1. A trustworthy partner

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1. Development of ProPILOT 2.0

After ProPILOT 2.0 (hereinafter referred to as “PP2.0”) was introduced to the market, journalists described it as “safe” and “comfortable” and also used terms such as “buddy” or “partner,” thus suggesting a new person-to-vehicle relationship. With the help of a researcher in psycho-informatics, the reasons for these responses were re-evaluated and three key points were identified:

1. Release from vigilance.
2. Control initiative and understanding others.
3. Skilled driving.

These key aspects indicate that the following development targets (as stated for the development of PP2.0) have been realized:

- The system is capable of automatic driving on highways in a “safe,” “secure,” “convenient,” and “comfortable” manner under certain speed conditions.
- The vehicle motion provides an “in-control” and “relaxed” driving experience to both the driver and the passengers.
- The vehicle exhibits natural traffic behaviors.

Our vision of “autonomous driving” is a “door-to-door” function. The ultimate objective is to transport individuals to nearly any destination that they have set. PP2.0 has now achieved this objective with the current technology.

The function realized by PP2.0 is “point-to-point” (hereinafter, “P2P”), a function that provides diverse assistance to drivers on highways, ranging from route planning to driving operation, when the destination is set in the navigation system. The technical aspects are lane keeping, lane changing, and following distance and vehicle speed control in traffic. In addition to the developments in each of these aspects, navigated route driving has been investigated, which involves route planning at the lane level considering junctions and exits.

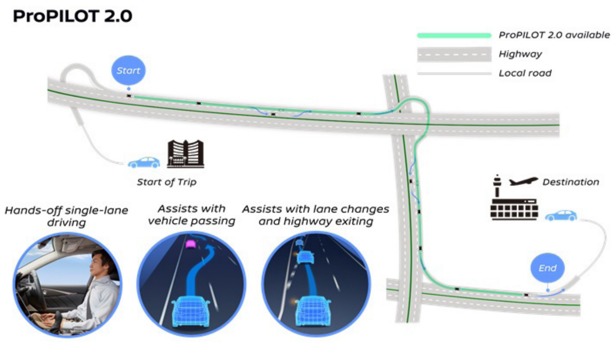

Fig. 1 ProPILOT 2.0 (P2P)

First, the crucial technology for realizing a P2P system is a 3D high-definition map (hereinafter, “3D HD map”), which contains more road surface data (such as the number of lanes, slope angles, and cants) than a standard map. These information data points are used in the driving system, and the P2P function is realized.

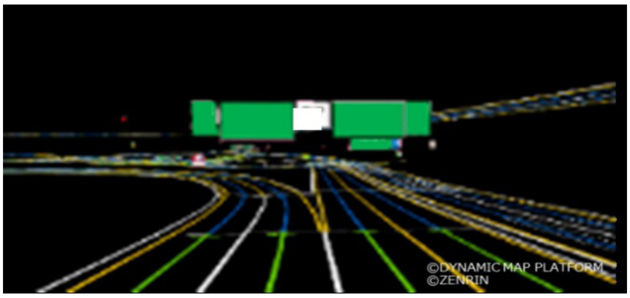

Fig. 2 3D HD map

Second, the development factors of PP2.0 include the key terms “reassurance” and “comfort.” Reassurance is fundamentally supported by dynamic performance (hereinafter, “DP”) technology, which is represented as fluent vehicle control, and it has been developed by Nissan Motors over many years. Expressed otherwise, in most road environments, the driver can control the vehicle at any time.

It is also important to clearly inform the driver about the current system conditions. A human–machine interface (HMI) enables the driver to understand how the system is recognizing and judging the surroundings, thus enhancing the trust of the driver. Therefore, a new interactive HMI was developed.

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Fig. 3 Intelligent interface

The other key term, comfort, is established based on the aforementioned reassurance. Vehicle behaviors that enable the driver to feel ease were identified through extensive DP/human research. Furthermore, comfort was improved by combining the P2P function with a "hands-off" (hereinafter, "H/O") function to reduce driving operation; consequently, the system reduces fatigue.

2. PP2.0 development target

The development concepts of PP2.0 were to "pursue values that customers can use" and to avoid "hard-selling the technology." The objective was to "provide new value with safe, reassured, convenient, and comfortable driving on the highway."

Based on DP/human research, which involves fundamental technologies, and the three key technological items of vehicle control, HMI, and safety design, reassurance and comfort were achieved by using the two characteristic functions of PP2.0 (i.e., P2P and H/O) in order to create new objective values. For the measurement of these values, the index of fatigue reduction (fatigue degree) was set, and the corresponding system was developed (Fig. 4).

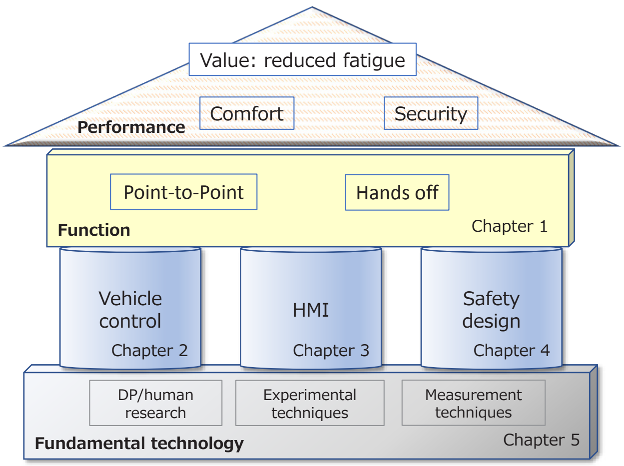

Fig. 4 System target and function hierarchy

To organize the relationships between physiological factors and the vehicle functions, the categories of physical and nervous fatigue reduction were defined as follows:

- Physical fatigue reduction: reduction of driving operations through the functions of H/O driving and automated lane changing.
- Nervous fatigue reduction: fluent behaviors (vehicle control) and timely provision of information regarding the surrounding conditions (HMI).

Even with the H/O driving and automated lane-change functions, fatigue can occur due to unsmooth vehicle motion or interference with the moving vehicle. Physical fatigue can be decreased by reducing nervous fatigue. By solving these issues, weariless driving can be provided, thereby ensuring reassurance and comfort.

3. Psychology of fatigue reduction

PP2.0, which was developed as described above, was assessed by test drivers from Nissan and also journalists. Moreover, as stated initially, to understand the impressions formed by individuals without automobile-related occupations, Prof. Takatsune Kumada (Laboratory of Psycho-informatics, Department of Intelligence Science and Technology, Graduate School of Informatics, Kyoto University) performed two test drives of PP2.0 on a suburban highway in Kyoto City (in November 2019 and October 2020). He provided feedback from the perspective of psycho-informatics. His opinions were as follows:

- It was a short test drive, and the stress and fatigue induced by driving were low.
- Little anxiousness and irritation were experienced when following a slower vehicle.
- A new person-to-vehicle relationship was anticipated.

These opinions and the corresponding hypotheses are discussed below.

<u>State of vigilance</u>

In a vehicle not equipped with PP2.0, deceleration in accordance with the surrounding traffic induces fatigue. Advanced research*1) explains this phenomenon as a state of vigilance, in which a continuous anticipatory attitude is retained toward infrequent, uncertain, and low-likelihood phenomena, such as collisions. In a 1956 U.K. symposium, vigilance was defined as "a state in which certain small changes generated at random intervals in an external environment can be detected and handled at all times"*2). Notable research on vigilance includes the famous studies conducted by Mackworth on radar monitoring. The PP2.0 test-drive response suggests that the partial release from vigilance leads to a more appropriate state for monitoring the surroundings, as compared to that when PP2.0 is not operating, which reduces the fatigue experienced.

<u>Control initiative and understanding of others</u>

It is generally considered that the loss of control initiative impressions can cause stress; however, PP2.0 achieves a suitable balance between control initiative and role assignment. Control initiative refers to the perception of driving a car by oneself. In other words, the objective of the driver (i.e., reaching the destination safely) is shared by the car, and the driver assists the car in achieving this objective. During this assignment, the car informs the driver (via the HMI) about what it recognizes and its control operations. In addition, the overall operational control belongs to the human because the car requests control permission from the driver. Consequently, the car acts as a partner to achieve the objective through joint efforts. By releasing the steering wheel when assigning the car to drive, the driver recognizes the role transfer clearly and independently.

This new human-to-car relationship can be interpreted as a development from the stage in which the human and the car recognize the same entities to a stage in which the controls assigned to the car are shared through communication (of shared intentions and targets) to generate a sense of security. A mechanism similar to the psychological concept of “understanding others”*3) may explain this phenomenon.

Skilled driving

Furthermore, after being commissioned to help reach the destination safely, the car also realizes comfortable driving. Car behaviors such as lateral movements and acceleration timing for overtaking are within the expectations of the driver and cause no unnecessary stress. Furthermore, during route-following, which is the lane-keeping driving mode, the driver feels as though the vehicle follows an endless stable line at the center of the lane, which creates a secure feeling and comfort. Such stability increases the trust of the driver in the car and appears to be one of the reasons for fatigue reduction.

It is assumed that these factors invoke moderate levels of trust in the car, creating a secure feeling and comfort during driving and also reducing stress and fatigue. However, the short test drive (~10 min in this case) did not lead to a human-to-car trust relationship. The psychological responses in the market may become apparent only after PP2.0-equipped vehicles are commercially available for use on public roads. Nevertheless, this is an interesting psychological research theme.


Fig. 5 Prof. Kumada (Kyoto University) and SKYLINE test-drive model

As described above, the development targets appear to have been achieved from a psychological perspective. In the future, continued research into “new human-to-car relationships” will be performed.

4. Summary

The current PP2.0 offers confident and feasible P2P and H/O functions. These have been designed through the multilateral combination of numerous world-first vehicle-control technologies, such as HMIs and safety design technologies. This was achieved through numerous foundational elements, such as DP/human research and experimental/measurement techniques, that required an extensive period for accumulation. We are proud of our ability to deliver the vision and consistent technological developments required for this endeavor.

Consequently, secure, comfortable, and fatigue-reducing performance could be achieved. This new human-to-car relationship has also been suggested from a psychological perspective, albeit further research is required.

This paper describes in detail the technologies required to realize PP2.0.

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Special Feature 1 : Future-oriented ProPILOT 2.0

2. New functions

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1. Introduction

ProPILOT 2.0 (hereinafter referred to as “PP2.0”) has substantially evolved from the first-generation ProPILOT to create the world’s first driving-assistance system that can guide a vehicle through a multi-lane highway, working in tandem with the navigation-system-planned route. PP2.0 can operate in hands off mode, provided the driver consistently monitors the objects and events and responds immediately to operate the steering wheel in response to the road, traffic and vehicle conditions. This chapter describes the new functions of ProPILOT 2.0.

2. New functions of ProPILOT 2.0

2.1 ProPILOT 2.0 summary

PP2.0 offers a point-to-point function allowing navigation linked driving such as merging on to a highway when destination is set in the navigation system. When the navigation linked driving is initiated, system supports driving through interchanges and assists overtaking another vehicle until reaching the relevant exit. Provided that the driver always attends to the road ahead and can operate the steering wheel with certainty and immediately in response to the road, traffic, and vehicle conditions, the system operates with hands off with in the same lane and provides wide range driving maneuver support to the driver. In addition, using the navigation data and information of the surroundings from a 360° degrees sensing, the system determines an appropriate lane-change starting point for branching or overtaking whilst following the planned route, and proposes the relevant actions to the driver. Lane-change assistance is initiated by the driver when both hands are placed on the steering wheel and the switch to approve the proposal is operated. Fig.1 illustrates the PP2.0’s operation.

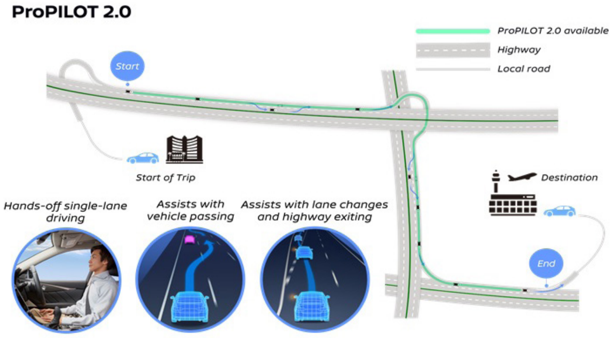

Fig.1 ProPILOT 2.0

PP2.0 integrates and uses seven cameras, five radars, 12 vehicle-mounted sonars, a global navigation satellite system, and 3D High-Definition map (hereinafter, “3D HD map”) data to collect information from the surroundings (i.e., not only from the front but also the right, left, and rear of the vehicle) and determines the correct position on the road. The 3D HD map data include information detailing the road structure, the number of lanes, and the positions of merging points, branching points, and intersections. These information allow system control that foresee the road structure ahead and realize smooth driving as that of an experienced driver. In addition, the vehicle is equipped with a driver-monitoring camera that continuously monitors the driver’s forward gaze.

The PP2.0 sensor-mounting configuration, a 360° sensing image diagram, and a 3D HD map data are illustrated in Fig.2, Fig.3, and Fig.4, respectively.

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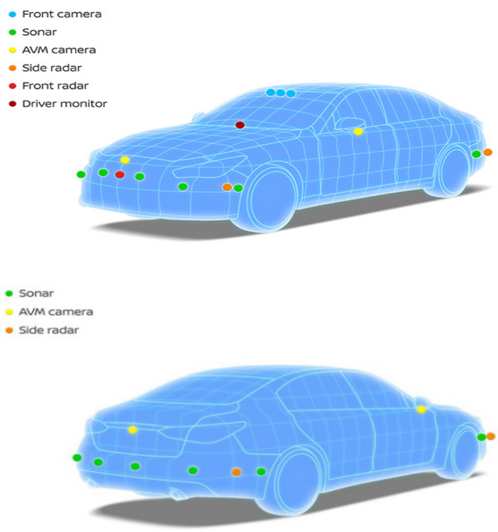

Fig.2 ProPILOT 2.0 sensor configuration

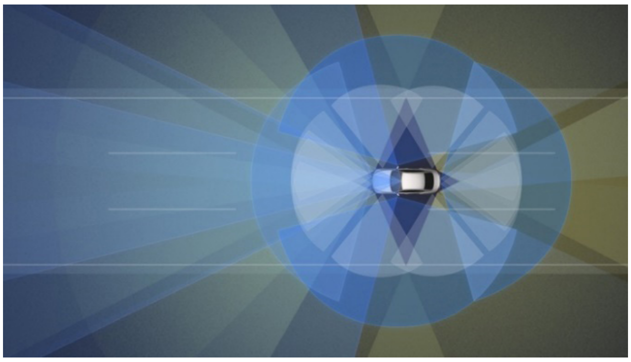

Fig.3 ProPILOT 2.0 360° sensing diagram

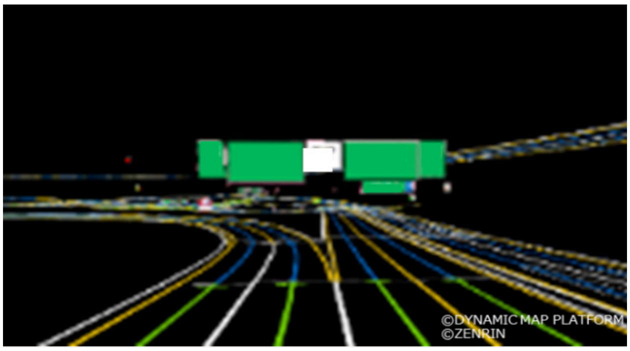

Fig.4 3D High-Definition map

2.2 Vehicle-speed/inter-vehicle-distance control functions

The system controls the vehicle speed to maintain the speed preset by the driver. Upon detecting a preceding vehicle, the system controls the headway distance so as to maintain a suitable distance to the vehicle ahead according to the host vehicle speed set by the driver as the upper limit. If the vehicle ahead stops, the PP2.0 vehicle is able to stop as well behind it. After the stop, stop/following driving can resume with respect to the vehicle ahead within 30 s.

If a curve is detected on the road ahead, deceleration control is performed to adjust vehicle's speed according to the magnitude of the curvature.

If the traffic sign recognition system detects a speed sign, the vehicle's speed is limited to the value detected.

2.3 Lane-keeping function

The system assists the driver with steering operations by controlling the steering so that the vehicle travels near the center of its lane. Drivers should remove their hands from the steering wheel as long as they are always attentive to the road ahead and are prepared to operate the steering wheel with certainty and immediately in response to road, traffic, and vehicle conditions.

2.4 Route-following assistance function

If a destination has been set in the navigation system, lane changing is proposed to the driver when such maneuvers become necessary to continue to follow the route (e.g., exiting/branching) or when lane-reduction point is reached. When the driver places both hands on to the steering wheel and presses the lane-change assistance switch (located on the steering wheel), the turn signal of the lane change direction begins to flash, and the steering wheel is controlled to assist the lane-change operation. If multiple lane changes are necessary to reach the target lane, sequential lane-change assistance is possible.

2.4.1 Lane-change assistance function

When the driver has both hands on the steering wheel and operates the appropriate turn signal device, the system controls the steering to assist the driver in executing the steering wheel operations required for a lane change.

2.4.2 Overtaking-assistance function

If a vehicle slower than the driver-set speed is detected ahead, overtaking is proposed to the driver. When the driver has both hands of the steering wheel and presses the lane-change-assistance switch located thereupon, the turn signal towards the overtaking lane is illuminated; then, the steering wheel is controlled to assist the lane-change operation. After passing the vehicle, the system proposes returning to the initial lane to the driver. If the driver presses the lane-change-assistance switch, the turn signal is illuminated towards the initial lane and the system controls the steering to assist the driver in executing the lane-change operation.

The next chapter describes the application of the 3D HD map data required for the lane-change-, overtaking-, and route-following-assistance functions.

3. Application of 3D High-Definition map data to lane-change assistance

This chapter explains the judgment process used to determine the feasibility of lane changes and the lane-level driving plan; for this, an example of the 3D HD map data used for the lane-change assistance function is given.

3.1 Judgment of lane-change feasibility

Acquiring information pertaining to the lanes ahead is one challenge in realizing lane-change assistance. At the start of the lane change, the camera may not be able to collect comprehensive lane information for the point where the lane change ends. Accordingly, if information is only received from the camera, the appearance of a dividing line forbidding lane changes during the lane change (or other operations) may prevent the lane change. Meanwhile, because the 3D HD map data include lane-level data (e.g., curvatures and dividing lines), the acquisition of road shapes beyond the camera's detection range allows lane-change opportunities to be judged by considering the section of any lane between the start and end points.

3.2 Lane-level driving plan

The lane-change-assistance function proposes lane changes at an appropriate timing (as determined by the system), to allow the vehicle to follow the route recommended by the overtaking-assistance function or navigation system. This judgment is realized through the use of a route plan generated by the system from the lane-level information included in the 3D HD map data. This route plan refers to the indication of the lanes in which the vehicle should remain for certain sections, as well as proposal for guiding the vehicle in to the proper lane.

Fig.5 illustrates the process of generating a lane-level route plan. First, for exit branching on an expressway, the system calculates the number of lane changes required to follow the route recommended by the navigation-system, as well as the distance along the route to the branching point; the results are used to select a lane.

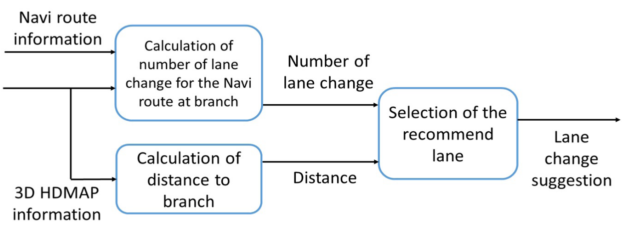

Fig.5 Process of generating lane-level route plan

Next section explains the process of lane-level route planning through an example. Fig.6 schematically shows the road configuration near a highway branching point. Consider that the route recommended by the navigation system extends to the exit (Point P). If the vehicles in the rightmost lane of the through traffic lanes as the exit approaches, the system recommends changing lanes toward the left until the vehicle is in the lane A, The system does not recommend moving to lane B because doing so will would increase the number of lane changes needed to exit from point P. If the vehicle is initially traveling in lane B, the system recommends changing lanes to the right and guides the vehicle into lane A. Regardless of the vehicle's starting lane, system recommends changing lanes so that the vehicle is ultimately guided in to lane A.

Furthermore, having a lane-level route plan allows proposals such as overtaking another vehicle ahead to be made at an appropriate time. For example, if the route to be followed specifies taking a branch road to the left and also that the distance to the branching point is close. In this case, the system judges that a proposal to pass the preceding vehicle is not given.

As described above, the lane-level route plan (based on 3D HD map data) enables the system to know in which lane the vehicle should travel and lane-changes to be proposed at appropriate timing.

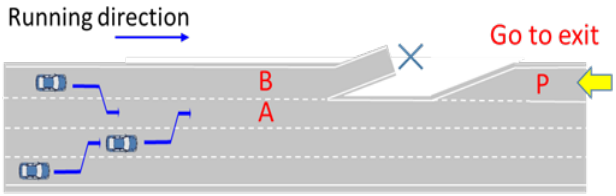

Fig.6 Schematic road layout near expressway branching point

4. Off-board linkage function

The PP2.0 system offers an off-board linkage function via a constant telematics communication channel to the server, to perform functions such as 3D HD map-data updating.

The off-board linkage function consists of a vehicle-side storage for the 3D HD map, a 3D HD map electronic control unit (ECU) for outputting the map data, a telematics control unit for communication, and a server for storing and distributing the most recent map data.

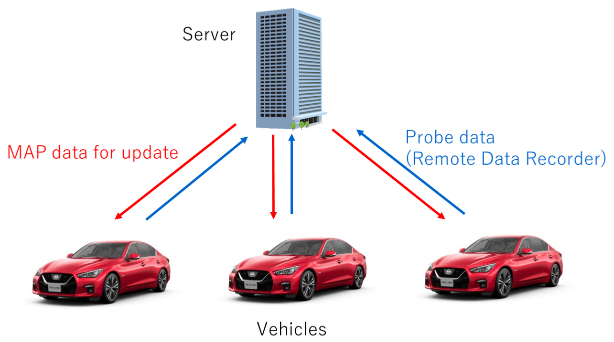

Fig.7 Off-board linkage-system arrangement.

The 3D HD map data are updated several times a year in order to timely capture the latest map data corresponding to the actual road shapes which can alter through the course of the year due to construction or other processes.

The 3D HD map ECU compares the latest server-held map data and the data in the ECU for each operation. If it detects any map data update, the most recent map data is downloaded from the server to update the ECU's map data, starting with locations nearest to the vehicle as higher priority. This ensures the latest available 3D HD map data to be always used for the driving assistance.

5. Summary

The development of this system has led to the commercialization of the world's first driving-assistance system that can guide a vehicle through a multi-lane highway working in tandem with the navigation system-planned route and provided the driver consistently attends to the road ahead and can operate the steering wheel with certainty and immediately in response to the road, traffic and vehicle conditions, the system can operate in hands off mode. As a result, more secure, comfortable, and stress-free driving experiences are available to customers.

In future, we hope to deploy this technology in regions outside Japan, to apply it to greater number of vehicles, and to pursue technological advancements to support driving operations across a wider range of scenarios thereby realizing a safer traffic society and offering new values to automobiles.

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3. Supported by vehicle-control technologies

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1. Introduction

Nissan has taken the lead in technological innovations for driver assistance technology as a pioneer in driver assistance technology this field for more than 20 years, developing many world's first technologies[1)-8)]. In 2016, put into practical use the ProPILOT (hereinafter referred to as "PP1.0"), which is an integrated driver-assistance technology in single-lane highway driving.[9)]Then, in 2019, Developed ProPILOT 2.0 (hereinafter, "PP2.0") which was substantially evolved PP1.0 technology.; it operates in tandem with the navigation system and can follow a predefined route (hereinafter, "navigated route-driving") on multiple-lane highways.

The vehicle-control technologies that realize ProPILOT have been based on the control technologies thus far accumulated through the development of various driver assistance systems.

Vehicle speed/vehicle distance control technologies are based on intelligent cruise control (ICC), which was released in 1999. Steering control and lane-keeping control technologies have developed from the lane keep support (LKS) system released in 2001.

This chapter describes the primary controls of vehicle-control technologies, which are essential to realizing the "reassurance" and "comfort" of PP2.0.

1.1 History of control development in driver assistance systems

Nissan's first driver assistance system was the ICC, applied to the CIMA in 1999. Fig.1 shows the driver assistance systems that Nissan has introduced to the market.

The ICC system is based on the vehicle speed control with a traction control, which controls the vehicle speed to a set speed; and constructed the vehicle distance control on top, which is controlled same as driver operation.

These control technologies (traction control/vehicle speed control/vehicle distance control) have also been applied to realize Distance-Control Assist and Forward Emergency Braking.

Furthermore, LKS has realized the steering controls based on vehicle motion characteristics, and the line trace control to the center of lane which was recognized by camera.

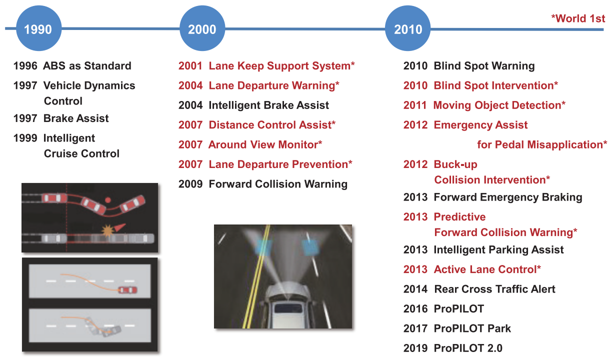

Fig.1 History of driver assistance system development

These control technologies have been evolution with the times and applied as base control technologies in PP1.0 and PP2.0.

2. Features of control systems

2.1 Vehicle speed control

In Nissan, the vehicle speed control development has a long history, started from early 1990s', when a control law (which combined robust and model-matching controls) was designed for the cruise control. (Fig.2)

Robust compensator is compensate a control performance to the ever-changing the plant, estimating changes in running conditions (e.g., vehicle characteristics and road gradients) and adjust the control inputs. Model-matching compensator sets the reference model of desired response characteristics, controls the plant which was compensated by the robust compensator. At this time, calculates control inputs as same behavior of reference model. (Model-matching control).

Constructing the control system in this way, realized vehicle-speed controller of high robustness for changes in running conditions (e.g., vehicle weight variations and road gradients). [10)]

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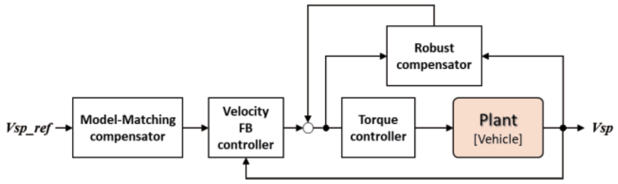

Fig.2 Vehicle speed control block diagram

2.2.Vehicle distance control

The vehicle distance controller used in ICC and PP1.0/PP2.0 was designed setting two design indexes, identified from analysis of human driving operations:

1) Should be able to set the trajectory after started of vehicle distance control
2) Should be stable control performance during vehicle distance control

To meet these requirements, a "two-degrees-of-freedom control based on a reference model" was used; in this, response characteristics and following stabilities can be designed independently. (Fig.3)

The plant should be written by the transfer function for easy to use. Therefore, the vehicle distance controller was built at class structure; using the compensated vehicle speed controller, not control vehicle distance directly. Herewith response characteristic of vehicle distance control is compensated the feed-forward compensator which was designed at the reverse characteristic of the vehicle speed controller. And the tracking performance which is keeping vehicle distance was designed the feed-back control by using pole assignment method. [11]

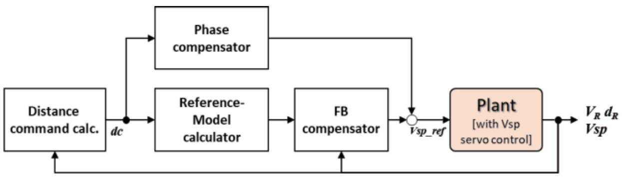

Fig.3 Vehicle distance control block diagram

Farther, natural behaviors not perceived by the driver to be strange, behaviors for controlling traffic congestion were required by the spread of ICC. An important aspect to achieve this is ensuring that the inter-vehicle-distance control characteristics do not cause changes in the speed of the forward vehicle to be amplified and transmitted to the behind vehicles, this prevents traffic-flow disturbances / unevenness and improves road transport efficiency. Expressed otherwise, vehicle group stability should be stabled. In general, to achieve vehicle group stability, the response of vehicle speed must be faster than the change of speed in the forward vehicle; however, it becomes a high gain control, and get worse in the ride quality during follow to the forward vehicle. Therefore, it was improved the vehicle distance controller to balance of vehicle group stability and ride quality in high level, and control response will be felt natural to the driver. [12] (Fig.4).

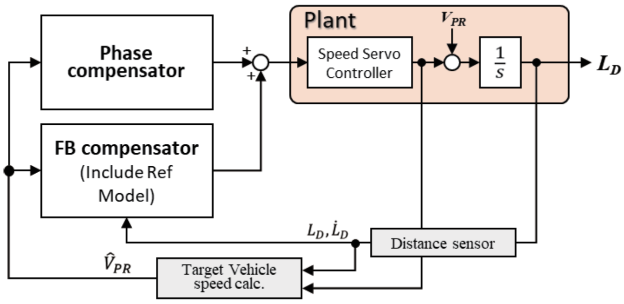

Fig.4 Vehicle distance control block diagram considering vehicle group stability

2.3 Lane-keeping control

The lane-keeping controls of PP1.0/PP2.0 are based on the LKS system first commercialized in 2001. The control performances required for LKS is improve and maintain line trace performance and disturbance stability. For control to the vehicle lateral motion, the controller was designed with a state feedback control based on the vehicle model; This controller has the observer which was designed Kalman filter, and using LQ control to meet the required control performance.

In addition, to improve the control performance on curve, controller was added the feedforward compensator which was used a curvature. [13][14] (Fig.5).

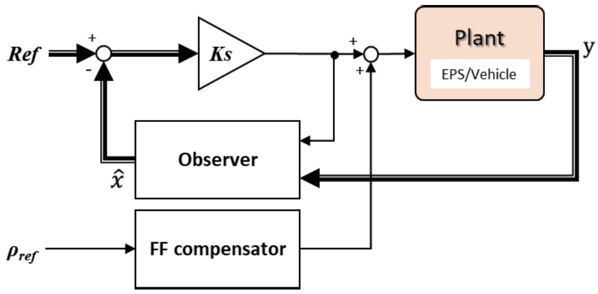

Fig.5 Lane-keeping-control block diagram

3. Steering control of ProPILOT 2.0

The steering control of PP2.0 is based on the aforementioned lane-keeping control; using information from camera and 3D High-Definition map (hereinafter, "3D HD map"), calculate a target steering angle for lane-keeping and assistance of lane-change.

3.1 Control-system configuration

Fig.6 is a block diagram of the steering control function incorporated in PP2.0. With this control configuration, real-time lane configuration information detected with the cameras is compared with 3D HD map data to enhance the reliability of the information. When it is difficult to secure 3D lane configuration information with the cameras, it is obtained from a 3D HD map to enable accurate calculation of the steering angle needed for the vehicle to travel in the center of its lane.

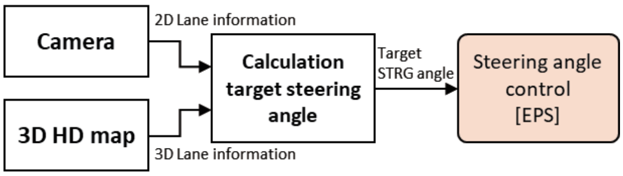

Fig.6 Block diagram of lane-centering control

To verify the steering control capability of PP2.0, tests were conducted on a Nissan proving ground test course to compare the performance of the system with that of a skilled test driver.

3.2 Test overview, and test results

Lane centering tests were conducted on a test course with a series of consecutive curves having a radius of 500 to 1000 m (500-1000 R). Data were measured and compared for a case with PP2.0's lane centering control and a case where the skilled test driver drove the vehicle without any lane centering control. The test driver was instructed to drive in the center of the lane as much as possible.

Fig.7 shows the lateral position from the lane center obtained with PP2.0's lane centering control and for the skilled test driver. Fig.8 shows the steering angle results. Fig.7 shows that the results indicate that the lateral position from the lane center was smaller with the control than for the skilled test driver, thereby confirming the high lane centering capability of PP2.0. Fig.8 shows that at the entrance and exit of curves where the steering angle changes, the data show that lane centering control smoothly controlled the steering angle without any overshoot just like the skilled test driver. In addition, on curves where the steering angle was nearly steady for approximately 50-150 s, lane centering control kept the steering angle change smaller than that seen for the skilled test driver.

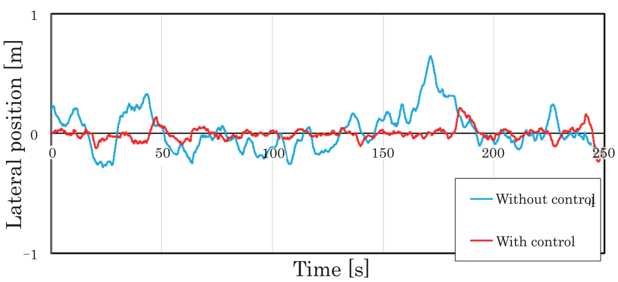

Fig.7 Lane-centering comparison results

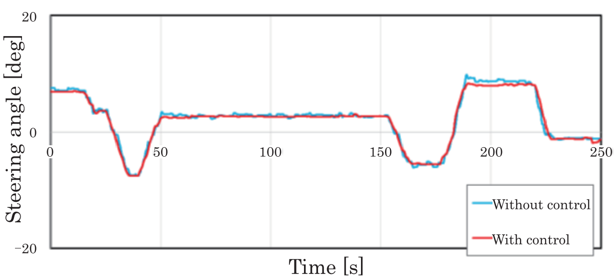

Fig.8 Steering-angle comparison results

From the results, it can be confirmed to enable PP2.0 to provide smooth steering angle control equal to or better than that of a skilled test driver.

4. Steer-by-wire technology to support steering control

The Nissan SKYLINE is adopt the direct adaptive steering (DAS) as a steering system. DAS is a by-wire system in which the mechanical connections between the steering wheel and tires are replaced with electric signals; both components can thus be independently controlled by disengaging the clutch in the steering shaft. The contribution of DAS to PP2.0 is presented here.

4.1 Compatibility of smooth steering-wheel motion and accurate line tracing

The steering control in PP2.0 precisely controls the tire angles, to thereby control the vehicle's lateral motion to a high degree of accuracy. However, the steering wheel motion is also an important factor. Smooth steering-wheel motion increases the system's sense of security. DAS adopts a disconnected steering wheel and tires to execute the control, as described below in terms of the compatibility of these two performance items.

The PP2.0 steering control is summarized in Fig.9. First, a tire-angle command (to perform line tracing) is generated by PP2.0; this command includes a component to determine the vehicle's rough motion and trajectory and a component to fine-tune trajectory shifts generated by road conditions and/or external forces from the road surface. From the PP2.0's tire-angle command, the DAS extracts components that determine the vehicle's rough motion and trajectory, to generate a steering-wheel-angle command for the steering wheel to follow. The steering-wheel motion is converted into a tire-angle command via an operation similar to that used for the driver's steering; this controls the vehicle's motion.

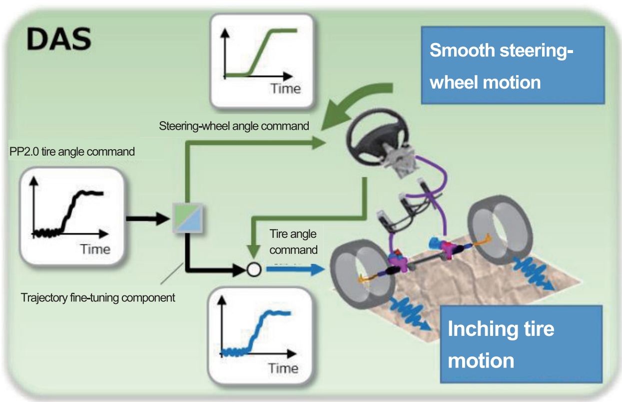

Fig.9 Summary of steering control during ProPILOT 2.0 operation

The structure of the DAS means that the vehicle can move exclusively via tire-angle control, without the steering wheel being turned at all; however, steering-wheel motion is effective in informing the driver of the vehicle's motion. By removing the inching motion that accompanies fine-tuning and considering only the rough-motion component of the steering-wheel-angle command, the steering wheel can be made to move stably and smoothly; thus, the vehicle's motion can be displayed more clearly to the driver. Several residual components of the tire-angle command are not included in the steering-wheel one; however, these are still directly adopted in the tire-angle control. This allows the tire angle to be controlled according to the full tire-angle command of PP2.0, to achieve accurate line tracing.

Fig.10 depicts an example of the steering-wheel (green) and tire (blue) angles during PP2.0 operation. The steering-wheel angle exhibits a stable, smooth motion, in which only the vehicle's rough motion is expressed. Meanwhile, the tire angles exhibit a continual inching motion, owing to the combination of rough motions and fine-tuning.

Thus, the mutual independence of the steering-wheel and tire controls renders compatible the smooth steering-wheel-angle motions and accurate line-tracing function.

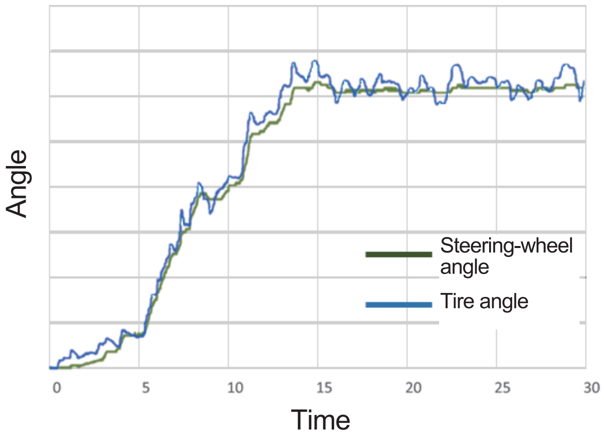

Fig.10 Comparison between steering-wheel and tire angle responses

4.2 Contributions to ease of steering override

Steering override, in which the driver corrects the vehicle's motion, can be executed during PP2.0 operation; for example, the override can be used to avoid fallen objects or to keep distance from vehicles traveling alongside by moving away from the lane center. The line-tracing control force continually acts upon the steering wheel during PP2.0 operation, and the driver must apply steering to override it. Therefore, steering input features allowing the driver to easily override the operating PP2.0 are important.

To this end, existing steering systems generally adopt an electric motor or hydraulic system to generate control forces and overcome external forces from the road surface or system friction. However, in DAS, the steering wheel and tires are disconnected; hence, the external force from the road surface is not transmitted to the steering wheel. Therefore, the flexibility of steering force design and ease of establishing target characteristics represent advantages of PP2.0.

Here, the steering inputs during PP2.0 operation are explained according to the schematic in Fig.12, where we take right-hand turning as an example. The dotted-blue line and red line indicate the steering input characteristics of a human driver (PP2.0 functions inactive) and PP2.0, respectively. To maintain the turning motion, the steering wheel must follow a steering-wheel-angle command. In DAS, the driver's steering input characteristics are offset, to make the steering force produced by a steering-wheel command as zero. This allows the driver to override the system with their own steering input when steering from a straight-line into a turn; this reduces the driver's burden.

Furthermore, when switching the PP2.0's operations off (i.e., when the driver's steering replaces it completely), the offset for a steering input of zero is gradually decreased, to ensure a smooth transition and a natural steering operation for the driver.

Thus, the DAS system's feature (i.e., the independent controllability of the steering wheel and tires) is utilized to improve PP2.0's performance.

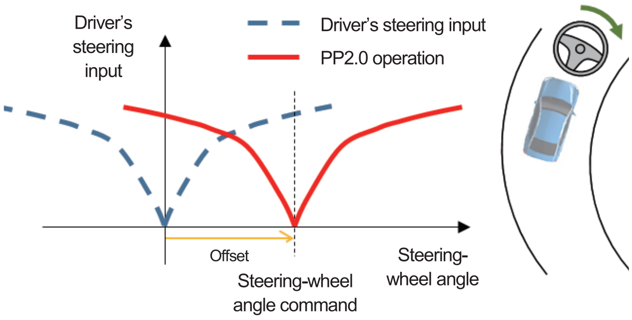

Fig.12 Steering input characteristics during ProPILOT 2.0 operation

5. Conclusion

Nissan has taken the lead in technological innovation, retaining its place as a pioneer in driver assistance technology for more than 20 years; in this time, it has developed numerous global technological "firsts."

First, control technology was established to control vehicle speed and vehicle distance at ICC system, and to control lateral motion and steering at LKS system. The combination of these technologies resulted in the development of PP2.0. Furthermore, the advantages of DAS (steer-by-wire systems) has facilitated line-tracing capabilities and smooth steering motions, contributing to driver reassurance.

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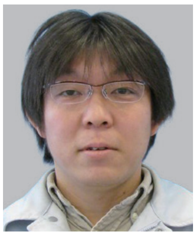

Naoto Sugawara

4. Intelligent interface

Nariaki Etori*　Shohei Nakamura*　Yasunori Nakazono**
Kiyoharu Ishigouoka**　Kenji Maeda**

1. Introduction

This chapter outlines the newly adopted intelligent interface as the human–machine interface (HMI) technology that is key to realizing the “safety ” and “comfort” in ProPILOT 2.0 (hereinafter referred to as “PP2.0”). The main functions as interactive HMI, 360° real-time surrounding display, and driver-monitoring system are explained in detail followed by the description on HMI verification methodology.

2. ProPILOT 2.0-specific intelligent HMI

The intelligent interface is a HMI uniquely designed to enable the driver to use the advanced driving assistance functions of PP2.0 both easily and appropriately. In other words, it is an intelligent interface for an intelligent driver assistance system, and consists of a HUD (Head up Display), a display on the meter display, operations on the steering wheel switches, and warnings by the driver monitoring system. (Fig.1)

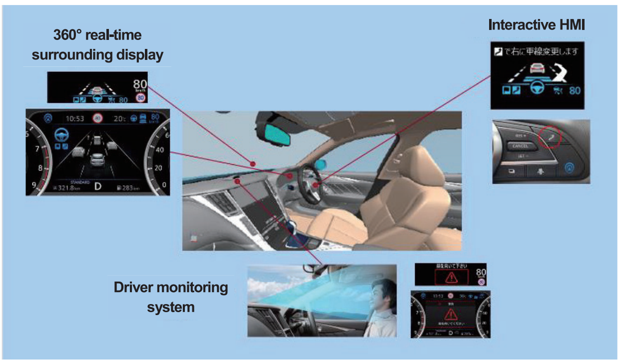

Fig.1 Intelligent interface

PP2.0 is a driving-assistance system in which the vehicle speed, inter-vehicle-distance, and steering control functions of the first-generation ProPILOT (hereinafter, “PP1.0”) have been enhanced by the addition of a hands-off function (for driving within a single lane) and a navigated route driving function that supports lane change at branches and exits and for overtaking.

PP2.0 has three activation states, up from two in PP1.0, due to the addition of hands-off function in the same lane. These modes are as follows: the Intelligent Cruise Control mode(hereinafter referred to as “ICC mode”), in which only the vehicle speed/vehicle to vehicle distance control are activated; the hands-on mode, in which both the vehicle speed/vehicle to vehicle distance control and steering control are activated, but the driver must be able to keep the steering control at all times; and the hands-off mode, in which both the vehicle speed/ vehicle to vehicle distance control and steering control are activated and allows the driver to take his hands off the steering wheel under certain situations, assuming that the driver’s attention is on the road ahead and the driver is ready to take over when required. The challenge for an HMI is to design a display system that allows the driver to identify these three states. When two modes are to be identified, an ON/OFF display element can generally be used; however, it is difficult for three or more conditions to be identified with this method. We have widely applied color-coding scheme, which encourages identification by differences in color, to both the functional (e.g., icons, indicators, etc.) and formative (e.g., dividing lines, backgrounds, etc.) display elements on the HUD and meter displays, and to render the three driving modes readily identifiable, we assign them the following colors: white for the ICC mode, green for the hands-on mode, and blue for the hands-off mode (Fig.2). Because color vision differs between individuals, the color-coding system here adopted uses colors selected through color-vision simulations, to incorporate such differences between individuals.

Fig.2 Color-coding for operating condition display

The navigated route driving function (a further function of PP2.0) assists in lane-changing maneuvers

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when branching is required by the route or overtaking a slower vehicle ahead. The system assesses the conditions and proposes lane-change assistance at an appropriate time; the lane-change assistance starts after the driver confirms the safety and approves the proposal. Here, one issue in HMIs that of constructing display systems that allow the driver to clearly and quickly understand the system's proposal and operation systems that allow the driver to enter their approval easily and without mis-operation. When solving this issue, it is extremely important to ensure that the proposal and approval processes do not prevent the driver from monitoring the surrounding traffic conditions, because PP2.0 is only a driving-assistance system and the driver remains obliged to monitor the surrounding traffic conditions and drive appropriately at all times. Therefore, the system's proposal is displayed in simple text and graphics on the HUD, and the driver approved input were assigned to the switch with the best visibility and operability among the steering switches. (Fig.3)

Fig.3 System's proposal and driver's approval of lane-change assistance operation

Thus, the driver is able to grasp the system's proposal without deviating their gaze too far from the surrounding traffic conditions, to continually check the vehicle's safety, and to approve the proposal while holding the steering wheel. If the system proposal and driver approval are completed in a short time and without stress, the driver's impressions of the HMI naturally change, from the current display/operation impression (i.e., as the driver's input (operation) vs. the system's output (display)) to a sense of enhanced interaction with the system. Thus, the HMI items used during lane-change assistance are referred to as "interactive HMI" and mediate communications with the user.

Driving with an interactive HMI is an unprecedented new driving experience, and we believe that it is a revolutionary HMI not only usability improvement but also in perspective of UX (User Experience).

Technological advances allow PP2.0 to a refined control performance (e.g., smooth acceleration/deceleration and lane-keeping stability), resulting in a highly advanced driving-assistance system. For the HMI of such systems, the driver's excessive trust, distrust, and-in particular-excessive trust prevention must be considered to the greatest possible extent. One method for achieving this is to ensure that the driver accurately understands the system's abilities and can use the system appropriately within the range of these abilities. Accordingly, the surrounding traffic conditions are detected by the system and displayed in 360° and real time on the meter display, to help the driver to understand the system's detection range and identification abilities at a glance. (Fig.4)

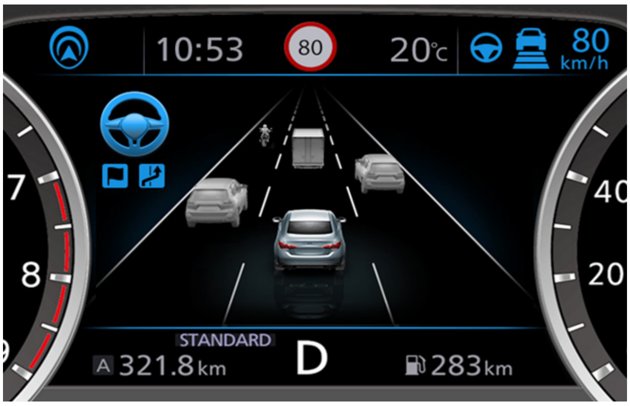


Fig.4 360° real-time surrounding display

Furthermore, a driver-monitoring system is installed to detect whether the driver is monitoring the road ahead; if they are not, the system warns them to attend more closely. This help prevents the driver from neglecting to monitor the surrounding traffic conditions when driving in the hands-off mode. (Fig.5)

Fig.5 Driver-monitoring system and its warning for the driver to attend to the road ahead

3. HMI Details

The details of the interactive HMI, 360° real-time surrounding-conditions display, and driver-monitoring device are here described.

3.1 Interactive HMI

To provide lane-change assistance during the branching or overtaking stages of the navigated route driving operation, the system considers the planned route, the speed of the vehicle ahead, and the surrounding traffic conditions; from these data, it proposes lane-change assistance via the HUD and meter display at appropriate timing. (Fig.6)

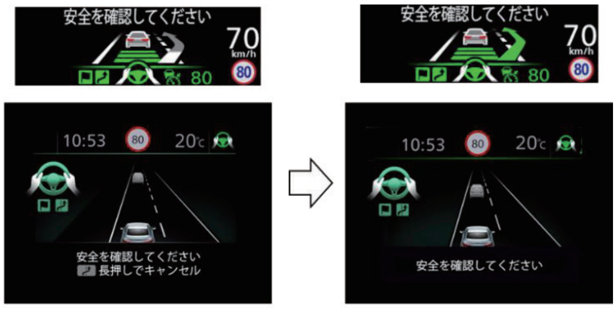
Fig.6 System's proposal for lane-change assistance

In the HUD, the arrow-shaped graphics indicate the proposal for lane change assistance and the text at the top prompts the driver for approval. The number of display elements is minimized, and these elements are arranged such that the driver's forward vision is not obstructed, to allow the driver to recognize the system's proposal safely. The reason for the lane change is simultaneously displayed on the meter display, to allow the driver can check it if necessary.

Once the driver checks the safety of the surroundings and presses the steering switch (Fig.3), lane-change assistance is started. Because this switch is often operated relatively quickly after the driver receives the system's proposal, it is placed in the upper region of the display, near the periphery of the steering wheel, in consideration of both visibility and operability. Once the driver is familiar with the switch operation, it can be pressed without looking.

During lane-change assistance, driver must place both hands on the steering wheel in preparation for overriding. Therefore, after lane-change assistance is started, the HUD and meter display switch from the hands-off mode (blue) to the hands-on one (green), to prompt the driver to grasp the steering wheel. It is here that color coding is most effective.

The animated display (i.e., the HUD's graphic arrow pointing from the near to far sides) is displayed from the moment of approval until the lane change commences, and text prompting the driver to check the safety of surrounding is displayed. When the system initiates the vehicle's turn signals to start the lane change, the HUD's graphical arrow becomes green and flashes at the same frequency as the turn signals, to inform the driver that the lane change is in progress. (Fig.7)



(From driver's approval to lane-change initiation) (During lane change)

Fig.7 Lane-change assistance display scenes

3.2 360° real-time surrounding display

To help drivers properly grasp the capabilities of the system, the system displays the road environment and traffic conditions that the system is detecting in 360° in real time.

As the road environment, the traveling lane, the adjacent lanes and the type of road boundary lines (e.g., solid white, broken white, solid-yellow, and double lines can also be displayed) (Fig.8). In this way, the ability of the 3D High-Definition map data and front camera to detect the surrounding road environment can be expressed in the display.

Fig.8 360° real-time display

As traffic conditions, other vehicles detected in traveling lane and the adjacent lanes are displayed for each vehicle type (e.g., passenger cars, large-sized vehicles, motorcycles, and unknown) (Fig.4); In addition, the distance of other vehicles in the display was repeatedly tuned to match the actual scenery, resulting in a non-linear scaling of the display position. This allows detected vehicles to be displayed by fusion-processing the outputs from the front camera, front radar, side radars, and other sensors. The driver can grasp the system's detection range and identification capabikity by comparing the actual space with the displayed one.

Through experiencing various scenes, the driver gradually learns the system's capability via the 360° real-time display, and will be able to to use the system appropriately within its capabilities. At the same time, the driver's trust in the system is also enhanced.

3.3 Driver-monitoring system

The driver-monitoring system checks the driver for any failure to monitor the road ahead, using the driver's face direction and eye-opening/-closing conditions. It can prompt the driver to attend more closely to the road ahead, to help prevent them from neglecting to monitor surrounding traffic conditions when driving in the hands-off mode. (Fig.5)

The driver-monitoring device is located at the center of the dashboard with its imaging field directed toward the driver's side. It features the following integrated components: a camera lens, infrared light source (LED), optical filter, infrared-light imaging device, image-processing circuit, universal operation circuit, and more. (Fig.9)

Fig.9 Driver-monitoring device position

The infrared LED periodically emits infrared light with a wavelength of 940 nm (i.e., the invisible range), and the infrared-light-imaging device synchronizes therewith to capture an image; thus, a clear depiction of the driver's face can be obtained in all light conditions.

The facial organs (i.e., the eyes, nose, and mouth) are extracted from the driver's facial image via pattern-matching processing, and the driver's face direction is calculated from the size and positional relationships of these organs. In addition, the eye-opening/-closing condition is assessed by detailed analysis of the regions surrounding the eyes. When the calculated face direction is oriented beyond a certain angle from the vehicle's direction of motion for a specified period, a monitoring failure is registered and a warning given (Note: when the turn signals are active, this warning is blocked). When the eyes remain closed for a specified time period or face direction or eye-opening/-closing conditions remain likewise unchanged, a failure to monitor the road ahead is registered, and a warning is given.

4. Verification of HMI

The verification process for the driving-assistance HMI is here introduced.

4.1 Examination of verification items

Using the verification items specified for each system-judgment-generated (i.e., automatically provided by the system, regardless of the driver's operation) and driver-operation-generated (i.e., provided by the driver's operation) information presentation (Table 1), we determined detailed verification items for each evaluation task.

Table 1. Verification items (major items)

Source of information presentation	Feature	Verification item (major items)
System's judgement	Difficult to notice because information automatically presented by system, regardless of driver's operations	• Time of information presentation is noticeable • Presented information is understandable • Correct actions can be taken
Driver's operation	System's response to an operation must be communicated	• Operation method is known • Correct operation is possible • Operation completion and control-condition changes are noticeable

4.2 Verification method

For each verification items, scene which lead to workload during recognition / judgement / operation processes were extracted Examples of the evaluation scenes used to identify tasks in the three operation conditions (ICC, hands-on, and hands-off modes) are shown in Fig.10.

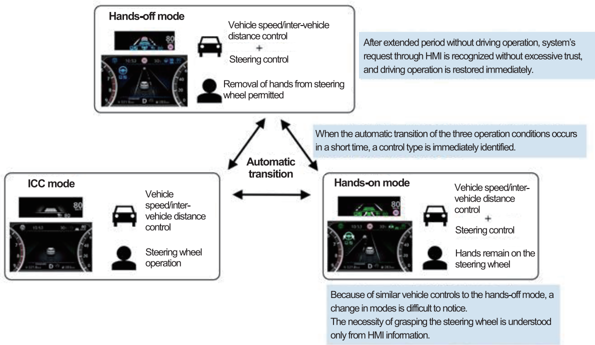


Fig.10 Evaluation scene extraction: identifying the three operating conditions

Simulators were constructed in which the recognition/judgment/operation processes of an extracted evaluation scene could be assessed; then, these were evaluated by experts and experimental participants (representing general customers).

For the simulators, the following two scenarios were prepared: a use case scenario, representing the control and HMI logic in writing; and a driving simulator (hereinafter, "DS"), reproducing the cockpit and vehicle's motion.

First, the use case scenario was used by the experts to verify the compatibility between the combined control and HMI logic and the recognition model for expected users. (Fig.11)

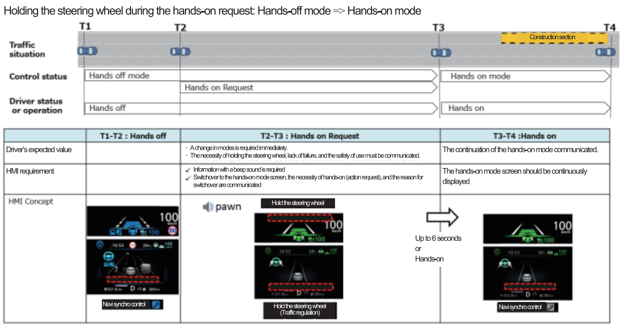


Fig.11 Example of desktop scenario

Next, the HMI specifications of the aforementioned use case scenario were reproduced as an actual driving experience in the DS, to allow the experts and experiment participants to conduct evaluations.

The DS reproduced the traffic flow around the vehicle as well as the surrounding environment (e.g., road structures); thus, the users were naturally motivated to attend closely to the road ahead. An actual road simulation was applied to convey the experience of driving-load reduction, security, excessive trust, and distrust under PP2.0. Specifically, after driving for tens of minutes, the vehicle's behavior and meter/HUD information provisions (according to the PP2.0's control conditions) were reproduced. (Fig.12)

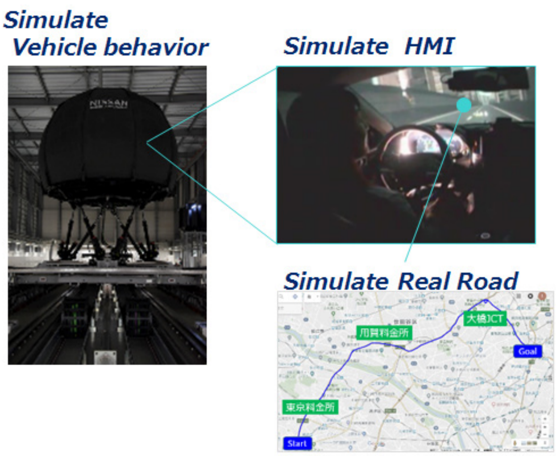


Fig.12 Driving simulator elements

The applied DS consisted a motion system which provided the vehicle's acceleration, an image-projection system which provided visual information, a cockpit system which provided sonic/reactive responses to controls, and a driver's seat. The dome and the projector system rested on the six-axis oscillation unit (referred to as a hexa-pot) which was mounted on the x–y translation unit allowing movement in the longitudinal and lateral directions, Built in the dome was a turntable that rotated independently of the translation unit and a mock vehicle-cockpit.. Screen surface covered the dome interior with seven projectors combined to project a 360° image. Fig.13 and Fig.14 depict the DS structure and control-system composition, respectively.

The various control signals (e.g., from the steering

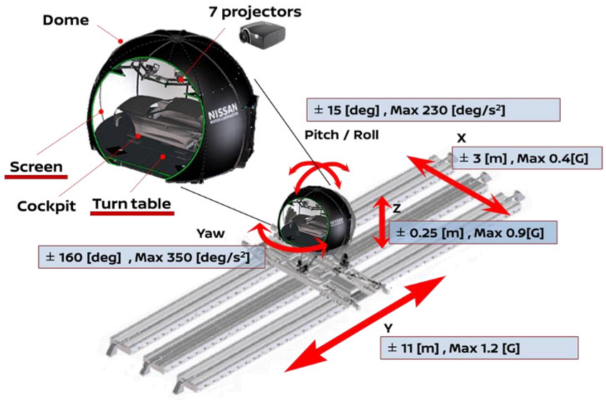


Fig.13 Driving simulator structure

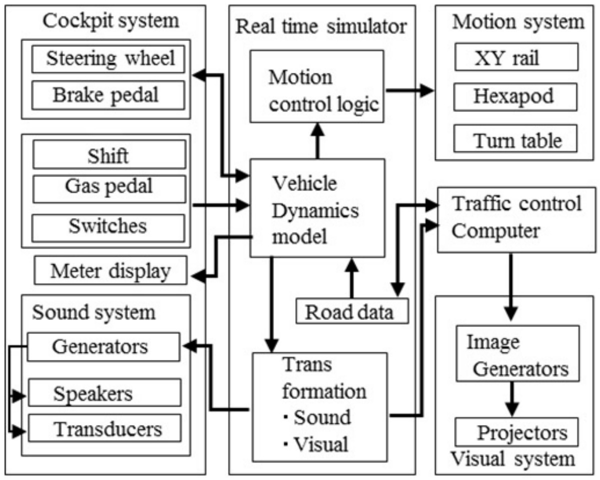


Fig.14 Driving simulator control-system composition

wheel, brake, and accelerator) and road-surface conditions were inputted to a vehicle-motion analysis model. The steering/braking responses to the controls were calculated and delivered to the driver. By minimizing the deviation to actual driving experience, the DS allowed long enduring tests without the subjects having motion sickness, and reproduced at high consistency driving experience which affect capabilities of driver recognition such as workload, sense of security, excessive trust, and distrust. To this end, the following design aspects were realized: [1)]

(1) The translation unit moved and responded rapidly whilst generating wide strokes in the x- and y-directions; thus, the drivers felt acceleration as high as that of an actual vehicle, with no delay.

(2) The large-scale dome displayed a 360° surrounding image with a high response rate, to enhance the realism and to reduce the unnaturalness caused by delayed imagery.

An example evaluation using the DS is here described.

For the scene in which repeated lane changes (to reach the exit of an expressway) were assisted, the following items were evaluated: batch approval, in which the driver approved all of the system's lane-change proposals at once and immediately; and separate approval, in which an approval operation was performed for each lane change. Driver experiences were used to evaluate these two approval types and their problem areas (Fig.15), and the scenarios were reproduced in the DS (Fig.16) to observe driving results and perform subjective evaluations. For both approval types, correct operations and satisfactory operability/convenience were confirmed. (Fig.17)

These evaluation experiments were repeated with several hundreds of participants before finalizing the HMI specifications.

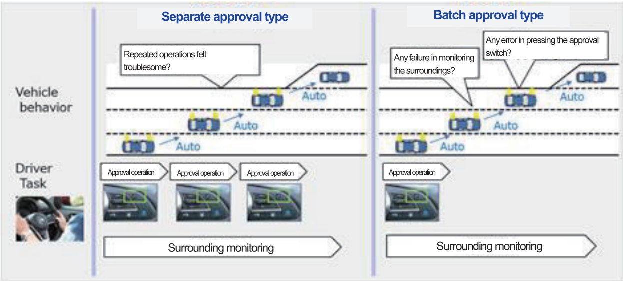


Fig.15 Driving simulator evaluation example: approval task for lane-change assistance to exit

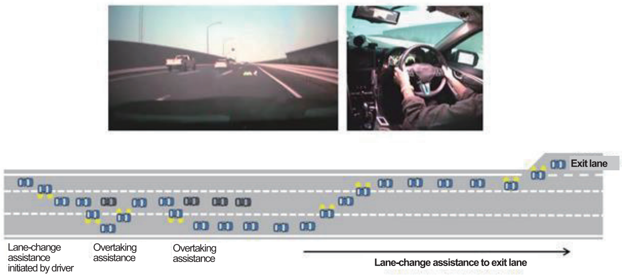


Fig.16 Driving simulator evaluation example: reproduced scene

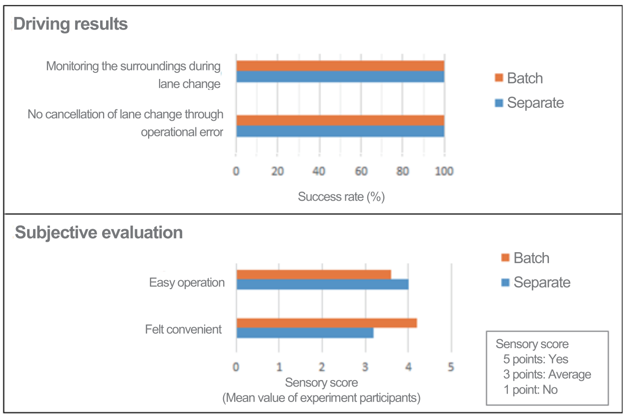


Fig.17 Driving simulator evaluation example: evaluation results

4.3 Verification stages

Through the desktop-scenario and DS evaluations, the HMI specifications were verified in the design phase, to enhance the accuracy of the design. In the evaluation phase, prototype vehicles were used to optimize the specification details (e.g., display timing). (Fig.18)

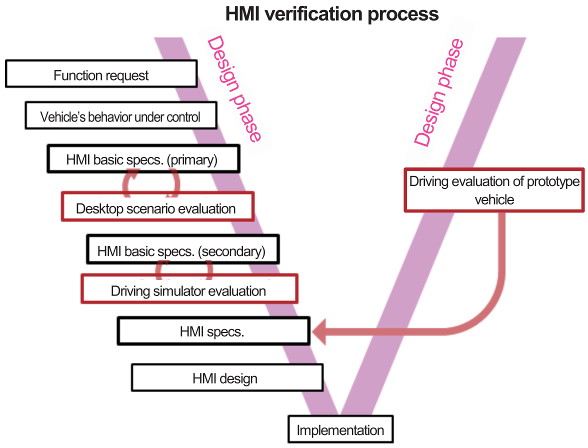


Fig.18 HMI verification process

5. Conclusion

The intelligent interface described in this chapter provided comprehensive means for the driver to readily understand the system's condition/abilities bthrough interaction and helped realize PP2.0, an advanced driving-assistance function , to be easily and appropriately used by the customers.

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5. Technologies supporting system reliability

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1. Introduction

The evolution of autonomous driving technologies has extended the range of driving-assistance functions they offer and increased the scope and importance of their functional safety designs.

The ProPILOT 2.0 (hereinafter referred to as “PP2.0”) system allows users to drive without holding the steering wheel in certain road environments, though they still monitor the road. The designs required to help support the safety of this operation differ from those of existing driving-assistance systems. For example, in the event of system technical issue, the first-generation ProPILOT (hereinafter, “PP1.0”) requires the driver to keep their hands on the steering wheel, to immediately override the automatic driving operation. In contrast, PP2.0 allows the driver to continue with “hands off” driving under the specific condition; thus, until the driver overrides the driving operation, the system shall handle the technical issue safely.

This chapter describes the safety/reliability designs essential to realizing “security” and “comfort” in PP2.0.

2. Concept of functional safety design

In existing driving-assistance systems (in which the driver always drives with their hands on the steering wheel), the functional safety design addresses safety by working to detect technical issues before they result in critically hazardous events, informing the driver, and terminating the mis-operating function (Fail silent).

Meanwhile, the functional safety design of PP2.0 not only works to detect technical issues and inform the driver; furthermore, it is designed to maintain operations until the driver takes over (Fail operational). (Fig.1)

To maintain safety after a technical issue, the steering and braking functions (which are continuously controlled by the system) and the “informing function” (i.e., that informs the driver of a technical issue) shall be retained; hence, safety is addressed by making each function redundant. If any of these functions fail, a switchover to an unaffected backup system is applied as a safety measure.

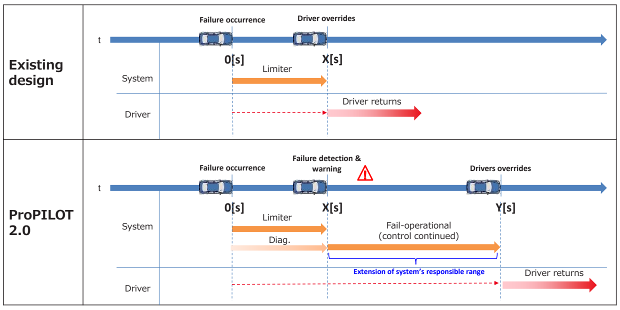

Fig.1 Difference between existing safety designs and ProPILOT 2.0

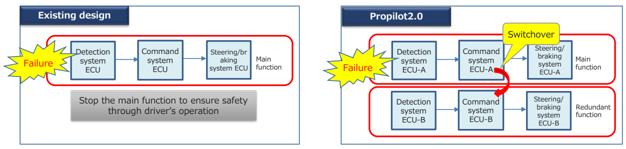

Fig.2 Existing design and ProPILOT 2.0’s safeguards against technical issues

To make a function redundant, its components (e.g., its electronic control unit (ECU) and actuators) and electric/electronic infrastructures (e.g., its power sources and communication networks) must also be made redundant.

Furthermore, an important design requirement for maintaining functions with redundant composition is “independence” for the main and backup function systems. Accordingly, this feature is designed to meet the following functional safety requirements:

1) A single technical issue must not cause both systems to fail simultaneously.
2) A technical issue that incapacitates one system must not produce a technical issue in another system.

3. Communication network architecture

For the ECU (as described above), if a technical issue occurs, the steering and braking functions are addressed through a redundancy system comprising multiple ECUs. To support the vehicle’s safe behavior, its communication network must also be redundant. Expressed otherwise, the communication network is constructed such that the

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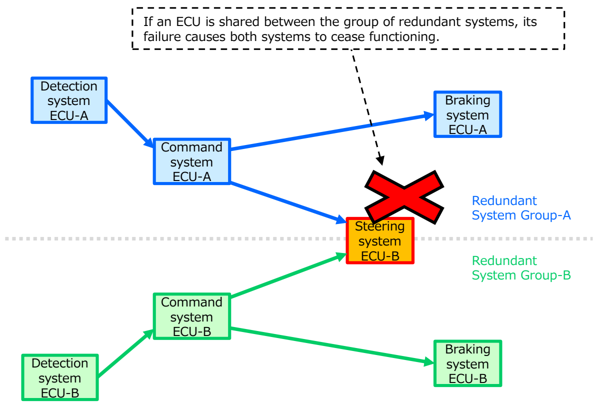
series of signal flows is uninterrupted in the event of abnormalities occurring in the body, harnesses, or other parts of the ECU. The requirements for achieving this can be roughly classified into two items:

1) Multiple communication routes (groups) must be ensured for “obstacle/white-line detection” → “command-value operation” → “actuator control.”
2) These communication routes must be mutually independent.

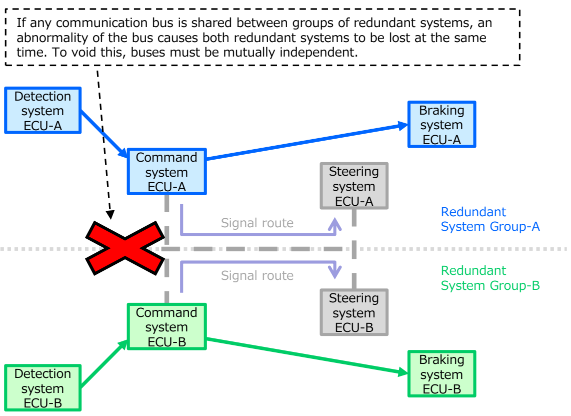
In communication-network designs, these two requirements can be more precisely broken down into the following four items:

a) Each group must contain detection-, command-, and steering/braking-system ECUs.
b) Each group must be composed of mutually independent ECUs (Fig.3).
c) Communication within each group must be conducted through mutually independent buses (Fig.4).
d) The ECUs contained in each group must be connected to mutually independent upstream power sources (Fig.5).



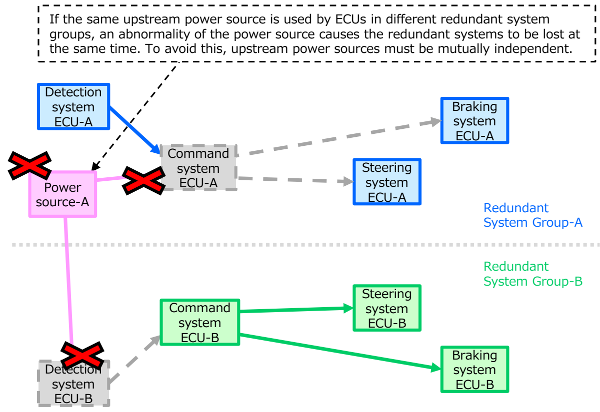
<Case in which steering systems in different redundant systems are controlled by common ECU>

Fig.3 Requirements for ECUs composing each group



<Case in which different redundant systems uses a common communication bus for control>

Fig.4 Requirements for buses composing each group



<Case in which different redundant systems use a common upstream power source>

Fig.5 Requirements for upstream power sources composing each group

A summary of the network topology satisfying these requirements is shown in Fig.6. Under normal conditions, driving assistance is performed by all ECUs depicted in the figure. The communication network is organized such that Group B and/or Group A continues to operate when an abnormality occurs in Group A and/or Group B. Moreover, a communication bus between the groups is provided, to allow each group to monitor and immediately detect abnormalities in its counterpart.

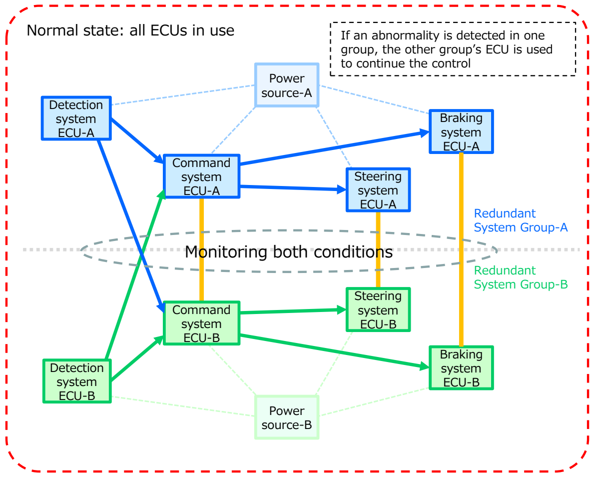


Fig.6 Communication network composition for ProPILOT 2.0

4. Power-source system for ProPILOT 2.0

4.1 New requirements for power-source systems

Because the all systems are operated by the vehicle’s 12 V power source, power-source maintenance is crucial in helping prevent the system from losing functionality.

If driving operations are controlled by vehicle, the following requirements are placed on the power-source system: (1) abnormally high/low voltages must not be allowed, even over short periods, because the ECU continuously maintains the necessary operation processes for driving assistance; (2) because the driver’s input is absent, the actuator consumes more power than existing assistance functions and 12Vpower-source is required higher voltage than the motor's electromotive force.

4.2 Summary of power-source system

The power-source system is composed of a main battery; a DC–DC converter, along with its relay and current sensor; a backup battery, along with its relay and sensor; and connecting harnesses. (Fig.7)

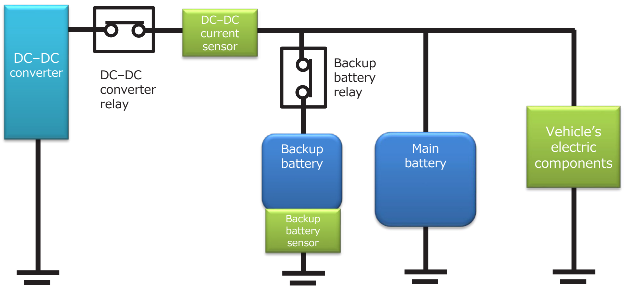


Fig.7 Composition of power-source redundancy circuit

During driving operations, the backup battery is connected to the vehicle's 12 V power system, and the vehicle's electrical components are operated by using power from three power sources: the DC–DC converter, main battery, and backup battery. Even if the DC-DC converter fails with a deterioration of the main battery, the backup battery can maintain the voltage and support the driving-assistance which of system's continued operation.

Lead-acid batteries have achieved sufficient performance results on the market (as adopted in the SERENA S-HYBRID and other vehicles); hence, it was selected as the backup battery.

4.3 Power-source system problems

The backup battery, an important component in managing power-source redundancy, must continue to operate when the main power source fails; however, an increase in customer burdens (e.g., frequent parts replacement and checks) must be avoided. Therefore, the system itself must maintain its performance over a long period. As described above, actuators require a high power-source voltage, which cannot be maintained under deteriorated backup-battery; thus, to measures to safeguard against backup-battery deterioration and to ensure accurate battery status diagnoses are essential.

Meanwhile, the DC-DC converter have failure modes of high-voltage and internal short circuiting. These failure modes make it impossible to maintain the power-source voltage by using the backup battery, Therefore some safeguard were also examined against DC–DC converter technical issues.

The technical issues for power-source-system redundancy are as follows:

1. Suppressing deterioration for backup-battery.
2. Correctly diagnosing backup-battery conditions.
3. Handling DC–DC converter short-circuiting/high-voltage technical issues.

4.4 Measures for controlling backup-battery deterioration

To apply same size/type lead-acid battery for the main and backup will result in a similar deterioration process in both. Thus, when the main battery reaches its life-span, the sub-battery will do likewise, and its backup function will be lost. Therefore, the backup battery must have a longer life-span than the main one.

The stress applied to a lead-acid battery cannot often be eliminated, because of the battery's functions. However, the backup battery is different from the main battery; for example, no dark-current supply is required during parking, which reduces the battery stress. As described above, the backup battery's long life-span was addressed by thoroughly investigating the deterioration factors of lead-acid batteries and implementing measures to reduce stress. Here, we describe the process of eliminating the main factor: stress-induced capacity reduction of the lead-acid battery.

First, the backup-battery relay was placed upstream of the backup-battery circuit, to disengage the circuit during parking and prevent its discharge through the vehicle's standby current. (Fig.8)

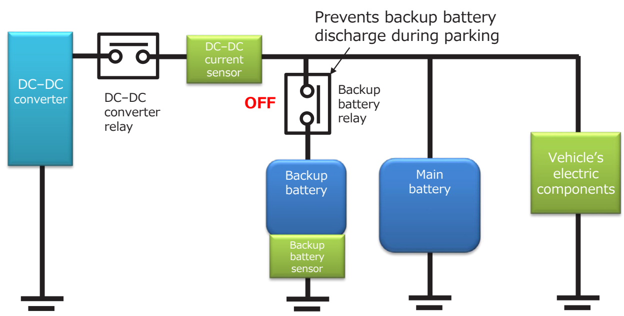


Fig.8 Backup battery relay circuit

Moreover, because excessively high or low charging voltages shorten lead-acid-battery life-spans, the backup battery was placed in parallel with the main battery, such that the applied voltage from the DC–DC converter (including the voltage drop due to the harness) was equalized between both batteries.

These measures ensure that the backup battery can retain a high charging capacity, to control deteriorations produced by a low-capacity state. In consideration of the vehicle's quietness, a semiconductor relay (which makes no operation noise) was adopted as the backup battery relay.

4.5 Backup-battery condition diagnosis

Lead-acid batteries are prone to multiple deterioration/failure modes, owing to their chemical/structural characteristics. As described above, the backup battery is managed such that most deterioration modes are controlled, which makes condition diagnosis relatively easy. Meanwhile, the externally observable parameters are limited to voltage, charging/discharging current, and temperature. To diagnose backup-battery conditions with high precision, a circuit configuration designed for more accurate measurement was adopted.

In particular, the battery voltage suffered from larger measurement errors, attributable to the effects of the generator/other-battery voltage, voltage drops through discharge from the measured battery, and other factors. These factors arise because the battery must be connected to a 12 V power grid during measurement.

As a countermeasure, the error factors were eliminated by switching off the backup relay and measuring the voltage with the battery disconnected from the vehicle's circuit.

4.6 Handling DC–DC converter short-circuiting/ high-voltage technical issues

In the event of a short-circuiting/high-voltage technical issue in the DC–DC converter, the battery must be disconnected from the vehicle's 12 V power grid; to this end, a DC–DC converter relay was placed between the DC–DC converter and battery. (Fig.9)

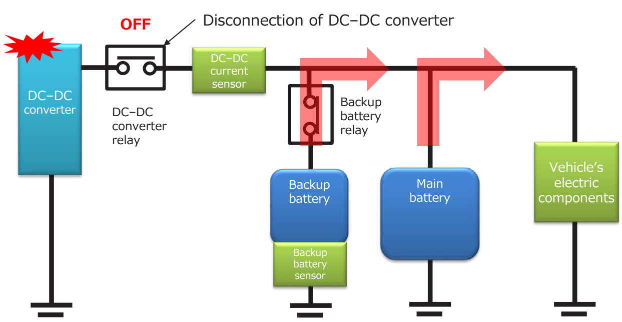


Fig.9 DC-DC converter disconnection during technical issue

This circuit configuration was designed such that its fundamental power-source function was unobstructed. To minimize the relay induced voltage drop, we chose a semiconductor relay, because it can realize a lower ON resistance, large current-carrying capacity, superior durability, and lack of operation noise.

In addition, the backup-battery and DC–DC converter relays are controlled by mutually independent ECUs; this enhances system reliability, because the ECUs cannot be simultaneously switched off by microcomputer runaway during PP2.0 operation.

5. Human-error-secure safety design

As the driving-control functions of systems have become more advanced, the potential for increased risk associated with driver errors, such as overreliance on the system and misunderstanding of system function, has increased. A system such as PP2.0, which allows for switching between the driver's driving mode and system-assisted modes, requires measures to address errors in recognizing the system's operational status (mode confusion) or conflicts between the driver's and system's intentions.

Here, methods of analyzing predictable human errors are explained. Previously, when human-error-derived hazardous event scenarios were analyzed, experts applied brainstorming methods. However, demonstrating the results of such methods is difficult in terms of logicality or comprehensiveness.

In this research, a new analysis method was developed for PP2.0, to objectively and comprehensively deduce hazardous scenarios produced by human errors. The risk analysis was conducted via four steps:

1. Specify an object person (who).
2. Specify a phenomenon (how).
3. Specify an object (what).
4. Specify an environment (where).

This concept was visualized with a description method that imitated goal-structuring notation (GSN), to increase the objectivity of the demonstration. (Fig.10)

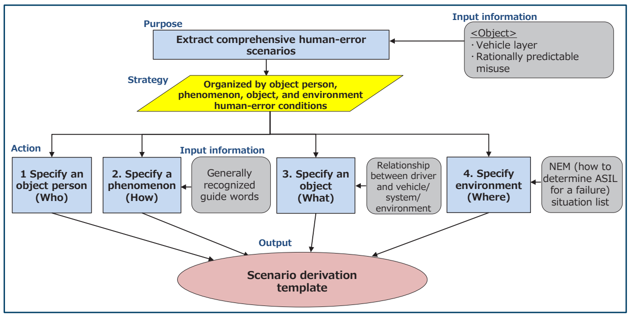


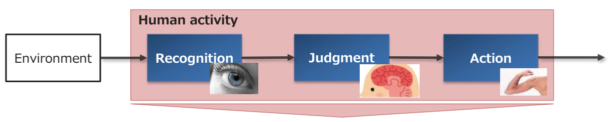
Fig.10 Concept of human-error analysis (GSN)

5.1 Specify an object person (who)

First, we specified the object causing the human error; this could include the driver, a passenger in the passenger seat, or passengers in the rear seats.

5.2 Specify a phenomenon (how)

Next, we specified a phenomenon for the object person's human error. Human activities were categorized into "recognition," "judgment," and "action." Possible human errors were comprehensively defined. Among them, highly probably phenomena were specified. (Fig.11)

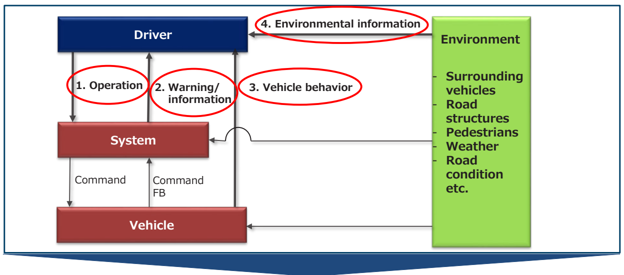


Human activity	Phenomenon of human error	Example
Recognition	1. Ignorance/not understanding	Not informed correctly
	2. Misunderstanding	Information oversight/misreading
Judgment	3. Judgment error	Bias/assumption causes error in judgment
Action	4. Mistake	Performing unintentional operation
	5. Intention	Violation of manners/rules
	6. Inability	Cannot perform as expected

Fig.11 Human-error analysis

5.3 Specify an object (what)

Next, we specified the object of the human error; this represented the relationship between the driver and environment/system/vehicle in the systems-theoretic process-analysis control structure. As a result, objects exerting identical effects on the driver were comprehensively extracted; through this, we restricted the number of objects. (Fig.12)



Object of human error	Example: Not understanding
1. Operation	"How to operate" is unknown
2. Warning/information	Meaning of "warning/information indication" is unknown
3. Vehicle behavior	Why such "vehicle behavior" was performed is unknown
4. Environment	Meaning of "traffic sign" is unknown

Fig.12 Relationship between driver/system/vehicle/ environment

5.4 Specify environment (where)

Lastly, we specified the environment that produced the human error, to derive the final hazardous scenario. (Fig.13)

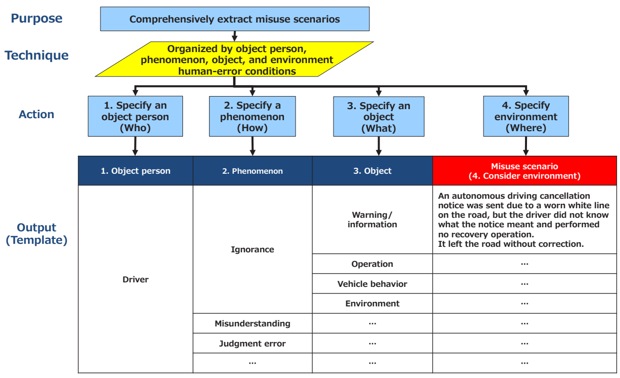


Fig.13 Derivation of human-error scenario

This analysis method was applied to the PP2.0 system, to extract human-error-related scenarios and break down safety measures into functional requirements.

Moreover, this method was proposed to ISO TC22 SC32 WG8 and adopted in ISO PAS 21448 "Road vehicles – Safety of the Intended Functionality," issued in January 2019.

6. Summary

The method described in this chapter allows PP2.0 to be designed with advanced safety standards. From the developed safety-design method, PP2.0-specific requirements were derived, and the functional safety design was realized by adding new features. This allowed complicated designs to be avoided and high reliability to be achieved.

7. References

1) ISO26262-1～10 Road vehicles -Functional safety-

Authors

Takashi Sasayama

Kouji Shionome

Akira Teranishi

6. New experimental verification techniques

Yumi Kubota*　Koji Sasaki*　Shimpei Nagae　Kenji Ogino*****

1. Customer values and their verification

Compared to the first-generation ProPILOT (hereinafter referred to as "PP1.0"), ProPILOT 2.0 (hereinafter, "PP2.0") adds two new intelligent items: Navigation-route-following function, including lane-change assistance (point-to-point); and a hands-off function when remaining in the same lane.

To realize the navigation-route-following and lane-change-assistance functions, more complicated controls are required to handle multiple lanes instead of single ones. Because lane-change and overtaking scenarios are more complicated, simulation techniques have been used to verify that the relevant systems function appropriately under numerous traffic-flow conditions.

Meanwhile, a crucial aspect of the lane-maintaining hands-off function is the feeling of safety of the vehicle's motion. For a long time, Nissan Motor has developed technologies to provide customers with a dynamic driving performance over all road conditions and at all times; the results have received customer approval. Numerous research results regarding customer's perceptions of vehicle behavior and the human mechanism which explains their intention for these behaviors have been incorporated into PP2.0. Here, we discuss this in detail.

This development has been undertaken to facilitate cooperative human–vehicle driving relationships that provide not only convenience but also a sense of mutual interaction towards a destination. The development paths were as follows: knowledge of "how to move a vehicle," obtained through dynamic performance research, was maximized and utilized; simulation techniques were actively applied; and techniques accumulated through the development of numerous driver-assistance/safety systems, the evolution of intelligent technologies, and human research were combined. The following items represent the PP2.0's performance-target settings considered in realizing the above, as well as their verification:

・Verification of lane-change actions in complicated traffic environments.

・Vehicle-behavior target settings for controlling discrepancies perceived by the passenger, as well as their verification.

2. Verification of lane-change action in complicated traffic environments

To evaluate a lane-change-assistance function (including its relationship to adjacent vehicles), comprehensive verification procedures are required. Accordingly, a coupled simulation environment combining multiple tools was constructed to reproduce traffic flows, the PP2.0 system (sensors and control logic), and vehicle behavior interactions (Fig.1). To ensure the reproducibility of the yaw response to steering (an important feature of lane-changing motions), a highly accurate vehicle model (also used for stability performance evaluations) was adopted, to accurately reproduce the mutual relationships between sensors, control logic, and vehicle behavior (Fig.2).

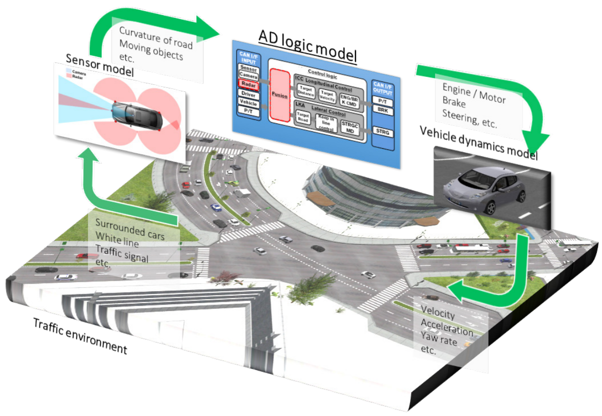


Fig.1 Autonomous driving (AD) simulation platform

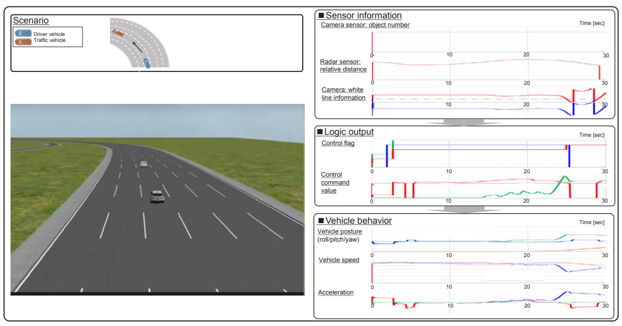


Fig.2 Results of sensor/AD-logic/vehicle-behavior simulations

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Next, a simulated branching scene was considered, to examine lane-change motions for a complicated traffic environment. Here, to reproduce multi-vehicle traffic flows (for which practical reproductions are difficult), the PP2.0 vehicle's surroundings were divided into nine blocks. Large-sized vehicles (e.g., buses and trucks) were placed at random in the adjacent divisions, using one vehicle per division (Items 2, 3, 6, 7, and 8 in Fig.3); furthermore, standard-sized passenger cars were placed at random in the forward/backward positions, with one vehicle per division (Items 1, 4, 5, and 9 in Fig.3). Here, the standard-sized passenger cars were described by dynamic traffic parameters (e.g., vehicle speed and acceleration/deceleration), and the lane-change times were set to different levels.

For the simulation evaluations, 1376 test-case patterns were automatically generated using the aforementioned preconditions. Numerous scenes (for which the handling appeared challenging for PP2.0) were included amongst these cases (e.g., a standard-sized passenger car suddenly cutting in from the blind spot of a large-sized vehicle when performing a lane change).

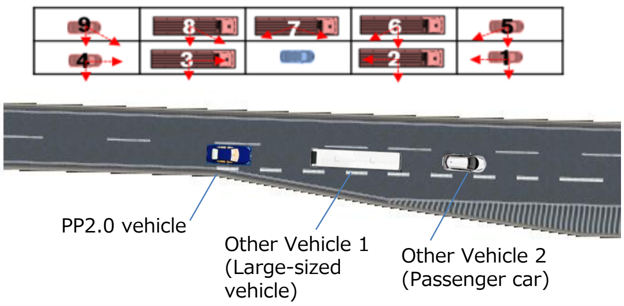

Fig.3 Layout of PP2.0 and other vehicles in branch scene

Furthermore, to process the simulation results, the following list of fully determined results were outputted for several minutes: the relative positions of the PP2.0 and other vehicles; the time-to-collision considering relative speeds; and the successful operation of the control logic (Fig.4).

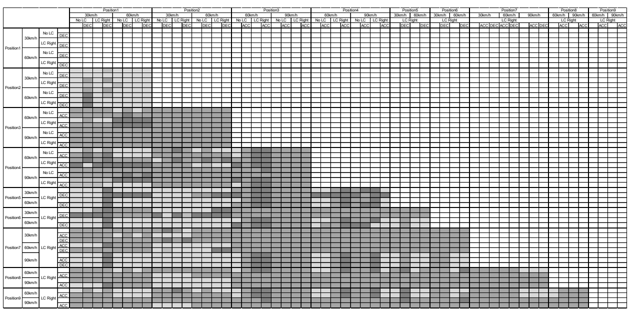
Fig.4 List of simulation results for branching scenes

As described above, performing verification with not only actual vehicle but also simulation environments, which reproduce vehicle behaviors when the lane-change-function is activated under any road-shape/traffic-flow conditions, enables more accurate analyses and measures for whether the PP2.0 system exhibit any problems, and if so, what caused them.

3. Vehicle-behavior target settings for controlling passenger-perceived discrepancies, and their verification

PP2.0 features a hands-off function for driving within the same lane. Because the driver does not perform driving operations in this mode, conditions of involuntary (passive) motion can be assumed. As shown in the lower part of Fig.5, under involuntary motion conditions, motion compensation (based on motion-estimation results from the brain model (internal) model) is not performed. Therefore, a discrepancy often arises between the amount of perceptions a person receives from the sensory system (i.e., actual perceptions) and the amount subconsciously estimated (i.e., not perceived), which may cause sensory confusion. For the driver to maintain safety during the hands-off mode, generating vehicle behaviors that do not cause sensory discrepancies seems necessary.

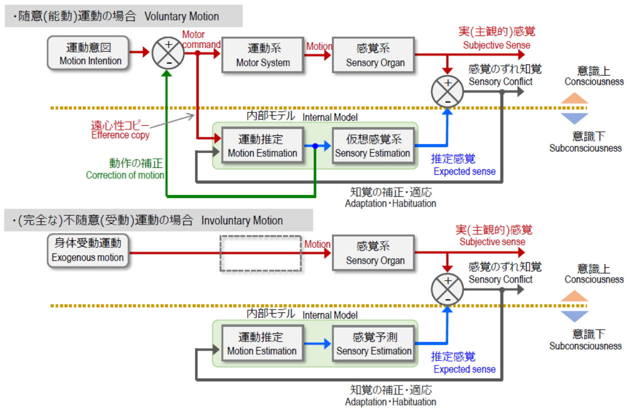

Fig.5 Passenger perception model for voluntary motion/ involuntary motion

Nissan Motor has been accumulating research regarding vehicle-motion controls for enhancing passenger comfort. By treating the amount of vehicle operations and the passenger's visual and bodily behavior-related movement perceptions as parameters, optimal vehicle-behavior identifying methods have been constructed. Comfort-enhancing parameters include the in-lane lateral traveling speed (perceived visually), steering speed, bodily received acceleration, and time change thereof (jerk). Next, the vehicle-behavior performance targets were set by assuming that minimizing these perceptions reduces the prevalence of human-perceived discrepancies, leading to feelings of safety.

For example, Fig.6 depicts the time change in the vehicle's lateral acceleration and the angular acceleration of the passenger's body under changes in vehicle-motion parameters[1]. V0 specifies the extent to which steering operation was minimized, assuming an improvement in the comfort of a driver performing driving operations (voluntary motion). R1 specifies the direction in which the body roll angular acceleration (a type of movement perception) is minimized, assuming an improvement in passenger comfort (involuntary motion). This vehicle behavior can be reproduced with a steering robot (as shown in Fig.7) or with a driving simulator. From the results of the subjective vehicle-behavior evaluations performed with in-house participants, the following results were obtained: V0 provided a smooth motion, but a larger perceived posture change, and R1 provided a smaller posture change and a greater perception of parallel motion.

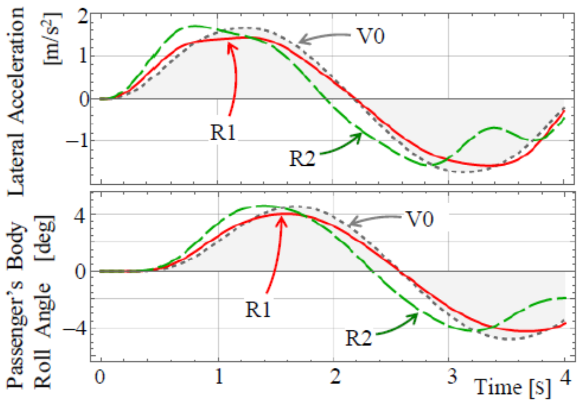

Fig.6 Passenger body angular acceleration vs. time and lateral G vs. time in vehicle, assuming comfort improvement in voluntary motion/involuntary motion

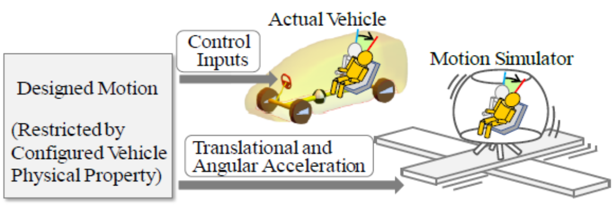

Fig.7 Vehicle behavior evaluation with steering robot/driving simulator

Here, we explain our evaluation of the perceptions received from the sensory system by passengers. The developed vehicle's success in achieving the desired vehicle behavior was evaluated via driving experiments on a proving ground. In these experiments, to check whether the new performance targets were met, we considered the results of two evaluations: subjective (performed by evaluators who actually drove the vehicle) and quantitative (from the measurement data for the actual perceptions). These were regarded as passenger inputs in the passenger perception model (Fig.5). Nissan Motor owns the Rikubetsu Proving Ground (Fig.8), which facilitates evaluations in expressway type environment; the ground includes various road conditions, such as multiple lanes, large-radius turning, complex turning, and undulating road surfaces. Moreover, a high-definition map (essential for realizing PP2.0 functions) of the grounds is available. These evaluations were performed by comparing PP2.0's driving with that of an experienced driver familiar with the proving ground.

Fig.8 Nissan Motor's Rikubetsu Proving Ground

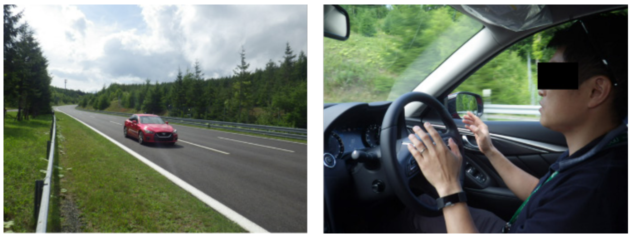

Fig.9 ProPILOT 2.0 evaluation conditions on proving ground

First, a subjective evaluation of PP2.0's hands-off operation (within the same lane) was performed. The following evaluation results were obtained. When driving through a curve, the steering function was initiated early and the amount of corrective steering was small; this realizes a very high level of stability and maximizes the duration of smooth driving operations.

Measurement data to quantitatively support the subjective evaluation results included the in-lane traveling speed (related to the degree of visual perception), steering speed, and distance from the lane center. The comparison results are shown in Fig.10 to Fig.12.

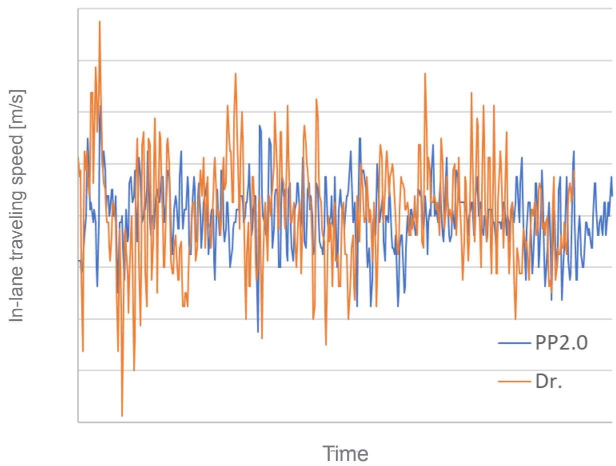

Fig.10 In-lane lateral traveling speed

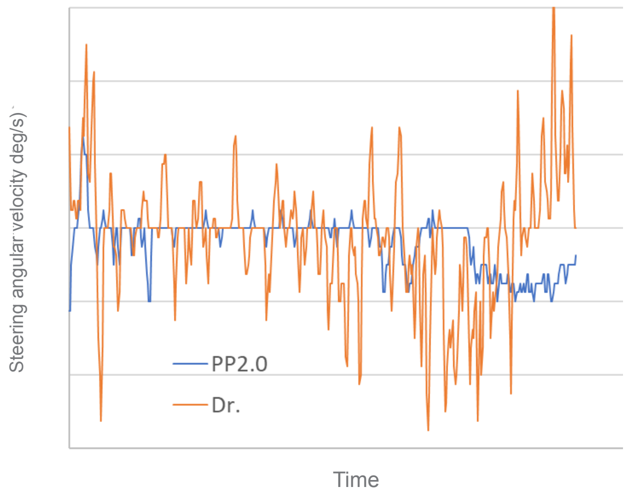

Fig.11 Steering angular velocity

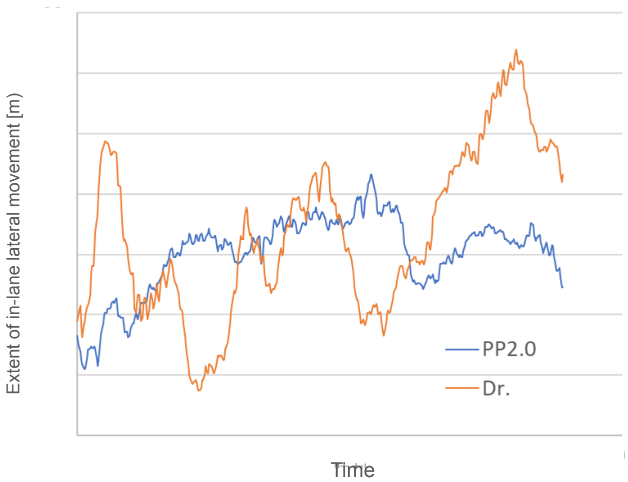

Fig.12 Extent of in-lane lateral movement

Compared to the experienced driver, PP2.0 maintained smaller variability in these values. Therefore, PP2.0 remained at the lane center, controlled the corrective steering, and realized stable behavior.

Meanwhile, as physical quantities related to movement perceptions, longitudinal/lateral accelerations during driving on the S-shaped section were measured. The results are shown in Fig.13, where the vertical and horizontal axes represent the longitudinal acceleration (acceleration G/deceleration G) and lateral acceleration (lateral G), respectively. The two types of G–G diagrams (one for PP1.0 (hands-on) and one for PP2.0 (hands-off)) are shown in different colors. The comparison revealed that the PP2.0 hands-off function maintained the lateral G value for longer, regardless of variation in longitudinal G; furthermore, the right/left lateral G levels were similar, resulting in gentle driving through the S-shaped section. This shows that PP2.0 processes the shapes of upcoming corners beforehand, using the high-definition map; hence, it gently decelerates before entering a corner, requiring only a slight lateral vehicle control when passing through.

As described above, it was confirmed that PP2.0 generated vehicle behaviors that controlled and reduced the amount of visual and movement perceptions, thereby reducing the risk of sensory confusion.

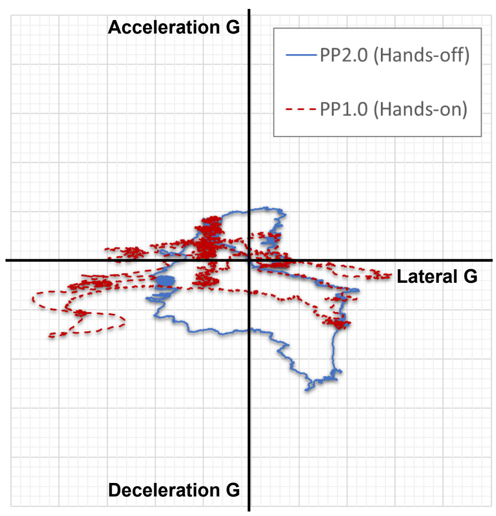

Fig.13 Acceleration/deceleration G and lateral G whilst driving through S-shaped section (G–G diagram)

4. Verification of ProPILOT 2.0 fatigue-reduction effect

Finally, to verify whether the target output was achieved in the passenger-perception model (Fig.5) (i.e., whether the passenger experiencing no discrepancies felt safety), the fatigue-reduction effect of PP2.0 over long-distance operations was evaluated in a practical environment (public road), in which customers use the car. User impressions of “ease” were confirmed from the data.

The large quantities of active oxygen generated through excessive physical/mental activities can damage cells; this can produce fatigue factors (FF) [2]. FFs cause fatigue in the brain, resulting in symptoms such as abnormal autonomic nerve functions[2]. The condition of the autonomic nerves can be evaluated using the low-frequency-to-high-frequency ratio (LF/HF) (which indicates the balance between the sympathetic and parasympathetic nerves) and the coefficient of component variance total power (ccvTP) (which indicates the amplitude of activity for the entire autonomic nervous system)[3]. Therefore, we evaluated the fatigue-reduction effects of PP2.0 by measuring heartbeat fluctuations, from which the aforementioned parameters can be derived.

<u>Measurement of heartbeat fluctuation</u>

In the experiments, a portable heart-rate meter (MF100, Murata Manufacturing Co., Ltd./Fatigue Science Laboratory Inc.; Fig.14) was used to measure heartbeat fluctuation; the data were converted into the R–R interval with a sampling rate of 100 Hz, and a power spectral density function was found. Then, the LF component (0.04–0.15 Hz), which reflects the acceleration of the sympathetic nervous system, and the HF component (0.15–0.4 Hz), which reflects the acceleration of the sympathetic and parasympathetic nervous systems, were calculated; next, the LF/HF was found by dividing the former by the latter. In addition, the square root of the sum of the LF and HF components was divided by the mean value of the R–R interval, to calculate the ccvTP. To remove the influence of age/sex[4], the ccvTP was converted into a deviation value using the ccvTP data for 10000 people or more (grouped according to generation/sex) and the population ratios of each group[5].

Fig.14 MF100 device

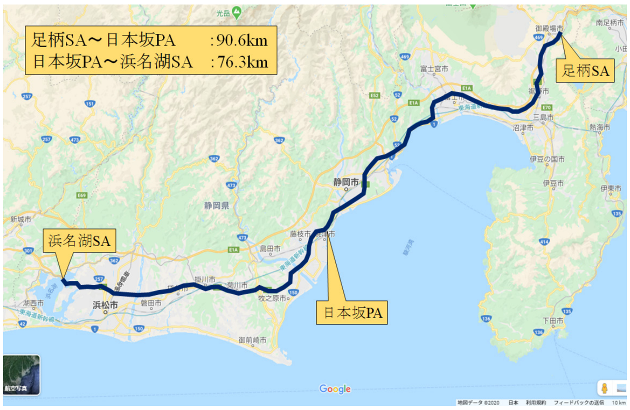

Fig.15 Driving route

Driving conditions

The experiments were performed on the 167-km road section shown in Fig.15. Experimental participants were grouped into down- and up-route drivers prior to the experiment. Both driver groups were stopped at Nihonzaka PA. The experiment participants drove unassisted on one day and used PP2.0 on the other. The driving modes on the first day were counterbalanced between the experiment participants. Under PP2.0 ON, the PP2.0 mode was applied for as long as possible (except for emergencies). Instructions were left that if the mode temporarily switched to OFF (e.g., due to traffic congestion or construction work), it should be returned to ON immediately after passing the section. The upper limit of the vehicle's speed was set to 100 km/h. Changing the vehicle's speed setting and overtaking were allowed within a safe range. For driving with PP2.0 OFF, participants were instructed to drive as usual at a guideline speed of 100 km/h.

Experiment participants

The experiments were inspected and approved beforehand by the Experimental Ethics Committee of Nissan Motor Corporation. The experiment participants consisted of 13 people ranging from their thirties to sixties (11 males and two females). Two of them had routinely used autonomous driving functions of Level 1 or higher, as defined by the Society of Automotive Engineers (SAE).

Moreover, the experiment participants were instructed to refrain from the following: drinking alcohol or staying up late on the day before driving, skipping breakfast on the day, and smoking, drinking anything besides water, or eating in the hour before driving.

Procedure

Once the experiments were prepared, the down-route drivers drove to Ashigara SA (the starting point of the down-route experiments); for this, no driving modes (PP2.0 ON/OFF) were applied. Upon arrival, they took a 15-minute rest before the experiment. First, their heartbeat fluctuations (at rest with eyes closed) were recorded for 2 min. The participants were instructed to mute any audio and to refrain from speech, excessive movement, deep breathing, and so on whilst heartbeat fluctuation was measured. Next, they drove to Nihonzaka PA according to the driving conditions of the day. Immediately after arrival, they measured their heartbeat fluctuation again. After completion, they drove to Hamanako SA. After arrival at Hamanako SA, they measured their heartbeat fluctuation in the same way, to complete the down-route driver experiments. After a 30-minute lunch break, they took a 1-hour rest in Hamanako SA. The up-route drivers were instructed to refrain from smoking, drinking anything besides water, or eating during the rest. Next, a similar procedure to that applied for the down-route drivers was performed, using Hamanako SA as a starting point. We decided to divide the data into first-half and second-half sections (with Nihonzaka PA as the mid-point) for analysis.

Results

The LF/HF and ccvTP results are shown in Figs. 16 and 17, respectively. The LF/HF was converted into common-logarithm decibel units. We conducted repeated measurement variance analyses for each of the two factors (i.e., PP2.0 ON and PP2.0 OFF × the driving section (first, second, and entire sections)). The interaction ($F = 8.96$, $p < 0.01$) was found significant for LF/HF, and the main effect of the driving condition ($F = 9.21$, $p < 0.05$) was found significant for ccvTP.

In the sub-effect test results for LF/HF interaction, the driving condition was identified as having a simple main effect in the first-half section ($F = 7.84$, $p < 0.01$), and the driving section was likewise found to have a simple main effect for both PP2.0 ON ($F = 4.02$, $p < 0.05$) and PP2.0 OFF ($F = 3.55$, $p < 0.05$). Meanwhile, in the ccvTP results, a simple main effect of the driving condition was only found to be significant across the entire route ($F = 7.05$, $p < 0.05$). Based on the above results, it was shown that, compared to PP2.0 OFF, PP2.0 ON had a significant calming influence on the autonomic nerve balance in the first section, whereas the ccvTP only indicated a significant difference in autonomic nerve activity over the entire route.

In the ccvTP results (Fig.17), the use of PP2.0 functions can be seen to reduce fatigue. In addition, the ccvTP results for PP2.0 ON tended to be high in both sections and similarly high over the entire route; thus, it can be assumed that fatigue was continuously accumulated from the first section, such that a significant difference

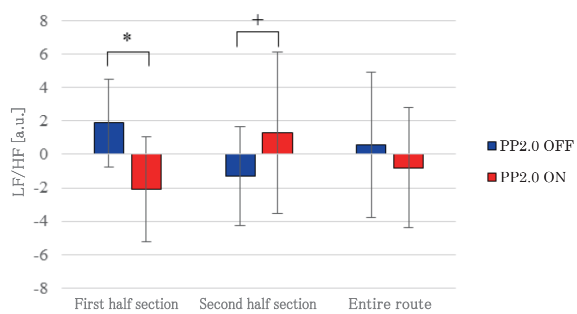

Fig.16 LF/HF comparison

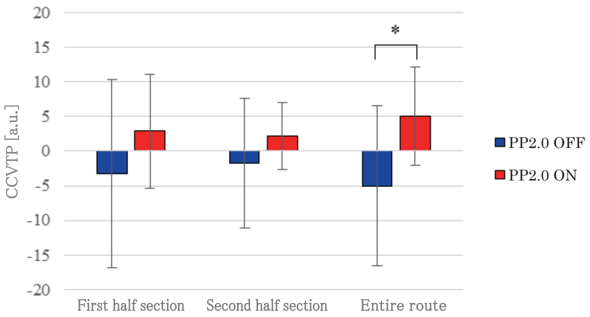

Fig.17 ccvTP comparison

appeared only after driving the entire route. Meanwhile, in terms of LF/HF, PP2.0 OFF and PP2.0 ON produced high excitation trends in the first and second sections, respectively (Fig.16). It is thought that LF/HF increases according to the acceleration of the sympathetic nervous system or the control of the parasympathetic one, and the long continuous acceleration of the sympathetic nervous system produces fatigue[3]. Thus, it seems that with PP2.0 OFF, the sympathetic nervous system was accelerated in the first section, leading to fatigue accumulation, and the parasympathetic nervous system was accelerated in the second section, which controlled the degree of fatigue accumulation. Meanwhile, with PP2.0 ON, the fatigue accumulation in the first section was small, so that the LF/HF for the second section showed a relative increase.

From these results, we confirmed that in long-distance driving using PP2.0 functions, fatigue accumulation was controlled to be smaller than that measured under normal driving. This suggest that under all traffic environments, PP2.0 can perform lane-change maneuvers with a feeling of safety and produce comforting vehicle behaviors, presenting no discrepancies to passengers.

5. Summary

As described above, Nissan Motor's experimental techniques were applied to set targets and evaluate the success of PP2.0 from the perspectives of dynamic performance, control technology, and human science. As a result, PP2.0 has been described by many customers and journalists as not only a convenient function but also as a "buddy"[6] [7] [8].

These results are primarily possible because of Nissan Motor's long-term accumulation of experimental techniques, which could not have been achieved in a short time. Finally, we would like to add that these results were achieved through considerable effort, involving the construction of the world's largest driving simulator (introduced above), a bench-test system of model-/hardware-in-loop simulations, integrated driving-vehicle measurement techniques, and large-scale data-analysis procedures.

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