VEHICLE DYNAMICS

1 Introduction

As Japan enters its new era of Reiwa, the rapid advance of IT technology continues to make its outcomes and impact an integral part of society as a whole. In contrast, the appreciation of the yen and effect of the U.S.-China trade friction had repercussions on the Japanese economy, with the average Nikkei stock price falling below 20,000 yen in early 2019. These repercussions were exacerbated by the increase of the consumption tax to 10% in October of the same year. Amid this turmoil, the automotive industry is facing a wave of change, highlighted by technological innovations such as CASE and MaaS, which has been described as a once in a century transformation.

The field of vehicle dynamics has been the subject of longstanding research, which has been especially proactive in the areas of studying the basic vehicle characteristics that facilitate driver operations while cruising, and subjective driver evaluations. This is being complemented by a growing body of research on the autonomous driving (A) and electric vehicle (E) aspects of CASE. The government set the goal of commercializing full (level 4) autonomous driving on expressways by 2025 in the 2017 Public-Private ITS Initiatives/Roadmap, and automakers are striving to achieve conditional autonomous driving (level 3). Autonomous driving is seen as one of the promising solutions to the issue of accidents involving elderly drivers, which has reached a nationwide scope. In terms of vehicle dynamics, the control used in autonomous driving calls for easy-to-control aspects of vehicle performance such as responsiveness and stability.

The need to suppress CO_2 emissions in response to global efforts to preserve the environment is leading to a worldwide transition toward electric vehicles. In 2017, for example, France and the U.K. announced a policy to ban domestic sales of new internal combustion engine vehicles. China has announced a regulation making it mandatory for automakers to include a set proportion of new energy vehicles as part of their production or imports starting in 2019. In terms of vehicle dynamics, electric vehicles require securing the acceleration and deceleration dynamic characteristics due to the higher vehicle mass resulting from mounting a battery, and to the torque characteristics of the motors.

2 Tires

Vehicle motion is a physical phenomenon caused by the forces (lateral, longitudinal, and vertical forces) generated between the tires and road surface, as well as the hydrodynamic force generated by the air. The contribution of the forces generated by the tires is notably high. In addition, the conservation of energy and greater fuel efficiency make the reduction of tire rolling resistance a crucial issue. Research and development to balance that issue with vehicle dynamic performance is ongoing. This research includes a report on elucidating the mechanism of the running resistance caused by the camber angle and identifying the initial camber and toe angles that achieve a balance between equivalent cornering power and rolling resistance(1), as well as a report on deriving rolling resistance when cornering force is generated, taking the adhesion and slip zones into account, or based on energy dispersal if camber thrust is generated(2). Using a statistical tire model—a type of empirical model—to estimate rolling resistance has made the previously difficult prediction of rolling resistance when changing tire size possible. In the early stages of development, this enable a high precise study of performance trade-offs such as maneuverability and fuel efficiency(3).

Similarly, the balance between decreasing rolling resistance and wear performance must be considered, and analysis models have long been used to predict wear performance. A higher precision analysis model, which incorporates changes in the ground pressure distribution, belt deformation due to lateral force, belt torsion caused by self-aligning torque, the dynamic friction coefficient dependency on sliding rate, and a sliding model for composite loads involving brake power and lateral force to improve prediction accuracy, has been proposed(4). The tire pressure monitoring system (TPMS) function that estimates tire wear has also been added(5). In this system, an acceleration sensor is installed on the backside of the tire tread. It senses changes in tire vibration and relies on the principle that tire wear increases the spring constant of the tire rubber block, causing a higher natural frequency.

The delay in the generation of tire lateral force is an extremely important aspect of vehicle dynamics that is strongly impacted by the lateral rigidity of the tire. Conventional measurements were typically made in a stationary state with no tire rotation. In newer proposals, the total displacement and force on the contact surface during tire rotation is measured and tire lateral rigidity is calculated. These values are then applied to the design of tire patterns(6).

To improve performance with respect to noise, vibration and ride comfort, experimental statistical energy analysis (SEA), an analysis method still uncommon in this field, is being used to analyze vibration inputs from the road surface to the tires and evaluate the characteristics of differences in applied load between tires, differences in road surface profiles, and differences in tire size(7).

3 Braking and Driving Characteristics

In addition to the basic performance aspects of acceleration and deceleration, vehicle dynamics during braking and driving involves ABS, ESC, and other systems that improve vehicle maneuverability and stability at the road surface friction limit. Torque vectoring technology, which enhances maneuverability by actively controlling the driving force to all four wheels, is also the subject of intensive research. Going beyond past systems by covering not only vehicle behavior in the non-linear range of longitudinal and lateral motion between the tires and the road surface, but also ease of driving during normal cruising, the newly commercialized G-Vectoring Control technology controls the drive torque and coordinates it with steering operations.

Observations on the differences between the characteristics due to the front getting pulled and those due to the rear getting pushed in vehicle pitching behavior stemming from braking and driving force, which has a major impact on ride comfort and driver operations, has been published(8). Those observations demonstrated that drivers can feel the difference between the two types of characteristics and that driving is easier in the case of forward pitching resulting from the rear getting pushed. With respect to pitching behavior during acceleration and deceleration, or when driving on an uneven road surface, semi-active suspensions are effective at balancing stability and ride comfort, but achieving wider adoption in mass production vehicles requires reducing their cost. To that end, research on the viability of avoiding the use of dedicated semi-active suspension sensors and relying on vehicle state estimation (VSE) to extrapolate the dynamic state of the vehicle based only on CAN signals is underway(9).

4 Directional Stability and Steering Responsiveness

This field is the subject of extensive research on normal driving, focusing particular on ease of operation by the driver in straight-line cruising and the on center area when starting to steer away from straight-line cruising. Other topics include observing the relationship between subjective evaluation and the physical characteristics of the vehicle (e.g., dimensions, mass, moment of inertia, or suspension and tire characteristics), as well as the aforementioned coordination of braking and driving force and steering aimed at improving running performance. Basic research and observation for subjective evaluations relies on driving simulators and statistical analysis.

In terms of enhancing the sense of the steering wheel being on center, work that (a) used a 10-element Masing model to study the friction torque rise characteristics when the driver starts to turn the wheel and controlled the electric power steering current to refine the apparent steering friction torque characteristics to the desired rise(10), as well as (b) focused on steering force and, through evaluation by monitors using a simulator, made a comparison with hydraulic power steering characteristics and demonstrated that friction characteristics have a considerable impact(11).

Using a driving simulator, the steering force and yaw angular velocity discerned by drivers were identified, and the relationship between steering force necessary to trace the driving line accurately and the yaw angular velocity dead zone was quantified in the contest of determining the steering force and yaw characteristics that improve line traceability in the minute steering range frequently encountered in everyday driving by ordinary drivers. That research demonstrated that a weak steering force and narrow yaw rate dead zone generally led the vehicle to cut inward, while a strong steering force and small yaw angular velocity dead zone resulted in swerving outward(12).

In the past, evaluations of lane changing performance relied on subjective evaluations by test drivers. One attempt to extract quantitative evaluation scores focused on three driver model parameters (the prediction time τ_h, the steering gain relative to the deviation from the gaze point h, and time loss τ_L) and analyzed their respective contributions. The results notably indicated a positive correlation between the prediction time τ_h and the difference between the target arrival time and time loss τ_L, a strong negative correlation between the prediction time τ_h and steering gain h, and a strong correlation between steering responsiveness and time loss τ_L.

5 The Human-Vehicle-Environment System

The large number of serious accidents involving elderly drivers has become a social issue. Although the number of elderly people giving up their license is increasing, doing so in regional municipalities without a fully established public transport system can make everyday life unsustainable. Autonomous driving technologies are drawing attention as one of the solutions to that issue, as well as to distracted driving, drowsiness, or other forms of driver inattention, and are the subject of intensive research.

Methods of accurately measuring the behavior of the driven vehicle in autonomous driving include using yaw angular velocity, acceleration, and wheel speed sensors, as well as making calculations based on camera image information. One reported technique for high-precision prediction of the behavior of the driven vehicle involves mounting a high-speed stereo camera along the longitudinal axis of the vehicle and reducing the amount of computation to estimate the dense feature point motion constituting optical flow between frames within a short time(14).

The visual simultaneous localization and mapping (SLAM) method, which uses monocular cameras and internal sensors to determine location and map the surroundings at the same time, has been applied in autonomous driving. Visual SLAM makes use of data captured by cameras. However, that method by itself cannot determine location with sufficient precision, and the addition of an angular velocity sensor to the camera has been reported to raise the precision of localization(15).

Assigning a score to vehicle driving conditions and sending appropriate feedback to the driver is used to foster a shift in consciousness regarding traffic safety skills. Using a driving simulator, test subjects were asked to drive on everyday day roads, and positive or negative scores for safe driving behavior were instantly displayed in the center of the simulator screen. This was reported to foster higher awareness of safe driving among the drivers(16).

Research on systems for autonomous driving that learn individual styles during manual driving to offer individually-tailored autonomous driving include a study on modeling the timing for braking at intersections(17).

When a lane departure prevention warning system is active and the driver turns the steering wheel, the vehicle ends up having two drivers. The concept of driver and system cooperation is therefore critical. Strong control torque applied by the lane departure prevention warning system makes it easy for the driver to understand what the system is doing. There is an appropriate range of control torque enabling the driver to maintain control of the vehicle, and within that range, a higher setting has been reported to be preferable(18).

According to research on occupant comfort, mitigating physical behavior and perceived motion in occupants other than the driver is crucial to enhancing the comfort of those passengers. In that respect, the application of optimal control covering both occupants and the vehicle (inverse dynamic analysis) has successfully mitigated body posture changes and acceleration(19). Performance evaluations using a nonlinear autoregressive exogenous model (NARX), in which both sides of the human-vehicle system mutually affect one another, have also been carried out. The results indicated that high-frequency gain could be reduced while suppressing phase lag, clear demonstrating the possibility of improving stability and controllability(20).

Two examples of research related to the vehicle surroundings are presented below.

(1) Using data made public by the Institute for Traffic Accident Research and Data Analysis (ITARDA), trends in frontal collision, pedestrian, and motorcycle accidents

were identified and applied to accidents that occurred in Hiroshima to estimate the effectiveness of safe driving support vehicles at reducing damage to occupants. Lane departure is involved in approximately 80% of the cases analyzed. At the same time, a 10 to 16% drop in the number of accidents resulting in fatalities or serious injury was reported when collision damage mitigation brakes reduced the impact velocity by 10 km/h(21).

(2) Based on danger prediction knowledge obtained from near miss details recorded in a database of close calls, a danger anticipation model that predicts a safety cushion time has been built to anticipate sudden near-miss hazards such as pedestrians or bicycles unexpectedly coming out of a blind spot on the road. The model is proving useful in automatic brake control(22).

6 Limit Performance

For limit performance, securing rollover performance in vehicles with a high center of gravity such as tall wagons or SUVs. At the same time, vehicle controllability must be satisfied for spinning, plowing or other course deviations, particularly on slippery road surfaces. The height of the center of gravity, tread size and other vehicle dimensions, tire cornering characteristics (especially maximum cornering force), and the vehicle understeering characteristics have a major impact on rollover characteristics. Similarly, the vehicle understeering characteristics and tire cornering force characteristics strongly affect course tracking performance. The torque distribution to each wheel (torque vectoring) also makes a significant contribution. The ongoing adoption of vehicle dynamics control systems such as AEB and ESC has helped achieve considerable improvements in limit performance. Vehicles with in-wheel motors achieve highly precise control of brake and driving torque for each individual wheel, and could lead to a new form of dynamic control different from that seen in conventional internal combustion engine vehicles. However, it will be necessary to achieve balance with tire wear performance.

Yaw moment control provides effective control of vehicle dynamics, but the behavior of the vehicle can become unstable if it is subjected to a large yaw moment. Optimizing the control yaw moment amount applied to the vehicle based on the intensity of the lateral acceleration it is subject to has been shown to provide effective control of vehicle behavior (spinning, plowing) at the limit of that lateral acceleration(23).

7 Intelligent Controls

Trends in research on control systems for autonomous driving have been presented in the preceding section. This section will therefore focus on advanced control systems involving aspects of vehicle dynamics such as ride comfort.

Skyhook control has traditionally been proposed to achieve high levels of ride comfort. An extended triple skyhook damping, which avoids the addition of sensors and reduces sprung mass acceleration over a broad range of frequencies using a simple control principle has been applied to semi-active suspensions and confirmed to be effective(24).

In electric vehicles, vehicles with on-board motors exhibit resonance in the direction of rotation due to components such as the driveshaft, while vehicles with in-wheel motors present the benefit of low-frequency resonance over a substantially broad range. A controller that mitigates longitudinal acceleration based on an accurate control model derived from frequency characteristics was proposed to suppress the vibration from spring resonance in the secondary band (10 Hz and higher), and tests in actual vehicles confirmed its effectiveness(25).

Three examples of intelligent control involving recognition of the surroundings are introduced below.

(1) To avoid accidents in situations where it is difficult for the driver to react, such as the sudden appearance of a pedestrian, a driver model that simulates the driving behavior of a veteran driver and anticipates driving conditions a few seconds ahead was built and used to develop a lookahead braking system that slows down to an appropriate speed ahead of time(26).

(2) High-precision technology using millimeter wave radar was built for autonomous driving adapted to all weather conditions. It demonstrates the efficiency of long short term memory (LSTM), which is capable of handling time series data. Experiments showed that using a reflection intensity map and bidirectional LSTM rather than the usual time sequence increased recognition accuracy(27).

(3) Autonomous driving and platoon driving studies are underway as part of efforts to conserve energy and reduce the burden on drivers in the logistics industry. Platoon driving systems involve control that provides feedback on the differences in following distance and speed relative to the vehicle ahead, and cause the follow-

ing vehicle to speed up or slow down slightly to match the preceding vehicle. This can lead to poorer fuel efficiency. A dynamic simulation was used to simulate this phenomenon and determine a control coefficient that meets the target performance(28).