VEHICLE DYNAMICS

1 Introduction

The European-led policies to ban the sale of gasoline vehicles and strongly promote electric vehicles showed signs of slowing down as a result of the insufficient electricity supply caused by the shortage of crude oil and natural gas supply triggered by Russia's invasion of Ukraine in February 2022, as well as by the German policy of abolishing nuclear power plants. Nevertheless, the trend toward electrification remains largely unchanged. In 2022 in the U.S., California introduced a regulation that requires 100% of new car sales to be ZEVs by 2035 in the wake of the 2021 Biden Presidential Decree requiring ZEVs to constitute 50% of new car sales by 2030. These regulations, in conjunction with the purchase subsidies under the *Inflation Reduction Act*, are anticipated to make electric vehicles more widespread.

In addition to the electrification aspect of CASE noted above, progress has also been made in the areas of connectivity and autonomy. The *Public-Private ITS Initiatives/Roadmap*, first formulated in 2014 and revised annually since then. With the establishment of Digital Agency in 2022, the roadmap was expanded with a look at defining a future traffic society making use of digital technologies to formulate the *Vision of Mobility and Society 2022*, which retains the goal of commercializing automated driving on expressway set in past initiatives. The necessary legal framework was established with the issuance of the revised *Road Traffic Act*, which finally permits Level 4 automated driving and self-driving robots on public roads, and of attendant legislation. This will enable patrol services using autonomous vehicles on public roads, provided that remote monitoring and other conditions are met.

In the EU, the European Commission officially announced the proposed new Euro 7 emissions regulation, which sets emission standards for pollutants from vehicles, in November 2022. In addition to tightening the existing regulations for NOx and CO, the proposal includes new emission standards for brake and tire particles. The various organizations involved are still working together to finalize undetermined matters such as the test methods and regulatory values for the particles, and the regulation will come into force as early as July 2025 if everything proceeds smoothly. The wear resistance performance of brakes and tires, which affect particle generation, is perceived to involve a trade-off with friction characteristics. In the context of vehicle dynamics, the increased vehicle weight due to electrification is anticipated to result in more severe requirement characteristics.

2 Tires

Tires are the only component that connects the vehicle to the road surface while the vehicle is in motion, and are important in determining vehicle stability, braking, comfort, and fuel efficiency. For a long time, tires have been designed to have low rolling resistance for fuel-efficient performance, and technologies to achieve both low rolling resistance and dynamic performance have been accumulated in this effort. Social expectations concerning fuel consumption regulations, noise regulations, and dust regulations have been making it more challenging to satisfy tire performance requirements.

Research on tread deformation while the tire is rolling is being carried out in the context of the general tightening of regulations on tire noise, and notably the scheduled 2024 introduction in Japan of the UN R51-03 Phase 3 noise regulation addressing that issue.

According to one report, using a stroboscopic camera or a micro-accelerometer/microphone to measure the strain, acceleration, and radiated sound of a single tread block in a rotating tire, and comparing the results to the frequency characteristics of tire noise, showed that the sound radiated at about 1 kHz is not generated from the tire tread block alone, but constitutes an overall vibration.

In addition, appropriate tire performance becomes even more important as the load on tires tends to increase with electrification. Cornering stiffness has strong nonlinear characteristics relative to load, and the lateral rigidity of each portion of the tire strongly affects those characteristics. A physical properties tire model that features enhanced modeling of the tread portion and is intended to design those characteristics has been proposed. A report confirming that the model was experimentally validated using a testing machine capable of measure the distribution of the force generated on the rolling tire contact surface has been released.

Attempts to measure the displacement of the tire contact surface during actual driving have also been reported. Another report validated improvements in dynamic performance achieved by changing the specifications during actual vehicle driving by analyzing the actually measured tire force. That force was measured with a technique that uses a camera installed inside the tire to photograph a lattice-like sheet attached to the back of the tire ground contact surface, and then estimates the generated force based on the three dimensional displacement calculated trough image analysis and the pre-measured rigidity. Analyzing tire behavior and forces generated during driving has largely been made possible by progress in making accelerometers, cameras, and other equipment necessary for measurements smaller, lighter, and less power hungry, enabling their installation inside the tire. It is hoped that progress in efforts to elucidate the mechanisms underlying tire noise and envelope characteristics will result in technological advances that prevent adverse effects on tire dynamic performance.

3 Braking and Driving Characteristic

The practical appeal of EVs as environmentally friendly cars is increasingly being complemented with the creation of added value in the form of dynamic performance achieved through drive and stability control that make use of the high response and high torque characteristics provided by motors. In the field of braking and driving control, that trend has led to a considerable amount of research on controlling vehicle behavior based on the control of the braking and drive forces of electric motors. Mechanisms that mechanically distribute drive force have not actively relied on drive torque control as a means of controlling vehicle behavior (yawing, pitching, rolling) when an internal combustion engine is used as a power source due to cost and feasibility issues. However, in electric AWD drivetrains equipped with multiple high-power motors, the multiple power sources and responsiveness of the motors make it possible to rely on torque control to actively control vehicle behavior. Automakers are developing vehicles with AWD systems featuring multiple motors on the front and rear axles to capitalize on that benefit. In one example, complementing yaw and pitch control based on differences in drive force with output/regeneration control carried out while detecting the slip ratio of each wheel was reported to achieve high levels of maneuverability, ride comfort, and peace of mind on any road surface in mass-produced vehicles.

In an AWD with a front and rear motor layout, differences in driving torque characteristics make tire slip more likely than in a conventional ICE AWD. On slippery road surfaces, line tracing performance may be impaired by the sudden decrease in lateral force when accelerating while cornering. Research focusing on that point has proposed a method of determining the required yaw moment from the difference in speed between the left and right wheels after calculating the tire friction circle based on the individual wheel loads estimated from driver operation and vehicle posture, and optimally distributing drive force between each wheel. Validation with an actual vehicle has confirmed the feasibility of achieving both good acceleration and good line tracing performance even on slippery road surfaces.

Elsewhere, technologies to design drive force characteristics that focus on everyday user friendliness, ease of driving, or other aspects of sensibility, rather than on areas of limit performance, are also under development. In another report, ease of driving was defined as vehicle behavior giving the sensation of longitudinal acceleration matching the driver's accelerator pedal operation, and that ease of driving was uniformly incorporated into drive force characteristics by setting indices for jerking, pedal reaction force and even acceleration sound in various driving scenarios, and identifying their proper values.

4 Directional Stability and Steering Responsiveness

Electric power steering (EPS) has become widely used due to the improved fuel efficiency and high degree of assist options freedom it provides. Most recently, EPS has also come to play an important role as an advanced driving support system, leading to demand for improved reliability. Consequently, redundancy in basic functions such as drive motors, control circuits, and torque sensors, as well as the digitization of sensor signals with excellent noise immunity, have been implemented. However, the phase delay introduced by digitization led to the problem of poorer steering response in EPS systems equipped with a digital torque sensor. A model incorporating digital latency was used to examine phase compensation as a solution to this problem. An approach seeking to achieve steering response without delay by combining phase compensation at frequencies below 10 Hz, where phase delay becomes apparent, with a compensator that dampens resonance around the 20 Hz frequency at which delay increases, has been reported.

The downsizing and improved reliability of EPS has led to reports of mass producing 4WS systems serving as rear-wheel steering actuators. The oldest examples of 4WS system adoption to improve maneuverability at low speeds and vehicle stability at high speeds date back to the 1980s. However, driver discomfort with reverse phase steering at low speeds has been a problem. According to one report, the feeling of discomfort at low speeds has been addressed by focusing on the target yaw rate transient response and the target steady gain of the body slip angle as control parameters, and clearly identifying the region that does not cause discomfort. Doing so resulted in proposing, a technique to achieve a natural steering feel by linearizing the relationship between the yaw rate and lateral acceleration. This, in turn, led to mass production after practical issues found during starts and stops, as well as in the small steering angle range, were overcome.

High expectations are placed on 4WS in terms of improving maneuverability in cases where the shift to EVs is making vehicles larger due, for example, to extending the wheelbase, as well as in achieving steer-by-wire advances in automated driving.

In a different vein, there have been initiatives to discuss whether a method to evaluate the energy transfer characteristics of a two-degree-of-freedom vibration system for yaw and roll motions based on the statistical energy analysis (SEA) method used in acoustics could be applied to steering response.

5 The Human-Vehicle-Environment System

Following the announcement of revisions to the *Road Traffic Act* and to attendant laws and regulations, which allow Level 4 automated driving and self-driving robots on public roads, various companies are conducting research and development ahead of that legislation coming into effect in 2023. The importance of the affinity between drivers and the vehicle systems in this field has led to numerous cases of research into the human-vehicle-environment system.

One investigation of human acceptance of various driving support systems used a driving simulator to look into the difference in the burden felt by drivers in a following vehicle engaged in heavy-duty vehicle platoon driving equivalent to Level 3 automated driving, and by drivers operating the vehicle manually. The fluctuation of the driver's pupil diameter was used to eliminate the influence of drowsiness during the test on the results. The sense of burden was evaluated based on the pupil diameter and the NASA Task Load Index (NASA-TLX), and the results demonstrated that drivers in a following vehicle engaged in platoon driving equivalent to Level 3 automated driving felt less burden than those driving manually.

A different study on acceptance for a communication-based driving support system to prevent collisions with cyclists reported the results of using a driving simulator to look into how differences in age group and support level affected driving behavior after receiving support in the context of a crossing collision at an unsignalized intersection, which is the most common type of accident involving the sudden appearance of a cyclist.

Research and development on the vehicle and environmental aspects of automated driving and driving support is also underway.

Realizing advanced active safety functions and automated driving requires accurate recognition of the road conditions surrounding the vehicle. It is also important to estimate whether the vehicle can proceed safely. Therefore, there is a strong emphasis on developing technologies that use on-board cameras and radar information as a basis for analyzing three-dimensional information from images and point groups to make decisions. In a deep learning-based estimation of the drivable range that used those images and point groups as input, weighting in feature quantity integration was used to analyze the degree of influence and role of the individual images and point groups. The results showed that the images were used more actively than the point groups to estimate range, while the point groups mainly served to distinguishing three dimensional objects or other features outside the range.

Infrastructure-related research is exhibiting a new trend of transmitting road friction information to vehicles for safer motion control and driving support. The premise that doing so requires a road friction database for general roads has led to a report on a proposed method of continuously measuring friction characteristics on general roads using a trailer that measures the friction coefficient at the target slip ratio. The measurement results obtained on actual roads were used to investigate change and velocity dependence based on dry and wet conditions, and it was found that there was no velocity dependence even on wet roads.

Efforts to quantify human-centered sensory characteristics such as driving pleasure and comfort have been made for many years. In terms of steering feel, EPS offers a high degree of freedom in the design of steering torque, and its integration is attracting attention in anticipation of the adoption of steer-by-wire systems. Steering feel sensitivity was evaluated based on a technique that makes a quantitative assessment using the physiological indices of heart rate for comfort/discomfort, and brain waves for alertness. Principal component analysis and other statistical methods were used to propose a technique to comprehensively evaluate the steering feel in the off-center region, and design guidelines tailored to preferences and other driver characteristics were presented.

6 Limit Performance

Initiatives to improve the dynamic performance near the tire limit by controlling the braking and drive forces of the four wheels have a long history. Direct yaw moment control, which generates a direct yaw moment from the difference in drive force by distributing and controlling the drive and braking forces to the right and left wheels, as well as approaches such as controlling the distribution of the drive force of the front and rear wheels, have been researched. Conventional methods to achieve this require a complex drive force distribution mechanism to distribute the power generated by the engine. The recent shift from internal combustion engines to electric motors has made it possible to realize drive force distribution control that relies on multiple motors to reduce the number of mechanical drive force distribution mechanisms in addition to applying control based on the high response and high torque characteristics of motors. The spread of ABS and ESC has also led to the concurrent use of braking force control at each wheel. The resulting increase in the number of dynamic performance control devices, and the coupling of the forces they generate with sprung motion, requires developing complex control. Research focusing on that need has presented a method that considers the design of vehicle integrated control systems from the standpoint of envisioning what forces should be generated to realize an ideal six degree-of-freedom motion. Using that control design method as a base, the research further demonstrated that dynamic performance can be improved by finding the optimal solution for brake output and independently controlling the planar and sprung motions, even in inexpensive individual wheel brake control.

Other research has presented a dynamic stability evaluation using a closed-loop that incorporates a driver model. The evaluation incorporates the tire cornering dynamic characteristics that represent the tire lateral force generation delay, and then performs a closed-loop calculation on a driver model defined by a forward gaze model that determines the steering angle according to the difference in angles between the intersection of the target circle and the traveling direction. Based on the root of the characteristic equation representing lane change transient characteristics on a straight traveling path, that calculation demonstrated that the lateral rigidity difference between the front and rear wheels, which benefits stability, is not dependent on factors such as vehicle speed or human parameters (predicted time and delay time).

7 Intelligent Controls

Reports presenting the results of high-precision stability control, ride comfort control, and vehicle dynamics control research and development undertaken from a new perspective have been released.

Focusing on the unease felt by the driver due to heave from jack up forces lifting the vehicle body in situations involving a strong cornering acceleration when a high rear roll center is set, one initiative involved developing control that uses the anti-lift force from the combination of suspension geometry and braking force controlled according to the difference in the speeds of the left and right wheels to suppress heave during strong acceleration cornering. The effectiveness of that control has been confirmed in actual vehicle evaluations.

Another study into active suspension control effective at improving ride comfort sought to realize a low-cost semi-active suspension that does not use sensors on all four wheels by applying machine learning to the data in a standard vehicle CAN, and forming a neural network that estimates the vertical sprung rate and piston speed of the four wheels.

Applying road surface preview control to actively control the suspension has also been reported to improve ride comfort. One road surface sensing proposal consists of a method that detects the position of speed bumps or other unevenness by calculating the height and distance of the road surface on the travel path of the vehicle from three-dimensional point groups formed using left and right images taken by a stereo camera, which has a lower cost than lidar.

A preview control method that uses the self-position estimation and a road surface information database rather than relying on road surface sensing by the vehicle, has also been proposed. That method seeks to solve preview control problems such as road surface estimation accuracy and phase deviations due to filtering by mapping self-position information and riding comfort sensor values collected beforehand and processed offline in the form of high-precision unsprung state quantity into the cloud, and then applying online active suspension control in combination with the high precision self-position estimation of the running vehicle. Examples of validating the effectiveness of that control in actual vehicles have been reported. One proposed method in the area of vehicle self-position technology involves a technique that estimates the reflected light component from the ratio of pixel values and the calculated illuminating light component to compensate for the brightness-induced loss of accuracy weak point of omnidirectional cameras. The method then combines the results with an RGB-D map to estimate self-position.