Free-flow tolling system for expressway with fusion of 5G communication and high-precision positioning technology

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ABSTRACT

This study tackles the inefficiencies of the prevalent electronic toll collection (ETC) systems on expressways, which are hindered by limited communication ranges and notable processing delays that significantly reduce actual transportation throughput compared to theoretical capacities. To address these issues, we have developed an innovative free-flow tolling system that integrates cutting-edge 5G communication and high-precision localization technologies, aiming to streamline the tolling process and boost efficiency.We constructed a comprehensive traffic flow model that factors in diverse vehicle classifications and distinct driving patterns. This model serves as the foundation for simulating the tolling operations and evaluating the performance of the proposed system. Employing a cellular automaton framework, our simulation study meticulously assesses the service level of the tolling system, enabling us to fine-tune the design of tolling channels and enhance traffic organization schemes.The findings indicate that the proposed system has the potential to significantly improve traffic flow, minimize congestion, and elevate the overall efficiency of expressway transportation networks. Our research provides robust theoretical support and practical insights for the deployment of future expressway free-flow tolling systems.

Keywords: traffic engineering, simulation studies, toll collection systems, traffic flow modeling, traffic cellular automata

1. INTRODUCTION

Toll booths are an essential part of the expressway in China, contributing to its operational management, statistics and maintenance replenishment[1]. Since the invention of Electronic Toll Collection (ETC), it has been used in conjunction with Manual Toll Collection system (MTC) to improve the service level of toll booths[2]. ETC adopts Dedicated Short Range Communication (DSRC) to complete the vehicle-circuit communication and realize non-stop toll collection[3]. However, DSRC has short communication distance, high delay, small capacity and other defects[4]. Therefore, in order to ensure the vehicle detection rate, the ETC toll lanes in practical applications only allow a single vehicle to pass at a time and limit the lower passing speed, which makes it difficult to achieve the expected service level.

In recent years, many toll stations have tried to use more advanced Internet communication technology with better performance to realize vehicle identification. For example, the Nanning Shajing-Wuwei expressway in Guangxi, China, uses Long Term Evolution (LTE) cellular networks to realize sensorless toll collection[5]. Past research comparing LTE cellular communications and DSRC communications has consistently found that LTE outperforms DSRC in terms of range and packet rates[6]. Nevertheless, it's worth noting that certain scholars have highlighted instances where competitive DSRC devices demonstrated comparable performance to LTE devices under controlled laboratory conditions[7]. Since 2015, 5G communication technology has exploded[8]. Millimeter waves are sent and received through Multiple Input Multiple Output (MIMO) antennas to achieve high speed, low latency, and high capacity mobile communications[9], providing reliable support for multi-system information fusion[10]. Carnegie Mellon University has tested this 5G-enabled intelligent transportation system, with trials confirming a 26% increase in trip speeds and a 21% reduction in emissions[11].

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At the same time, increasingly sophisticated high-precision positioning technologies are being used for lane-level positioning of vehicles and distribution of location information[12], which supports the interconnection of smart vehicles and can assist in the auditing of travel paths[13]. At the same time, increasingly sophisticated high-precision positioning technologies are being used for lane-level positioning of vehicles and distribution of location information, which supports the interconnection of smart vehicles and can assist in the auditing of travel paths[14]. A high-precision positioning device with a 5G communication module is equipped on an intelligent networked vehicle[15]. When the vehicle enters the toll collection area, th e vehicle's precise location information is sent to the toll management system in real time through the 5G network, and the toll management system automatically calculates the amount of toll collection based on the vehicle's specific traveling path, time, road section and other information[16].

Toll collection systems are still being upgraded with the advancement of communication technology[17-18], while new toll collection systems also affect the form of traffic through the toll booths, the efficiency of which is affected by the volume of traffic, the system's availability, the organization of traffic flow and many other factors[19-20]. Based on the field research, this paper proposes a new type of expressway toll collection system that integrates 5G communication and high-precision positioning technology (Hereinafter referred to as 5G-HP toll system). A model-driven approach is used to carry out simulation, evaluate the service level assessment of the toll collection system, and propose a corresponding traffic organization scheme.

2. DESIGN OF 5G-HP TOLL COLLECTION SYSTEM

Relying on the increasingly mature 5G Telematics technology and high-precision positioning technology, the 5G-HP toll collection system completes vehicle identification through high-speed and low-latency data interaction between Roadside Unit (RSU) and On-Board Unit (OBU). The 5G-HP tolling system consists of five main components, which are free-flow toll booths, roadside communication facilities, in-vehicle terminals, edge computing platforms and back-end processing centers. The specific workflow of the system is as follows, the back-end processing centers process the vehicle identification information and track information uploaded from each toll booth to complete the road audit, and calculates the passage fee according to the driving track of the vehicle. Then sends the bill through the network. Users complete account registration and information entry online and pay the travel bill through the network. The system components and communication modes are shown in Figure 1.

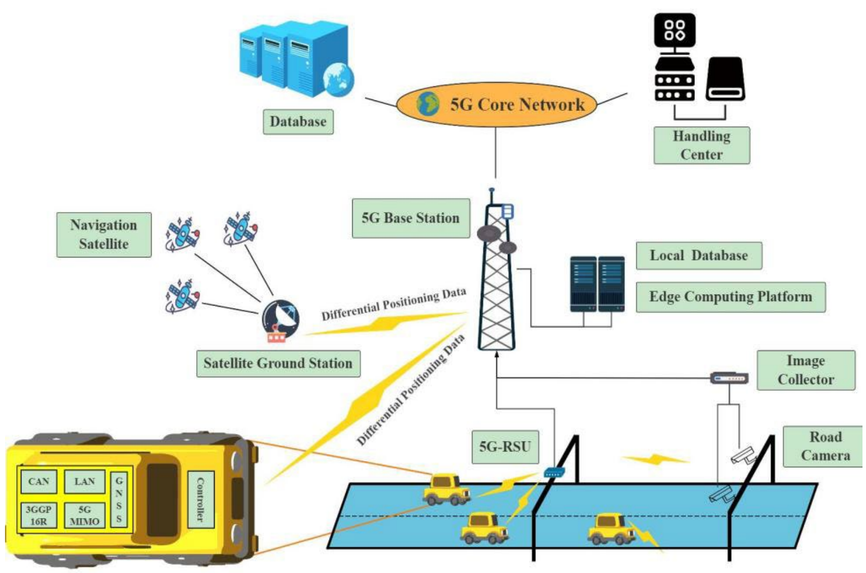


Figure 1. Schematic diagram of 5G-HP charging system.

The traffic organization design of the 5G-HP toll booth is shown in Figure 2. The design retains manual semi-automatic toll lanes because the transition from manual to smart tolling is a long process[21-22]. Vehicles equipped with OBUs drive out directly from the left free-flow toll lane, and the rest of the vehicles drive out from the right manual semi-automatic toll lane. A removable soft barrier is provided between the two types of lanes to allow vehicles to cross or turn around in case of unexpected situations. In addition, the design also takes into account the consideration of weighted toll trucks, with weighing scales laid on the floor of the MTC toll lanes[23-24].

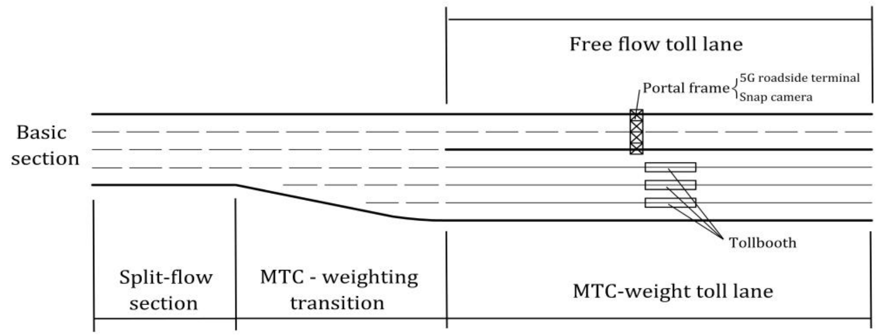


Figure 2. Traffic organization design for 5G-HP toll booths.

3. DISCRETE TRAFFIC FLOW MODELING

In this section, a discrete traffic flow Cellcular Automata (CA) model and a service level evaluation model for the 5G-HP tolling system are designed.

3.1 Cellcular Automata Model

The model developed in this paper is based on geometric design of the mainline toll booth, including the basic mainline segment (segment A), the diverging area (segment B), free-flow toll collection segment (segment C, D), and MTC-truck toll segment (segment E). The maximum width of the cross-segment is Wsum. There are hard isolation facilities between segment C and segment D, E, as shown in Figure 3.

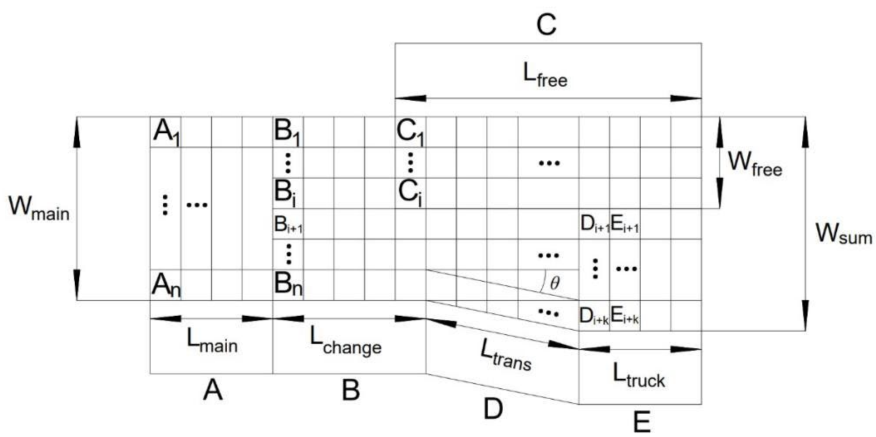


Figure 3. Diagram for CA model.

Considering the variety of vehicle types, vehicles are divided into two categories: small cars and toll-by-weight trucks, while the traffic volume proportion of these two categories is set to be 5:2. Considering the driving characteristics, drivers are divided into two types: aggressive drivers and conservative drivers[25]. The existing probabilities of the vehicles to the two types of drivers are P_{aggr} and P_{cons}, $P_{cons} = 1 - P_{aggr}$. Assume that the difference between the two types of drivers only exists in acceleration and deceleration behavior.

The warning signs for the toll booths are set up 2km in front of the toll plaza transition section. The road section between the warning sign and the beginning of the diversion area is set up as the mainline segment, with a lane width of 3.75m, a length of L_{main}, a total width of W_{main}, and the number of lanes n. The index of the lanes are $A = \{A_1, A_2, A_3, \dots, A_n\}$ (numbered from the center of the road to the outside), and the speed limit is $V_{max} = V_{car}, V_{truck}$, where V_{car} denotes the speed limit for cars and V_{truck} denotes the speed limit for trucks. The OBU-equipped and non-OBU-equipped vehicles are divided in lane-changing segment. The index of the lanes are $B = \{B_1, B_2, B_3, \dots, B_i, B_{i+1}, \dots, B_n\}$, in which the lane 1 to i are connected to free-flow toll lanes and lane $i+1$ to n are connected to MTC-weighting toll lanes. The MTC-truck transition segment refers to the connection lanes between the lane-changing segment and the MTC-truck toll lanes. The angle between the right curb and the basic mainline segment is θ. The lane width is 3.75m and the length is L_{trans}, The index of the lanes are $D = \{D_{i+1}, D_{i+2}, D_{i+3}, \dots, D_{i+k}\}$.

The width of free-flow toll lane is $3.75m$, the total width is W_{free}, the length is L_free, and the number of lanes is i. The index of the lanes are $C = \{C_1, C_2, C_3 \dots C_i\}$. The width of MTC-weighting toll lane is 3.50m, the total width is W_{MTC}, the length is L_MTC, and the number of lanes is K. The index of the lanes are $E = \{E_1, E_2, E_3 \dots E_i\}$.

3.2 Rules of motion for vehicles

Vehicle motion rules are the core of traffic cellular automata. In this paper, based on the geometric design of 5G-HP toll booth and traffic organization, we develop the speed change and lane change rules for vehicles in the cellular automata model.

3.2.1 Rules for mainline

Considering for acceleration. The aggressive drivers tend to accelerate rapidly, and vehicles accelerate directly to the maximum speed limit or following the front car tightly in the next moment, while the conservative drivers tend to accelerate steadily with one cell (4m/s) once. Considering for safe deceleration. The aggressive drivers tend to decelerate at the lowesthighest rate , while the conservative drivers tend to decelerate at a relatively lower rate. In addition, random deceleration for vehicles occurs due to the changes of drivers' psychological condition and environment and the possibility is p_{slow}. The rules for velocity changing are shown in Table 1.

Table 1. Rules for velocity changing in mainline.

Type	Formula
Acceleration	$v_q(t+1) = \begin{cases} min(v_{max}, gap_q(t) - 1), \; p_{\text{aggr}} \\ min(v_{max}, v(t) + 1), \; p_{cons} \end{cases}$ (1)
Safe Deceleration	$IF \;\; v_q(t) \geq \; gap_{q(t)} + v_{q+1}(t) \; THEN \;\; v_q(t+1) = \; gap_{q(t)} + v_{q+1}(t+1) - 1$ (2) $IF \;\; v_q(t) \geq \; gap_{q(t)} \; THEN \;\; v_q(t+1) = \; gap_{q(t)} - 1$ (3)
Random Deceleration	$v_q(t+1) = \; v_q(t+1) - 1 \;\; IF \;\; v_q(t) = \; v_{max}$ (4) $v_n(t+1) = \; v_q(t+1) \; IF \;\; v_q(t) \neq \; v_{max}$ (5)

$v_q(t)$ is the speed of the qth vehicle at moment t; $gap_q(t)$ is the distance between the q^{th} car and its front car.

When the vehicle is about to enter the toll booth from the mainline, drivers will consciously maneuver their vehicles to change lanes to the appropriate toll area after noticing the roadside toll booth signs. OBU-equipped vehicles tend to shift to the left lanes, while MTC-tolled vehicles and trucks tend to shift to the right lanes, which is a mandatory lane change for destination considerations. In addition, the lane-changing rules involve random lane changing for efficiency purposes[26]. The rules for lane changing are shown in Table 2.

Table 2. Rules for lane changing in mainline.

Type	Formula
Changing to the Left	$WHEN \;\; D_q^{l+}(t) \geq D_q^+ \;\; AND \;\; v_q(t) \geq \; D^+$ (6) $IF \;\; D_q^{l-} - [v_q^{l-}(t) - v_q(t)] > 1 \;\; THEN \;\; lane_q(t+1) = lane_q(t) - 1, \;\; p_{C_{left}}$ (7)
Changing to the Right	$WHEN \;\; D_q^{r+}(t) \geq D_q^+ \;\; AND \;\; v_q(t) \geq \; D^+$ (8) $IF \;\; D_q^{r-} - [v_q^{r-}(t) - v_q(t)] > 1 \;\; THEN \;\; lane_q(t+1) = lane_q(t) + 1, \;\; p_{C_{right}}$ (9)

$D_q^{xy}(t)$ stands for the distance between the q^{th} vehicle and the vehicle next to it in the direction along the road, when x is l or r, which refers to the left or right lane, and x, y is $+$ or $-$ which refers to the front or rear. For example, $D_q^{r+}(t)$ refers to the distance between the q^{th} vehicle and the vehicle in its right-front direction at moment t; Also, $lane_q(t)$ stands for the lane the q^{th} car is driving on for moment t; p_C and p_T refers to the probability of lane changing to the left for cars and trucks.

3.2.2 Rules for lane-changing segment

In lane-changing segment, all vehicles must change lanes when necessary. That is, vehicles must enter the appropriate lane based on the different toll collection methods. When the conditions for performing a lane change are not met, the vehicle should slow down slowly and wait for the opportunity to change lanes. For a free-flow toll vehicle, when it reaches the first cell in Section B, it will determine whether the conditions for a lane change are met:

$$WHEN\ \ Loc_{q(t)}\ =\ B(i,1) \tag{10}$$

$$IF\ road_{left}\ =\ free\ \ THEN\ \ v_q(t+1) =\ v_q(t) - 1 \tag{11}$$

$B(i,j)$ refers that the vehicle is at the cell in row i, line j of segment $B.\ road_{left}\ =\ free$ indicates that there is no vehicle approaching behind the left lane of the vehicle and it is safe to change lanes. When the safety conditions for lane change are not met, the honking rule will be introduced. That is, the driver honks to signal approaching vehicles in the target lane to slow down in order to prevent a collision:

$$v_q^{l-}(t+1) = D_q^{l-} - \left[v_q(t) + 1\right] \tag{12}$$

3.2.3 Rules for segment C and D

The rules for acceleration and deceleration for free-flow toll vehicles in Segment C are the same as for the mainline, except that they may not change lanes. When a car or truck using MTC reaches the last cell in Sector D, it will make a lane change decision, giving priority to the toll lane with the shorter queue.

3.2.4 Rules for MTC-weighting lanes

Vehicles are not allowed to change lanes after entering segment E, and they will slow down until they come to a stop. The speed of these vehicles is updated according to the rules below.

$$\text{WHEN}\ Loc_q(t) = E(i,1) \tag{13}$$

$$\text{THEN}\ v_q[t + (1+\lambda)\Delta t] = v_q E(i,1) - \frac{v_q E(i,1)^2}{50} \cdot \Delta t \tag{14}$$

N_{Ei} is the number of queued vehicles in the i_{th} toll-by-weight lane, Δt the travel time of vehicles in segment E, and λ the brake delay factor of the toll-by-weight truck, which is related to the truck brake performance and road condition. When $Loc_n(t) = E(i,25)$, the vehicles stop to pay tolls.

4. METHODOLOGY FOR SERVICE LEVEL EVALUATION

We set the average delay time as a quantitative index to evaluate the service level of the 5G-HP toll booth, as it can reflect the service time, traffic density, and speed distribution of vehicles passing through the toll collection lanes and can also indirectly reflect the psychological condition of drivers when passing through the toll collection lanes.In this paper, we define the delay as the the difference between the actual time for vehicles passing through toll collection lanes and the expected time for vehicles passing through toll collection lanes at a designed speed uniformly.

$$D = \frac{1}{n}\sum_{i=1}^{n}\left(T_i - \frac{L_j}{v_j}\right) \tag{15}$$

D is the average delay; n is the total number of vehicles passing through the toll booth; T_i is the time for the i^{th} vehicle passing through the toll lane, L_j is the length of the j^{th} toll collection lane and vj (m/s) the design speed for vehicles passing the jth toll collection lane.

5. EXPERIMENTAL RESULTS

5.1 Experimental setup and parameterization

MATLAB R2022a serves as the programming platform for implementing the cellular automata program that embodies the traffic organization scheme and traffic flow model presented in this paper. Set the parameters of the simulation as follows, n= 4, i = 2, k = 2, θ = 15°, and the length of a cell is $4m/cell$, $L_{main}\ = 2000m(500cells)$, $L_{trans}\ = 75m(about19cells)$, $L_{truck}\ = 100m(25cells)$. The model adopts the condition with open boundary, and the random slowing rate for vehicles is $P_{slow} = 0.25$. The proportion of aggressive drivers is $P_{aggr} = 0.8$,while the proportion of conservative drivers is $P_{cons} = 0.2$. We set the simulation time to be 5000 simulation seconds, and to ensure the simulation effect is real and stable enough, the data are recorded from the 1400^{th} simulation second and collected within 3600 simulation seconds. The four cells at the entrance of the road are departure areas. In order to approximate the lateral distribution of traffic volume in real roads, we set the departure areas for different vehicle types according to their arrival possibilities. The cells at the entrance of lanes 1-3 are set as the departure area for small cars, while the cells at the entrance of lanes 3-4 are the departure area for trucks.The process of vehicle input is shown in Figure. 4. In the figure, Q_{input} is the theoretical input traffic volume and Q is the actual input traffic volume; p_{jr} denotes the probability of issuing a minivan at the rth iteration of the jth issuing metacell, and p_{jr^*} is the probability of issuing a truck at the r^{th} iteration of the j^{th} issuing metacell, following the relationship of the formulas given in the Figure 4.

The effect of different flow rates and lane-changing segment lengths on passing efficiency is explored. The input flow rate is set to increase from $1000veh/h$ to $2000veh/h$ at intervals of $100veh/h$, covering both low and high flow rates. The length of the lane-changing segment was incremented from $100m$ to $1000m$ at $100m$ intervals, and the time from when a vehicle enters the diversion segment to when it leaves the toll lane was collected to calculate the delay. In addition, the results for different Market penetration rate (MPR) were considered.

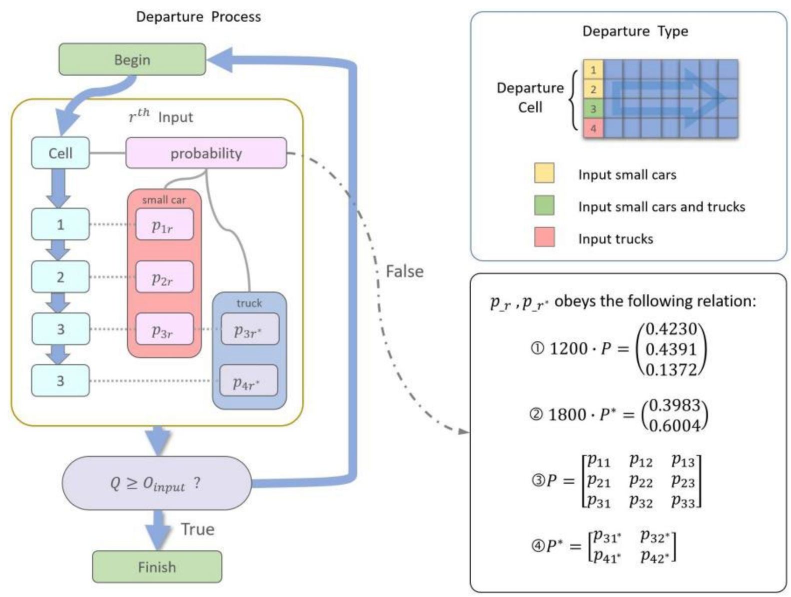
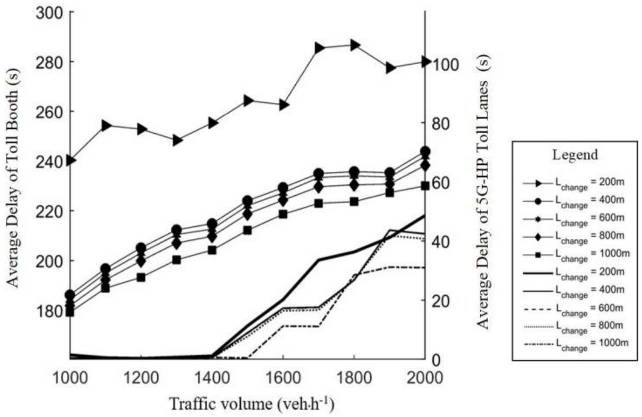


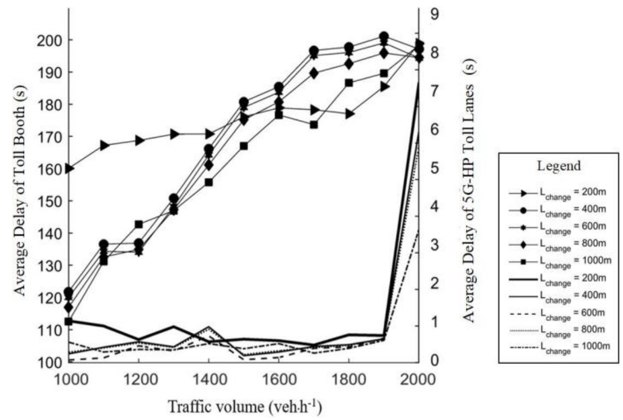
Figure 4. Schematic diagram of the process of vehicle input.

5.2 Discussion of results

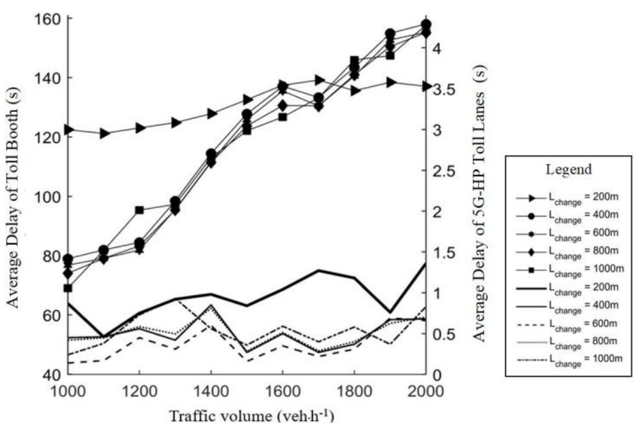
Figure 5 illustrates the experimental results. Under a permeability of 0.1, lane-changing sections spanning 400 to 1000 meters outperform the 200-meter counterpart, albeit with negligible service enhancement beyond 400 meters. At a penetration rate of 0.3, the toll system's average latency escalates as traffic volume attains 1500 vph, and dramatically amplifies within the 5G-HP lanes as the volume inflates to 1900 vph. Given the lane transition prerequisites, an 800-meter lane-changing section is advised. With penetration rates of 0.5 and 0.7, the toll booth's average delay remains below 1.5 seconds, denoting a free-flow state. Interestingly, the average delay of vehicles traversing different lane-changing lengths significantly intertwines around 1800 vehicles/hour. Hence, a 400-meter lane-changing segment is suggested for traffic volumes below this threshold, while a 200-meter length is optimal for higher volumes. At a 0.9 penetration rate, the toll plaza's integrated service level is superior, with a 200-meter lane-changing segment significantly outshining those between 400 and 1000 meters. Post a traffic volume of 1800 vehicles/hour, a 600-meter lane-changing segment is advocated.The graph reveals that when the penetration rate surpasses 0.5, vehicles in the 5G-HP lane experience virtually zero delay.



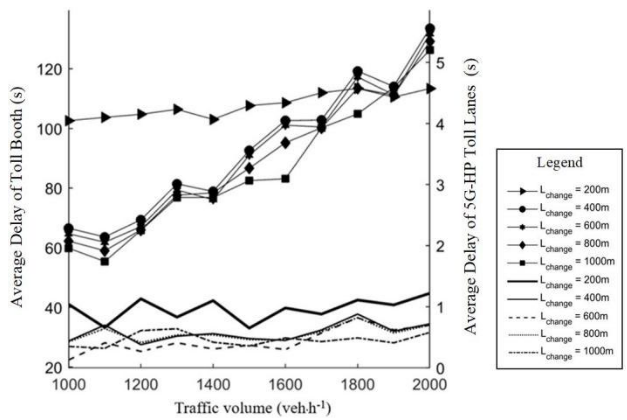
(a) Experimental results of MPR 0.1.



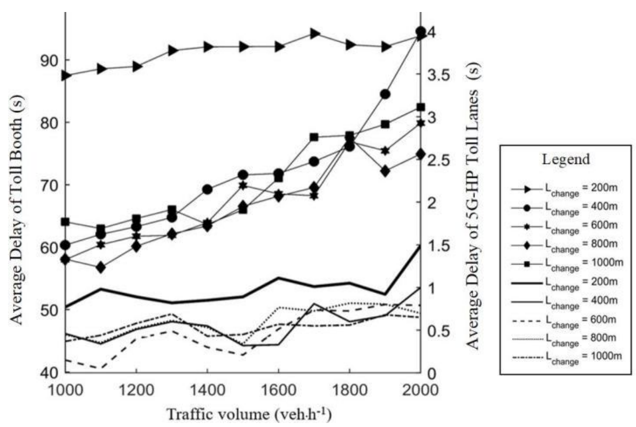
(b) Experimental results of MPR 0.3.



(c) Experimental results of MPR 0.5.



(d) Experimental results of MPR 0.7.



(e) Experimental results of MPR 0.9.

Figure 5. Experimental results of average delays at toll booths and 5G-HP toll lanes.

5.3 Comparison with field research data

We conduct on-site investigation on several MTC-ETC hybrid toll plazas, and place vehicle detectors at the junction of the basic road section and the toll plaza, as well as at the end of the toll lanes, respectively, and obtain the actual vehicle passage time by calculating the time difference between the vehicles passing through the two detectors, as shown in Figure 6. The total length of the investigated road section is divided by the vehicle speed limit to get the theoretical vehicle passing time. Among them, the vehicle speed limit of the toll lane is 40 km/h according to the traffic regulations.

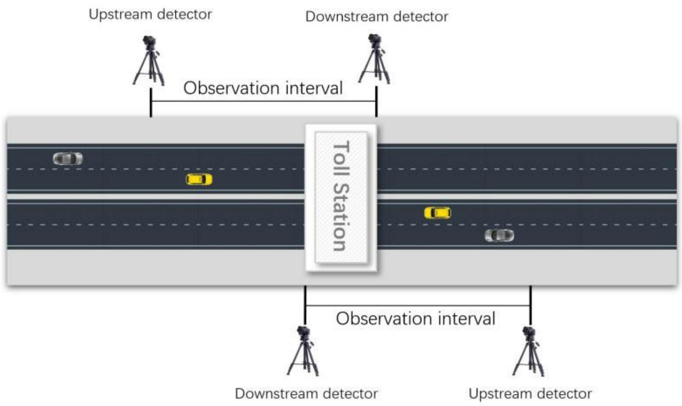


Figure 6. Schematic diagram of the location of the instrumentation for delay detection at toll booths..

The length of observation is 1 hour, the measured flow rate is 1341veh/h, and the average delay time frequency for single ETC and MTC lanes is shown in Table 3.

Table 3. Field research data.

Lane	Delay(s)	Frequency
ETC	0-1	45
	1-2	71
	2-3	111
	3-4	118
	4-5	74
MTC	10-11	177
	11-12	74
	12-13	106
	13-14	86
	14-15	114
	15-16	91

As can be seen from the figure, ETC lane delays are concentrated in the range of 2-4 seconds, and MTC lane delays are concentrated in the range of 11-15 seconds. Therefore, compared to the traditional MTC-ETC hybrid toll booth, the 5G-HP toll booth has a higher level of service.

6. CONCLUSION

Tollbooth operations are a key component of roadway operations, as they both expand the means of revenue and contribute opportunities for roadway management. Toll booths must have sufficient service capacity to handle the expected traffic volume safely and efficiently without excessive queues and delays. The explosive development of Internet communication technologies in recent years has continued to drive optimized iterations of toll booth operation models and traffic organization. This paper proposes a new type of toll collection system based on 5G communication technology and high-precision positioning technology, which integrates identity auditing and path auditing through information fusion technology, realizes free-flow toll collection, and greatly improves the service level of the toll booth under heavy traffic.

Toll stations control the entrance and exit of the expressway, and their service level greatly restricts the overall service level of the expressway. Analyzing and evaluating their service level can provide valuable guidance for the transformation and operation of toll stations. In this paper, we design a cellular automata model to formulate speed and position update rules for different types of vehicles on different road sections according to the geometric design of a new type of toll booth and the operational characteristics of the traffic flow, respectively. Unlike expressways and intersections that have standards for evaluating service effectiveness, toll booths do not have uniform service level evaluation indexes. In this paper, we characterize the service level as delay time, and analyze the average delay of toll booths through microsimulation by considering different traffic volumes, length of lane-changing section and market penetration. Meanwhile, based on the survey data, the results are compared and analyzed with the simulation results, which show that the 5G-HP toll collection system has a higher service level compared with the traditional MTC and ETC hybrid toll collection system, and the average delay of free-flow toll lanes stays below 1.5 seconds and the average total delay of the toll booth stays below 160 seconds when the system adoption rate is greater than or equal to 0.5.

The results of this paper enrich the research in the field of toll collection system based on information fusion technology, and fill the gaps in the research on the service level of this type of toll booth. The results of the proposed model provide valuable insights into the operation and management of expressway toll booths. The conceptualization of traffic organization in this paper appears to be overly idealized, overlooking the intricate complexities inherent in real-world traffic flow operations. Moreover, the practical implementation and deployment of the proposed charging system demand a thorough consideration of the precision and reliability of wireless communication environments, along with the integration of high-precision positioning mechanisms.

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