VEHICLE DYNAMICS

1 Introduction

The year 2016 can be described as one of upheaval with major impacts on the world economy, from the Brexit decision by the UK to leave the European Union (EU), to the declaration by the United States that it would pull out of the Trans-Pacific Partnership (TPP). With respect to the Japanese economy, the Bank of Japan introduced a negative interest rate, and the government decided to extend the increase in the consumption tax rate for two and a half years due to increasing economic uncertainty. Japanese automobile manufacturers have continued to see increases in their earnings since the global financial crisis, but the tide has started to turn in 2016 as earnings tended to decrease compared to the previous year due to factors such as the appreciation of the yen. These circumstances call for technological advancements in the field of vehicle dynamics to develop appealing automobiles offering both robust safety features and fewer negative impacts on the environment.

The Japanese government is implementing policies to improve infrastructure and update relevant laws in an effort to realize automated driving systems and vehicles in time for the 2020 Summer Olympic Games in Tokyo. The research, development, and planning of automated driving systems are all conducted through the Strategic Innovation Promotion Program (SIP) of the Cabinet Office. The relevant legislation is being prepared despite the fact that the United Nations and other countries are lagging behind the schedule in the original plan. Standards concerning automatic steering and automatic lane changing are about to be enacted, and discussions on the mass production of automated vehicles are actively under way.

Automobile manufacturers are also revealing their future visions and plans for automated driving, and semi-automated driving systems (Level 3) is expected to be available in the market sometime between 2019 and 2020. Vehicle dynamics will play a large role in realizing such automated driving systems, which means an evolution of vehicle dynamics as it relates to automated driving is necessary.

Next, efforts are being made to improve safety and convenience through functions that connect people and society to automobiles through the Internet. Various initiatives in new fields, such as leveraging cloud computing and big data or combining them with artificial intelligence, as well as technologies related to the Internet of Things (IoT), are becoming essential to automated driving and the next-generation vehicles known as connected cars. In the United States, smart city initiatives have resulted in demonstration testing of smart parking and other ideas to alleviate traffic congestion. In addition, car sharing is being promoted in an effort to realize new smart societies, while other tests look to improve logistics by having commercial vehicles drive in platoons. At the same time, various issues are being raised about the necessity for stronger cyber security capabilities and technologies to prevent hacking. From the standpoint of vehicle dynamics, the development of technologies to ensure the safe and secure operation of the new vehicles resulting from the fusion these new fields is essential.

In 2016, the 22nd session of the Conference of the Parties (COP 22) to the UN Climate Change Conference was held in Marrakesh, Morocco. During this conference, the agreement of each participating country was obtained in the course of examining the detailed rules of the new global warming countermeasure represented by the Paris Agreement. In addition, the German Parliament has adopted a ban on the sale of new vehicles equipped with internal combustion engines by 2030 and many countries are continuing to strengthen their regulations concerning vehicle exhaust emissions in an effort to eventually realize zero-emissions vehicles (ZEV). Not only has the number of regions around the world with greenhouse gas emissions regulations been rising, but these regulations also continue to become more stringent. Automobile manufacturers now find themselves facing even greater demands to comply with fuel economy regulations. All of these various initiatives have a large impact on vehicle dynamics, creating expectations for the development of various new technologies to make vehicles more environmentally-friendly.

2 Tires

As the only parts of a vehicle in contact with the road surface, tires play a major role not only in vehicle dynamics, but also in fuel consumption and ride comfort. Achieving high performance in both of these areas is a major challenge. Examples of recent reported efforts concerning the on-bench characteristics of tires include, efforts to transiently control the flat belt and reproduce the characteristics that occur during actual vehicle driving[(1)], and efforts to reproduce the differences in transient characteristics that result from the differences in tire structure during on-bench testing[(2)]. From the standpoint of autonomous driving as well, a better understanding of the dynamic behavior of the tire is anticipated to enable more natural control, and there are growing expectations for the expansion of this field.

At the same time, from the standpoint of reducing automobile traffic noise, the Uniform Provisions Concerning the Approval of Tires with Regard to Rolling Sound Emissions and to Adhesion on Wet Surfaces and/or to Rolling Resistance (UN/R-117-02) regulation has been introduced in Japan[(3)]. The new regulation concerning vehicle external noise emissions, UN/R51-03, has also gone into effect. Consequently, reducing tire noise has become an issue for manufacturers, and reports on the results of efforts to address this issue have been released. These included efforts to quantitatively evaluate tire noise during bench testing[(4)], a method for improving the prediction accuracy of pattern noise through data mining[(5)], and a method of measuring the correlation between the tire structure and the sound radiated from the tire using a statistical energy analysis method[(6)]. Technologies that can reduce tire noise without compromising safety are expected to be achieved.

3 Braking and Driving Characteristics

Research on the braking and driving characteristics of automobiles has expanded from ABS and ESC systems, which improve the safety when the vehicle is being driven at its performance limits, to direct yaw moment control (DYC), which improves the cornering performance during normal driving. More recently, these functions have been combined with front and rear, as well as left and right wheel driving torque controls (torque vectoring systems) to develop even more advanced vehicle dynamics control systems. One example of a vehicle with these systems released in 2016 is the Honda NSX Sport Hybrid SH-AWD, which is equipped with a 3.5-liter V6 twin-turbo engine, as well as two electric motors in the front, and one in the rear. The independent left and right front motors were adopted to control the left and right side distributions of the drive torque and the deceleration energy regeneration in an effort to improve line traceability.

Another recent initiative involves using an engine with a high response and high precision drive torque control system that enables fine deceleration control down to about one tenth the level of a conventional engine in an effort to achieve a more comfortable G (acceleration) connection by linking the longitudinal acceleration to the lateral motion caused by steering wheel operation[(7)]. This technology is called G-Vectoring Control and it is already used on commercially available vehicles, such as the Mazda Atenza released in 2016.

The reduction of energy consumption has remained one of the biggest issues for automobiles in terms of trying to conserve the natural environment. In the field of braking and driving characteristics, research continues on the relationship between driving force distribution and energy consumption. For example, one study looked at the relationships between the driving force distribution, tire load factor, and slip ratio on uneven terrain[(8)], while another study looked at the slip loss due to the type of drivetrain and the tire contact area[(9)].

At the same time, in the motorcycle market, bikes with two front wheels and one rear wheel continue to grow in popularity due to their high levels of stability and driving performance comparable to that of a standard two-wheel motorcycle. Bikes with two front wheels and one rear wheel have a smaller amount of tire contact pressure per wheel, resulting in a higher friction coefficient that enhances braking performance. One study that examined this case via vehicle testing and simulations has been released[(10)].

A major trend in the automotive industry is the research, development, and sales of vehicles driven by electric motors, such as hybrids and electric vehicles carried out by all manufacturers. Upcoming research in the field of braking and driving characteristics is expected to focus on the best methods of improving running efficiency and vehicle dynamics through more precise drive controls under the premise that these methods will soon be applied to electric motor-driven vehicles.

4 Directional Stability and Steering Responsiveness

In 2016, ongoing basic research into both vehicle behavior and driver behavior resulted in many reports on indexing and modeling to ensure higher stability and responsiveness. One example was research attempting to approximate the driver sensory evaluations through a vehicle behavior simulation that used a driver model which drove on a narrow twisty road to identify a suitable stability factor value[(11)].

In addition, research was also carried out on vehicle dynamics verification technology for bench testing on the assumption that this will be applied to future model-based development. One report stated that flat-belt bench testing equipment was used to measure the suspension dynamic characteristics under conditions closer to those of actual driving as well as to analyze transient response characteristics more accurately[(12)].

Furthermore, as mentioned in Section 3 of this article, realizing vehicle stabilization technology that utilizes a broader range of vehicle integrated control was reported to improve responsiveness to the lateral acceleration caused by steering, while also improving the vehicle behavior and posture through extremely precise control of the driving force[(7)]. At the same time, the EPS simulation analysis method was reported to ensure the robustness under complex integrated control, such as automated driving and advanced steering support[(13)]. Another report discussed cooperative control between the driver and the system in the context of steering support[(14)].

As integrated control technologies continue to evolve and automated driving technologies advance and become more widespread, similar progress is expected to continue in the development of vehicles that can be driven with even greater peace of mind.

5 Limit Performance

Lately, torque vectoring control (TVC) has frequently been equipped not only on luxury-class vehicles, but also on vehicles in the mid-class range and below to improve the turning performance of the vehicle. In sports cars and SUVs, it contributes to improving the limit performance. A few years ago the SH-AWD drivetrain, which can variably distribute the drive torque to the front and rear, as well as left and right wheels, was equipped on the Honda Legend and other luxury models. This drivetrain applies the turning force directly by distributing the drive torque differently to the left and right wheels when the vehicle starts to move forward. It is composed of electromagnetic clutches and requires a system to distribute the drive torque to each wheel making its overall structure complex and also increasing the weight of the vehicle. These drawbacks have prevented its wider adoption and dissemination.

In contrast, the TVC equipped on recent vehicles in the mid-class range and below uses braking control to closely approximate the functions of ESC (electronic stability control), which is standard equipment on new models, to achieve the same functionality. This version applies braking to the inner wheel during cornering, creating a relative torque difference between the left and right wheels to generate turning force. In addition, the independent, left and right in-wheel motors equipped on some electric vehicles can also achieve the same effect. A case in which TVC was applied to driving wheels with high axial loads to improve turning acceleration has also been reported[(15)]. This suggests it contributes as a control element that secures the ideal traceability envisioned by the driver and also enhances the limit performance of the vehicle. Other recently reported methods of expressing the limit performance of vehicles during cornering include a proposed method for graphically expressing the longitudinal and lateral acceleration (G-G) diagram[(16)], a case where the braking performance of a three-wheeled motorcycle (two front wheels and one rear wheel) was improved[(10)], and research into a method of estimating the road friction coefficient using GPS data[(17)].

Further improving traceability will require paying attention to research trends focused on torque vectoring control and other forms of control directed at enhancing the limit performance of vehicles.

6 The Human-Vehicle-Environment System

Society is expressing growing interest in automated driving, but there are still many issues yet to be solved, including technical aspects and legal reforms, before it can become a reality. One of the most important issues is the affinity between the driver and the system, especially in automated driving at SAE level 2 or 3. Therefore, a great deal of research is currently focused on the driver–vehicle–environment system.

Various research projects are now examining the delegation of authority to drivers when the automated driving system reaches a functional limit. One example is research that examined the control margin time necessary when delegating authority from automated driving back to manual driving[(18)-(20)]. This was done with a drive simulator (DS) that controlled the state of the driver between normal driving and engaging in non-driving tasks. In a different example, a significant difference in response dependent on the proficiency of the driver was reported[(21)]. In yet another example, the mirrorless system was removed from the human-machine interface (HMI), which supports appropriate operations such as lane changes after the delegation of authority, and experiments using the DS showed that a smooth transition of authority was possible and effective with standard external mirrors[(22)].

An extensive amount of research on security and safety is also being pursued in relation to automated driving. The research on safety mainly focuses on engineering-based approaches from the standpoint of preventing traffic accidents, while the research on security is struggling with the fact that the definition of the concept itself is unclear and the research methods have not been established. To examine the factors necessary to create this security, one research project[(23)] focused on the necessity of understanding the basic processes concerning the occurrence and mitigation of uneasiness, a concept opposite to security. Consequently, the different types of uneasiness that occur during driving were identified and categorized for the purpose of gaining a broader understanding of the uneasiness about driving in general, without limiting it just to accidents. The factors that trigger these different types of uneasiness were then interpreted using clinical psychology.

Another report described research into the evaluation of the driving skills of elderly drivers and the development of driving support methods[(24)]. After recording and collecting driving behavior data using a DS, analyzing the relationships between various driver biometric measurements, such as driving state and cognitive function revealed that visual information processing ability and attention allocation and maintenance ability affected the collision rate. In addition, the potential of self-awareness of one's own driving abilities to mitigate the influence of these biological functions on the collision rate was demonstrated.

Next, several examples of research concerning human-vehicle systems from the viewpoint of conventional vehicle behavior control will be described.

There were several examples of research into the factors that influence vehicle dynamics (such as responsiveness). The themes covered included the friction characteristics of dampers[(25)], as well as friction bodies as rigid elements of vehicle bodies[(26)]. Other research examined the response to steering force input, such as one case that reported a method of expressing the steering force as the vehicle instability region during force control[(27)] and another case involving research into optimal control of steering reaction force control using a bar-type steering wheel[(28)]. As electric power steering (EPS) and steer-by-wire systems are brought into practical use, enhanced sensor resolution is contributing to the improvement of steering reaction force control. The concept of G-Vectoring control was already touched on in Sections 3 and 5 of this article, but the difference in transient vehicle responsiveness changes the steering behavior of the driver. As a result, it makes a good example that ties into differences in performance. A significant amount of research related to these topics has been conducted[(29)-(31)]. One can imagine that these differences in the extent of control will improve vehicle dynamics, which in turn will lead to improvements in safety. Further developments in human-vehicle system technologies are looking promising.

7 Intelligent Controls

In 2016, various countries actively hosted research and academic conferences on automated driving, and both government- and private enterprise-led demonstration tests on public roads are also underway. Ensuring the safety and convenience of automated driving requires making further advancements in the intelligent vehicle behavior control technologies that are capable of responding to drivers, surrounding roads, and changes in the driving environment. Various research projects concerning driving support technologies to ensure the safety of the driver while the vehicle is being driven are being pursued. For example, one project seeks to provide driving support via a system that predicts and anticipates driver actions to identify and cope with both obvious and latent risks to the driver[32][33]. Another project is looking to define a set of allowable behaviors for driver operations and have the system provide driving support through the HMI or driving operation intervention depending on whether the driver's operations fall within that set of allowable behaviors[33]. There is also active research on technologies, such as technology for camera-based pedestrian recognition, that recognize the surrounding environment and offer anticipation capabilities[34].

Another research project presented a proposed advanced driving support system aimed at preventing accidents involving the elderly in urban areas[35]. Using a reverse collision model, this system statistically analyzes normative driver behavior data to find the optimal route that minimizes latent risks in situations involving the presence of various traffic participants. A different report describes the development of a driving route planning method for lane changes during automated driving[36]. Under an unrelated purpose, research on optimizing the routes for EVs to reduce the amount of consumed battery charge has also been conducted[37].

There has also been research on indices that would uniformly express the importance of safety and security of driving support functions[38] and future research in fields such as this is anticipated to only continue to grow in importance for purposes such as determining the value of a wide range of driving assistance functions.

In addition, other research evaluated driver overconfidence deriving from the application of driving support[39]. This research examined the factors that led to overconfidence by classifying elements that increased safety, as well as those that decreased it, as a result of the driver receiving support. It then summarized the items to consider during the design process to mitigate the generation of overconfidence in the driver.

Such research is expected to promote the advancement of automated driving and driving support functions, and eventually lead to the realization of safe, secure and accident-free, as well as convenient, and appealing, new automobiles.

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