VEHICLE DYNAMICS

1 Introduction

In 2017 Volkswagen (VW) sold the most vehicles around the world for the second year in a row, and every other automobile manufacturer also recorded high sales. Nevertheless, every manufacturer is finding itself in a desperate fight with its competitors in the face of the numerous challenges looming on the horizon, which include reducing CO_2 emissions, realizing automated driving via the use of artificial intelligence (AI), further propagating electrification, and expanding vehicles sales in emerging nations. With respect to automated driving, the Strategic Innovation Promotion Program (SIP) of the Cabinet Office has the set goals of reducing accidents and traffic congestion, promptly realizing and disseminating an automated driving system, and establishing a public system that is friendly to the elderly as part of its aim to implement practical quasi-automated driving (level 2) by the time of the 2020 Tokyo Olympic Games and Paralympic Games. Industry, academia and the government are cooperating to tackle these challenges, and large-scale demonstration projects on public roads have already begun.

At the Tokyo Motor Show in 2017, many automobile manufacturers were showing off their future visions and plans in advanced fields such as automated driving, electrification, and connected vehicles. In the arena of technical development , the automobile industry is currently engaged in vigorous competition to seize the initiative. As automated driving technologies are heavily intertwined with vehicle dynamics, it will be necessary to develop handling stability and ride comfort, as well as braking and driving performance, tailored to autonomous vehicles, which will make the tastes in design of manufacturers an object of ongoing attention.

Driver support technologies aimed at elderly drivers are also increasingly coming into the spotlight. Even K-cars have gradually been equipped with collision mitigation braking systems and unintended acceleration suppression devices, illustrating the growing spread and adoption of advanced vehicle control technologies.

At the same time, the pressures of shortening development periods and reducing costs for automobile development, as well as advances in the area of virtual development, have led to numerous cases of applying model-based development (MBD), making that approach increasingly commonplace. Quantifying vehicle dynamics is essential to applying MBD to vehicle dynamics, and difficulties, such as the quantification of human feelings have yet to be solved.

These and other technological developments are expected to lead to the development of safe, secure, and comfortable vehicles with a lower impact on the environment that also contribute to the betterment of society.

2 Tires

As the only points of contact between the vehicle and the road the tires are automotive parts with a major influence on fuel economy, braking, steering stability, and ride comfort.

As such, efforts to improve fuel economy, which focused on decreasing rolling resistance, have recently been complemented with research taking a more comprehensive approach to fuel economy that encompasses drive efficiency, while other research has sought to balance good fuel economy with other aspects of vehicle performance.

The introduction of 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 in Japan has led to initiating research that employs statistical energy analysis to model the problematic high frequency range tire vibrations that produce tire rolling noise[1][2].

Beyond these demands on characteristics of tires covering aspects of performance that fall outside the scope of vehicle dynamics, research focused on characteristics related to aspects of vehicle dynamics performance include a report that examined the relationship between sensory evaluation results and the differences between types of tires when the actual vehicle behavior and tire characteristics were simultaneously measured in a vehicle in motion[3], as well as research that looked into the influence of temperature on the tire characteristics[4]. There is also continuing research into a tire model driving on sandy surfaces rather than a flat, dry surface[5]. Research in such areas is expected to lead to improved accuracy in vehicle dynamics predictions.

3 Braking and Driving Characteristics

Research on the braking and driving characteristics of automobiles has expanded from a focus on ABS and ESC systems, which improve stability when the vehicle is being driven at its performance limits and apply controls to ensure safety, to other areas such as direct yaw moment control (DYC), which provides driving assistance control in the normal driving range. ABS and ESC systems are now increasingly required as mandatory equipment on automobiles. Similarly, DYC systems, previously mainly seen on luxury cars and sports cars, have been making their way into some passenger K-cars and, moving forward, are expected to be adopted on an ever expanding selection of vehicles regardless of segment or class.

One example of development related to DYC systems is a study that verified the effect of yaw moment control on the difference in the front and rear distribution ratios of the braking force (brake fluid pressure) as part of an examination of a yaw moment control method based on the lateral jerk of the vehicle, and sought to identify they vehicle characteristics that made them easy for people to drive [6].

The increasing electrification of vehicles is also spurring advances in the research and development of systems with braking and drive characteristics that differ from those that came before.

One difference is the increasing adoption of braking systems that do not use the negative pressure of the engine as an energy source prompted by environmentally friendly measures such as turning engines off when the vehicle comes to a stop and the replacement of gasoline engines with electric motors. In this context, one report described the construction of a technology to predict the brake pedal feeling performance in an integrated braking system for a light-duty vehicle without negative engine pressure[7].

The number of hybrid vehicles (HVs) and electric vehicles (EVs) on the roads continues to increase year after year is prompting further advances in research and development focused on the specific characteristics of these vehicles, such as the ability to brake using the regenerative torque from the motor, the high-band torque response thanks to motor-produced drive, and higher levels of acceleration performance. For example, a system that coordinates electronic control of the motor regenerative torque and brake friction torque to make it possible to decelerate the vehicle using only the accelerator pedal, without stepping on the brake pedal, and also supports the stopping of the vehicle was developed to realize more intuitive accelerator pedal operation[8]. Another reported involved development of EV drive motor control technology that achieves the braking system described above[9]. The Nissan Leaf released in 2017 is equipped with this technology in the form of the e-Pedal, and more such systems will undoubtedly continue to be developed and adopted.

At the same time, focusing on the ability to place electric motors in a variety of different locations on the vehicle that characterizes EVs has led to advances in the research and development of EVs that use in-wheel motors (IWMs). One example is a proposed high-band vibration damping control method based on the experimental mode analysis of IWM vehicles[10].

The further development of technologies in the field of braking and drive control is expected to lead to improved performance in the normal driving range, as typified by DYC, and research and development related to the application of electric motors as the source of drive power in the vehicle, as typified by HVs and EVs, will also continue to be actively pursued in the future.

4 Directional Stability and Steering Responsiveness

Active research on the topics of directional stability and steering responsiveness was also carried out in 2017. Previous experiments and testing have made it well known that reinforcing the vehicle structure improves steering stability, but there are few examples of rigorously understanding this phenomenon through engineering. One example of research focusing on vehicle body rigidity is a report discussing the use of both sensory evaluations and the analysis of measured data to apprehend the relationship between vehicle body reinforcement and steering stability, and build a framework to analyze the underlying mechanism[11]. Research on rigidity also included a report of the results of a verification of the influence of wheel rigidity on the dynamic characteristics of tires and steering stability[12].

The growing interest in automated driving technologies has prompted a review of their importance to driving performance, one of the most basic types of vehicle performance, and research cases reported in 2017 examine both the vehicle behavior and driver behavior aspects of this issue. One example of research on vehicle behavior focused on the aerodynamic forces that affect driving stability, especially the unsteady flow of air that affects vehicle behavior, rather than continuing to pursue the reduction of steady lift, using an unsteady flow analysis method that relies on fluid analysis techniques[13].

In contrast, research that focused on driver behavior sought to understand the steering characteristics of drivers with respect to the state of the vehicle in a closed loop and reported that defining the specific states that make drivers feel the vehicle is behaving as intended will allow a clear identification of the vehicle characteristics that realize this state[14]. The booming topic of integrated vehicle controls has also been the subject of many research reports. One example focused on the possibility of vehicle stability control via rear wheel steering control within the process (transition zone) from the linear to the limit region of vehicle motion. In terms of the individual effectiveness of steering control, DYC via braking and drive force control, and braking control[15], even in a system configuration providing only steering control and brake controls on each wheel without driving force control, rear wheel steering control was as effective as DYC while generating very little deceleration. These results demonstrate that these characteristics can be expected to improve the level of driver comfort when vehicle stability controls are in operation.

Research targeted at the dynamic characteristics of the yaw rate with respect to steering indicated that indirect yaw moment control (IDYC) improved responsiveness and convergence through the use of left and right in-phase drive forces[16]. This research team also reported finding a method to improve pitch motion via drive force distribution control since the drive force input into the vehicle behavior in IDYC changes acceleration in the longitudinal direction as well as pitch motion.

Vehicle integrated control technologies, which are closely related to the base running performance and automated driving technologies are anticipated to continue to evolve even further to realize the soon-to-come fully autonomous driving operations (level 5).

5 Limit Performance

In the context of vehicle limit performance, regulations requiring the mandatory installation of electronic stability control (ESC) devices on passenger vehicles and electronic vehicle stability control (EVSC) devices on heavy-duty vehicles continue to expand around the world, spurring advances to improve active safety at the edge of those limits. Before the end of 2018, Japan will also make it mandatory to install ESC not only on registered passenger vehicles, but also on existing K-cars (existing models still in production), and will also gradually expand the mandatory installation of EVSC. Furthermore, technologies extending those systems to control the braking and driving torques of the left and right wheels using DYC and the IWMs in electric vehicles, as well as to improve the tracing and cornering limits, are being actively researched and developed.

The next stage in active safety, represented by ongoing research and development into advanced driving assistance systems (ADAS) and automated driving systems is also leading to progress in collision avoidance functions that combine both deceleration and steering. Research and development on a collision avoidance support system that not only realizes a guidance system that avoids conflict between the attempt to avoid a collision made by the driver through manual steering and that made by automated steering, but also initiates automatic control that takes tire force saturation into account when avoiding a collision manually has become difficult, has begun[17].

At the same time, demand is rising for an entirely new category of transportation. Currently, commercial research and development, trial operations, and public demonstration testing on personal mobility vehicles (PMVs) are underway in a variety of forms. The dynamic functionality envisioned for this completely new form of transportation that breaks away from convention has triggered various forms of research and development. Examples includes research on a three-wheeled PMV with two wheels in the front and one in the back that leans to the left or right when turning, which examined the special characteristics and advantages or disadvantages of front- or rear-wheel steering on this type of vehicle from the standpoint of using lateral movement to avoid obstacles when driving, such as when going past an oncoming vehicle[18]. Another case examined the dynamic rollover limit characteristics using a multi-degree of freedom kinematic simulation[19].

These examples of new research and development, as well as the development of new technologies will not only improve the basic performance that allows vehicles to respond quickly and avoid danger in accordance with driver intention, but also offer the promise of further improvement of the active safety in critical situations of vehicles.

6 The Human-Vehicle-Environment System

Public interest in the topics of automated driving and driver support systems has been rising dramatically. The Society of Automotive Engineers (SAE) has proposed definitions for the different levels of automated driving. Currently, various assessments to introduce Level 2 (system that control of the vehicle in the longitudinal and lateral directions under constant monitoring by the driver) and Level 3 (systems that do not require constant monitoring by the driver, but can delegate driving authority to the driver as needed, such as in an emergency) technologies are progressing at a rapid pace. Improving the affinity between the driver and the vehicle (including the control system) is now a major issue because the ability to switch between automated driving and manual operation without a sense of discomfort has a large influence on safety and security. Various new studies will be necessary to improve the affinity between the driver and the vehicle due to individual differences between drivers, driver states, and a wide diversity of other related factors, such as the conditions, assumptions, and environment that lead up to the transition of authority over the vehicle. As exemplified by research that sought to verify the influence of the content and order of operations in an authority delegation request (in other words, a takeover request (TOR)) on the driver's driving behavior[20], various studies are using a driving simulator (DS) to examine the receptivity of drivers who receive a TOR. Beyond the software aspect, various other studies have also investigated the hardware aspects, such as the human machine interfaces (HMIs) and display modality, in the context of smoothly presenting the TOR. Examples of such studies include an attempt to experimentally verify the effect that the positioning and method of displaying the TOR had on the driver[21] as well as an examination of the effectiveness of using audible and tactile cues in combination with visual stimuli for the TOR[22]. Research into automated driving is expected to continue to advance even further since the conditions that need to be examined are so diverse.

On a different front, there are growing expectations that driver assistance systems will support the mobility and independence of elderly drivers, while also reducing the number of traffic accidents, particularly in light of Japan's aging society. Examples of recent research in this field include an examination of the receptivity of drivers to a system that predicts dangerous situations often overlooked by elderly drivers and then automatically applies the brakes in advance[23]. Another study examined whether the use of a head-up display (HUD) when this kind of predictive braking was activated would improve the receptivity of drivers[24]. The receptivity of the drivers when these kinds of driving assistance systems activate is an important key to ensuring their safety and security.

It is essential to improve the affinity between people, vehicles, and the environment to realize fully automated driving (Level 5) in the future. Consequently, there are strong expectations for even further technical developments in this field.

7 Intelligent Controls

The public and private sectors in Japan are working together to improve automated driving technologies and commercialize quasi-automated driving (Level 2) by the year 2020, as indicated in the Public-Private ITS Initiatives & Roadmap 2017 (currently being revised for the fourth consecutive year). Demonstration projects and testing on public roads were conducted in 2017 and more full-fledged operations are predicted to begin in 2018 and onward.

Securing the concept represented by the "safety" and "security" key words in automated driving will require a dramatic evolution of intelligent control technologies capable of dealing with various situational changes (e.g., drivers, roads, and environments). Various automated driving control systems, such as advanced emergency braking systems (AEBS), lane keeping assist (LKA), adaptive cruise control (ACC), emergency steering obstacle avoidance support systems, and automatic parking systems exist and have been the subject of numerous research reports. For example, there was research that proposed a new index using a logistic regression model for the coexistence of the inoperative and unnecessary operations that constitute a trade-off relationship in AEBS[25]. Another case examined the receptivity of drivers to LKA and ACC systems depending on the order of the switch between automated and manual driving[20]. Another report discussed obstacle avoidance route optimization and driver receptivity to the system after an obstacle was avoided with respect to emergency steering obstacle avoidance support systems, a technology that has been garnering attention to prevent accidents when driving at high speed[26]. Clearly, there is a wide variety of different automated driving systems and extensive research is being carried out on the intelligent controls necessary to allow these systems to cope with every possible situation.

However, it is difficult to verify the effectiveness of these systems using real vehicles due to safety issues and the huge diversity of hypothetical driving situations to envision. Consequently, verification testing relying on a DS and the use of MBD (model-based definition) using the model identified by that simulation has become essential. The obvious importance of identifying the proper model has led to various forms of validation. For example, one case tried to model (quantify) the driving of a skilled driver when they made a right-hand turn[27]. Another case sought to model vehicle movement and parking using a Markov model and then verified it based on person trip data[28]. In addition, on the topic of driver assistance functions, one case examined the kind of steering characteristics exhibited by the driver during precise control due to shared control with the system[29], exemplifying the amount of research concerning the affinity of human beings and automobiles mentioned in the previous section.

The ongoing progress and evolution of research into the numerous types of intelligent controls related to automated driving and driver assistance systems advances and develops holds the promise of the arrival of a "convenient" automotive society that is free from accidents, safe, secure, and decreases driver burden.

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