Intelligent Transportation and Smart Cities
V. Mezhuyev et al. (Eds.)

doi:10.3233/ATDE250253

Research on Beidou-Based Free-Flow Toll Collection Technology Based on Segmented Billing

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Abstract. With the rapid development of intelligent transportation systems, Beidou-based free-flow toll collection technology has become an important research direction to improve road traffic efficiency and toll management level. Addressing issues such as the ambiguity of routes and large trajectory deviations caused by inaccurate positioning results in the current Beidou Free-Flow tolling, which mostly adopts a holistic pricing approach, this paper proposes a Beidou Free-Flow tolling technology based on segmented pricing and designs a corresponding Beidou Free-Flow tolling system. Through real-road tests, the Beidou free-flow toll collection technology based on segmented billing proposed in this paper reduces construction costs and decreases the difficulty of auditing, while ensuring the accuracy and reliability of billing. At the same time, this technology also has good scalability and compatibility, which can provide strong support for the construction of future intelligent transportation systems.

Keywords. Beidou, free-flow, segmented billing, highway

1. Introduction

With the rapid development of China's transportation industry, highways have become important links connecting major cities and economic regions. However, traditional toll collection modes, such as manual toll collection and electronic toll collection (ETC), have exposed many problems in dealing with the growing traffic volume [1]. Manual toll collection requires a large amount of manpower, resulting in high management costs and low efficiency; while ETC, although realizing non-stop toll collection, still has technical problems such as path ambiguity and adjacent lane interference, affecting the accuracy and efficiency of toll collection. Therefore, it is particularly important to research and develop new highway toll collection modes [2].

The Beidou Satellite Navigation System is a global satellite navigation and positioning system independently developed and operated by China. The system has the functions of real-time navigation, rapid positioning, accurate timing, position

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reporting, and short message communication services. Its high-precision positioning technology has broad application prospects in the transportation field [3]. Especially in the highway toll collection system, Beidou high-precision positioning technology is expected to realize accurate tracking and positioning of vehicles, thereby solving the problems existing in the current toll collection mode [4].

Free-flow toll collection is a new type of toll collection mode, whose core concept is to realize non-stop toll collection of vehicles on highways [5]. This toll collection mode can not only significantly improve the traffic efficiency of highways but also reduce management costs and enhance user experience. Based on the Beidou free-flow toll collection system, through the vehicle trajectory information uploaded by the Beidou vehicle-mounted terminal, the background can accurately restore the vehicle's driving path, complete the toll calculation, and realize online real-time deduction [6]. Compared with the traditional toll collection mode, Beidou-based free-flow toll collection has higher accuracy and efficiency [7].

This paper aims to in-depth explore the principles, technical implementation, and application prospects of the Beidou-based free-flow toll collection system. Through research on Beidou high-precision positioning technology, and in response to issues such as route ambiguity and significant trajectory deviations due to poor positioning results in the current Beidou Free-Flow tolling, which mostly adopts a holistic pricing approach, this paper proposes a segmented pricing system for Beidou Free-Flow tolling and verifies its feasibility and effectiveness. This paper not only has important theoretical significance but will also provide strong technical support and practical guidance for the improvement of China's highway toll collection mode.

2. Beidou Free-Flow Toll Collection Principle

2.1. Basic Principle

Satellite-based electronic toll collection employs Vehicle Positioning System (VPS) electronic toll collection technology, which has attracted considerable attention in recent years. It utilizes satellite positioning systems and global mobile communication systems to achieve non-stop toll collection through communication with on-board devices, as shown in Figure 1. Currently, many countries abroad are researching and applying free-flow technology for road toll collection [8-12], and Germany, the Czech Republic, and Singapore have already adopted GNSS-based road toll systems [13-15].

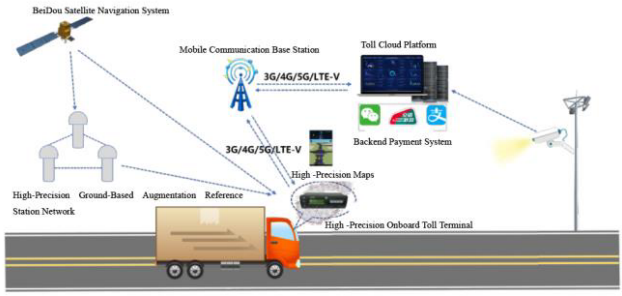

Figure 1. Principle diagram of satellite-based electronic toll collection.

The tolling principle of Beidou Free-Flow is to use the Beidou Navigation Satellite System to locate vehicles in real-time and obtain precise location information of the vehicles. Based on the vehicle location information and combined with high-precision map data, the driving trajectory of the vehicle on the expressway is plotted. The toll fee to be charged is then calculated according to factors such as the length of the driving trajectory, vehicle type, and road type, based on predefined rate standards. The fee calculation formula is as follows:

$$S = L \times R \tag{1}$$

In the above formula, S represents the toll fee to be collected (in yuan); L represents the travel distance (in meters), which is calculated based on the actual driving trajectory of the vehicle; and R represents the rate (in yuan per meter), which is a predefined rate standard based on factors such as vehicle type, road type, and time (e.g., peak hours, off-peak hours).

Currently, inland provinces in China have established ETC-based electronic toll collection modes on highway networks, while Beidou-based free-flow toll collection technology has been tested by the China Communications and Transportation Information Center on partially closed sections of highways in Jiangxi Province. Additionally, domestic ride-hailing platforms all use satellite positioning for billing and settlement. According to data released by Didi, there are currently 21 million driver users, 450 million daily users, and 25 million daily orders. The application of ride-hailing demonstrates that satellite positioning meets the application scenarios of high-volume, high-concurrency, and high-reliability highway toll collection.

2.2. Segmented Billing Principle

The traditional Beidou free-flow billing method is overall billing, which means that the path is restored based on the vehicle's entry and exit points of the highway, and then the toll is calculated accordingly, as shown in Figure 2.

The fee calculation from point A to point B is shown in the following formula:

$$S_{AB} = L_{AB} \times R_{AB} \tag{2}$$

When there are unfavorable factors such as weak signals or environmental obstructions, the holistic tolling method is prone to reconstructing erroneous travel paths due to poor positioning accuracy and point drift, leading to incorrect tolling and charging. As shown in Figure 2, during the vehicle's journey from point A to point B, it exits the highway at point C and re-enters at point D, continuing to drive until reaching point B. In such cases, when the satellite signal is weak, the reconstructed travel path may still be A-C-D-B, but the actual toll fee calculation should be as shown in formula (3), resulting in incorrect tolling and charging.

$$S_{AB} = (L_{AC} + L_{DB}) \times R_{AB} \tag{3}$$

Segmented tolling divides the route into different tolling segments based on points of traffic volume change, ensuring that each tolling segment is unique regardless of which highway entrance or exit the vehicle uses. Each tolling segment serves as a tolling unit, with an electronic fence constructed within it. When a vehicle enters the electronic fence, it triggers the acquisition of vehicle information, simultaneously completing path reconstruction and tolling, as shown in Figure 3. The final toll fee is the cumulative amount of tolls from each tolling unit, as shown in formula (4).

$$S_{AB} = S_{AC} + S_{CD} + S_{DB} \tag{4}$$

In cases similar to those described in formula (3), since the vehicle does not enter the tolling segment CD, the electronic fence of the tolling unit in segment CD will not

be triggered. Therefore, there will be no incorrect accumulation of toll fees for segment CD, ensuring accurate tolling.

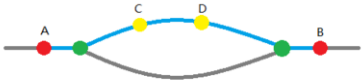

Figure 2. Principle of overall billing.

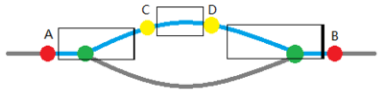

Figure 3. Principle of segmented billing.

Table 1. Comparison between Overall Billing and Segmented Billing

	Overall billing	Segmented Billing
Complexity	High, requires solving the problem of ambiguous paths	Low, cumulative calculation for each segment based on records
Loss of Path Information	High, toll is calculated based on the shortest path according to the last path information point	Low, only the toll for the billing segment where the path information point is located is lost
Extensibility	Low, only suitable for highways with a small number of controllable entrances and exits	High, can be extended to national, provincial, and urban expressways
Need for Supplemental Points	Medium, supplemental capture points need to be set up in sections with heavy traffic	Medium, supplemental capture points need to be set up at entrances and exits with heavy traffic
Difficulty of Point Selection	Medium, there is a problem of limited capture distance due to short ramps and large turning radii	Low, the difficulty of selecting points on the main line is low, and the linear conditions are good

As shown in Table 1, segmented billing outperforms overall billing in terms of complexity, extensibility, difficulty of point selection, and integrity of path information. Segmented billing reduces construction costs, decreases the difficulty of auditing, and ensures the accuracy and reliability of billing.

3. Beidou Free-Flow Toll Collection System Design

Beidou free-flow toll collection leverages Beidou positioning technology to accurately determine the travel trajectory of vehicles equipped with Beidou in-vehicle electronic units or terminals on the road network. By binding to a backend account and adopting a "vehicle positioning + cloud billing" approach, the backend collects vehicle mileage tolls.

Beidou free-flow toll collection only requires defining virtual toll zones in the cloud-based electronic map according to the segmented billing principle and constructing electronic fences. Coupled with inspection facilities and supporting policies, there is no need to construct toll stations. By simply supplementing auxiliary inspection equipment in sections with high traffic flow as needed, mileage tolls can be collected. This is suitable for a toll-free mode and a "full throttle" toll collection mode.

With "cloud (service platform) + end (Beidou in-vehicle terminal)" as the main components and roadside facilities (edge) as a supplement, the overall system architecture is simpler, suitable for application scenarios with a large scale of road toll collection users, a wide road network, and high flexibility.

First, the cloud (platform) is a unified data processing and storage platform built on cloud computing technology. By collecting and processing data from vehicle terminals and edge devices, the cloud realizes accurate recording and measurement of vehicle travel routes. The cloud has efficient data processing capabilities and large-scale storage capacity, which can support real-time processing and analysis of a large amount of vehicle data to achieve accurate charging for vehicles.

Second, the edge (roadside inspection facilities) refers to vehicle terminals and edge devices, including DSRC devices and video recognition equipment. By collecting vehicle location information, video recognition data, and other data, edge devices transmit this data to the cloud for processing. Edge devices have real-time data

transmission capabilities and a certain processing capacity, which can enable real-time monitoring and identification of the vehicle's driving status.

The terminal refers to the terminal device installed on the vehicle, namely the Beidou in-vehicle terminal. The terminal device uses the Beidou system for positioning, obtains the vehicle's location information, and transmits it to the edge device or cloud for further processing through a certain method.

In the process of realizing the integration of cloud and edge, it is necessary to establish a communication connection between the cloud and the edge and formulate rules and protocols for data transmission and processing. Through cloud computing technology, seamless integration and collaborative work between edge devices and the cloud can be realized to provide more efficient and accurate mileage calculation and vehicle location information transmission services.

4. Beidou Free-Flow Toll Collection System Testing and Verification

4.1. Test Scenario

The test section is part of the G98 Ring Highway. The starting point is located at K0+000 south of the Longqiao Interchange on G98; the test section runs north-south, passing through Ding'an County and reaching Qionghai City; the end point is south of the Qionghai Interchange. The capture checkpoint at the end point of the mainline is located at K79+350. The total length of the test section is approximately 80 kilometers. It includes 6 service-type interchanges and 6 service areas. The Ding'an Interchange, where G360 intersects with G98, is currently under construction. The entire line adopts a dual four-lane highway standard with a design speed of 100 km/h.

The 6 service-type interchanges are Xicun, Xinpo, Dingan Dingcheng, Juding, Huangzhu, and Qionghai interchanges. Among them, the Qionghai Interchange is a single trumpet-shaped interchange, while the rest are diamond or variant diamond interchanges. All service-type interchanges have 2 entry ramps and 2 exit ramps.

4.2. Test Method

The test method adopts the true value test method through on-site actual tests. Real vehicles were used for on-road tests on the Hainan G98 highway. First, the true value was determined, which is the specified vehicle driving route, and the toll toll for the specified route is the true value of the toll. All test vehicles traveled according to various specified routes, and the billing results output by the system platform for the test vehicles were the test results. By manually recording the test results and comparing them with the true values, and conducting comprehensive statistics on the test vehicle data with a certain sample size, the toll accuracy can be obtained. At the same time, roadside equipment such as cameras and integrated radar and vision devices were introduced. For social vehicles passing through during the test, the true value of driving and billing was confirmed through video comparison. This was compared with the output results of the Beidou standard device installed on the vehicle in the billing platform.

4.3. Test Vehicles

A total of 63 test vehicles were used. According to the vehicle type, the mileage toll was calculated, and the national unified vehicle type classification standard was adopted, specifically referring to JT/T 489-2019 "Vehicle Type Classification for Toll Highways". Currently, vehicle types for toll highways are classified into three series: passenger cars, trucks, and special-purpose vehicles. Subcategories are divided from Class 1 to Class 6; it is necessary to distinguish between chargeable and free vehicle types.

4.4. Test Results

During the test period, 256 test vehicles were tested, and in the downstream direction of the specified test interval (Qionghai-Ding'an), a total of 2,058 road section tests were completed, and 3,493 road section tests were completed for the whole road section; within the test interval, 4 vehicles did not complete billing due to terminal problems, and the rate of fee charging was 99.81%, and the accuracy rate of billing was 99.95%, according to the billing accuracy of the fee charging; and there were 18 times that the billing accuracy rate was 99.94% due to the data transmission problems of the terminal. The data transmission problem of the terminal did not complete the billing, the collection rate was 99.48%, and the billing accuracy rate of successful billing was 99.94%.

At the same time, the test of the G98 Longqiao-Qionghai section was added, and the final on-road test results are shown in Table 2.

On the test section (Qionghai-Ding'an), a total of 61,174 yuan was collected. Among this, trucks accounted for 38,394 yuan, representing 62.7% of the total toll, while passenger cars accounted for 22,780 yuan, representing 37.3%. Trucks contributed a higher proportion to the total toll. According to the statistics of the expected toll on the test section (Qionghai-Ding'an), the total expected toll was 61,202 yuan, with a difference of 28 yuan compared to the actual toll. Among this, trucks were expected to contribute 38,394 yuan, accounting for 62.8% of the total expected toll, and passenger cars were expected to contribute 22,808 yuan, accounting for 37.3%, as shown in Figure 4.

On the entire G98 (Longqiao-Qionghai) section, a total of 128,984 yuan was collected. Among this, trucks accounted for 77,538 yuan, representing 60.1% of the total toll, while passenger cars accounted for 51,446 yuan, representing 39.9%. Trucks also contributed a higher proportion to the total toll. According to the statistics of the expected toll on the entire G98 (Longqiao-Qionghai) section, the total expected toll was 129,061 yuan, with a difference of 77 yuan compared to the actual toll. Among this, trucks were expected to contribute 78, 765 yuan, accounting for 61% of the total expected toll, and passenger cars were expected to contribute 50,296 yuan, accounting for 39%, as shown in Figure 5.

Overall, the toll collection rate for both passenger cars and trucks on the Qionghai-Ding'an section was high, reaching 99.9%, and the difference between the actual and expected total tolls for both passenger cars and trucks was relatively small. According to statistics, the toll during the test phase was 500,000 to 600,000 yuan per day, of which the total toll for passenger cars accounted for about 61.8% and the total toll for trucks accounted for about 38.2%. Based on the above scale calculation, the estimated annual toll for both directions of the test section is expected to reach 360 million to 430

million yuan.

Table 2. Test Result Analysis

Time		2022.12.16	2022.12.17	2022.12.18	2022.12.19	2023.1.2	2023.1.3	Total	Capture Rate	Billing Accuracy Rate	Billing accuracy	Billing Timeliness Rate
Number of Test Vehicles		51	49	37	43	36	40					
Test Section (Qionghai-Ding'an Southbound)	Number of strokes	357	362	287	366	317	367	2058	99.91%	99.91%	99.95%	99.95%
	Vehicle passing amount on platform	562	576	485	595	521	599	3338				
	Number of vehicles	565	576	485	595	521	599	3341				
	Billing correct	354	362	287	365	319	367	2057				
	Chargeable Amount (Yuan)	10600.1	10193.35	8761	10442.16	10024.6	11182.075	61203.285				Toll Collection Rate
	Actual charge amount (Yuan	10580.6	10193.35	8761	10434.41	10024.5	11181.625	61175.485				99.81%
Additional Test Section (G98 Longqiao-Qionghai)	Number of strokes	591	648	466	644	535	609	3493	99.92%	99.92%	99.94%	99.94%
	Vehicle passing amount on platform	1290	1361	1054	1392	1196	1359	7652				
	Number of vehicles	1296	1361	1054	1392	1196	1359	7658				
	Billing correct	576	648	466	641	535	609	3490				
	Chargeable Amount (Yuan)	23276.62	22473.45	19101.68	23419.12	18416.9	22374.92	129062.39				Toll Collection Rate
	Actual charge amount (Yuan)	23206.77	22473.45	19101.68	23411.37	18416.9	22374.92	128985.1				99.48%

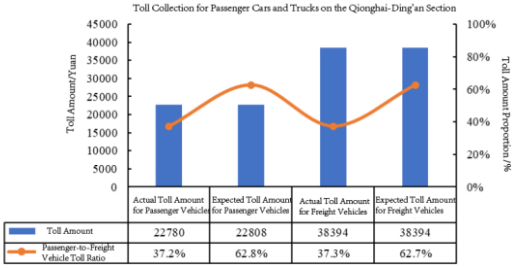

Figure 4. Toll collection for passenger cars and trucks on the Qionghai-Ding'an section.

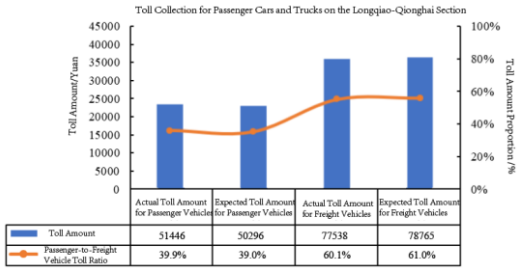

Figure 5. Toll collection for passenger cars and trucks on the entire G98 (Longqiao-Qionghai) section.

5. Conclusion

This paper comprehensively explores the research and testing of Beidou-based free-flow toll collection technology. By in-depth analysis of the principles of Beidou

positioning technology and its application in highway free-flow toll collection systems, this paper proposes a Beidou-based free-flow toll collection technology based on segmented billing and conducts detailed testing and verification of the free-flow toll collection system.

The results show that the key performance indicators of the Beidou free-flow technology on the test section can reach over 99.9%, meeting the relevant technical requirements for highway toll collection. The Beidou-based free-flow toll collection system based on segmented billing has the characteristics of high precision, high reliability, and strong real-time performance. It can accurately track and locate vehicles and automatically deduct tolls based on the driving distance and time, significantly improving the traffic efficiency and toll management level of highways.

In the future, with the continuous improvement and popularization of the Beidou satellite navigation system, Beidou-based free-flow toll collection technology is expected to be more widely applied in China's highway toll collection field.

This study was supported by the National Key Research and Development Program Project - Comprehensive Service Platform and Application Demonstration of Wide Area Transportation Spatiotemporal Big Data (2022YFB3904405).

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