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Design and implementation of electronic toll collection system based on vehicle positioning system techniques

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ABSTRACT

Currently, most electronic toll collection (ETC) systems around the world are implemented by DSRC (dedicated short range communication) technology. However, area wide integrated MLFF (multilane free flow) road charging system is now currently on its development to replace DSRC-based ETC systems. VPS (vehicle positioning system) based ETC system is a category of location based service which tolls vehilces by determining if they move into the charging zone. It is an evolutional technology for area wide integrated road charging solution, which achieves the goal of electronic payment or electronic toll collection by a totally different scheme comparing to traditional DSRC-based technology. In this paper, the design and implementation of VPS-based ETC system is detailedly discussed, and a debit transaction VPS system field test had been practiced in the freeway of Taiwan.

1. Introduction

Electronic toll collection (ETC), also known as electronic payment and pricing system, is one of the major research topics in intelligent transportation system (ITS) [1]. ETC is an implementation of a road pricing concept in order to create benefits such as increasing the capacity of toll stations, reducing toll paying time, enhancing the convenience and safety of travelers, and minimizing air pollution and fuel consumption. It enables freeway toll plaza, bridge, tunnel, and turnpike operators to save on staffing costs while reducing delay for travelers and improve overall traffic performance. ETC system determines whether the vehicles passing are enrolled in the program, alerts enforcers for those that are not, and debits electronically the accounts or the amount in the IC card of registered cars without their stopping. The traditional technologies used in ETC system are classified as DSRC (dedicated short range communication) system since the on board unit (OBU) installed in the vehicle can only communicate with the road side unit (RSU) within a short range area, for example, 30 m. The technologies used in DSRC-based ETC system are classified by two categories: infrared and microwave, which are named by their communication media. The evolution of ETC technology has brought DSRC-based ETC system from SLFF (single lane free flow) to MLFF (multilane free flow), which do not constrain the vehicle moving on single lane while moving through the tolling zone. However, there are several drawbacks in DSRC-based ETC system: complexity, cost ineffective, difficulty in system integration, and lack of RSU re-location flexibility.

Area wide integrated MLFF road charging system is now currently on its development to replace DSRC-based ETC systems. Vehicle positioning system (VPS) technology has become the new trend for road charging system, which implements ETC system based on positioning and mobile communication technologies. There are two major differences between VPS-based and DSRC-based ETC systems: communication mechanism and toll collection media. The communication mechanism used in VPS is mobile communication such as GPRS/UMTS/HSPA, which are the standard mobile communication protocols. Although there are some standards or protocols for DSRC-based ETC, most of them cannot cooperate with each other. Comparing to DSRC-based ETC system, VPS-based ETC system has following advantages: cost effective, RSU simplification, no communication zone restriction, service extensibility, and easy to migrate from lane-based to distance-based toll collection scheme. The toll mechanism in VPS is based on interaction between OBU and backend system through mobile network instead of the communication with RSU in the DSRC-based ETC system. The advantage of this mechanism is that there is no need to build up complex RSU as in DSRC-based ETC system, which has the flexibility of tolling zone relocation. The cost of system construction and maintenance can be largely reduced. For the extensibility issue, since there are mobile communication, positioning and electronic payment mechanisms in VPS-based ETC system, it can be

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easily extended to telematics service or m-commerce service without extra facilities in in-vehicle device (OBU), for example, park fee collection, vehicle navigation, etc. Furthermore, OBU in DSRC-based system is usually proprietarily owned by operator or manufacturer, but it is users' choices in VPS-based ETC system, such as dedicated OBU, VPS enabled smartphone/PDA/PND (personal navigation device)/UMPC (ultra mobile PC), etc.

ETC system is operated by the coordination of several subsystems, including debit transaction subsystem, enforcement system, OBU, mobile communication system and the backend system. Enforcement subsystem consists of AVI (automatic vehicle identification) and license number recognition. In this paper, we discuss the design issues about VPS-based ETC system, and a prototype system including backend system (debit transaction subsystem) and frontend devices (OBU) are designed and implemented for field test. The system adopts GPRS mobile network and GPS positioning system as the basis. Several types of OBU including dedicated OBU, smart phone, PDA are implemented. Field test is carried out in the National freeway No.1 and No.3 in Taiwan for several months and a testing fleet consisting of 10 freeway scheduled buses is created in cooperation with the bus company.

The following sections are arranged as follows. Section 2 introduces the background and related works of VPS-based ETC system and some systems are discussed, Section 3 discusses the system architecture and tolling process of VPS. The design and implementation of VPS components is discussed in Section 4, including OBU, messages protocol, enforcement system and backend system. In Section 5, units test and field test are discussed. Besides, a debit transaction system had been implemented, where a test fleet consisting of 10 vehicles were joined for field test in the national freeways in Taiwan. Finally, concluding remarks and future research are given in Section 6.

2. Background and related work

DSRC-based ETC technique is in its development towards to the precision of MLFF [2] and optimum configuration [3]. Currently in worldwide, many countries and cities have conducted the DSRC-based ETC system for their road pricing or congestion pricing policies, and many schemes have been adopted: Stop and Go, SLFF, and MLFF [4,5]. For example, Taiwan [6] and South Korea [7] have announced the national wide ETC service using the DSRC-based ETC system since 2006. On the other hand, ANPR (automatic number plate recognition) technique is also applied for the urban cities road pricing, which is adopted by several cities: London, Rome, Edinburgh, etc. However, the identification precision of ANPR technique which is not as good as the DSRC or VPS technique may result in extra manual operation cost. It is considered more suitable to apply to the enforcement system as a backup of toll collection system.

Vehicle positioning technique currently has been applied to many popular applications, including vehicle navigation, vehicle tracking, fleet management, location based services, and telematics services. VPS-based ETC system is a category of location based service which tolls the vehicles by determining if they move into the tolling zone, and it can be used for the freeway toll collection or the road pricing in the urban area. The concept of toll collection by VPS scheme began in [8], and the first VPS field test project ERP (electronic road pricing) was carried on in Hong Kong in 1997. The overview and design issues of the VPS-based ETC system were further discussed in [9] and [10]. Currently, there are some countries have conducted or prepared to conduct VPS based toll collection scheme for road pricing. Toll Collect Project [11,12] for the trucks on Autobahns in Germany has been in operation since 2005, which tolls the trucks by mileage based scheme calculated by the OBU, but the enforcement system is still based on the DSRC technique. HVF (heavy vehicle fee) project [13,14] in Switzerland combines DSRC and VPS technique to collect toll fee for heavy vehicle. In US, traffic choices study project had a field test for road pricing by VPS technique in Puget Sound [15]. Eight cities in Europe had joined the PRoGRESS project [16] for urban road pricing, which has the goal of "demonstrate and evaluate the effectiveness and acceptance of integrated urban transport pricing schemes to achieve transport goals and raise revenue" [16]. The comparison of technology and the toll schemes adopted by these cities are listed in Table 1. Among them, three cities adopted VPS technique including Copenhagen, Bristol, and Gothenburg for different toll schemes: cordon-based, zone-based, and distance-based.

3. VPS system architecture

The system architecture of VPS-based ETC system is illustrated in Fig. 1, which includes four key components: OBU, enforcement system, mobile communication system, and backend system. It combines several technologies including vehicle positioning, mobile communication, vehicle detecting, and classification, and auto license plate recognition, OBU and backend system. OBU is a device installed in the vehicle, with computing, positioning (GPS) and

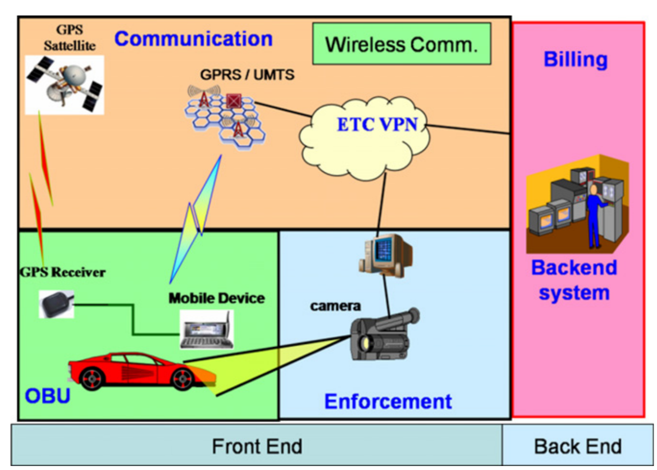


Fig. 1. Architecture of VPS-based ETC system.

Table 1
Comparisons of the toll scheme and technology adopted in PRoGRESS [16]

Scheme concept	Road-pricing technology basis		
	DSRC-electronic tag	ANPR	GPS
Cordon (per trip)	Rome, Helsinki	Bristol, Genoa, Rome	Copenhagen, Bristol
Cordon (per day)		Edinburgh	
Zone (per trip)	Trondheim, Helsinki		Copenhagen
Distance-based			Copenhagen, Gothenburg, Bristol

communication modules. Mobile communication network, such as GPRS/UMTS/HSPA, provides the communication media between OBU and the backend system. Enforcement system is used in reducing unpaid tolls by vehicle image capture, automatic vehicle classification and automatic number plate recognition. Backend system is in charge of all the information processing including online data collection and processing, billing transactions, customer service center, and traffic information, debit transaction and enforcement post matching, etc. OBU and backend system communicate each other through the dedicated VPN (virtual private network) based on GPRS/UMTS/HSPA mobile network provided by telecommunication operator.

The tolling process is carried on at predefined toll areas, known as virtual toll stations, where vehicles will be tolled when it moves into these toll areas. As shown in Fig. 2, a toll zone is a rectangle area identified by a pair of coordinates $\{(x_1,y_1), (x_2,y_2)\}$, which covers all the vehicles moving possibilities area in the same moving direction. There are two parts in the tolling zone: notification area and toll area. The vehicle installed with an OBU moving into the notification area will be notified that a tolling transaction is going to be carried out, and the debit transaction is going on when the vehicle passing through the toll area. A virtual toll station has two tolling zones, one for each direction. Enforcement line is a gantry lies across these two tolling zones and has enforcement devices such as cameras, vehicle classification sensors installed on it in order to identify the vehicle class and capture the vehicle license plates. Camera modules in the enforcement system takes pictures for every vehicle entering the toll area and license plate recognition module recognizes license plate number by image processing technology in order to discriminate the registered and un-registered vehicle by matching the license number with the tolling transaction information. The matched results provide the information and evidence for post processing and law enforcement. If unregistered vehicles enter into the tolling zone, pictures and license plate taken by enforcement system cannot be matched with the debit information. Based on the license plate number, the system can get more detailed information about the violated vehicles such as their names and addresses through the support of the vehicle management system of the government for the violation processing.

All the virtual toll stations coordinates are secure packed as toll zone table and kept in the storage of OBU. OBU detects whether if the vehicle (OBU) is entering into the toll zone (notification area and toll area) by the current vehicle position coordinate read from the GPS receiver, and sends transaction request message to the backend system by the communication module through mobile network when it is confirmed that the vehicle is entering in the toll area. The registered vehicle license number information is sent to the enforcement system in the RSU for the license plate recognition and matching when the backend system receives the transaction request, and the account of the registered vehicle will be debited by querying the toll table and the tolling transaction is processed by the backend system. The OBU then receives and displays the transaction result and local traffic information replied by the backend system after the transaction request is done.

4. VPS components design

VPS system and components as well as the communication protocol between OBU design issues are detailedly discussed in this section. As illustrated in Fig. 1, the key components in VPS system include OBU, enforcement system, and the backend system. In order to meet localized ETC requirements, there are several issues and principles in the VPS system design, including: (1) support both tollbooth based and distance based ETC, (2) adopt standard mobile communication, such as GPRS/UMTS/HSPA, where users are free to choose mobile network service providers, (3) support flexible toll fee management for different area and different time division, (4) safety of the debit transaction must be assured, (5) violation vehicles should be punished by the enforcement system, and (6) debit transaction should be survivable when the mobile network signal is unavailable or the communication module malfunctions. These key components as well as VPS message protocol design and implementation details are discussed in the following subsections.

4.1. OBU

There are several modules in OBU: positioning, mobile communication, computing, and human interface. The computing capability is used for running the VPS client program. There are several design principles of OBU to be considered: (1) OTA (over the air) software update capability, (2) GPS and cell ID dual mode positioning, and (3) transaction message request resend capability. Two types of OBU, smart phone OBU and dedicated OBU, are designed and implemented for the VPS system, as shown in Fig. 3(a and b), respectively. The smart phone OBU designed for testing functionality and compatible with client consumer products such as smart phone, PDA, etc, has the goal of minimizing the hardware effort in OBU. The dedicated type, on the other hand, is designed for testing stability and solidity, and is used for the field test project discussed in next section.

A smart phone version is implemented as a sample for open platform OBU. Windows Mobile® operation system and Windows Dot Net compact framework is chosen as the VPS client program execution environment. As illustrated in Fig. 4, there are several indicators of user interface listed in Table 2 to illustrate the main window. For example, item G shows the user's account balance and item I is the message area which shows the VPS client status or traffic information messages. The implementation of dedicated type OBU consists of hardware design as well as software design. Fig. 3(b) shows the hardware figure of the dedicated type OBU, which is a single chip computer added on with several peripheral modules, such as GPS positioning module, GPRS communication module, etc. There are three LED signal indicators in this type

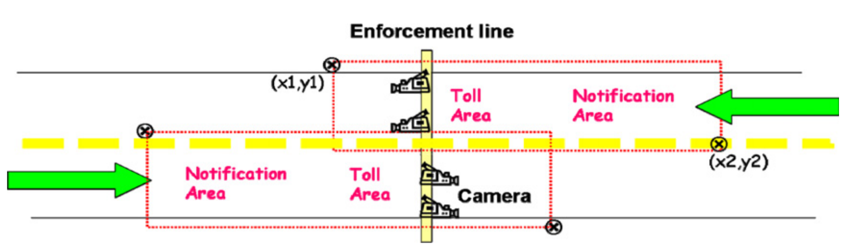
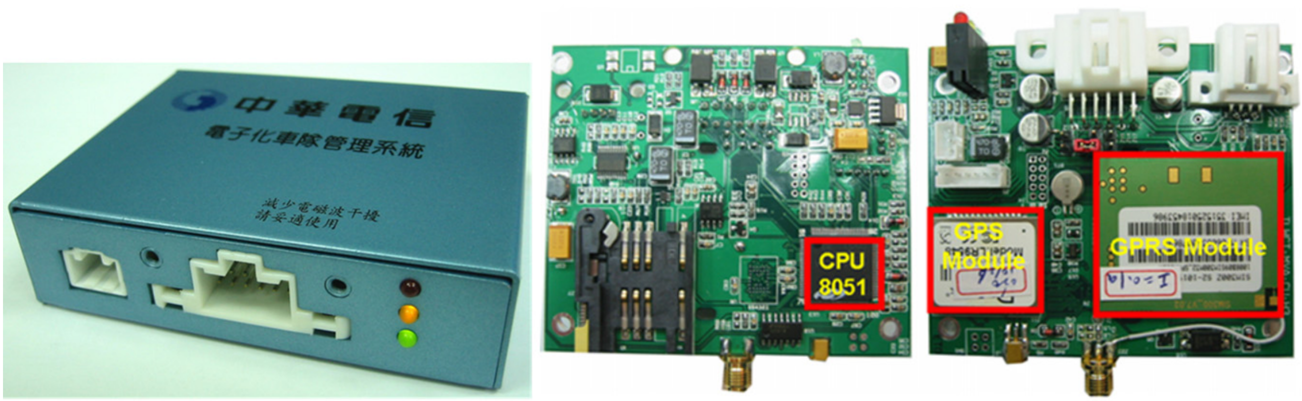


Fig. 2. Virtual toll zone configuration in VPS system.

(a) Smart phone OBU



(b) dedicated type OBU

Fig. 3. (a) Smart phone OBU. (b) Dedicated type OBU.

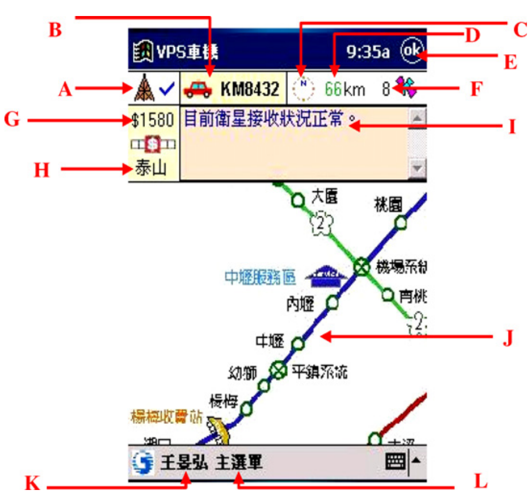


Fig. 4. User interface of the smart phone type OBU.

OBU, which indicate working status, GPS status and GPRS status, respectively.

4.2. VPS message protocols

The message protocol plays key position in VPS system. OBU as well as the backend system must follow this protocol to interact each other. There are several messages defined for the VPS-based ETC system, as listed in Table 3. Each message definition consists of a pair of request and response. The request messages sent from OBU to the backend are named as tailed with 'S', and the backend response messages are named as tailed with 'R'. For example, 'BS' message stands for the OBU registration message which is automatically sent to the backend for checking the client registration and OBU version every time when the OBU gets started. The 'BS' message contains information such as OBU ID, profile, version, and OTA message. The data server in the backend will then verify the user's profile (balance, vehicle type, etc.), check the version information, change the status and then return 'BR' message to the OBU. If there is a new version for VPS client program or new definition of the toll zone tables, OTA software update procedure is then activated to update the OBU. A new 'BS' message is resent to the backend after the update procedure is done and the OBU is restarted. The debit transaction is done by the 'TS' or the 'RS' message, where 'TS' is the online transaction request message sent by OBU to the backend when the OBU detects itself is entering into the tolling zone. A debit transaction is being processing when the backend gets the 'TS' message, and returns 'TR' message to the OBU when the transaction is confirmed. Local real time traffic information is appended to the 'TR' message returns to the OBU to inform the driver local traffic status. If the OBU does not receive the 'TR' message, the debit transaction is kept in the storage of OBU and resend as 'RS' (batch transaction) request message after a sleep time period, where a 'RS' request message may contain one or more debit transactions which are not finished by online transaction 'TR'. These mechanisms ensure the toll transaction will finally be done whenever the vehicle entering into the tolling zone, even when the mobile network communication is not good in the tolling zone.

Table 2
Indicators and descriptions of OBU main window

Item	Name	Description
A	Status	Indicate the communication status between OBU and backend system
B	Vehicle information	Show the registered vehicle type and its license number
C	Direction	Instant direction of the vehicle
D	Speed	Instant speed of the vehicle
E	Close	The VPS program exits
F	GPS	GPS status /* the number of received GPS satellites signals */
G	Balance	The current balance of the ETC purse
H	Station	The name of next nearest toll station
I	Message area	Messages including the VPS status, traffic information, etc.
J	Map area	Show the map and routing choice near around the vehicle
K	Name	Name of registered user for the OBU
L	Main menu	Advanced functions /* registered profile option, traffic information detail, and debit transaction history, etc. */

Table 3
Messages protocol definition between OBU and backend in VPS

OBU	Message from OBU to backend	Data server	Message from backend to OBU
BS	OBU power on msg, registration	BR	Version checking and user profile verification
CS	Profile modification msg	CR	Confirm modification msg
TS	Online debit msg send tracks in toll zone	TR	Debit confirmation msg, return account balance
SS	Shutdown msg	SR	Shutdown confirm
RS	Batch debit msg	RR	Batch debit confirmation msg, return account balance
QS	Traffic info. Request msg	QR	Traffic info. reply

4.3. Enforcement system

The enforcement system is the key component of VPS-based ETC system because it provides a mechanism to deal with the violation. The design objective of enforcement system is that it should support lane-based free flow as well as multilane free flow enforcement mode, catching the license plate pictures of vehicles, and recognizing the license number in nearly real time. The actions of the enforcement system includes: (1) identifying vehicle: detects the vehicles which entering the enforcement line in real time and classifies the category of the vehicle, (2) taking picture: the camera module must catch the license plate of each vehicle correctly, (3) recognizing the license plate: automatic license plate recognition module should recognize the license plate number of vehicle by OCR, and (4) match pre-processing: the debit transaction data and enforcement information must be matched correctly.

It is a computing critical task for the enforcement system because all the missions should be done in nearly real time (within 1 or 2 s), and the computing capacity must accommodate all the vehicles passing through the enforcement line. In order to reduce the computing capacity in license plate recognition and raise the pre-matching accuracy, a heuristic skill is adopted in our implementation. The license plate number is sent to the enforcement system immediately by querying the registered user database in the backend system when it receives 'TS' message from an OBU. Thus whenever the OBU (vehicle) passes through the enforcement line, the enforcement system has the capability of 'prediction' the next coming registered vehicle license plate. This action improves the efficiency and accuracy of automatic license plate recognition and match pre-processing. The match pre-processing is done when the license number received from the backend is matched to the license plate number recognition, and all the images of unrecognized vehicle is stored in the backend database for the post matching and violation processing.

4.4. Backend system

Backend system is a general term for ETC, which consists of several subsystems, such as billing, clearing, customer service, web site, OBU management, system monitoring, violation processing, traffic management supporting, etc. As illustrated in Fig. 5, the major components in the backend system include data server, database, application server and web server. Data server is response for the data sending and receiving to OBU via mobile network and connects to enforcement system via ETC private network. Database keeps the registered user profile, communication logs, transaction records, and all the information in the system. Web server provides introduction pages and customer service web pages for the Internet users, sample pages is shown in Fig. 7. Registered users can modify personal profile or list personal transaction history by logining the web site. Application server plays a vital role in the VPS backend system. Several kernel jobs of the backend system including cache response module, debit transaction module, post matching module, violation processing module, etc. are processed in the application server, as illustrated in Fig. 5.

Debit transaction processing is one of the most important tasks in the backend system. The debit transaction module interacts with OBU to get the debit information ('TS' or 'RS' message packet) when OBU entering into the tolling zone. As illustrated in Fig. 6, the data server invokes the *do_TS()* function in the debit transaction module in the application server to complete the debit transaction

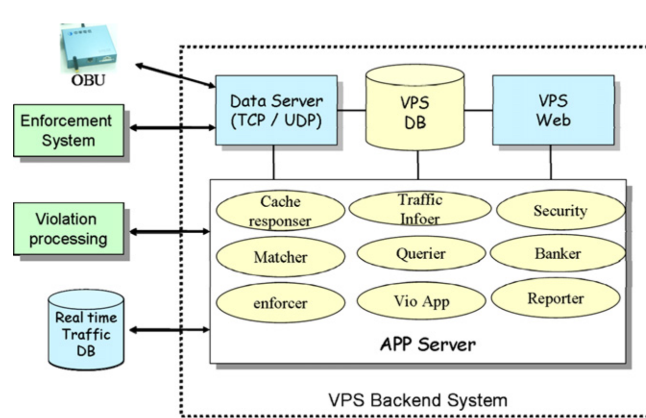


Fig. 5. The servers and modules in the backend system.

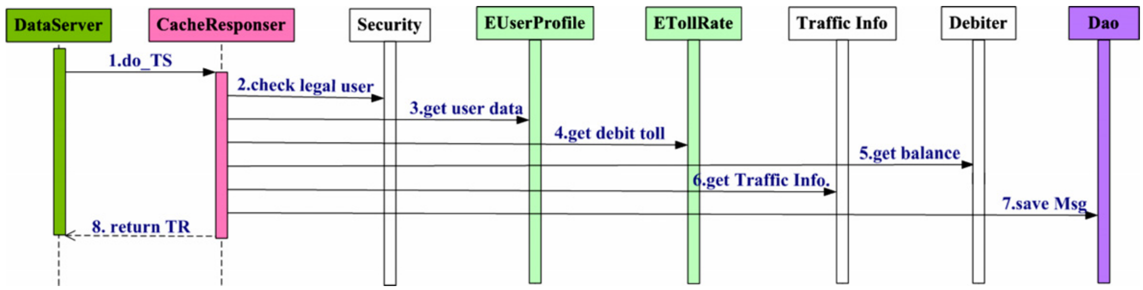


Fig. 6. Debit message (TS) process flow in application server.

when it receives the transaction request (TS) message from OBU. The debit transaction processes includes checks user account, makes a debit transaction, queries traffic information and returns the 'TR' message packet which includes transaction result, account balance and local real time traffic information to the data server. The traffic information includes the estimated journey time in minutes to the next toll station and real time events ahead of the vehicle to notify the user, for example, a passenger car accident ahead 2 Km away. OBU will vocally speak out the message by the text to speech module and also display it on the message area of terminal (smart phone type OBU).

The backend system includes a web site for the customer service of registered user and the internet guest. It provides many services such as debit transaction history query, traffic information, and estimated traveling time, as illustrated in Fig. 7. The remaining jobs of the backend system, such as matching, billing, clearing, violation processing, will be automatically done as batch jobs in the backend system.

5. Unit test and field test

5.1. Mobile communication and positioning unit test

Since mobile communication and positioning modules play the key roles in VPS-based ETC system. Unit tests of these two modules are necessary in order to know how well the characteristics of them. The purpose of mobile communication unit test is to summarize the average delay time of GPRS packet from the OBU to the data server. It facilitates to comprehend the time out threshold between the message request and response in OBU. On the other hand, the positioning unit test helps understanding the GPS signal variation and average shift deviation in a fixed location.

The unit test of communication and positioning modules are carried on together at some fixed locations and running unit test program for a period of time. For the communication unit test, in order to calculate the packets lost rate and average packet delay of the adopted GPRS mobile network, the testing program in OBU pings two data servers in the backend by sending three TCP/IP packets via GPRS network, each packet contains 16 bytes data, and there are 10 ping actions in one single test. The time delay of each test is the average delay of all the 30 packets time difference between the GPS satellites timestamp and the system timestamp in the data server. For the time delay calculation accuracy, the data server must be synchronized to universal time by NTP protocol connecting to time server. The GPRS unit test result is shown in Fig. 8(a), where total 12,347 tests are proceeded. The response time threshold is set to 5 s, and the packet response time over the threshold is regarded as GPRS packet lost because the packets must return to OBU in the toll zone to confirm the user transaction is done in this time threshold. In the GPRS unit test,

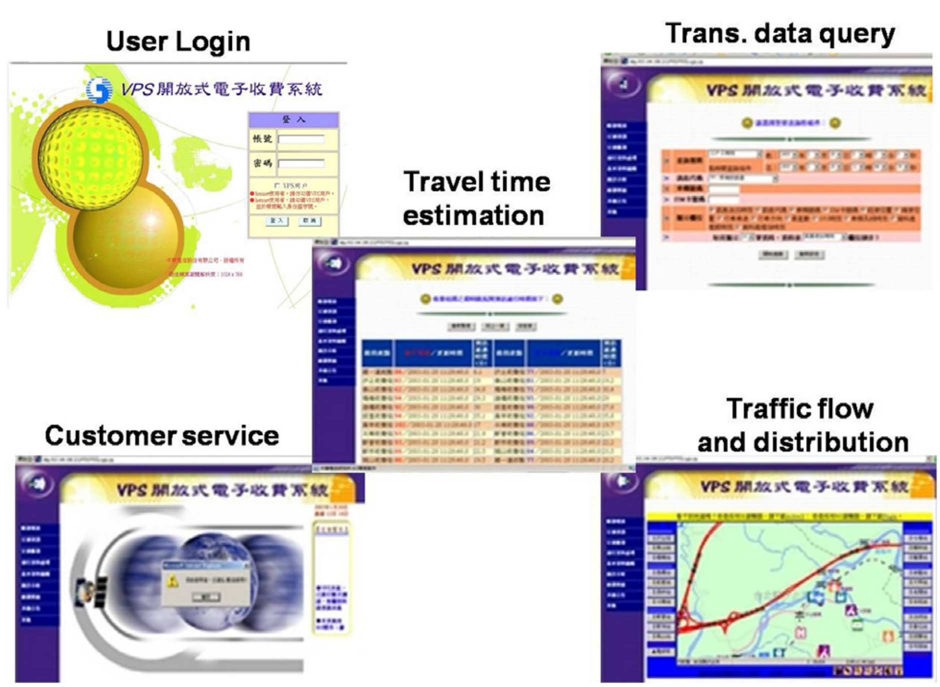


Fig. 7. Web site for customer service in VPS.

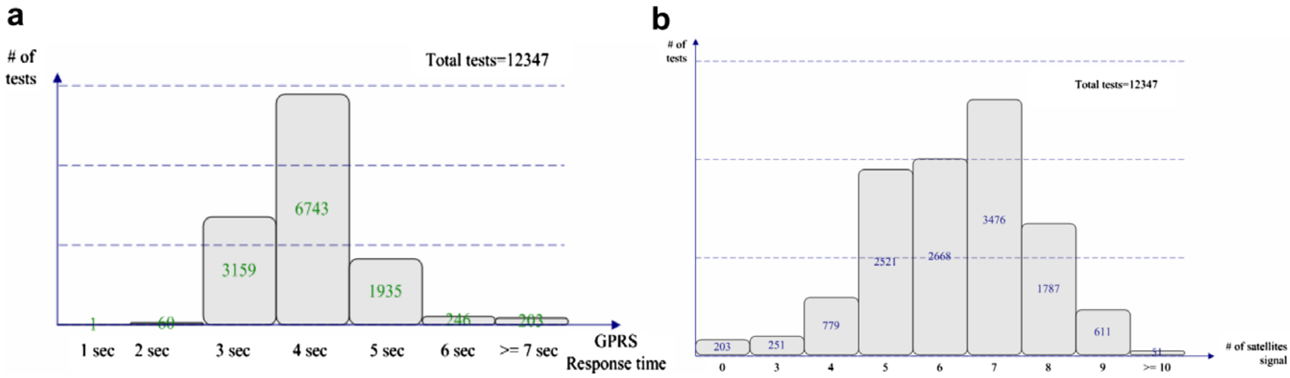


Fig. 8. (a) Response time of GPRS unit test. (b) Satellites signal of GPS unit test.

the response time over the threshold (lost rate) is 3.64%, and for the packets response within the threshold, the average response time is 3.9 s.

The positioning unit test is proceeding in parallel with the communication unit test because the GPS positioning signal and GPS satellites timestamp information are read from GPS module concurrently and sent by the GPRS same packet to the data server. The positioning unit test helps understanding the GPS satellite signal status in a long period of time at fixed location, and gaining the knowledge of average location shifting deviation. The result of positioning unit test is illustrated in Fig. 8(b). For the number of satellite signal over four satellites signal then the OBU can read the correct coordinates from GPS module. So the number of satellite signal less than three is regarded as positioning failure, which is 3.68%.

5.2. Freeway field test

In order to test the functionality and stability of VPS system, field test was carried out with a 10 vehicles fleet in the national freeway No. 1 in Taiwan, and the field tests are done in two parts: first test (2006/12/09–2007/01/02) and second test (2007/07/13–2007/07/19). In these field tests, only debit transaction system (OBU and backend system) is test, enforcement system is excluded due to complexity and cost issues. Ten dedicated type OBUs (as shown in Fig. 3(b)) were installed on a fleet consists of 10 freeway passenger buses which have daily schedule journeys to and from Taipei to Kaohsiung, two large cities located at north and south of the island, respectively. There are nine toll stations between these two cities, which all have DSRC-based ETC system [5] in operation, and the 10 test vehicles equipped with DSRC OBU must drive through the DSRC ETC lane on every scheduled journey. In this freeway field test, the DSRC-based ETC system is the benchmark of this field test. We assume that the data provided by DSRC-based ETC system is 100% accurate. By comparing to DSRC-based ETC, these two phase test results are shown in Tables 4 and 5, respectively.

There are three possible cases when OBU moving through the virtual tolling zone: (1) transaction request message (TS) correctly sent to the backend system and acknowledge ('TR' message) received by OBU, (2) OBU resend transaction request because OBU does not receive 'TR' message before timeout, and (3) OBU does not send request or the request packet had lost during mobile network transmission. The first case listed in the column C in Tables 4 and 5 is a normal case, where backend system receives the transaction request (TS), makes a debit transaction, and returns 'TR' (transaction confirmed) message to OBU. But in Case (2), listed in column D of Tables 4 and 5, the resent transaction requests as well as original requests are received by the backend system. This may result in duplicated debit transactions, which is not acceptable. Fortunately, this case can be solved by adding a spatiotemporal checking rule in the debit transaction module in the application server. It filters out the duplicate transaction request by checking the recently requests by each OBU. The result of Case (3) is listed in the column E of Tables 4 and 5, the lost packet won't be collected by the backend and thus results in un-debit case. The accuracy of VPS debit transaction system is calculated by the ratio of correct debit and DSRC-based ETC records, as listed in the last column of Tables 4 and 5. The average accuracy the two field tests are 86.87%, 84.96%, respectively. However, the accuracy of two vehicles (No.1 and No.7) are much worse than the others. After recalling the vehicles and checking the OBU, we found that the GPS positioning modules of OBU installed in these two vehicles were malfunctioned. This can be corrected by replacing the positioning

Table 4
First field test result of VPS debit system (in the view of vehicle)

Vehicle No.	DSRC ETC records (A)	VPS ETC records (B)	VPS debit correct (C)	VPS debit duplicate (D)	VPS un-debit (E)	Debit accuracy (C/A) (%)
(1)	629	38	38	0	591	(6.04)
2	596	596	596	0	0	100.00
3	594	594	594	0	0	100.00
4	597	596	596	0	1	99.83
5	647	629	629	0	18	97.22
6	587	587	587	0	0	100.00
(7)	636	435	435	0	201	(68.40)
8	631	631	631	0	0	100.00
9	631	631	631	0	0	100.00
10	635	634	634	0	1	99.84
Sum./Avg.	6183	5371	5371	0	812	86.87
Sum./Avg. (without No. 1, No. 7)	4918	4898	4898	0	20	99.59

Table 5
Second field test result of VPS debit system (in the view of vehicle)

Vehicle No.	DSRC ETC records (A)	VPS ETC records (B)	VPS debit correct (C)	VPS debit duplicate (D)	VPS un-debit (E)	Debit accuracy (C/A) (%)
(1)	181	41	41	0	140	(22.65)
2	133	133	133	0	0	100
3	124	124	124	0	0	100
4	44	44	44	0	0	100
5	185	180	180	0	5	97.29
6	97	97	97	0	0	100
(7)	117	76	76	0	41	(64.96)
8	108	108	108	0	0	100
9	117	117	117	0	0	100
10	131	131	131	0	0	100
Sum./Avg.	1237	1051	1051	0	186	84.96
Sum./Avg. (without No. 1, No. 7)	939	934	934	0	5	99.47

Table 6
Field test result of VPS debit system (in the view of toll station)

Tolling zone ID (Direction)	DSRC ETC records (A)	VPS ETC records (B)	VPS debit correct (C)	VPS debit duplicate (D)	VPS un-debit (E)	Debit accuracy (C/A) (%)
102(N)	342	293	293	0	49	85.67
102(S)	342	296	296	0	46	86.55
103(N)	355	307	307	0	48	86.48
103(S)	356	313	313	0	43	87.92
104(N)	359	308	308	0	51	85.79
104(S)	361	313	313	0	48	86.70
105(N)	360	311	311	0	49	86.39
105(S)	361	311	311	0	50	86.15
106(N)	361	313	313	0	48	86.70
106(S)	136	119	119	0	17	87.50
107(N)	361	315	315	0	46	87.26
107(S)	359	309	309	0	50	86.07
108(N)	351	310	310	0	41	88.32
108(S)	349	304	304	0	45	87.11
109(N)	360	315	315	0	45	87.50
109(S)	359	311	311	0	48	86.63
110(N)	353	312	312	0	41	88.39
110(S)	358	311	311	0	47	86.87
Sum./Avg.	6183	5371	5371	0	812	86.87

module. If the test samples of these two vehicles are excluded, the accuracy of VPS debit transaction system in these two field tests can be achieved to 99.59%, 99.47%, respectively.

It is possible that OBU does not send transaction request message (‘TS’) while the toll zone definition is not correct. This is because the coordinates of tolling zones have not been correctly surveyed. In this case, all the vehicles going through the tolling zone will not be debited. Spatial dimension test result analysis (in the view of toll station) for the first field test is shown in Table 6. The accuracy of all the tolling zones are almost the same and the un-debit records are almost equally spreading to all the toll stations. This indicates that the incorrect toll zone definition case does not exist in this field test, and the un-debit records are mainly caused by two the mal-function OBUs.

On the other hand, the online transaction may not success during the short period when the vehicle passing through the tolling zone due to several reasons: delay of mobile network (congestion, handover, weak radio signal, etc), weak GPS signal, or delay of the backend system. The batch transaction message (‘RS’) is designed for the backup of the online transaction request message (‘TS’). If a ‘RS’ message is received by the backend system, it implies a ‘TS’ transaction request does not get a ‘TR’ confirmation during the timeout threshold period when the vehicle moving through the tolling zone. The ratio of the ‘TS’ message compares to the total transactions record (‘TS’ + ‘RS’) received by the backend system indicates the successful rate of online transaction request, which can be further analyzed in two dimensions: OBU and tolling zone. In the OBU point of view, if the successful rate of one OBU is lower than the average, then the communication module of that OBU may have problems. As shown in Table 7(a), the summary of 97.65% online transaction successful rate. Besides, there is no big difference between each OBU and average online transaction successful rate, which indicates the communication module of these OBUs are all in good working status. In the tolling zone point of view, lower successful rate in tolling zone indicates the tolling zone may be too small to complete the online transaction, which is important information for re-defining the coordination of the zone. Table 7(b) shows the statistics of each tolling zone are near around the average value except the toll station ID *109(N)*, which indicates the zone area of *109(N)* should be revised to raise the successful rate.

6. Conclusion

VPS is an evolutional technology for area wide integrated road charging solution, it achieves the goal of electronic payment and electronic toll collection by a totally different scheme comparing to traditional DSRC-based ETC technology. It is cost effective and

Table 7
Online debit transaction successful rate

Vehicle No.	TS (A)	RS (B)	Online transaction successful rate A/(A + B) (%)
(*a*) *By the OBU point of view*			
1	894	24	97.39
2	5337	88	98.38
3	5466	97	98.26
4	4316	106	97.60
5	5249	132	97.55
6	5654	136	97.65
7	1145	29	97.53
8	4846	118	97.62
9	5633	140	97.57
10	5440	189	96.64
Sum./Avg.	43980	1059	97.65
Tolling zone ID (Direction)	TS (A)	RS (B)	Online transaction successful rate A/(A + B) (%)
(*b*) *By the tolling zone point of view*			
102(N)	2287	39	98.32
102(S)	2265	34	98.52
103(N)	2444	34	98.63
103(S)	2448	30	98.79
104(N)	2482	41	98.37
104(S)	2456	62	97.54
105(N)	2493	47	98.15
105(S)	2466	57	97.74
106(N)	2713	73	97.38
106(S)	2699	69	97.51
107(N)	2746	41	98.53
107(S)	2697	57	97.93
108(N)	2306	44	98.13
108(S)	2333	34	98.56
109(N)	**2164**	**245**	**89.83**
109(S)	2284	56	97.61%
110(N)	2356	36	98.49%
110(S)	2312	60	97.47%
Sum./Avg.	43951	1059	97.65%

has the advantages of simplicity and flexibility comparing to DSRC-based ETC, and the virtual toll zone can be changed easily by modifying the toll zone coordinates table. This feature provides a way to migrate from the lane-based toll collection scheme to the distance-based or area wide toll collection scheme, which is fit in with the policy of toll collection scheme in many countries. Besides, OBU is easy to integrate with telematics service because they have the same key components: positioning, mobile communication, computing, and human interface. The transaction capability also enables the mobile electronic commerce. In this paper, we discussed the design and implementation details of VPS-based ETC system, and unit tests as well as a debit transaction field test had been practiced in the freeway of Taiwan. The results show that the accuracy of debit transaction is satisfiable if the malfunction OBU data is excluded. In addition to the debit transaction, enforcement system and the matching mechanism for enforcement and debit transaction are also playing a key position in the VPS system, which will be the major issues of our future work.

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