VEHICLE DYNAMICS

1 Introduction

The COVID-19 pandemic that has swept the world since early 2020, had a strong impact on the automotive industry as, with some degree of variation from one manufacturer to another, global production by Japanese automakers dropped by 20 to 30 percent from January to October 2020. The major lifestyle changes imposed by the pandemic, including the widespread adoption of telework, restrictions on movement and travel, and the need to avoid closed spaces, crowds, and contact has led to taking a fresh look at the value of automobiles in terms of mobility that ensures a private space.

Within this changing environment, research in the field of vehicle dynamics has been particularly proactive in the area of human-vehicle systems, such as the basic vehicle characteristics that facilitate driver operations while cruising, and subjective driver evaluations. There is also a significant body of research surrounding the autonomous and electric aspects of the connected, autonomous/automated, shared, and electric (CASE) concepts. In line with the Public-Private ITS Initiatives/Roadmap, the Road Traffic Act and Road Transport Vehicle Act have been revised to allow automated driving (Level 3) on public roads for the first time in the world. In terms of vehicle dynamics, the control used in automated driving involves not only improving vehicle responsiveness and stability, but also securing leeway within the traffic environment by drawing out the full potential of vehicle dynamics. Corporations and other groups are conducting various forms of research designed to achieve precise and stable driving in rapid traffic flow.

Following the November 2020 announcement that the ban on sales of gasoline and diesel vehicles would be pushed forward from 2035 to 2030 by the UK government, along with Japan's policy of achieving net zero domestic emissions of CO_2 and other greenhouse gases, have escalated discussions on promoting electrification, and moving the timetable up in that respect is perceived as a business opportunity and leading to active development. Electrification also requires vehicle dynamics to depart from traditional fields and approaches to accommodate changes in vehicle weight distribution due to mounting a battery, control of the inverters involved in the rotation speed of the motor during acceleration, and other factors.

2 Tires

As the only points of contact between the vehicle and the road, tires are represent a part with a major influence on fuel economy, braking, handling stability, and ride comfort. Addressing ever more stringent fuel economy regulations in various countries have been driving research and development on tires that maintain dynamic performance while reducing rolling resistance. Dynamic performance remained the subjects of reports in 2020. One such report introduced tire grip performance predictive technology consisting of a bench evaluation capable of reproducing both the surface and internal temperatures of the tire. Researchers focused on the surface layer of the tread rubber in contact with the road surface, as well as the internal tread characteristics that affect adaptability to road surface irregularities and shear deformation to reproduce the tire load and temperature conditions found in actual driving situations. This approach demonstrated the possibility of reproducing the changes in cornering force (CF) due to differences in tread rubber blends. The ability to alter the temperature in a time series manner and measure the maximum CF has made it possible to ascertain cornering performance in actual driving situations.

A different report presented a method of evaluating changes in tire contact surface caused by dynamic alignment variations during driving. Vehicle alignment has an impact on dynamic characteristics and tire wear. Therefore, the ability to observe dynamic tire contact patch behavior while changing the slip and camber angles should provide useful data for tire development. The contact patch of the tire varies according to the slip angle, and observing the changes in contact surface behavior using a tire dynamic contact force test device confirmed the existence of an equivalent shape line driving condition that maintains lateral symmetry by applying a suitable counterbalancing camber angle that cancels the variation. Identifying the tire specifications, load dependency, differences in outside and inside wheels during cornering, and other aspects of the contact patch in actual driving is expected to prove useful in studying the affinity between the vehicle and tires with respect to optimizing development.

Tire spring characteristics exhibit strong nonlinearity and the difficulty of considering their dynamic behavior analytically is well known. Nevertheless, advances in analysis methods have been reported. A new thermodynamics model variant of the Magic Formula was proposed as a tire model to predict the impact of temperature and rolling speed on tire performance. Accurately predicting vehicle performance under a broad variety of conditions such as changes in temperature due to seasonal conditions, or ABS, is expected to reduce the current gap between forecast and actual results.

3 Braking and Driving

Research and development in the braking and driving fields has covered control technology that ensures safety such as ABS and ESC, as well as direct yaw moment control to improve handling stability and controllability in the linear range. In addition, the shift toward electrification has involved research capitalizing on the high response control characteristics of motors and expanded R & D efforts into the area of relying on longitudinal or lateral braking and driving distribution control to improve vehicle dynamics.

One study making use of EV motor drive characteristics to improve vehicle dynamic performance was presented in 2020. This particular case distinguishes itself by combining the application of normalized yaw rate to feed-forward control calculated from the internal vehicle model with feedback control that compensates for the difference between the normalized and actual yaw rate. Doing has demonstrated that controlling drive force according to the vehicle behavior relative to various road surface disturbances, results in stable and less burdenful driver operation, and enhances ride comfort.

Research on various EV drive systems has notably progressed for in-wheel motors (IWM), which have the advantage of enabling independent control of each of the four wheels. The yaw moment can therefore be controlled directly, further helping to achieve stability and controllability during ordinary driving, and a stable performance during under limit conditions. Conversely, IWMs have also presented the issue of increasing spring load, causing ride comfort to worsen due to changes in suspension characteristics. In 2020, however, research on control that eliminated that structural worsening of ride comfort impediment through a compensator structure accounting for tire time weighting was announced.

Research focusing on the transient alignment changes during braking was also presented. Braking pitch and bounce behavior perceived as feeling right by drivers, as well as control of braking distribution before and after that behavior, was demonstrated. Currently, the mainstream EV systems coordinate regenerative and friction brakes, but research on systems that place regenerative motors in each wheel to eliminate friction brakes through the full braking range has been announced. If research and development on extending the range of regenerative braking progresses further, more precise control of performance ABS, ESC or other hydraulic brakes must supplement will become possible, and creating expectations of technology that will reach new levels of environmental performance and safety.

4 Directional Stability

Existing mechanisms are no longer sufficient to meet the diverse requirements drivers have for vehicles, and research on expanding functionality using actuators or other components are underway. However, focusing exclusively on enhancing functions can result in a mismatch between human perception and vehicle behavior. Therefore, research on preventing a sense of discomfort is also underway.

Rear-wheel steering systems, which enable not only the front, but also the rear wheels, to be steered, are a typical additional function. Enabling rear-wheel steering is anticipated to offer handling impossible to achieve with front-wheel steering alone at low speeds, as well as to improve direct vehicle stability at high speeds. Providing excessive control of low-speed handling, however, results in discomfort for the driver and passengers in the rear seats. Consequently, development to eliminate that discomfort by setting target values for physical properties that affect human sensation and determining thresholds experimentally is being pursued. Similarly, research on not only improving handling by making the layout more resilient to restrictions, but also reducing running resistance by enabling left- and right-wheel steering using independent actuators in front-wheel steering systems is being carried out. The above examples illustrate how the addition of new functions or control opens up possibilities that cannot be realized using only existing systems.

At the same time, a fundamental understanding of vehicle dynamics is essential to improving performance through such functions and control. Although theoretical studies based on generally-used vehicle model simulations produce a single response for specific inputs and initial conditions and make it possible to obtain quantitative trends from the results of modifying parameters, intuitively interpreting their physical significance is difficult. A technique to comprehensively evaluate performance as a whole various conditions is required. Analysis methods that also take the strongly nonlinear limit area into account have been proposed in the past, and a technique relying on contour maps of state velocity to enable an intuitive interpretation of many physical properties using existing methods has been reported. The technique was used for chassis control and demonstrated the feasibility of an overall evaluation that cannot be obtained from singular time-series data.

5 The Human-Vehicle-Environment System

Level 3 automated driving systems have been commercialized, freeing the driver from driving operations under limited circumstances. Even when they are not carrying out driving operations, humans are the ones occupying the vehicle and determining whether its vehicle is good or bad. Discrepancies between the vehicle behavior under mechanical operation by a system recognizing the driving environment, and under human operation will induce stress and uneasiness in the occupants. Studies on effectiveness at reducing fatigue from the point of view of the occupants, gaze characteristics, ride comfort and other factors, are being conducted in anticipation of the coming age of automated driving.

The effectiveness of automated driving systems at reducing fatigue in long-distance driving is being validated in a quantitative manner. The extent of driving fatigue was analyzed from the three viewpoints of subjective sensation of fatigue, muscle activity indicating physical fatigue, and functional autonomous nervous systems indicating psychological fatigue. Reduction was reported to be significant in all three cases. Another result was a reduction in the time and frequency of the driver focusing on the preceding vehicle during following, which translated into paying broader attention to other factors. This result was more prominent in inexperienced than in veteran drivers. Research on ride comfort is also moving forward. When drivers do the actual driving themselves, maneuvering the steering wheel provides ancillary physical support. During automated driving, however, that support is lacking and their bodies become more susceptible to the effects of vehicle behavior. This physical behavior varies due to the change in body posture caused by braking patterns, and smaller changes in the angle of the shoulders under those conditions are associated with greater ride comfort.

Accurate environmental recognition is essential to achieving the aforementioned high-level automated driving. The growing use of information from global navigation satellite system (GNSS) and high-precision 3D maps is gradually making it possible to retrieve not only the position of the vehicle on the map, but also the position of road structures within a margin of a few centimeters. While GNSS offers the benefit of convenience and ease of operation, it also has the drawback of losing accuracy in tunnels, urban areas with high rises, or other situations where the sky is blocked and satellite signal reception is poor, or in locations involving multipath or other factors that can produce errors in the transmission path. Map matching technology is a technology being developed as a technique that does not depend on GNSS. A method aiming to achieve the superior robustness of being unaffected by the weather and improved precision by matching the results of the lidar and millimeter wave radar sensor fusion with high-precision map data to estimate the position of the vehicle has been proposed.

Lastly, conditional automated driving at Level 3 or lower must hand driving operations to the driver in response to a system intervention request. A safe and smooth transfer of driving authority from the system to the driver requires the system to be aware of the driver's state. Technologies based on abnormal posture, eye closure, or a lack of steering wheel operation to detect a driver's inability to drive due to distraction or a sudden medical condition are being developed, and guidelines covering such situations are being formulated. Systems that recognize divergences from the normal in driving operation and gaze behavior to detect warning signs before the driver becomes unfit to drive have also been under development.

6 Limit Performance

After making ABS and ESC mandatory in Japan a few years ago, the Ministry of Land, Infrastructure Transport and Tourism (MLIT) announced its intention to also make the installation of advanced emergency braking systems (AEBS) mandatory in December 2019. The application of that policy to fully redesigned and new domestic models starting in November 2021, among other factors, will lead to the adoption of various vehicle dynamics control systems and contribute significantly to improving limit performance.

Among cornering performance technologies, torque vectoring, which mitigates understeering during cornering by distributing torque between the right and left wheels is frequently adopted, and systems that help improve both cornering and stability by also simultaneously regulating the front and rear drive force through AWD control are becoming more common. Drive mode select, which enables switching to the optimal driving and braking force control in different driving situations, is becoming more widespread. This has made it possible to improve the performance required by various driving situations, including better off-road performance and stability in the snow, or enhanced traction and maneuverability in circuit driving.

In electric vehicles (EVs), precise control stemming from high motor responsiveness is expected to mitigate slippage due to tire spinning on slippery road surfaces (e.g., snowy roads). However, quickly suppressing the sudden rise in motor rotation speed due to tire spinning requires detecting tire slippage in the inverter precisely and promptly. Therefore, a spinning determination method that does not require vehicle body speed information and achieves early identification of tire spinning while avoiding erroneous detection has been proposed.

7 Intelligent Controls

The 2020 Public-Private ITS Initiatives/Roadmap sets the goal of commercializing full (Level 4) automated driving on expressways by 2025. In 2020, the legal framework to enable conditional (Level 3) automated driving on expressways was established. Control systems for automated driving are called upon to secure sufficient leeway in driving environments such as roads packed with snow that have a low surface coefficient of friction to provide safe and precise driving. Improvements in not only outside world recognition and other automated driving-specific functions, but also vehicle dynamics and driving position control technology will be essential to realizing such systems. A technique that looks at the optimal vehicle slip angle during cornering from the standpoint of drawing out the maximum lateral force of the front and rear wheels and intentionally generate the slip angle that brings the vehicle body inward relative to the direction of travel has been proposed. That technique has been reported to largely eliminate errors in tracking the target trajectory on packed snow roads.

Skyhook control is a typical ride comfort control that applies speed feedback from sensors attached to the vehicle springs to improve the damping they provide and prevent a worsening of the road surface inputs in circumstances involving simultaneous road disturbance and driving operation inputs, such as driving through an uneven corner. Simultaneously reducing vibration and suppressing changes in posture in such control is difficult, and it is not always possible to obtained sufficient effectiveness. Therefore, a new skyhook theory has been proposed. That theory estimates roll motion relative to steering inputs from CAN information (steering angle and vehicle speed) and combines it with the actual roll motion retrieved from the signals of the vertical acceleration sensors attached to the springs to separate roll motion into a driving operation and a road surface disturbance component and apply independent control coefficients to each component. Validation using a test vehicle demonstrated higher levels of compatibility in both suppressing posture changes in the low frequency range and damping vibration in the medium frequency range.