System Evaluation Test of Global Navigation Satellite System-based Road Pricing System

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An autonomous road pricing system charges according to the charging points that the car has passed and the travel distance, based on location information provided by the Global Navigation Satellite System (GNSS). It is expected that this system will solve problems related to automobile traffic through the reduction of economic loss due to traffic congestion, the lowering of environmental burden, the recovery of road maintenance costs, etc. In order to bring an autonomous road pricing system into practical use, it is necessary to obtain the trust of stakeholders including drivers. This is achieved by demonstrating that the system can levy charges consistently and stably regardless of the travelling patterns or positioning errors that may be magnified depending on the environment. Mitsubishi Heavy Industries, Ltd. (MHI) has been enhancing the reliability of charging functionality through the improvement of positioning accuracy with use of the dead reckoning and map matching methods. Furthermore, MHI has recently improved the reliability of the system from the driver's perspective by eliminating inconsistencies in the position/timing of indicating and informing the driver of the charge. The developed system has been field tested widely on public roads (expressways, general roads, in urban and rural areas, etc.) in Singapore where MHI aims to put this system into practical use, and has confirmed that its reliability and accuracy are sufficient therefore.

1. Introduction

As a road pricing system designed for the reduction of traffic congestion and toll collection, the DSRC (Dedicated Short Range Communication) system is widely used. However, the DSRC system requires equipment including radio communication antennas for each point where the charging is performed, and is not suitable for accurate charging at multiple points and frequent road changes subject to tolls depending on the traffic congestion conditions.

On the other hand, an autonomous road pricing system using Global Navigation Satellite System technology has the advantages of being able to charge accurately according to the travel distance and easily change the toll setting. Therefore this system is attracting attention as a method not only for the alleviation of traffic congestion, but also for the collection of road maintenance costs to replace the fuel tax.

In fact, autonomous road pricing systems have been increasingly introduced in European countries including Germany[1] and Slovakia[2]. These introductions aim to collect road maintenance costs. The rough traveling routes and distances travelled by heavy vehicles can be identified and accumulated, and tolls collected later.

In Singapore, there is a move to replace Electronic Road Pricing (ERP), which is a tolling method using the DSRC system that has been used for the alleviation of traffic congestion, with an

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autonomous road pricing system. The reasons include the reduction of roadside equipment and the elimination of unfairness felt toward charging points. For this "congestion charging," it is necessary to charge on certain roads and areas where the alleviation of traffic congestion is desired while informing drivers accordingly. Satisfying stricter conditions related to accuracy on roads subject to toll, the correctness of charging, real time information capacity (accuracy of indicating position), etc., is required in comparison to prior European examples. It is also necessary to assure the correctness and reliability of the enforcement system in order to maintain the operation.

MHI, the supplier of the ERP system currently used in Singapore, has been developing an autonomous road pricing system that meets globally unprecedented demanding requirements.[3][4] Aiming at practical application, MHI performed a large-scale evaluation test to verify the functions and reliability of the entire system in Singapore in 2012. In this evaluation test, the system was exhaustively tested based on the performance indicators for each of charging accuracy (checking if the correct toll is levied), charge display timing (checking if the driver can be informed of the charged amount without geographical variation around charging points), and detecting illegality (checking if illegalities such as vehicles having no onboard unit can be found).

2. Overview of Autonomous Road Pricing System

The autonomous road pricing system levies charges according to the charging points that the car has passed and the travel distance, based on location information provided by the On-Board Unit (OBU) mounted on a vehicle. This system consists of four subsystems: the Central Computer System (CCS) that collects information as shown in **Figure 1**, the Enforcement System (ES) that detects illegality, and the Roadside Unit (RSU) antenna that transmits and receives traffic and location information to and from vehicles, in addition to the OBU. An overview of the subsystems is described below.

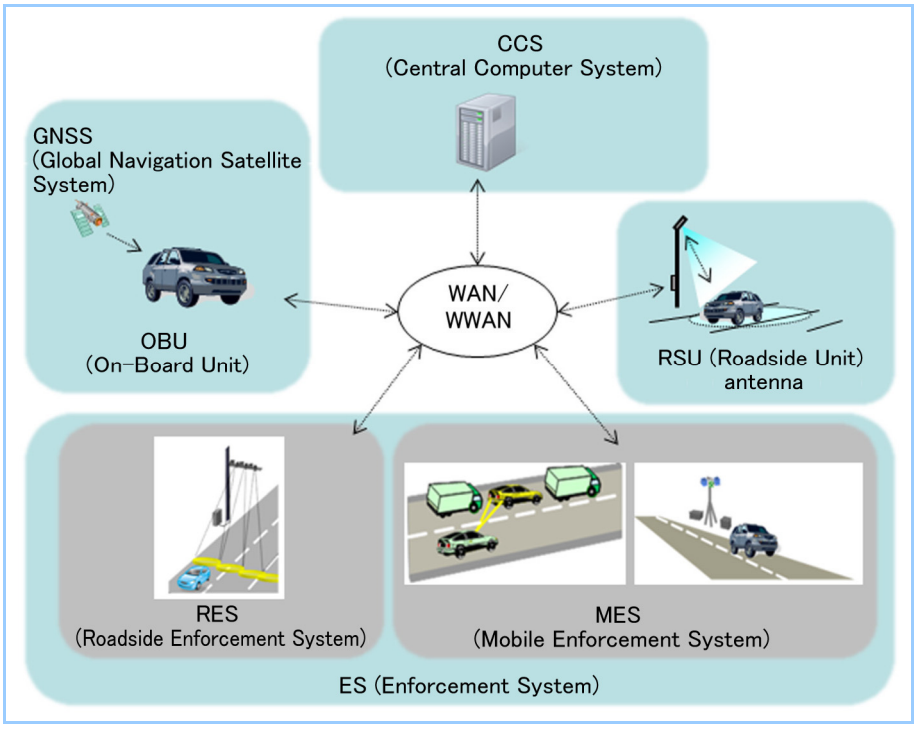

Figure 1 System diagram

2.1 OBU (On-Board Unit)

The OBU is mounted within a vehicle and performs charge levy processing independently based on the positioning results. It also transmits information about the charging result and the vehicle location to the CCS. In order to attain stable charging regardless of variations in the GNSS signal, the OBU has acceleration sensors and gyroscopes, and information from the sensors is used for estimating position with GNSS information to improve positioning accuracy. The use of this technology is referred to as the dead reckoning method. Using map matching (technology for associating location information with a digital road map) of the obtained location information, the

travel route and the charging points that the car has passed are determined on the map, and then charging is performed. In addition, the processing time needed is compensated for by predicting the vehicle location after several seconds, and therefore the user can be informed when passing a charging point without delay.

2.2 CCS (Central Computer System)

The CCS is a central system that transmits and receives information to and from each subsystem. To and from the OBU the CCS receives charges levied and transmits a schedule of charges. From the ES the CCS receives monitoring information to summarize violations. From the RSU the CCS collects vehicle information based on the results of communication with the OBU and transmits traffic information to the OBU to guide vehicles to less congested roads to support comfortable driving.

2.3 ES (Enforcement System)

The ES has two types as shown in Figure 1: The Roadside Enforcement System (RES), which is a fixed monitoring system on the road, and the Mobile Enforcement System (MES), which is a simple monitoring system using monitoring equipment mounted on a vehicle or the road shoulder. Both types have a license plate number recognition function and a communicating function with the OBU through the DSRC, and check the obtained information to detect violations such as the failure of charging due to the lack of a stored value card being inserted into OBU.

2.4 RSU (Roadside Unit)

The Roadside Unit (RSU) is communication equipment installed on the roadside that transmits traffic information and positioning augmentation signals to vehicles/OBU passing by. The positioning augmentation signal provides location and road information to the OBU when the vehicle is in a high-rise area where GNSS positioning accuracy worsens or at a branch where the determination of actual location is difficult with only location information. The RSU is also used to collect traffic information from the OBU.

3. System Evaluation Test

In 2012, MHI performed a large-scale system evaluation test over a period of 7 months in Singapore to confirm that its functions, accuracy and reliability were sufficient for practical operation.

3.1 System Function Test

This test aimed to verify that the autonomous road pricing system satisfied the functional requirements of the pricing on traffic congestion, and was performed in a limited area in Singapore using a several hundred meter-long, three-lane test road (**Figure 2**). In this test, the charging, the enforcement and the back end system were function-tested under various assumed conditions over a period of 5 months as noted below.

Figure 2 System function test

- Test of compatibility for all vehicle types (passenger vehicles, motorcycles, heavy vehicles, double-decker buses, etc.)

- Tests with more than 100 combinations of driving patterns, driving speeds and driving formations of multiple vehicles.
- Evaluation of real time performance of the indicating of charges levied on the OBU display and the transmitting of results to the CCS at charging points
- Night driving test (to achieve a system performance level the same as daytime driving)

A total of more than 300 driving test scenarios were performed, and it was verified that the system was sufficient for practical operation.

3.2 System Reliability Evaluation Test

Following the system function test, the system was field tested on public roads in Singapore over a period of two months to evaluate its reliability.

The enforcement function was tested by installing the ES on a road with heavy traffic consisting of trucks and passenger vehicles. Vehicles equipped with the OBU ran among the normal traffic flow and the reliability of illegality detection/determination was evaluated quantitatively.

The positioning accuracy and the charging reliability were tested by driving through multiple test areas sampled from public roads such as a cluster of high-rise buildings, an elevated road, a tunnel, etc., in order to confirm reliability under conditions of varying GNSS signal environment and traffic flow. The next section explains the results and details of this evaluation.

4. System Performance Evaluation

4.1 Testing Environment and Performance Evaluation Method

(1) Test Courses

To cover various road traffic conditions, evaluations were performed in the five selected test areas as shown in **Table 1**. Vehicles equipped with the OBU ran among general vehicles and positioning/charging accuracy was evaluated under realistic driving conditions similar to actual use, including the driving speed, driving lane, etc.

Table 1 Overview of Test Environments

Environment		Characteristics
Tunnel		- Unable to receive the GNSS signal - The charging point is set just after the end of the tunnel
Cluster of high-rise buildings		- Positioning errors occur due to reflection of the GNSS signal - Frequent stops and starts in rush-hour congestion
Underneath an elevated expressway		- Necessary to distinguish between the elevated expressway and the general road underneath it, both of which run in parallel - Charging points are set on both the elevated expressway and the general road underneath it
Suburbs		- Good receiving sensitivity of GNSS - Wide and narrow roads coexist - Roads are intricately tangled
Expressway		- Excellent receiving sensitivity of GNSS - Correct charging is needed even in high-speed driving

(2) Evaluation Points and Evaluation Method

The reliability and accuracy of the system is evaluated from two perspectives: (1) the correctness of charge levied and an indication for the driver, and (2) the proximity between the charging point and indicating point.

As shown in **Figure 3**-1, reflective markers were placed on the roadside at points +/-2.5 m, +/-7.5 m, and +/-12.5 m from the charging point. The test vehicle was equipped with displays indicating the charge levied, a video camera and a clock on the left rear seat as shown in Figure 3-2.

By evaluating two OBU, compatible and incompatible with reception of the positioning augmentation signal, simultaneously in a single vehicle, the positioning augmentation effect of the RSU was verified. The video camera was positioned so that video of the displays and outside of window (the reflective markers described above) could be recorded simultaneously in order to read the indication of the displays and the vehicle position from the video. Four to seven points at which this evaluation was performed were set for each test area (travel time 15 to 30 minutes) and 10 vehicles drove for 5 days in each test area, for a total of 25 days. The total number of trips was approximately 10,000 and the total number of evaluated points was approximately 50,000.

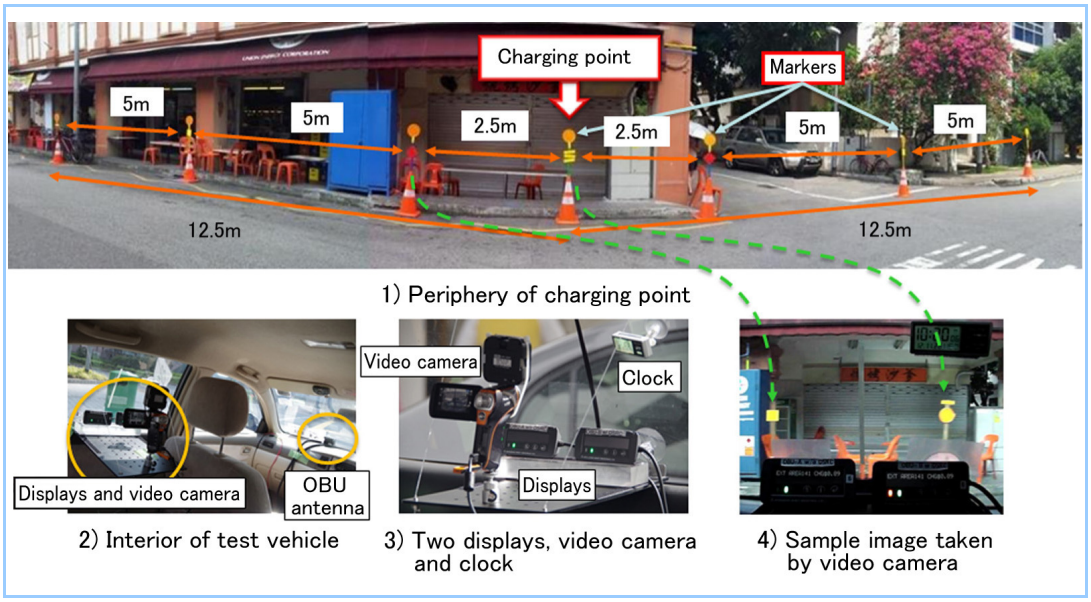

Figure 3 Test environment for system performance evaluation

4.2 Evaluation Results

(1) Suburbs

Figure 4 shows the test results on a general suburban road. This chart represents the distribution of the distance between the position where the charging amount was indicated on the OBU display and the charging point. In the suburban area, the ratio of cases where the correct charge levy was indicated on the display within +/-2.5 m from the charge levying point was approximately 45%. In almost all cases, the correct indication could appear on the display within +/-12.5 m from the charge levying point. This evaluation confirmed that the charge levying/indication accuracy of this system was comparable to the DSRC system.

(2) Expressway

On the expressway, the vehicle passed the charging point at a speed of approximately 100 km/h. As shown in **Figure 5**, however, the evaluation resulted in similar variations in the levied locations to those on the general suburban road. This means that the driver can be informed of the charge levied at the correct location regardless of driving speed due to the compensation of the time period needed for the calculation process by predicting the future vehicle location and calculating the charge levy beforehand.

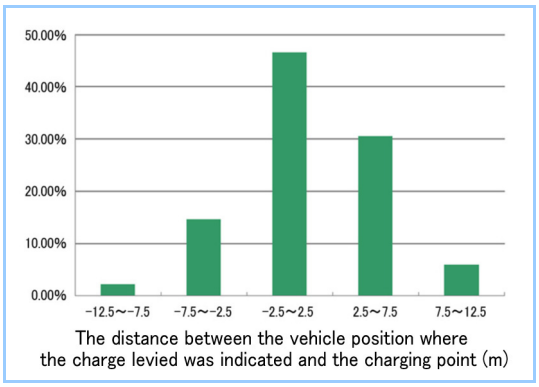

Figure 4 The distribution of the distance between the vehicle position where the charge levied was indicated and the charging point (suburbs)

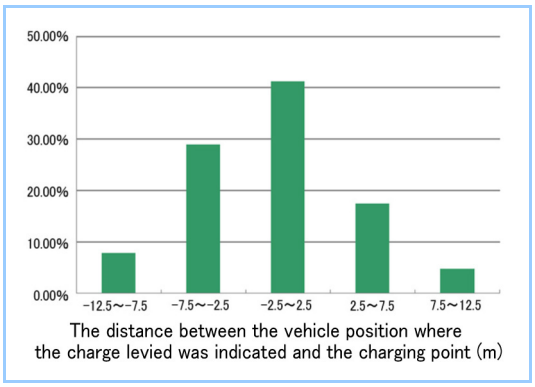

Figure 5 The distribution of the distance between the vehicle position where the charge levied was indicated and the charging point (expressway)

(3) Cluster of High-rise Buildings

Figure 6 shows the results of evaluation in a cluster of high-rise buildings under conditions where the positioning augmentation signal was not used. The ratio of cases where the charging amount was indicated at a location relatively distant from the charging point was higher than that of the suburban road/expressway. This was because the location accuracy deteriorated due to the reflection or suppression of the GNSS signal caused by high-rise buildings. Nevertheless, charging and indication could mostly be done within +/-12.5 m from the charging point. The evaluation of the charge levy yielded consistent results due to map matching.

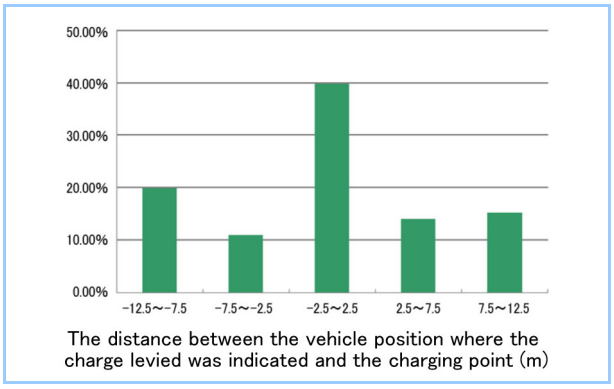

Figure 6 The distribution of the distance between the vehicle position where the charge levied was indicated and the charging point (cluster of high-rise buildings)

5. Conclusion

The application of an autonomous road pricing system based on GNSS to the ERP system in Singapore brings a big challenge. ERP using the DSRC system has a record of operation over a period of more than 10 years and is completely absorbed into the daily life in Singapore due to its reliability.

The new system is required to attain flexibility and meticulousness of charging setting, while maintaining reliability and simplicity for drivers. In addition, the difficulty level is enhanced by the need to deal with the world famous high-rise buildings and the city area where narrow roads are intricately tangled.

Under such demanding requirements, MHI has completed large-scale tests of the developed autonomous road pricing system in an actual traffic environment and demonstrated its reliability. This means that the system has reached the level where it can be used as a decisive solution for global issues such as the elimination of traffic congestion and the fair allocation of road maintenance costs to users, rather than a special or complementary charging method as seen in

prior examples in Europe.

To establish this system into practical application and start its actual operation, the layout design of charging points and the positioning augmentation RSU for poor GNSS reception conditions, a plan for migrating from the current ERP system to the new system, and the explanation and understanding of people's concerns, including the protection of personal information, are required.

MHI will try to resolve the issues described above through cooperation with local authorities based on the advantages that MHI has as the current ERP system provider, as well as by leveraging newly accumulated knowledge about the autonomous road pricing system. MHI will then contribute to the further development of Singapore, a leading city state in Asia. Simultaneously, MHI will promote the customization and cost reduction of the system for areas with different situations, and also try to extend the system’s applicability.

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