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SIMULATOR STUDY ON DRIVER'S BEHAVIOR WHILE DRIVING THROUGH A TUNNEL IN A ROLLING AREA

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ABSTRACT

Driving-simulator (simulator) and real road (road) experiments were conducted to investigate effects of tunnels and other road structures on driving behavior. We measured driving behavior on a road with a tunnel using a 180-degree-view simulator with a hexapod motion platform. We validated the simulator experiment using measurements from an instrumented vehicle in the road experiment. The target tunnel was on a national route under construction in a rolling area. The road section including the tunnel was represented in the simulator using CAD data for the road design. The real road experiment was conducted before the road section was open to traffic. In the analysis, we focused on the accelerator stroke since it could be an index of the driver's stress while driving. In the experiments, we examined trips in different directions. We conducted the experiments both in daytime and nighttime conditions. Results showed that there was decrease in the accelerator stroke when the vehicle left the tunnel, for both directions, in the simulator and road environments, and in daytime and nighttime conditions. We observed this accelerator release just before entering the tunnel in the real road experiment, but only in one of two directions of the simulator experiment. We accounted for this difference by considering the difficulty of representing the dynamic range of the visual environment between inside and outside of the tunnel. This difference also suggested that not only the change in the visual environment but also the road structure affected this behavioral change. We also observed this change in accelerator control in the reverse curve and in the intersection. This suggested that the visually perceived road structure could be evaluated by drivers' behavior when using the simulator.

INTRODUCTION

Driving a vehicle on a road with a tunnel is one of the situations in which a driver's workload increases (1). When approaching a tunnel, the driver perceives the entrance as a dark hole because of the high contrast between the outside and inside of the tunnel, and it is not always easy to perceive the linearity of the road inside the tunnel. This happens particularly in mountainous areas because areas for straight-line construction are limited.

Since drivers feel stress when going through the tunnel, there have been many efforts to alleviate the driving workload. There are various design possibilities for a tunnel (e.g., entrance design), its road (e.g., linearity, width, and shoulders), and a driving assistance information system (e.g., delineators and guide signs) to reduce a driver's workload going through a tunnel. However, it is difficult to evaluate these designs on the road. A simulator that can represent tunnel and road design structure has a great advantage in assessing possible designs because they can be examined before they are actually constructed (2).

Subjective evaluation (e.g., subjective rating and a paired comparison) is a common way to assess the design of roads and other structures. This evaluation can be more valid if measures such as driving behavior can be quantified. It is difficult, however, to measure this driving behavior for evaluation in the real-road environment in traffic. Yet we can obtain the driving behavior under a well controlled traffic situation with a simulator. We can use the measured, behavioral data obtained by a driving-simulator study as a tool for design alternatives of roads and their structure. We can also apply the measured behavioral data to predict traffic flow on these roads. This is useful information for the road administrator. Therefore, we must validate the behavioral data obtained in the simulator study by comparing it with that obtained on the road. We conducted the driving-simulator experiment, in which subjects drove a vehicle along a rolling road with a tunnel, and we also conducted the road experiment with the tunnel that was represented in the simulator study. We then examined the behavioral data in the simulator study and that in the road study.

ROAD AND TUNNEL

Target Road and Tunnel

The road and tunnel examined were in a section of a national route that was under construction in a rolling area. (This is a hilly area between a flat area and a mountainous area. The road in this study is constructed along a river.) The road section was 1.9 km long from east to west and there was a tunnel in the middle of it. The tunnel length was 325 m, and there was a curve in it with R=500. The eastern exit of the tunnel was part of the transition section of the curve. The gradient of the road in the tunnel was 2.274% (upgrade) from the eastern end to the western end. There were left and right curves at both ends of the tunnel. There was a rock-shed (i.e., a concrete roof over the road for blocking falling rocks) of 56 m length at 380 m in the eastern end of the tunnel (for detail, see below). In the simulator, we duplicated the eastern end of the road section and connected it to the western end, so that the subject drove the road section twice in one trip, providing two behavioral data sets in one condition.

We developed the visual database according to the CAD data of the road under construction. The horizontal and vertical alignments of the road were rendered as designed. We also generated the structure of the tunnel according to the CAD data. The actual road as finally constructed was not exactly the same as its original design. They designed it with an intersection and traffic light at one of the curves, but changed the plan for several reasons. Thus, there was no intersection in the actual road.

Change of Brightness

The luminance design of the tunnel determined the distribution of brightness from the road surface in the tunnel. The visual image of the inside of the tunnel as seen from outside was dark, but we changed the image to a brighter one at distances less than 100 m. to simulate the effect of adaptation of vision when going into a tunnel. The illumination inside the simulator cabin darkened when the vehicle was five meters inside the tunnel to give an impression of the sudden change of environment. The illumination inside the cabin did not shine directly into the driver’s eyes.

For nighttime conditions, the brightness inside the tunnel was greater than that outside. We generated the distribution of luminance on the road surface according to the designed value of the luminance inside the tunnel nighttime conditions.

Change of Sound

The amplitude of the road and exhaust noises from other vehicles (produced by the sound system) increased when the vehicle was inside the tunnel to simulate the reflection of vehicle sound on the wall of the tunnel.

SIMULATOR EXPERIMENT

Hardware Configuration

The simulator used in the experiment was a high-fidelity, dynamic simulator with a hexapod motion platform (3). The cylindrical screen with a 180-degree field-of-view was fixed on the floor surrounding the motion platform (Figure 1). The maximum displacement of the motion platform was about 20 cm for longitudinal, lateral and vertical directions. The maximum tilting angle was about 12 degrees for pitch, roll, and yaw rotation. The

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maximum displacement velocity was 300 mm/second, and the maximum angular velocity was 20 deg/second. An actual the vehicle cabin was fixed on the motion platform. A subject in the cabin controlled the vehicle using the steering wheel, brake and acceleration pedals as in a normal car.

The audio system can present various sounds that can be heard while driving, including the engine and exhaust sounds from the driving vehicle and the road and exhaust noises from other vehicles. The vibration on the steering wheel and the cabin floor presented to the driver create the realistic impression of vehicle motion (4).

FIGURE 1 Driving Simulator.

Computers

We used aWindows-2000 host computer to calculate the vehicle dynamics according to the driver's control maneuvers and the traffic flow along the road. Another Windows-NT computer provided the servo system for the steering wheel. We used the SGI Onyx 2 with Infinite Reality2 engine (8 processors and 3 pipelines) for the image generator. With this image generator, images were updated at 60 Hz.

Vehicle Dynamics Model

The vehicle dynamics model used to simulate the user-driven vehicle was based on the magic formula tire model with a single body (5). The tires were connected to the body with four-wheel, independent suspension.

We determined the output torque of the engine by the amount of the acceleration stroke and the torque curve, and converted the engine torque into the driving force using the torque-converter model. We calculated the longitudinal and lateral force of the tire with the magic formula tire model, according to the slip ratio and the slip angle, thus obtaining the resultant force vector of the tire.

The user-driven vehicle was a front-wheel-drive vehicle. The weight of the vehicle was 1100kg, the maximum power of the engine was 73.5 kW (110 PS), and the maximum torque was 259 Nm (26.4 kg-m).

The gradient and cant angle (i.e., a lateral inclination that is a downgrade slope to the inside of the curve) of the road affected the vehicle-dynamics model of the simulator. The direction of gravity on the vehicle changed according to the gradient. The weight distribution ratio between left and right wheels changed according to the cant angle.

Steering Feel and Floor Vibration

The steering-feel control system realistically controlled reactions in response to driver input, vehicle motion, and road/tire interaction during vehicle maneuvers. The torque and force were controlled by the stepping servo-motor system, and changed as a function of velocity, front-wheel load, and road friction.

Experimental Procedure

Subjects were asked to drive the vehicle at 60 km/h, which was supposed to be the average speed on the actual road. They were to make one round trip to accommodate in the simulator environment before the recording sessions.

We examined two factors in the experiment. The first factor was the direction of the trip, so the subject drove both westbound and eastbound in order to examine the differences in behavior due to the direction of the road. The second factor was the time of the day, so the subjects drove both in daytime and nighttime conditions to examine the differences in the visual environment change (from bright to dark, or from dark to bright) when going through the tunnel.

We balanced the order of driving conditions among the subjects. Ten male subjects, ranging from 29 to 49 years of age, and from 4.6 to 28 years of driving experience, participated in the experiment. Since the subject drove the target road section twice in any one-way trip, we obtained twenty behavior data sets for each condition.

ROAD EXPERIMENT

Road Conditions

We conducted the driving experiment and recorded driving behavior on the road to compare the results with those obtained in the simulator experiment. Since the target tunnel and road section were under construction, we conducted the experiment a few days before the road was open to traffic. The dimensions of the road the same as those in the simulator. Figure 2 shows samples of the driver's view in the simulator and the road along the road section. We selected the illumination inside the tunnel and that for the road (in the nighttime conditions) to create the same conditions as those for public use.

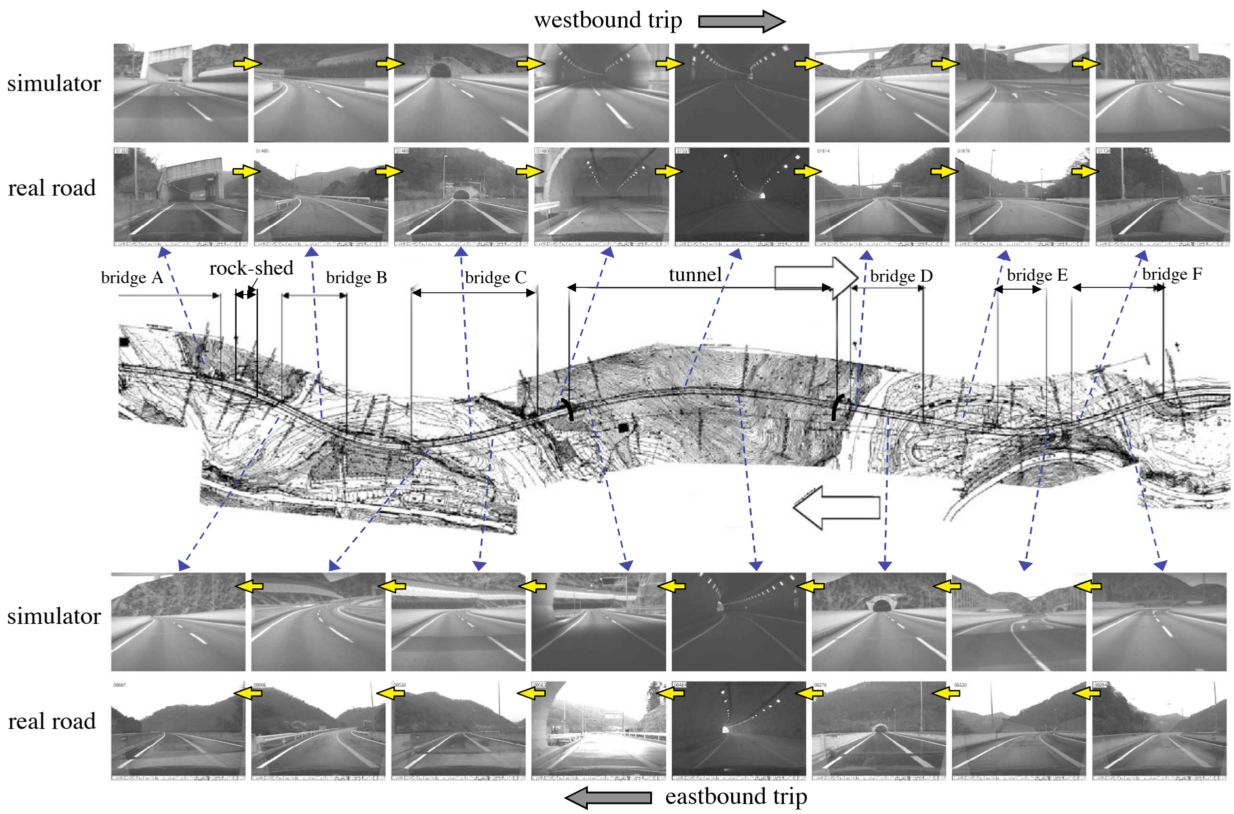

FIGURE 2 Driver's view in the simulator and the road environment.

The difference between the road section in the simulator and the real road was the existence of an intersection, as described earlier. When the road section was designed, there was an intersection 200 m from the western exit of the tunnel. In the simulator, there was a traffic signal at that point and the road width was split into three lanes; one for eastbound, one for right turn in the westbound, and one for going straight in the westbound. Before and after the intersection, the central line was painted yellow indicating that passing was prohibited in this section. There was no intersection at that point on the actual road because the road administrator had decided not to build the intersection, for several reasons. Therefore, the road width was split into two lanes. The central line was painted yellow from start to end of the actual road section to prohibit passing in that section. Regulatory signs (e.g., signs for speed limit) were not yet installed in the road.

Measuring Driving Behavior

Instrumented vehicle

We developed vehicles with a driving-recorder system. The system consisted of various sensors, small CCD cameras, a signal-processing device, and a laptop computer. We designed and installed vehicle instrumentation to be as unobtrusive as possible to encourage natural driving behavior (Figure 3). We recorded the sensor data at 30Hz, and recorded images from the cameras at 8 Hz.

FIGURE 3 Drive recorder system in the instrumented vehicle.

Added encoders on the wheel and levers detected steering wheel angle, turn signal, and wiper activation as manual operations. Potentiometers sensed and measured the stroke of the brake and accelerator pedals as foot operations.

A D-GPS sensor indicated the geographical position of the vehicle. A six-axis G-sensor and a gyro sensor detected the state of the vehicle. A pulse signal from the wheel speed sensor indicated the speed of the vehicle. Accumulated detected speed provided the trip distance. We measured the distance and speed relative to the leading and following vehicles using two (front/rear) laser radar units fixed within the bumpers. A small CCD camera, fixed on a door mirror and directed toward the road surface, detected a line on the road to measure the lateral position of the vehicle within a lane.

The vehicle was a front-engine, rear-wheel-drive, mid-size car (TOYOTA PROGES NC250). It weighed 1.52 tons and its engine displacement was 2.5 liters. The maximum power of the engine was 147 kW (220PS) and the maximum torque was 294 Nm (30 kg-m). We developed the instrumented vehicles to collect data about driving behavior on an actual road and to establish the driving behavior database (6). We used this vehicle for our experiment, so the dimensions and engine performance of the instrumented vehicle were not the same as those in the simulator.

Experimental Procedure

The same ten subjects who participated in the simulator experiment did two round-trip drives during the daytime along part of the new road section including the tunnel. The eastern end point was 610 m from the eastern exit of the tunnel. The western end point was 495 m from the western exit. The total distance of a one-way trip was 1,425 m. One trip extended from the eastern end point to the western end point, where the driver made a U-turn, and started again from the western end point to the eastern end point. The other trip went the opposite direction.

Half of the subjects first drove from the eastern end point and then drove from the western end point. The other half of the subjects first drove from the western end point to cancel the ordering effect. We asked them to drive the vehicle at 60 km/h.

After dark, we conducted the nighttime experiment. The procedure was the same as the daytime experiment, but only six of the ten subjects did two round-trip drives due to the limited time. The weather on the day of the experiment consisted of a little rain but no fog.

RESULTS OF ANALYSIS ON DRIVING BEHAVIOR

Simulator Environment and Road Environment

We explain the road design in detail before describing the results of the experiment for help for understanding (Figure 4). For the westbound trip, the road was an upgrade of 1.12% with a slight right curve (R=800 m) at the start point. The radius of the right curve decreased to 280 m, and there was the rock-shed. The gradient then decreased and became negative (downgrade). There was a reverse curve from right to left just before the gradient reached the steepest downgrade level (1.6%). During the left curve (R=200 m), the gradient changed from a downgrade to an upgrade (i.e., sag). The gradient reached 2.5% and stayed at that level for 130 m. The gradient then decreased to 2.27%, and it stayed at this level for 610 m. There was a slight right curve (R=500 m) after the left curve.

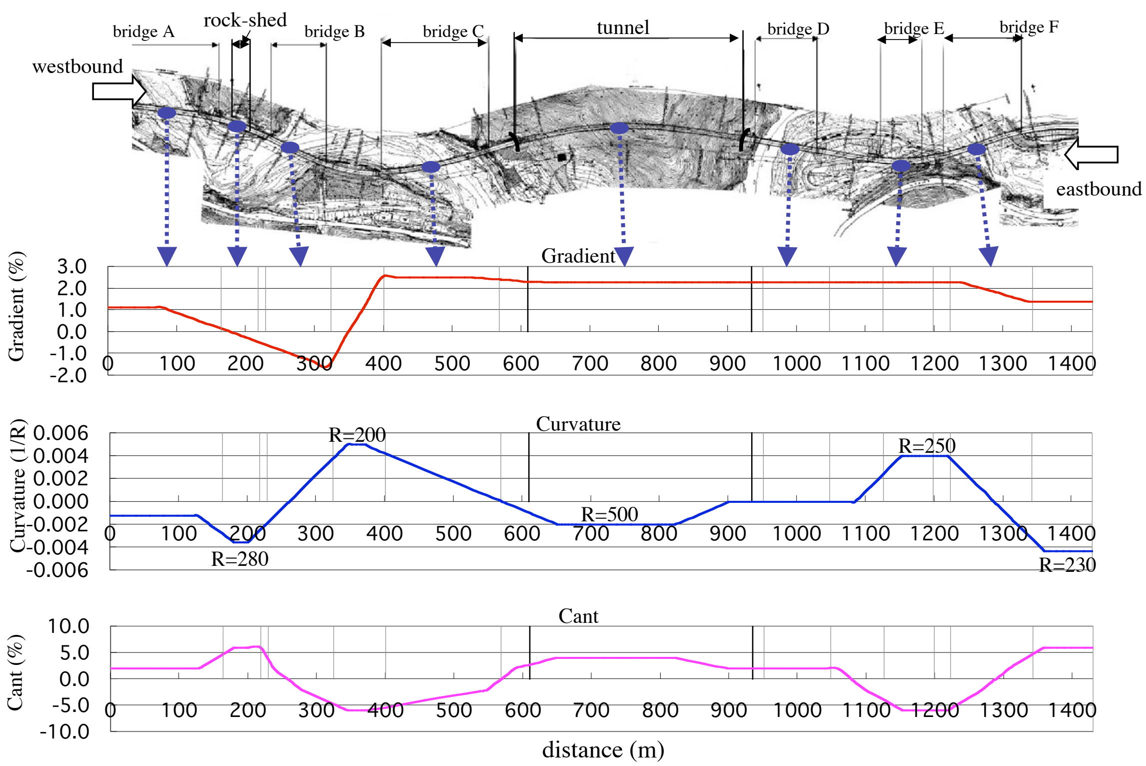

FIGURE 4 Top view, vertical profile, curvature and cant of the road section

The tunnel started right after the gradient became 2.27%. The eastern end of the tunnel was positioned along the transition section of the right curve. About 200 m of the right curve (R=500 m) was in the eastern part of the tunnel. The transition section in the tunnel followed, for 100m, and then the road became straight before the western exit of the tunnel. The distance of the straight part was about 30 m. After the tunnel exit, there was a left curve (R=250 m) followed by a right curve (R=230 m). In the simulator, there was an intersection with a traffic signal at the middle of the left curve. However, there was no intersection at that place on the actual road.

There were several points for analysis of the behavioral differences along the road section. For the westbound trip, the first point was the rock-shed. The second point was the reverse curve after the rock-shed because there was a sag in the reverse curve. The concurrence of the reverse curve and the sag could make the driving difficult. The third point was at the tunnel. There was stress here for drivers since there was both a curve and a gradient in the tunnel. The fourth point was the intersection that existed in the simulator environment but not in the real one. For the eastbound trip, the effect of the downgrade was marked in addition to the above points.

Driving behavior was analyzed in speed, pedal and steering control. In this paper, we compared the speed-control maneuver because speed control could be affected by the driver's stress level. We focused on the accelerator maneuver as the speed-control maneuver because the speed itself was less sensitive and nobody used brakes along the target section. The following figures present the experimental results as the mean plus or minus the standard deviation of the accelerator stroke (or the vehicle speed for figure 6) along the road. These statistics were calculated from the data obtained from two repeated drives by the 10 subjects (20 data sets in total) for both daytime and nighttime conditions in the simulator experiment. In the real road experiment, they were obtained from the data from two repeated drives by the 10 subjects for the daytime condition (20 data sets in total) and by the 6 subjects for the nighttime condition (16 data sets in total).

Comparison of Accelerator Control Behavior For Westbound Trip In Daytime Conditions

Rock-shed

There was a rock-shed 164 m from the eastern end of the road section. The accelerator stroke decreased when going through the rock-shed in the simulator environment (Figure 5, arrow A), beginning about 50 m before the rock-shed and possibly triggered by approaching it. However, we could also account for the decrease because it occurred at the same point that the gradient decreased from +1.12% upgrade to a downgrade. It was thus difficult to determine a single cause for the decrease. In the road environment, the stroke of the accelerator decreased 50 m before the rock-shed and stabilized closer to the rock-shed. The trip started 200 m before the rock-shed, and the first increase of the accelerator for 100 m was to increase the vehicle speed to the target speed. Therefore, it is difficult to clearly see the effect of the rock-shed and the gradient change in the road environment.

Sag and reverse curve

After the rock-shed, the transition section of the right curve was followed immediately by the transition section of the left curve (i.e., reverse curve). During the left curve, the gradient changed from downgrade to upgrade (i.e., sag). Just after negotiating the rock-shed, there was a clear decrease in the accelerator stroke in the simulator experiment (Figure 5, arrow B). A similar, clear decrease was also observed in the road experiment. As shown in Figure 2, the driver could see the left curve and the inclined road at the point where the driver released the accelerator. Perceived visually, the complex road structure affected the accelerator control both in the simulator environment and in the road environment.

Tunnel

Before entering the tunnel The accelerator stroke increased before the tunnel in the simulator experiment, to maintain the speed because the road became an upgrade. The accelerator stroke remained almost constant in the road experiment. We accounted for this difference by the difference in vehicle performance for each experiment, because the vehicle speed in the simulator experiments decreased even when the accelerator stroke increased. In contrast, the speed was remained in the real road experiment (Figure 6, arrows A and B). The vehicle in the simulator was a small car with a small engine, and the vehicle in the road experiment was a mid-sized car with a

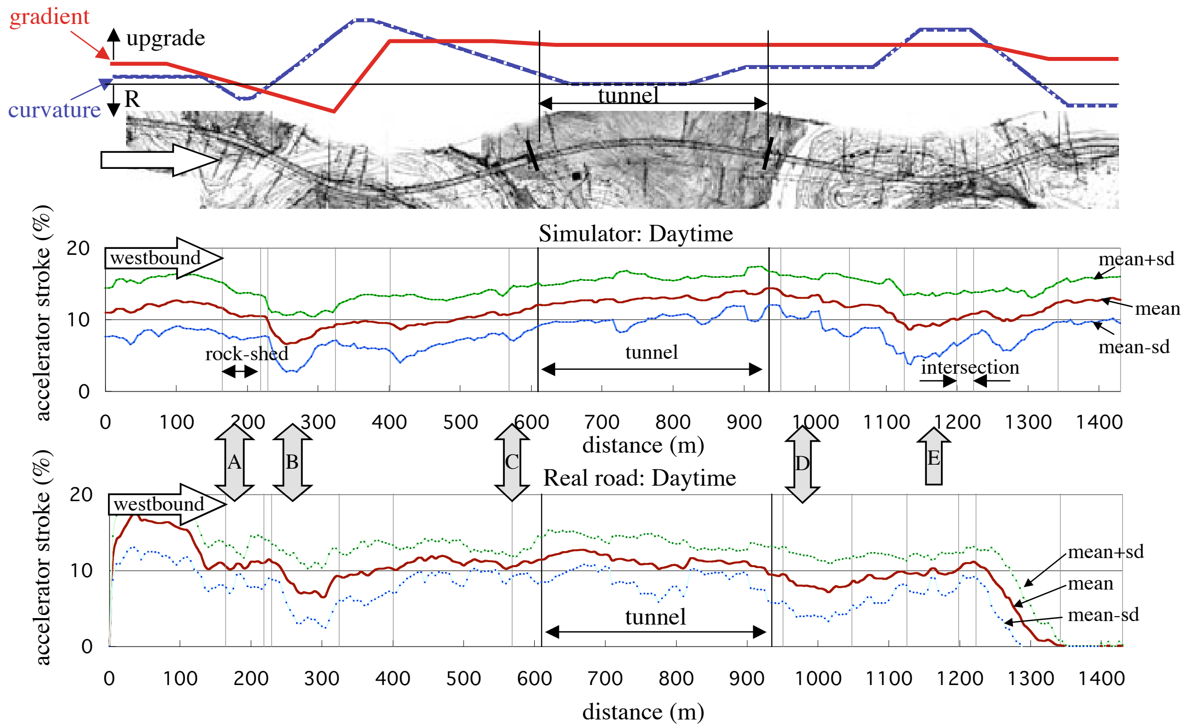

FIGURE 5 Accelerator stroke for the westbound trip in daytime conditions

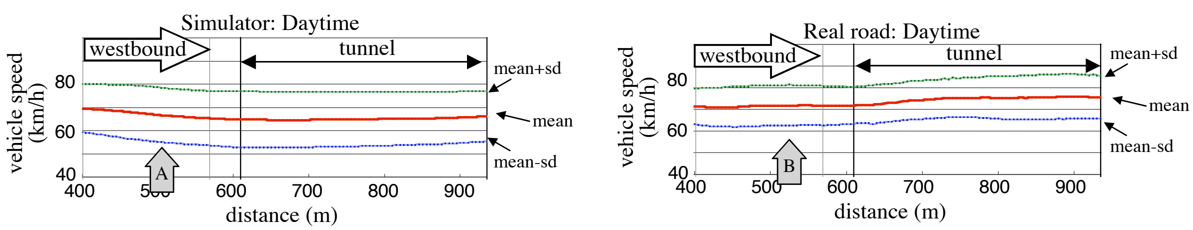

FIGURE 6 Vehicle speed before and along the tunnel for the westbound trip in daytime conditions.

powerful engine. It was necessary to increase the stroke of the accelerator to maintain speed on the upgrade with the small engine, but not as necessary with the powerful engine.

When entering the tunnel When we focused on the maneuver just before entering the tunnel, there was a small decrease in the accelerator stroke about 50 m before the tunnel in the road experiment (Figure 5, arrow C). This might represent driving stress before entering the tunnel based on mental stress or hesitation on entering a tunnel with a different visual environment from that on the outside. In addition to the difference in brightness, the eastern end of the tunnel was in part of the transition section of the right curve. When approaching the tunnel, the wall of the tunnel was facing the driver. The mental stress of entering the tunnel might be higher than that for tunnels on straight roads. A decrease of the accelerator stroke was also observed in the simulator experiment, but the decrease was not as remarkable as for the road experiment.

While traveling through the tunnel The accelerator stroke gradually increased along the tunnel in the simulator environment, but it remained almost constant along the tunnel in the real environment (Figure 5, middle). We accounted for the difference in the tunnel by the difference in vehicle performance for each experiment. Another possible explanation was a lack of feeling oppressed by the tunnel wall in the simulator environment. When we analyze the vehicle speed in the tunnel, we found that the speed was kept constant along the tunnel in the difference was almost constant in both conditions although the speed is 20 to 30% higher in the road experiment (Figure 6). Since the vehicle speed was determined by both the driver's accelerator control and the vehicle properties, the driver had to press the accelerator to maintain the speed when driving the vehicle with a small engine. A similar phenomenon was observed before entering the tunnel, so the behavioral difference could be explained by the vehicle performance.

When exiting the tunnel The accelerator stroke decreased when exiting the tunnel in the simulator experiment. The gradient was constant and the road was straight at the western end of the tunnel (Figure 5, arrow D). Therefore, we believe the change in the accelerator stroke was based on the driver's behavior as affected by exiting the tunnel. We observed a similar change in the road experiment. Driver stress when entering a tunnel is caused by stress due to the limited size of the tunnel opening. Thus, exiting a tunnel seems to be the situation where the stress is relieved. The accelerator decrease observed in both experiments suggests that the driver's behavior was affected not only by stress from the tunnel entrance but also by the environmental change, from tunnel to open road.

Intersection with traffic light

There was an intersection with a traffic light in the simulator environment about 200 m from the western exit of the tunnel. The accelerator decreased remarkably before the intersection (Figure 5, arrow E). The timing of the onset of this decrease could be estimated as 100 m before the intersection. Since the traffic light remained green throughout the experiments, the subjects would not expect the light to change to yellow or red. Therefore, the accelerator decrease was not preparatory behavior for a changing traffic light. In addition to the traffic light, the lane narrowed before the intersection due to a traffic island with road markings. The traffic island was designed to reserve a lane for a right turn (driver's side turn). The complex intersection structure could be the cause of the behavioral change in accelerator control. In the road environment, there was no intersection at this point, and no change of the accelerator stroke occurred. This also supports our interpretation that the intersection affected the accelerator control in the simulator experiment.

Comparison of Accelerator Control Behavior for Eastbound Trip in Daytime Conditions

Effect of intersection with traffic light

Most of the eastbound trip was downgrade, except at the sag point close to the eastern end. The western end point of the eastbound trip was in part of the left curve. After starting from the western end, there was a transition section from a left to a right curve. The drivers could see the intersection positioned in the right curve when they came to the transition section in the simulator environment (see Figure 2). There was a remarkable decrease in the accelerator stroke at that point (Figure 7, arrow A). The accelerator stroke started to decrease about 100 m before the intersection. This position was the opposite of the place on the other side of the intersection, where the drivers released the accelerator in the westbound trip. In the road experiment where the intersection did not exist, the accelerator stroke did not decrease. These findings prove that the visual information of the intersection triggered the accelerator release.

Effect of the tunnel

When entering the tunnel Before entering the western side of the tunnel, the acceleration decreased in the road environment, as was observed when entering the tunnel in the westbound trip. However, this was not observed in the simulator environment (Figure 7, arrow B). The western side of the tunnel was on the straight part of road. Therefore, driver stress when entering the western side of the tunnel was less than that entering the eastern side of the tunnel. Even in the westbound trip, the decrease in the simulator environment was not as remarkable as that on the road.

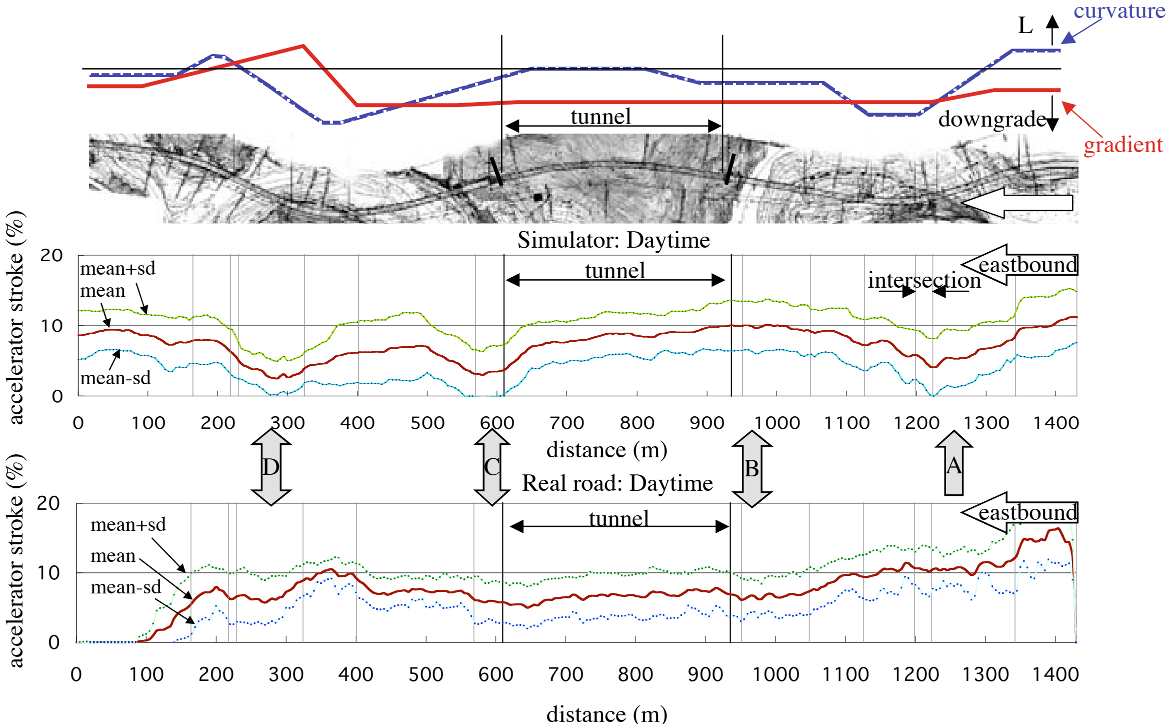

FIGURE 7 Accelerator stroke for the eastbound trip in daytime conditions

While traveling through and exiting the tunnel The accelerator stroke decreased while running in the tunnel both in the simulator and the road experiments as adaptive behavior to the downgrade. We observed that the effect of the downgrade was reproduced in the virtual environment. When exiting the tunnel, there was a remarkable accelerator decrease in the simulator (Figure 7, arrow C). This was the same phenomenon observed when exiting the tunnel in the westbound trip. Although the acceleration decreased in the road environment, the amount of the decrease was not as clear as that in the simulator environment. In observing individual trips, the accelerator stroke stayed at a certain level (5% to 15%) while going through the tunnel in the simulator environment but often dropped to 0% while going through the tunnel in the road environment. Since the vehicle was heavier in the road experiment, the drivers more often released the accelerator while running through the tunnel to maintain speed in the downgrade. As acceleration sometimes dropped to zero in the tunnel, the onset of the behavioral change observed in the average value when exiting was unremarkable in the road experiment.

Effect of sag and reverse curve

Before arriving at the eastern end, there was a section combining a sag and a reverse curve. The drivers released the accelerator when going through this section both in the simulator and road environments for the westbound trip. We observed a similar phenomenon in the eastbound trip under both conditions (Figure 7, arrow D). The acceleration dropped to the minimum, 70 m after the center of the sag and 20 m before the center of the reverse curve (1/R=0) for the eastbound trip. For the westbound trip, this was 100 m before the center of the sag and 20 m before the center of the reverse curve. Although we could not separate the effect of the sag and the reverse curve from the data in the westbound trip, by combining the findings from both trips, we concluded that the accelerator release was caused by the reverse curve, not by the sag, since the results were symmetrical to the center of the reverse curve.

Comparison of Daytime and Nighttime Conditions

Difference of the accelerator operation in the westbound trip

We compared the acceleration during the westbound trip in the simulator for nighttime conditions with that in the road experiment. The overall pattern was the same as that on the road. The accelerator stroke decreased when entering and exiting the tunnel (Figure 8, arrow B and C). Contrary to daytime conditions, the illumination inside the tunnel was brighter than that outside. However, the accelerator release was the same as observed in daytime conditions. This suggests that the drivers were stressed entering a place where the environmental conditions changed, both from bright to dark and from dark to bright.

The effect of the reverse curve and the intersection was also the same as observed in the daytime condition (Figure 8, arrow A and D). These road structure could be perceived visually even in the nighttime condition.

Difference of the accelerator operation in the eastbound trip

In the road environment, the acceleration change along the eastbound side under nighttime conditions was the same as that of the daytime conditions, with accelerator release when entering and exiting the tunnel (Figure 9, arrow A and B). As we observed in the westbound trip, the drivers had stress when environmental conditions changed. In the simulator experiments, although we observed this phenomenon in the westbound trip, there was no acceleration decrease when entering the tunnel in the eastbound trip even under nighttime conditions, as that of the daytime condition. As described earlier, the driver's stress thus might be lower in the eastbound trip and may explain why we did not observe the same decrease in the eastbound trip also in the nighttime condition.

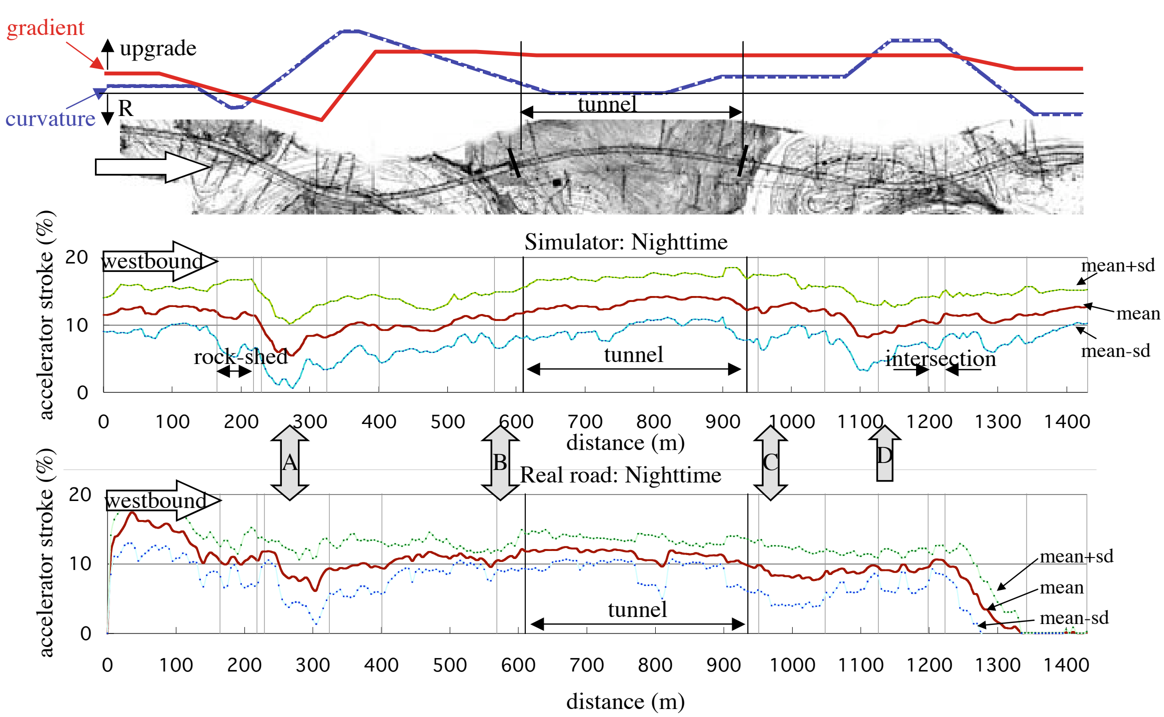

FIGURE 8 Accelerator stroke for the westbound trip in nighttime conditions

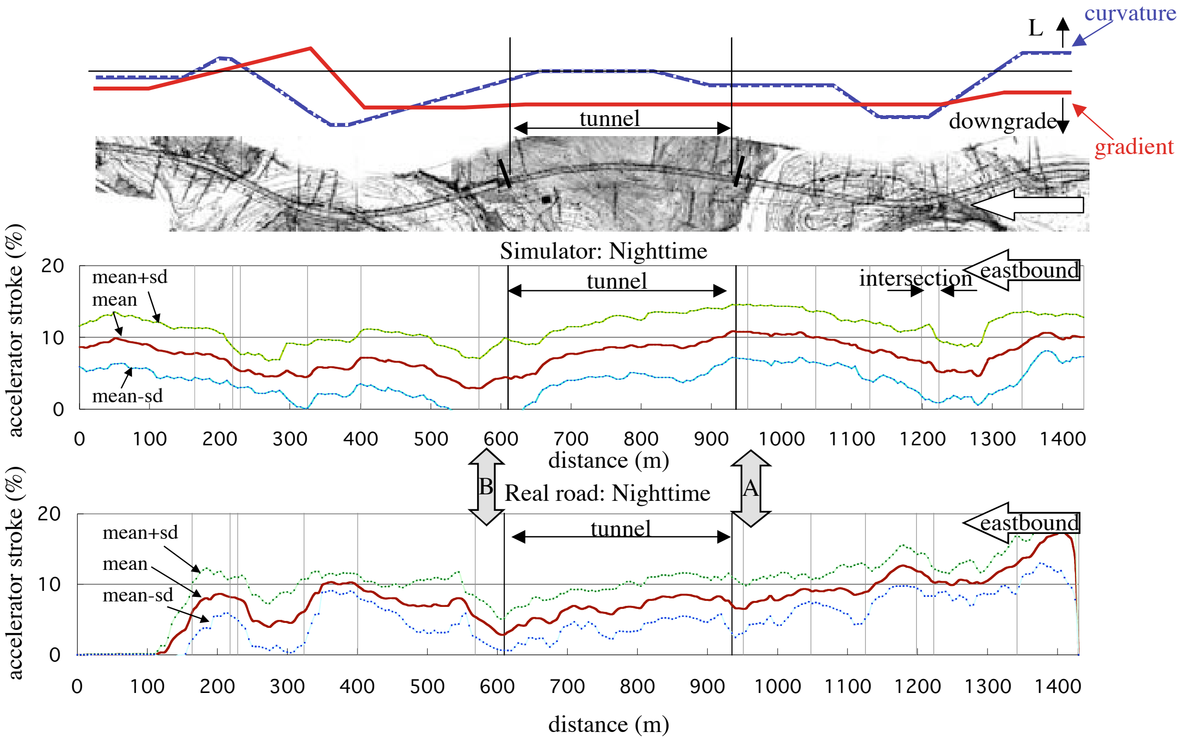

FIGURE 9 Accelerator stroke for the eastbound trip in nighttime conditions

DISCUSSION

The simulator was a good tool to subjectively evaluate candidates for tunnel design (1) and guide sign design (7). We can obtain objective measures of driving ability as well as subjective reports from the simulator study. Since the behavioral measure is persuasive evidence in evaluation, the simulator can be a powerful tool for evaluating roads and their structure. Therefore, we conducted a series of experiments to measure driver behavior in the simulator and road environments, and compared them in order to investigate the possibility of using the simulator to objectively evaluate roads and their structure.

We used the common subject group both for the real road experiment and the simulator experiment. This is the condition for which the most consistent results could be obtained. However, a sample of ten is a small number of subjects for evaluating the road structure because the road user population is much higher. Therefore, a larger number of subjects is necessary for evaluating the road structure and the driving assistance system. However, it is difficult to obtain a large number of subjects, mainly because of availability of the real road for the evaluation and the difficulty in keeping the experimental conditions constant. However, a large number of subjects can be used for the simulator experiment because the simulator can provide the same experiment conditions every time. From this point of view, there is a great advantage in using the driving simulator.

In this study, we focused on the accelerator operation as a quantifiable measure. The accelerator control combined with the gradient of the road was the main factor for change in vehicle speed while driving in at a relatively constant speed. The speed change could be an index of a driver’s stress or feeling of risk because that is when drivers tend to reduce speed. The speed change is also important for traffic control because it can be a trigger for unstable traffic flow. We compared the accelerator control between the simulator and the road, between the westbound trip and the eastbound trip, and between daytime and nighttime conditions. Using these comparisons, we analyzed behavioral characteristics of driving in a tunnel in a rolling area, and we investigated the validity of the simulator for evaluating the road structure. From the behavioral data, we found that acceleration decreased when the driver entered or exited the tunnel in the road experiment in the westbound and eastbound trips. The decrease of accelerator stroke observed here was a similar finding to the vehicle speed change in the entrance zone of tunnels on a highway in Germany (8). However, they did not report about the speed change in the exiting zone of tunnel. Difference between a highway and a road in rolling area might be a reason for the difference in driving behavior.

We observed this phenomenon in both daytime and nighttime conditions on the road. Therefore, we believe the visual environmental change, from bright to dark or from dark to bright, gave stress to the drivers and affected the accelerator control. In the simulator experiments, we observed the accelerator decrease when the vehicle exited the tunnel. We found this behavioral change in both the westbound and eastbound trips for daytime conditions. However, when entering the tunnel, we observed only a small accelerator decrease in the westbound trip, and none in the eastbound trip. The failure to observe the same phenomenon in the simulator environment could be due to lack of sufficient representation of the change in the visual environment. The dynamic range of brightness on the road was much higher than that in the simulator environment. The dynamic range should be compressed within the range of intensity for the projector in the simulator environment, therefore, we could not make the tunnel entrance realistic enough to observe the same behavioral changes.

It is interesting that the behavioral change was the same in the westbound trip but not in the eastbound trip in simulator conditions. Since the difference between the trips was in the gradient and the curvature of the road, it means that both the change in brightness and the curvature and gradient affected the behavioral change. When the visual environmental factor and the road structure factor were combined, the same behavioral change in the simulator was observed in the real environment. This suggests that, even in the simulator environment, when the driving stress reached a certain level, the behavioral change appeared as the same as it did on the road.

We also observed in the reverse curve the behavioral changes that were caused by the road structure, apart from the tunnel. Release of the accelerator was the behavioral change on the road at the point where the reverse curve and the sag were combined. The combination of reverse curve and dip might affect the driver's behavior, however, analysis of timing of the accelerator decrease, in both directions, showed that the release occurred when the vehicle approached the reverse point of the curve. This proved that the reverse curve, not the sag, caused the behavioral change. Although the sag generally affects driving, the behavioral analysis showed that the reverse curve strongly affected the driver's behavior in this section of road.

The intersection in the western part of the road section in the simulator did not exist in the road environment. The measured behavior showed that the accelerator decrease occurred only in the simulator environment. By this comparison, we showed that the existence of the intersection affected the driver's behavior. It is not yet clear whether the cause was the intersection itself, the traffic island, or the changes in the road width. Simulator experiments using different intersection designs will be able to identify the affecting factor.

Since behavioral changes at the reverse curve and the intersection were observed in the simulator environment, road structures that drivers can visually perceive affected the drivers' behavior in the simulator. This suggests that the simulator can be a good tool for evaluating visually perceived road structures. Good replication of the driving behavior in the simulator environment means that the road structure was well reproduced in the simulator. Therefore, the driving simulator can also be applied to evaluate driving assistance information systems installed in the road. Various on- road assistance systems, such as the variable message signboard (VMS) and the sensor-based delineator systems, have been proposed to improve traffic safety and traffic flow. The proposed systems should be validated using driving simulators before installing them along the road. The optimal information content, method of information presentation, and position of the information display can be specified without constructing the actual system. The driving simulator is thus useful for assessing future Intelligent Transportation Systems.

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