that are friendlier to the natural environment.

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