VEHICLE DYNAMICS

1 Introduction

In 2015, Japanese automobile manufacturers benefitted from a weak yen and low crude oil prices for to recover to a level of sales exceeding that prior to the economic crisis triggered the collapse of Lehman Brothers. The Japanese automobile market was affected by the 2015 increase in the light vehicle tax, and new vehicle sales decreased compared to the previous year. However, the Japanese market share held by foreign manufacturers of imported vehicles reached a new record high, making it desirable to enhance the appeal of Japanese vehicles.

Nevertheless, 2015 can also be identified as the first year of self-driving vehicles given the substantial start made toward the implementation of actual autonomous driving capabilities. The Japanese government announced it would carry out the development of infrastructure and the passing of related laws aimed at realizing self-driving vehicles in conjunction with preparations for the 2020 Tokyo Olympic and Paralympic Games. As part of its plan for the research and development of autonomous driving systems, the Strategic Innovation Promotion Program (SIP) administered by the Cabinet Office aims 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 beyond. The program has also set the goals of realizing a functioning semi-autonomous driving system (Level 3) in Tokyo for the 2020 Tokyo Olympic and Paralympic Games. The Japanese Ministry of Land, Infrastructure and Transport (MLIT) and the Ministry of Economy, Trade and Industry (METI) have been holding joint meetings to study the potential of automated driving businesses, and discussions concerning the eventual realization of automated driving systems are moving forward.

At the first Tokyo Motor Show in two years, the Smart Mobility City 2015 project showcased a vision of how automated driving systems would work, and presented a lot of information about automated driving from various points of view. Several automobile manufacturers displayed concept vehicles at the motor show that showed off automated driving technologies front and center, and some vehicles featuring automated driving systems equivalent to level 2 are expected to go on sale during 2017. Automobile manufacturers and research institutes are also beginning field tests of automated driving systems on public roads in Japan[1].

All this recent progress notwithstanding, many technical issues still have to be addressed. The more driving operations become automated, the smaller the workload on the driver, who will then be able to focus on activities other than driving the vehicle, creating concerns about a drop in the driver's awareness of the surrounding environment. Consequently, efforts are being directed at finding ways to enable the vehicle to recognize the driving environment and the state of the driver and ensure safety and stability. In addition, there are growing calls for automated driving systems that can safely return control of the vehicle to the driver or stop the vehicle in unusual situations. Vehicle dynamics will play a major role in producing vehicles with valuable automated driving functionality that will allow people to move about safely and securely.

The 2015 United Nations Climate Change Conference, COP 21, was held in November, and its resolutions included the adoption of the Paris Agreement. Japan announced its Actions for a Cool Earth: ACE 2.0 strategy during this conference, raising expectations for further initiatives and progress in regard to energy and environmental technologies achieved through joint public and private sector efforts.

It is hoped that efforts such as those outlined here will lead to safe, secure, comfortable, and fun-to-drive automobiles that are also environmentally-friendly and contribute to more fulfilling and prosperous lifestyles.

2 Tires

As progress is being made in reducing the rolling resistance and weight of tires from the standpoint of protecting the environment, research into technologies that can balance these tire characteristics with other areas of tire performance is being pursued. Examples include the development and specific application of new tires that achieve both low rolling resistance and good handling and braking performance[2], the use of a patterned tire groove to reduce the air column resonance noise while also improving steering stability[3] and the mounting of a resonator on the wheel to increase the efficiency of the air column resonance noise reduction effect[4]. New technologies such as these are being proposed to achieve higher levels of compatibility with noise reduction.

At the same time, grasping the state of the road surface and its slipperiness is a crucial issue in terms of active safety, and research into this area has been continuously pursued. Examples include attempts to estimate the shape of the road surface using a vehicle-mounted accelerometer[5], adding sensors to the tires to determine the state of the road surface from vibration waveforms, which was followed up with attempts to refine the precision of this determination and even predict future road surface conditions by obtaining information from a large number of vehicles[6]. There have also been attempts to use a non-contact method to quantify the slipperiness of the road surface and identify frozen surfaces[7, 8].

The importance of accurately grasping the state of the road surface and its slipperiness is expected to become even more important in the near future as automated driving functions and self-driving cars increase in number. Consequently, the development of new tire technologies is expected to make major contributions to enhancing the active safety performance of the vehicle, while also simultaneously achieving high-levels of environmental performance, handling capabilities, and noise, vibration, and harshness (NHV) reduction.

3 Braking and Driving Characteristics

Research on the braking and driving characteristics of automobiles has evolved from improving performance, as exemplified by the AWD system, which controls the front and rear driving force distribution and the ABS and ESC systems, which optimize stability control, to torque vectoring that provides independent control of the braking and driving forces applied to the front, rear, left, and right wheels, and direct yaw moment control (DYC). Currently, ABS and ESC systems are increasingly being made mandatory, and DYC is being installed on more and more vehicles, such as the Lexus RC F, which is equipped with the same torque vectoring differential (TVD) featuring independent control of the driving force applied to the left and right rear wheels as the Lexus GS F.

Given the major premise of the need to protect the environment, some research into future technologies is also focusing on reducing the consumption of energy. One example involves identifying the principle behind the optimal distribution of driving force to realize the minimum consumption of energy for the ideal DYC in terms of energy consumption and examining the relationship between this principle and vehicle dynamics[9]. Other examples include a proposal for a control design method that achieves both reduced motor power consumption and better stability when compensating for crosswind disturbance using the distribution of driving force to the left and right wheels[10], and an evaluative comparison of uniform tire load distribution control and consumed energy minimization distribution control using a vehicle with four-wheel independent steering and four-wheel independent driving force control[11].

At the same time, the research and development, as well as commercialization, of electric motor-driven vehicles, such as hybrids, electric vehicles, and even fuel cell vehicles is steadily increasing. This has led to continued research and development of in-wheel motor (IWM) technologies in anticipation of their eventual application to electric motor-driven vehicles. Examples include reducing low-frequency vibration during very low-speed driving by changing the structure of the motor unit, applying vibration damping control, and changing the resonance frequency of the IWM system[12], as well as applying vibration damping control to alleviate the longitudinal vibration occurring in IWM-equipped vehicles due to road surface disturbance. The effectiveness of this countermeasure was verified through both simulations and actual on-vehicle testing[13].

One of the disadvantages of IWM systems is the reliability and safety of the power supply and signal lines, but this may be solved by wireless power transmission. Furthermore, ongoing research into wireless in-wheel motors (W-IWM) is hinting at the future possibility of supplying electric power directly to the motor while the vehicle is being driven. Examples include a report detailing the composition and control of a W-IWM prototype unit, as well as the results of a driving test of an electric vehicle equipped with this W-IWM unit[14], as well as a report presenting verification testing results from on-bench testing carried out to examine the mechanical characteristics of a W-IWM[15]. Another example involves a wireless power transmission circuit with a series-series system of magnetic resonance coupling for which the transient response characteristics from the transmission function of the equivalent circuit were analyzed, an approximation model was derived, and the load voltage control was verified through simulations and testing[16].

Future research in the field of braking and driving characteristics is expected to focus on environmental friendliness and further electrification.

4 Directional Stability and Steering Responsiveness

Even as the above mentioned research into integrated control of four-wheel independent steering and four-wheel independent braking and driving[11] continues to be carried out, fundamental theoretical research is also still being pursued. Examples include research showing that when the steering–vehicle system is organized into a quartic characteristic equation, the dynamic characteristics of the steering system can be expressed by two independent parameters and demonstrating the utility of doing so[17], research using roll and planar motion to analyze the characteristic root of a coupled three-degrees-of-freedom model and examining the mutual relationship between the main parameters that govern the planar response characteristics and the main parameters that govern the roll characteristics to clarify the effect of that relationship on vehicle dynamics[18], and research where the natural frequency and damping ratio were formulated in the situation where driving was being performed using steering torque inputs and a setting policy was indicated for each parameter to improve vehicle responsiveness[19]. In yet another example, the steering system rigidity and front wheel roll steer were used as parameters to examine the possibility of attaining both steering responsiveness and stability[20]. In addition, the equivalent cornering stiffness of the tire taking non-linearity into consideration was used to construct a new braking and driving force distribution control to improve the steering characteristics by leveraging the influence of the tire's vertical load dependency and longitudinal force. The effectiveness of this newly constructed control was then confirmed using a full vehicle simulation[21].

At the same time, the use of bench testing has made it possible to take measurements that would be very difficult to obtain on an actual vehicle, and other initiatives to quantify the influence that component part characteristics have on the system are also underway. Examples include a scale model of the rear half of a vehicle constructed from the standpoint of developing a simple suspension analysis tool and a vehicle dynamics examination tool[22], the use of a dynamic motion simulator to quantify and evaluate the influence of the difference in the left- and right-side driving force change characteristics on the vehicle dynamics and the steering system characteristics[23], as well as the use of a chassis dynamometer to analyze the vehicle body behavior and engine behavior inside the vehicle during sudden acceleration and sudden stopping in order to evaluate the vehicle pitching motion[24]. The bench testing illustrated by these examples is more than just a means of identifying and elucidating various vehicle dynamics phenomena, and its integration in the development process is also expected to both increase development efficiency and promote the continuous development of new technologies.

Further advances in fundamental research in terms of both theoretical exploration and actual experimentation are fully expected to lead to greater improvements in automobile performance.

5 Limit Performance

The limit performance of an automobile is directly connected to the vehicle's safety. Examples include research to improve and optimize the performance of electronic stability control (ESC) systems to make vehicles compliant with the New Car Assessment Program (NCAP) rollover resistance ratings and Federal Motor Vehicle Safety Standard (FMVSS) No. 126, and research that looked into the motion of the vehicle when it entered into the non-linear region of the tires. As shown by the National Highway Traffic Safety Administration (NHTSA) announcement that it will introduce new regulations to make the installation of ESC systems mandatory on vehicles such as large trucks and buses, the process of making ESC systems mandatory is making steady progress worldwide. At the same time, DYC and automatic braking functions are also advancing and evolving, and it is probably safe to say that vehicle motion controls using ESC, including active safety controls, have evolved and fused together from the limit performance region all the way to the normal driving region.

Taking a look at this topic from a different perspective, there were also examples of technological development in the realm of motor sports, which involves competition at the limit of performance. In the 2015 Dakar Rally one of the vehicles in the truck category had a remodeled and improved suspension system that featured an increased stroke rate on the compression side, linearization of the spring characteristics, front and rear suspension aligned with the natural frequency, and an axle support structure capable of withstanding sudden acceleration and deceleration, all to go along with the higher output engine mounted on the vehicle[(25)]. In addition, an electric vehicle that competed in the 2014 Pikes Peak International Hill Climb race in the Electric Modified Class and achieved a second place finish was equipped with a newly developed integrated vehicle motion control system for electric vehicles[(26)].

It is hoped that even more highly efficient and fun-to-drive vehicles can be realized thanks to the new technologies and knowledge cultivated from motor sports competitions such as these that push vehicles to their performance limits.

6 The Human-Vehicle-Environment System

Automobiles are one means of transporting people and things from place to place, as well as a means of transportation that requires people to exercise judgment and remain aware of the driving environment while performing driving operations. In addition, the affinity between people and automobiles has become an important issue and research on this topic has been advancing for some time now. For example, when it comes to evaluating the feeling of the steering, there has been a continuous flow of research into the best method of quantitatively evaluating vehicle response characteristics, including the sensitivity of people, and the techniques needed to improve these characteristics. One study carried out in 2015 showed that people's perception of the steering reaction force was determined by the combination of the steering torque and the steering torque gradient (stiffness). This study also proposed a method of quantitatively evaluating the change in the steering reaction force based on a map of the perception constructed through experimentation[(27)]. In another study a simulator was used to collect and summarize the on-center steering characteristic requirements, and their effectiveness was then verified on an actual vehicle. In addition, the design characteristics of the steering system were also taken into consideration[(28)]. In another study, a steering system model capable of reproducing the friction characteristics of the actual equipment was constructed and used in combination with a full vehicle model to clarify how much each design element contributed to the steering feeling. These models were then utilized to help develop the steering feeling of the vehicle[(29)]. In another study the sliding friction characteristics of the suspension and steering systems were modeled, and a vehicle mechanical model was used to predict the influence that these characteristics had on the steering stability[(30)].

Other studies and research carried out in 2015 examined ways to make vehicles easier to drive and operate. One such study identified the driver steering parameters based on a driver model, and used them to evaluate the influence of the size of the vehicle roll on the ease of driver operation[(31)]. Another study focused on the balance of forces acting on the steering wheel and the shoulder region of the seat back, including the state of the driver. This study conducted various experiments to investigate the relationship between different methods of supporting the driver's shoulder blades and the ease of steering[(32)].

At the same time, vehicle motion control and active safety control technologies continue to evolve, driving ongoing advances in research on driver characteristics and vehicle-side technologies that monitor the state of the driver. In self-driving vehicles and automated operations, in particular, research has shown that there is a critical need for the vehicle to be able to predict when a driver is losing alertness and engaging in activities other than driving so the driver can be provided with appropriate information and enough time before shifting back to manual operation[(33)]. Both of these issues—inferring the state of the driver and grasping the driver characteristics—as well as the shift from automated operation back to manual operation, have become critically important.

There were numerous cases of research that looked into the state of the driver and driver characteristics in

2015. Examples include a study attempting to ascertain the degree of tension, sleepiness, and fatigue of the driver via the rise and fall of the heart rate and fluctuations in the variation component[34], a study attempting to detect unsteady driving, which is one manifestation of a lack in driving skill, by measuring various aspects of daily driving behavior, such as the driving position information, front image information, and vehicle behavior information[35], as well as a study using a driving simulator to verify the effectiveness of maintaining driver alertness through exposure to visual stimulation that induced saccadic eye movement[36].

In the field of driver behavior, one study showed that driving behavior could be expressed very well using a feedforward term determined from the curvature of the road ahead and a feedback term determined from a forward-looking third-order prediction model[37]. Other studies surveyed and analyzed the driving behavior characteristics of elderly drivers[38]–[41].

As mentioned previously, some research in 2015 began examining the methods for transitioning from automated operation back to manual operation. One study showed that it will become necessary to develop a method of providing notifications and information to the driver that does not depend on where the driver is looking and demonstrated that a human-machine interface (HMI) that provides visual guidance to lead the driver's line of sight in the necessary direction was an effective method of achieving this[42]. Another study used a driving simulator to examine the amount of time necessary to transfer control over vehicle operation from automated driving back to manual driving[43].

During automated driving, the vehicle will be aware of the state of the driver and make various judgments, and exercising some control on the driver is also necessary. Consequently, it is hoped that there will be further advancements in human-vehicle systems technologies.

7 Intelligent Controls

As mentioned in the introduction, in terms of intelligent controls, research related to automated driving has been promoted extensively through various government policies.

The following are some examples of research carried out in 2015 that examined route and speed planning to help achieve better collision avoidance. One study introduced a potential function that adapts to changes in speed and makes it possible to plan the route and speed of the vehicle to avoid obstacles[44]. In another study, the inclusion of an acceleration and jerk evaluation function made it possible to develop a method for determining the optimal route on the three-dimensional coordinates of a horizontal plane plus time axis that also took ride comfort into account[45]. Other research also provided examples of taking passenger comfort into consideration. This includes a study that constructed a pedestrian behavior prediction model as part of a vehicle speed control method that helped avoid collisions and minimized the jerk of sudden acceleration. The effectiveness of this method was verified through both simulations and actual vehicle testing[46].

Other research in the field of intelligent controls focused on awareness of the environment around the vehicle and predicting potential dangers. For example, one study attempted to use physical simulations to predict trajectories in combination with logical inference that drew on symbolic information, such as turn signals, to predict potential hazards[47].

Nevertheless, autonomous automated driving technology is subject to definite limits in terms of hazard prediction and increasing the efficiency of the overall flow of traffic. Additional breakthroughs in these areas will have to come from advances in road traffic infrastructure. Examples such as short-range automated driving induced by the infrastructure have demonstrated experimentally using a test vehicle that it was possible to apply external control by adding a communication device to a commercially available passenger vehicle[48]. Other ongoing research has also demonstrated through simulations and actual on-vehicle testing that vehicle-to-vehicle distance coordination via a server enabled multiple vehicles to be driven together efficiently[49]. This is being considered as a method to help realize the smooth flow of traffic when self-driving vehicles become common and are widely used. In the future, if self-driving vehicles do become commonplace, there are concerns that driver skill will decline and that the need for these kinds of "control towers" to help direct traffic and prevent accidents will only increase.

It is hoped that the development of intelligent control technologies such as these will contribute to creating of a safe and secure automobile society in which no traffic accidents occur.

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