VEHICLE DYNAMICS

1 Introduction

The year 2018 was one in which the trade policies of the United States and other countries spread protectionist restrictions around the world, ultimately having a great impact on the global economy. Automobiles also became potential targets for import restrictions, prompting concerns about repercussions on the automotive industry.

In addition to the promotion of electrification, recent technological trends observed at auto manufacturers around the world include the release of more and more models with connected technologies, and the application of artificial intelligence (AI) to interactive speech recognition systems. Vigorous technological development and competition is taking place in new fields. In Japan, initiatives related to autonomous driving technologies are being deployed through unified public and private sector cooperation. For example, the Public-Private ITS Initiatives & Roadmap has set the goals of establishing an environment that allows commercialization of level 3 autonomous driving by 2020 and the realization of level 4 autonomous driving on expressways by 2025. In addition, the Strategic Innovation Promotion Program (SIP) of the Cabinet Office is seeking to reduce traffic accidents and alleviate traffic congestion through research into (1) the development and field testing of autonomous driving systems, (2) the development of basic technologies to reduce fatalities in traffic accidents and alleviate congestion, (3) the building of international cooperation, (4) the deployment of these technologies for next-generation urban transportation, and (5) large-scale field tests.

At the same time, in the area of initiatives undertaken to address environmental issues, a topic drawing greater interest than ever before, countries around the world attended the 24th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 24) held in Poland in 2018, where they agreed to take steps, starting in 2020, toward implementing the Paris Agreement. One initiative undertaken in the automobile industry is the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), an international standard test method for fuel consumption and exhaust emissions introduced in Europe and Japan starting in 2018 is one example of the increasing pressure on automakers to meet stricter fuel economy and exhaust emissions regulations.

Amid the major trends of technological development in new fields, typified by autonomous driving, and the need to comply with various environmental regulations that become stricter with each passing year, there are ongoing expectations of achieving technological breakthroughs in enhancing driving pleasure, an area of longstanding research focused on enabling drivers to handle their vehicle with a sense of enjoyment and confidence.

2 Tires

Tires are the only points of contact between the vehicle and the road surface and therefore significantly influence not only vehicle dynamics, but also influence fuel efficiency. Most recently, the rolling resistance of tires has been actively reduced to reduce fuel consumption, but in terms of vehicle dynamics, striking a proper balance with steering stability, braking, and driving characteristics is a challenge. In response, approaches to decreasing fuel consumption that are distinct from reducing rolling resistance have been emerging. One research report described a method that uses computational fluid dynamics (CFD) to calculate the air resistance against a rotating tire, including the effects of complex tread patterns[1].

At the same time, the growth of electrification technologies in recent years has led to a higher relative contribution of tire noise to overall traffic noise as the noise from automobile power unit systems has greatly decreased. In an effort to reduce automobile traffic noise, the Uniform Provisions concerning the Approval of Tyres with regard to Rolling Sound Emissions and to

Adhesion on Wet Surfaces and/or to Rolling Resistance, UNECE R117.02, went into effect in April 2018, and a new regulation concerning vehicle external noise emissions, UNECE R51.03, is scheduled to come into force. Other efforts to reduce tire noise include research into a system that accurately measures the deformation of tire tread blocks, which cause noise due to repeated contact and separation from the road surface[(2)], and research aimed at reducing vehicle interior noise and exterior noise by evaluating the vibrations from tires during vehicle travel using statistical energy analysis[(3)].

As more stringent required characteristics are imposed on tires, there has also been research focusing on the characteristics of the wheel in combination with the tire, rather than just the characteristics of the tire itself, to assess responsiveness during the initial stage of steering[(4)].

With increasingly severe demands expected to be imposed on for fuel efficiency as well as noise and vibration performance, close attention will have to be paid to tire and wheel-related research and development trends seeking to achieve a high level of vehicle dynamics performance.

3 Braking and Driving Characteristics

Research into braking and drive characteristics has evolved from systems that enhance safety in an emergency or when driving at the performance limits, such as front and rear drive force distribution control for all-wheel drive (AWD), anti-lock braking system (ABS) and electronic stability control (ESC), to driver assistance technologies that operate within the normal driving range, such as direct yaw moment control (DYC) that controls the braking and driving force of the vehicle in both the longitudinal and lateral directions. In recent years, ABS and ESC have increasingly become mandatory, and the adoption of DYC is also expanding. In addition, G-Vectoring Control (GVC) has been introduced in mass-produced vehicles. The GVC technology uses an engine featuring a high response and high precision drive torque control system providing deceleration one tenth as fine as in a conventional system and generates longitudinal acceleration linked to the lateral movement resulting from turning the steering wheel to realize smooth cornering. A different report presents an initiative to reduce the burden of driving operations on the driver by linking this longitudinal acceleration to both roll and pitch movements[(5)]. Research and development seeking to link GVC with ESC to stabilize vehicle behavior in the region before the vehicle movement reaches its limits has also been carried out[(6)].

At the same time, the development of complex and sophisticated modern automobile control systems is recently carried out using model-based development (MBD), which models the functions of control devices and control targets, and bases development based on simulations to enhance its efficiency. Efforts to apply this approach to braking and drive control simulations using an environment that integrates various commercially available simulation tools have been introduced[(7)]. Rapid growth is anticipated in the development of MBD and other simulation technologies capable of handling the development of control systems projected to become ever more complex.

Finally, the development and mass production of vehicles driven by electric motors, such as hybrid and electric vehicles, is expected to accelerate even more in the coming years. In such vehicles, the mass of the electric drive units, and especially the batteries, tends to keep increasing, presenting the difficult challenge of achieving overall vehicle performance with tires adapted to the above-mentioned fuel efficiency and vehicle noise regulations. Promising research and development initiatives to improve the performance of vehicle dynamics through more precise control specifically targeting electrified vehicles are being carried out in the field of braking and drive characteristics.

4 Directional Stability and Steering Responsiveness

Research concerning directional stability and steering responsiveness was also actively pursued in 2018. First, the already active basic research on vehicle behavior has continued, producing many reports on efforts aimed at higher stability and greater responsiveness. One case focused on steering transient response, identifying a clear response index that correlates with drivers' evaluation comments about vehicle response at the time of transient steering input, and striving enable to the design to improve the driver evaluations[(8)]. In another case, efforts to elucidate the relationship of roll and yaw motions to vehicle body sideslip were made to clarify how roll motion impacts steering transient response[(9)].

The rigidity of the vehicle body is widely known to affect steering stability, but there are very few examples of rigorous engineering-based confirmation of that influence. One example of research focusing on vehicle body rigidity involved elucidating the underlying mechanism by looking into the relationship between unsprung vibration and steering force hysteresis through bench tests and simulations using different vehicle body rigidities[10].

Elsewhere, the promotion of electrification has been prompting efforts to cope with system layouts that differ from the conventional ones. One example is research to ensure, during the initial design stage, the potential of driving performance to impart a positive effect on performance evaluations of driving responsiveness in regard to steering, make the influence of the basic vehicle specifications on the vehicle response characteristics clear based on understanding advanced through previous research[11].

Other research and development has been taking full advantage of the recent progress exhibited by the control technologies equipped on vehicles. One report described research and development that built upon efforts to improve stability and responsiveness. A four-wheel steering system developed to control the characteristics of plane motion, such as the vehicle body slip angle, yaw rate, and lateral jerk, with a high degree of freedom was used as the basis for an active stabilizer system that can control the movement characteristics in the roll direction to achieve both better comfort and stability[12]. Another report introduced product development aimed at improving driver comfort by reducing the occurrence of deceleration due to ESC by coordinating it with ground load control using that active stabilizer system[13].

At the same time, there is active research into more advanced estimations of vehicle state, which are crucial to control. In particular, the vehicle body sideslip angle is an important state quantity for implementing control of the vehicle motion. Applying a non-linear noise filter was reported to successfully improve the accuracy of the sideslip angle estimation compared to the conventional approach relying on existing vehicle sensors for the measurements and estimation[14].

Research into basic technologies that support improved vehicle stability and responsiveness is also underway. Several examples have been reported. In one initiative, steering system rigidity was improved by enhancing the sensitivity of the torque sensor mounted on the steering shaft[15]. Another project researched a rubber bushing model that identifies the dynamic spring constant at any amplitude using only two general design parameters, the dynamic spring constant and the loss factor, and is then applied to performance examinations at the initial design stage when no parts exist[16]. Other research has led to the development of a hub bearing equipped with an active steering function[17]. A different initiative has sought to reduce costs by developing algorithms to estimate the vehicle state quantities required for semi-active suspension control without using dedicated sensors such as vehicle height and vertical acceleration sensors[18].

The growing need to ensure a means of transportation for the elderly has led to the emergence of a new and promising category of transportation known as the personal mobility vehicle (PMV), which is compact, and easy to use. Multifaceted research and development, as well as field testing, are being with an eye toward commercialization.

The PMVs are three-wheeled motorcycles that employ the same tilting mechanism as electric motorcycles to lean inward effectively while cornering. There have also been efforts to clarify the transient response characteristics associated with rider leaning[19].

There are expectations for further advances in the integrated control technologies that will enable the spread of electrification and autonomous driving technologies, as well as for improvements in the technical level of the base vehicle stability and responsiveness that support those control technologies.

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. This is spurring advances to improve active safety within the limit region. Furthermore, technologies that apply those systems to control the braking and drive torques of the left and right wheels, as well as to improve the tracing and cornering limits, continue to be actively researched and developed. In addition, basic research on independently controlling the front, rear, left, and right cornering forces by changing the wheel load according to aerodynamic characteristics has been conducted for the purpose of improving sudden obstacle avoidance performance on expressways. The effectiveness of this technology was verified via simulations[20].

At the same time, initiatives adapted to CAE use in the development of control systems for the limit region are being carried out. The sense of crisis felt by humans, converted to a risk potential using an exponential function, has been used to identify a driver model that represents driving behavior in situations involving strong, nonlinear vehicle movement, such as a double lane change or other emergency avoidance maneuver[21]. In addition, the proposed driver model could be broadly applicable to vehicle development for situations where differences in vehicle characteristics such as cornering performance and stability have no impact on that risk potential[22].

Research concerning emergency avoidance maneuvers by the PMVs described in Section 4 is also underway. One project focused on the risk of rollovers by PMVs with an active tilt mechanism and proposed solutions to the problem arising from vehicle response characteristics in sudden steering maneuvers[23]. Other research compared the obstacle avoidance ability of PMVs that actively provides a tilt angle along with the steering angle to that of passenger cars and motorcycles, and validated the suitability of such PMVs in the real world[24].

In addition to the established approach of improving vehicle limit performance using mechanisms and controls to allow danger to be avoided within the limit regions, there are growing expectations for advances in active safety technologies allowing safe emergency avoidance maneuvers performed in accordance with the driver's intentions as autonomous driving and driver assistance technologies are increasingly applied in research, development, and mass production.

6 The Human-Vehicle-Environment System

Although autonomous driving technologies and driver assistance systems are drawing increased interest from society at large, many technical and legal issues still have to be resolved. Nevertheless, automated driving technologies corresponding to the Level 2 (systems that control the vehicle in the longitudinal and lateral directions under constant driver monitoring) and Level 3 (systems that do require constant driver monitoring, but return control to the driver in an emergency or when otherwise required) SAE definitions are finding their way in more and more mass production of vehicles. In this field, the affinity between the driver and the system is important, and abundant research into the human-vehicle-environment system is being carried out.

The ability to estimate the state of the driver is essential in high-level autonomous driving systems. One example of research in that area involved asking drivers to carry out specific tasks in a driving simulator (DS) and verifying the effectiveness of a driver alertness estimation model based on how their driving ability changed over time[25]. Other research carried out DS experiments to examine the relationship between the driver's level of alertness before the autonomous driving system reached its functional limit and transferred authority to the driver and the driving operations after the driver takes over[26].

Another case examined how best to instill confidence and make the driver comfortable during autonomous driving. It focused on the road shape necessary to realize smooth cornering during autonomous driving, and applied the GVC concept discussed in Section 3 to a more relaxed curve in conventional road shapes. A DS was then used to evaluate a relaxed curve corrected for the longitudinal acceleration linked to lateral motion[27]. At the same time, separate research focused on general roads in urban areas, a traffic environment where drivers may feel at risk. A control target generation algorithm that expanded the concept of risk potential from the original steering control to vehicle speed control was verified through actual driving experiments, and ways to express the sense of danger perceived by the driver were sought[28].

Among research that examined driver assistance systems, one project that focused on preventing accidents with pedestrians when a vehicle turns at an intersection. Ways to allow intervention in vehicle operation by a driver assistance system designed to influence driver behavior toward moving in a direction that reduces the risk of collision, and their effectiveness, were evaluated using a DS[29]. Another initiative verified the effectiveness of a driver assistance system at reducing the risk of a collision using a driving simulator that combined augmented reality (AR) showing pedestrians as computer graphics (CG) with an actual passenger car[30].

More and more initiatives to evaluate vehicle motion characteristics make use of high-performance simulators in an attempt to better understand the relationship between people and vehicles. In one case, the changes in drivers' steering behavior caused by the minute pitch motion associated with the difference in height between the front and rear roll centers were measure in a DS to find clues that would lead to people-centric vehicle dynamics development[31]. In another case, the cerebral blood flow of drivers was measured and analyzed to elucidate how differences in vehicle steering response characteristics caused driver feeling evaluations to vary[32]. In still another case, a steering simulator was used to examine the steering feel produced by differences in the driving assist method employed by the electric power steering system[33]. Similarly, high-performance DS that reduce the differences in driving sensation between actual driving and simulated driving are being developed to promote research and development using simulators in the hope that they will be broadly applicable to vehicle dynamics[34].

Research on the social receptivity to personal mobility vehicles (PMVs), a newly proposed category of transportation also discussed in Sections 4 and 5 of this article, which will be necessary for their future commercialization and introduction to the market, is being carried out from the perspectives of both PMV drivers and the drivers of other nearby vehicles. Subjective evaluations during driving and DS-based evaluations have been used to clarify driving behavior characteristics, such as the length of forward gaze time depending on road shape, in PMV drivers[35]. Conversely, DS evaluations have also been used in attempts to clarify receptivity to PMV vehicle width and tilting behavior in drivers of nearby vehicles [36].

These human-vehicle-environment systems technologies are expanding into a wide range of fields, including autonomous driving and driver assistance systems, people-centric vehicle dynamics, and new categories of transportation, such as PMVs. Even further research and development progress is anticipated.

7 Intelligent Controls

The public and private sectors in Japan have been working together to improve autonomous driving technologies and commercialize Level 3 autonomous driving by 2020, as indicated in the Public-Private ITS Initiatives & Roadmap 2018. Many field tests on public roads, including government-led projects, were conducted in 2018. In that context, intelligent controls also represent an active field of research and development on autonomous driving and driver assistance systems.

To achieve higher levels of safety and comfort during autonomous driving, one research project studied steering control that reproduces the feature quantities obtained by expert drivers on curved roads and coordinates them with vehicle acceleration and deceleration to achieve an autonomous driving system that harmonizes steering control with vehicle acceleration and deceleration by applying the GVC concept introduced in Section 3[37]. Another approach aimed to realize smooth cornering during autonomous driving using versatile vehicle trajectory formulation that generates travel routes adapted to any real world road shape and equivalent to those an expert driver would choose[38].

At the same time, specific initiatives to spread and expand autonomous driving and driver assistance systems are being carried out. Japan is considering the introduction of autonomous buses to provide a means of transportation that addresses the growing number of people with limited access to transportation resulting from the aging of the population. Design guidelines for the steering control necessary to make buses autonomous have been proposed and validated in actual driving[39]. Although advanced driver assistance systems (ADAS) are still uncommon in mini-vehicles, refining the control in EPS systems subject to many technical constraints has enabled the installation of ADAS steering system control in mass-produced mini vehicles[40].

The use of GPS by the autonomous driving system to sense the driving trajectory with a high degree of accuracy is an example of basic technology that supports high-precision control in autonomous driving, and various efforts to realize this at a low cost have been undertaken[41]-[43].

The advancement of research into such intelligent controls will make it possible to provide safety and security even more widely in our future transportation society, and is also expected to lead to a more convenient and comfortable automotive society by making autonomous driving and driver assistance systems more widespread.

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