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Highway Toll Collection Method for Connected Automated Vehicle Platooning Using Spatio-Temporal Grid Reservation

Babakarkhail Habibullah[1], Rui Teng[2], Kenya Sato[2]

[1]Network Information Systems, Doshisha University, Kyotanabe, Japan
[2]Mobility Research Center, Doshisha University, Kyotanabe, Japan
Email: ksato@mail.doshisha.ac.jp

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Abstract

In the intelligent transportation system, the autonomous vehicle platoon is a promising concept for addressing traffic congestion problems. However, under certain conditions, the platoon's advantage cannot be properly developed, especially when stopping for electronic toll collection (ETC) to pay the toll fee using the highway. This study proposes a software architectural platform that enables connected automated vehicles to reserve a grid-based alternative approach to replace current highway toll collection systems. A planned travel route is reserved in advance by a connected automated vehicle in a platoon, and travel is based on reservation information. We use driving information acquired by communication mechanisms installed in connected automated vehicles to develop a dynamic map platform that collects highway toll tax based on reserving spatio-temporal grids. Spatio-temporal sections are developed by dividing space and time into equal grids and assigning a certain road tax rate. The results of the performance evaluation reveal that the proposed method appropriately reserves the specified grids and collects toll taxes accurately based on a spatio-temporal grid with minimal communication time and no data package loss. Likely, using the proposed method to mediate driving on a one-kilometer route takes an average of 36.5 seconds, as compared to ETC and the combination of ETC and freeway road lane methods, which take 46.6 and 53.8 seconds, respectively, for 1000 vehicles. Consequently, our proposed method's travel time improvements will reduce congestion by more effectively exploiting road capacity as well as enhance the number of platoons while providing non-stoppable travel for autonomous vehicles.

Keywords

Autonomous Vehicle Platoon, Highway Toll Tax, Grid-Based Toll Charges,

Spatio-Temporal-Grid, Dynamic Map

1. Introduction

Toll collection is a phenomenon used to reimburse infrastructure investments by those who use the infrastructure [1]. Tolls are collected and used for highway development, operation, and maintenance. The number of vehicles driving on highways continues to grow steadily, resulting in high maintenance costs and a peak in demand for highway expansion. The conventional method of toll collection is generally to mandate vehicles to stop or reduce speed for toll payment, which increases traffic congestion and fuel consumption. To efficiently address the challenges associated with manual toll collection, electronic toll collection (ETC) was introduced by William Vickrey, the Nobel Prize winner in Economics, who recommended equipping all vehicles with an electronic identification system [2].

To replace the manual method, the electronic toll collection method is introduced in which the vehicle slows down to pay the toll fee through the ETC electronic toll collection (ETC) method [3]. The terminology "electronic identification" refers to a transponder that sends a customized signal from certain road sections to a central computer for bill calculation (Kelly, 2006) [4]. In 1986, this concept was first utilized at toll booths in Norway. In 1991, Trondheim, Norway, became the world's first city to use unassisted full-speed electronic tolling [5]. This technique was beneficial since it significantly decreases the delays caused by toll payment as well as enhances the traffic congestion compared to the manual method of toll collection. As this design gained popularity, gantries quickly replaced traditional toll booths, allowing sensors to be added for better detection. Unfortunately, the use of gantries raised further challenges, such as not all vehicles having the required electronic devices to implement the ETC system. Therefore, by expanding and providing many lanes to collect toll fees from different vehicle types, as a result, toll both usages necessitated more highway space, resulting in higher installation and maintenance costs for electronic devices in all vehicles. For instance, toll both installation and maintenance costs for electronic devices in all vehicles' construction have become more expensive. Following that, gantry failure may disrupt toll collection, demanding regular maintenance. However, due to the toll plazas' vehicle service constraints, which are limited to 300 vehicles per hour, there are challenges arising with massive traffic jams, crowding, and vehicle congestion, resulting in both time and fuel loss.

Currently, the most promising and feasible ETC technologies in the world are based on DSRC (dedicated short-range communication) [6], which includes barcode and RFID (radio frequency identification), video tolling, which includes ANPR (automatic number plate reader), GPS or vehicle positioning system (VPS), and infrared short-range communication (ISRC) based on calm active infrared.

The barcode technology for automatic Electronic Toll Collection (ETC) systems was studied in order to prevent the ever-increasing stream of traffic and long queues at highway tollbooths. In the barcode-based method, the ETC has a bar-coded sticker placed under the wind shield of the vehicle that is read by a laser scanner when it passes through the toll plaza. It utilizes digital image processing techniques to scan the barcode and compare it with the stored database using decoded data [7]. Despite having the advantage of being simpler than other technologies, it has several disadvantages when used for toll collection systems, including a lack of reliability (because it is easily imitated), less accuracy in bad weather (especially when it is foggy), a lack of flexibility, a slow data read rate (it is usually affected by signal interference), less storage information, and is easy to be stolen [8].

The second technology is the RFID-based ETC system [9], which has an in-vehicle unit (IVU) installed on the front windshield of the vehicle. This IVU interacts with the RFID frequency reader or antenna at the toll plaza and the transaction is done accordingly. It contains a cash card for payment of road tax, which can either be prepaid or postpaid. It contains more information in comparison to a barcode, has a faster reading rate, is tougher to fraud than a barcode, and is also comparatively more reliable. It is also observed that sometimes it shows the problem of interference among the frequencies of devices (mobile phones, other IVU, walkie-talkies, FM radios, or other electronic gadgets) in the vicinity of the toll plaza or passing vehicles. The angle of installation and alignment plays an important role in the reliability and high accuracy of these systems.

The third important technology is ANPR [10]. It utilizes a stationary camera to record and identify the number plates of vehicles passing through toll plazas. The identified license numbers are matched in the database (connected with the transport office) and the toll is deducted. If the recorded number is not read properly or not found in the records, it issues an enforcement violation alarm to alert the authorities. In this way, it simultaneously solves two objectives: identification of vehicles for deduction of toll tax and issuing/recording violation enforcement alerts. It also has the constraints of high cost and reduced accuracy under tempestuous environmental conditions.

The fourth technology is calm active infrared [11]. It is a relatively new technology. It is the RFID system; the only difference is that it has an active infrared unit installed on the vehicle, which contains all the information. In comparison to RFID, it has a faster data reading rate, reliability, accuracy, and efficiency, and it works well in all environmental conditions. It also comes with the problem of interference, lack of interoperability, vendor support, and high cost are the roadblocks to utilize this technology. Apart from these, it is still under research and many other aspects need to be studied.

The fifth technology is the GPS-based [12] method of pricing with vehicle positioning systems (VPSs) that employ gates, electronic equipment, and digital communication and is supported by satellite aids. Several researchers study the Global Positioning System (GPS) as one of the solutions for the ETC challenge that might be to implement road pricing. A field test in Hong Kong supported the first GPS-based road pricing experiment in 1997 (Catling, 2000) [13]. In 1998, the European Union proposed using the Global Navigation Satellite System (GNSS) to tax vehicles depending on the distance traveled (Brussels, 1998) [14]. This preliminary effort generated more concepts and variations of GPS-based road pricing. Lee, Jeng, Tseng, and Wang [15] and Xu [16] conducted comprehensive investigations and analyses of the architecture of GPS-based toll collection systems, as well as addressed significant design challenges. Srinivasan, Cheu, and Tan introduced a road pricing system based on a map and GPS [17]. Ren and Xu proposed another node matching-based approach [18]. Dias, Matos, and Oliveira presented a smartphone-based toll collection system that could be used for both traditional ETC and contemporary GNSS tolling [19]. The GPS-technique [20] consists of worldwide satellite navigation system incorporation with a communication mechanism. It works with the help of a global positioning system (GPS) unit installed on the vehicle attached to an on-board unit (OBU), which stores the coordinates of the vehicle and sends the transaction information to the toll authorities via GSM (global system mobile communication). Saldivar *et al*. investigated the Signalized Corridor Timing Plan for connected vehicles (CVs) utilizing trajectory data and the deployment of a semi-automated adaptive control system. The vehicle trajectory data is used to compute corridor travel times for each side of the intersection, and the Purdue Probe Diagrams (PPD) are generated. The operational measurements such as arrivals on green (AOG), split failures (SF), and downstream blockage (DSB) are calculated using the PPDs using the Highway Capacity Manual (HCM) level of service (LOS) is estimated. The result shows that the implementation of the semi-automated adaptive control system had a significant positive impact on the freeway corridor [21]. This system is highly reliable, accurate, and efficient. The efficiency of this system is not affected by environmental conditions. It provides a payment option only for the distance travelled and is highly flexible in generating the corresponding payment details. This system's shortcomings include excessively high installation and maintenance costs; careful handling; and the need for additional power and other accessories.

Thus, we need a new method to overcome the difficulty of increasing road capacity while decreasing travel time and traffic congestion. In the meantime, how to collect the highway toll tax in the smart mobility era by not unchaining the platoon? Platooning may help to increase lane capacity if used with consistent spacing [22]. CAV platoons have the potential to improve vehicle safety, efficiency, mileage, and travel time while decreasing traffic congestion, pollution, and passenger stress [23] [24]. Moreover, platooning should be implemented with vehicles evolving on dedicated tracks and traveling nonstop from origin to destination to be beneficial in terms of traffic flow [25]. Consequently, it is not feasible to address the challenges arising from the current toll collection system for the platoon's smooth movement as well as collect toll tax without unchaining the platoon. As a result, if the stop-and-go problem of toll fee collection for platooning is solved, platooning could contribute to road capacity and enhance traffic flow. However, a link or network-level model for determining the effect of platooning on highway traffic and coordinating platoon movement on the highway toll collection system is still lacking.

Dynamic platoons [26] are classified into two types: real-time platoons [27] and opportunistic platoons [28]. The difference between these two is that in the real-time platoon scenario, individual vehicles broadcast a request to join an existing platoon, but there is no such platoon in the opportunistic platoon scenario. When attempting to join a platoon, individual automobiles must first locate vehicles with similar characteristics (e.g., destination, vehicle type, and route). They all accomplish the platooning aim in terms of functionality. However, there was a considerable difference between the two in terms of security. To begin with, an organization, such as a supermarket or logistics company, will usually establish a real-time platoon, so the original vehicles may be completely trusted.

On the other hand, vehicles in the opportunistic platoon do not recognize one another and are suspicious of one another. Second, because vehicles may have different destinations, the opportunistic platoon is more variable than the real-time platoon, and the platoon leader must manage extra authentication duties to realize vehicles joining or departing. Finally, the platoon leader (PL) is required to carry out more tasks than the platoon member (PM). At the moment, all vehicles must pass through the highway tollgate and must slow down or stop before passing through the Electronic Toll Collection system (ETC). Furthermore, in the case of freeway roads, the proposed method applies the reservation rule that all vehicles be easily identified and penalized for evading the toll charges.

Regarding evaluating the current toll collection systems for platooning, it is not feasible that the currently implemented technology and methods address the platoon challenges for toll collecting. When the ETC detects a vehicle, it lifts the barrier and releases the vehicle to travel through. To allow the ETC system to detect it, the following car must maintain a specific distance from the previous vehicle. As a result, while the vehicles may benefit from platooning, they would ultimately be separated and slower before crossing the ETC. Following that, vehicles must form a platoon once again, passing the tollgate. Obviously, this time-consuming process will diminish anticipation for the platoon. Furthermore, the platoon leader will face increased air resistance due to aerodynamics. As a consequence, no vehicle wishes to lead the opportunistic platoon once again. As well, it is easy to not register a car in a platoon and travel through a GPS system and not identify it in the case of eliminating the ETC system. Thus, a single vehicle may try to escape from the ETC charging by following the leader in the platoon to use the freeway road lane dedicated for platoons. If the ETC toll gate is installed on the freeway road for collecting the toll fee, it cannot handle toll fee collection for the platoon to smoothly travel together through tollgates. It is simple to avoid toll charges in the case of a real-time platoon assigned by the organization. In the case of an opportunistic platoon, a single vehicle may attempt to flee the ETC charging by following the platoon leader. There are no clear trade-offs among the above-mentioned technologies. Therefore, it is essential to have a novel system to address challenges in the era of future smart mobility.

Overall, none of all these methods can be considered a reliable technology for toll and road pricing collection. The high cost of implementation, conditional application, and inappropriateness for the smart mobility era are the common characteristics between them. Therefore, new technology must be researched for reliable application and ease of use in smart mobility. Therefore, this research proposes a novel framework for toll collection in the smart connected automated vehicles (CAVs) era by harnessing the concept of road pricing and combining it with the management of driving schedule information. In the new system, spatio-temporal sections are established as equal grids of space and time, though a designated toll tax is charged per each grid for road toll collection. Certainly, connected automated vehicles in a platoon well reserve the spatio-temporal sections by forming a planned travel route in advance and travelling according to the reservation information. Thus, with traffic management, the new method will accordingly save travel time for each vehicle and thereby improve the highway capacity. Furthermore, making a reservation rule for CAVs will collect toll fees and improve the number of generated platoons on the highway.

Our main contributions could be summarized as follows:

- The CAV platoons have the potential to significantly increase highway capacity, but the current tollgate system could not process the toll fee collection of different types of platoons. The proposed method provides a freeway mechanism for collecting toll fees without stopping or reducing speed for tollgates, thereby increasing travel time and the number of generated platoons on the highway.
- It is simple to avoid toll charges in the case of a real-time platoon assigned by the organization, as well as in the case of an opportunistic platoon. A single vehicle may try to escape from the freeway charging or ETC method by following the leader in the platoon. In the proposed method, each vehicle will reserve the road and travel based on the reserved information, which will smoothly collect toll fees from all types of platoons as well as enhance the highway capacity.
- Since all travel is based on the pre-reservation rule, it will provide a well-managed highway system where routes can be reserved in a time frame based on the traffic demands with a pricing-based control-charging system over traffic density to reduce and manage traffic congestion.
- Tax charge accuracy is essential for both individual toll fee payers and the government's total tax collection. As a result, a system that collects highway

tolls accurately is required. The performance evaluation results of the proposed method show that it is capable of collecting toll fees with high accuracy and no data package failures, as well as providing detailed travel and toll tax information to the user for their audit.

The rest of the paper is organized as follows. In Section 2, proposed method structure and system module are presented. In Section 3, describes our system's implementation. In Section 4, performance effectiveness of the proposed method. In Section 5, simulation for travel time and platoon measurement. In Section 6, result and discussion. Finally, the conclusion and describe future work is given in Section 7.

2. Proposed Method System Framework

This section presents the overall framework of the proposed system for the real-time reservation of (virtual) spatio-temporal sections of a road as grid/millisecond units for the highway toll-fee collection for CAV vehicles in platoons.

2.1. Proposed Method

In the proposed method, a configuration system platform is developed by providing a freeway to collect tolls on the highway without stopping or reducing the speed for ETC. The platform includes the network management center, a viewer/user, and a billing center. The CAV vehicle, which is pre-designed for dynamic platooning, assumes the functions of a vehicle or user in order to send positions and driving data obtained from various sensors to the network management center/server. Each CAV vehicle reserves a planned travel route on the platform and travels according to the reserved information. When the CAV vehicle in a platoon starts driving on a highway, it communicates to the server the targeted departure time, vehicle ID, origin, and destination position information. The network management center communicates with the CAV vehicles and creates a database as a dynamic map from the collected data. The dynamic map is utilized to create the spatio-temporal grid, by dividing time and space into equal grids, the grid reservation on the road in real time is easy.

Dynamic mapping is a platform that is used to show dynamic spatial phenomena or to display spatial information in a dynamic way that incorporates and displays the time dimension in a map. Implementing the dynamic map platform, as studied by Netten, L. Kester *et al.* [29], will satisfy the primary criteria of real-time data collection and display, such as automobile reflection on the map, transmission, registration of vehicle information, and static map information. Due to the aforementioned benefits of the dynamic map platform, we developed a web-based dynamic map to implement the proposed methods.

The travel distance by grid/millisecond unit is computed and the designated toll fees are applied to each independent grid, which is converted based on the fuel consumption for each kind of vehicle. When the server reserves the grid, computes the toll fee, and saves the data in Mongo DB, at the end offers CAV vehicle users with detailed information regarding travel distance and toll charges. The role of the finance office is that if the user does not pay the toll fee, the management center compiles and transmits a monthly charge invoice to the vehicle owner. The viewer shows the server's dynamic map and gives detailed travel and tax information to the vehicle user through an API, as described in Figure 1.

When a CAV in a platoon proceeds to drive on the highway, it transfers the user's information and requests to the network management center to reserve the grid along the route. When the server receives the request, it first checks the dynamic map for occupancy and decides on a grid reservation and responds to the vehicle with grid and route reservations. The server sends the detailed travel and toll charge information when the vehicle arrives at the destination. Furthermore, it stores the specified data. If the vehicle fails to pay the toll fee, the monthly bill will be sent to the vehicle owner, as shown in Figure 1.

2.2. Dynamic Map Implementation

To implement a dynamic spatio-temporal section on highways in a real-time grid/millisecond unit-charging system, the server environment is developed in Node.js and a web application framework called Express. A spatio-temporal grid is a collection of grids or cells formed by evenly dividing time into one millisecond intervals and space into latitude and longitude and expressing them in a nested document structure. We created spatio-temporal grids utilizing MongoDB, a document-oriented database like the Relational Database Management System (RDBMS) that allows for nested document structures. A one-kilometer

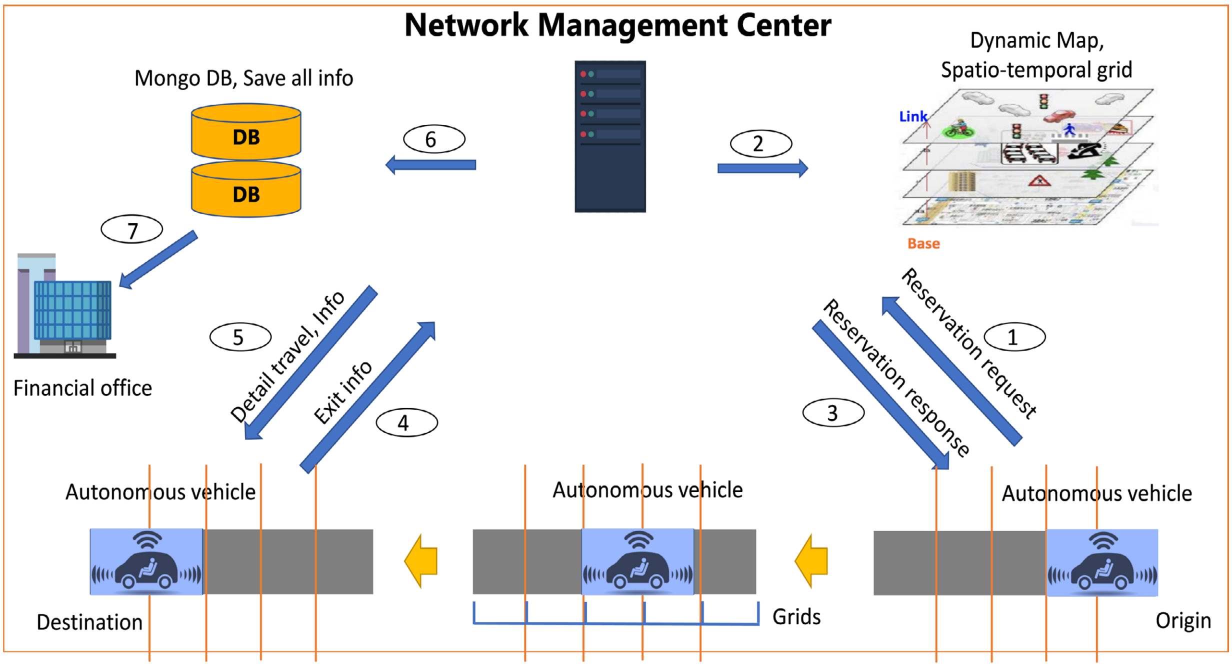

Figure 1. The proposed method sequence diagram.

road environment is created by dividing a space equally into a spatio-temporal grid and defining independent cells. Figure 2 illustrates the spatio-temporal grid mechanism, where green cells represent reserved grids along the route, empty cells represent unreserved grids, and red arrows represent the vehicle travel route.

To manage the reservation process accurately, the CAV vehicles must travel in a defined time frame and interact with their surroundings environment. As a result, the CAV vehicle provides vehicle information to the server, such as the actual departure time, origin, and destination position. When a CAV vehicle reserves the grid and route for the first time, the server assigns each vehicle a unique ID. Before reserving the grid, the server checks the vehicle on the dynamic map to confirm the registration and then reserves the grid and route. If a vehicle requests to reserve a grid and route that is already occupied by another vehicle, the server responds by requesting a pause (in yellow cell) and a callback for the reservation, as demonstrated in Figure 3. The server creates a database

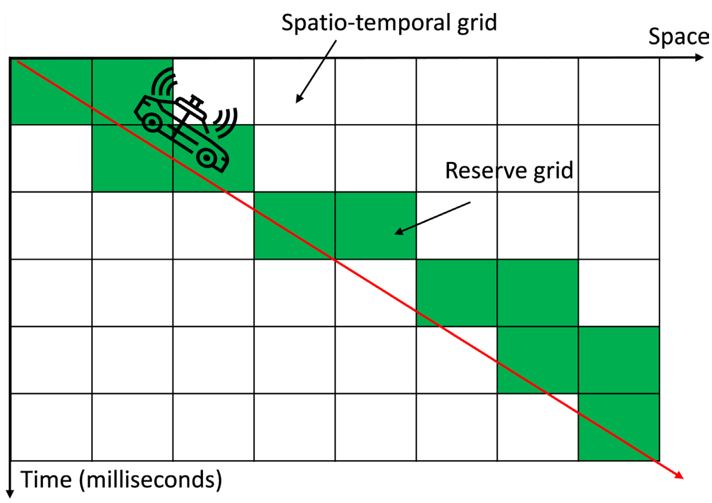

Figure 2. Structure architecture of reserving grid-based charging method.

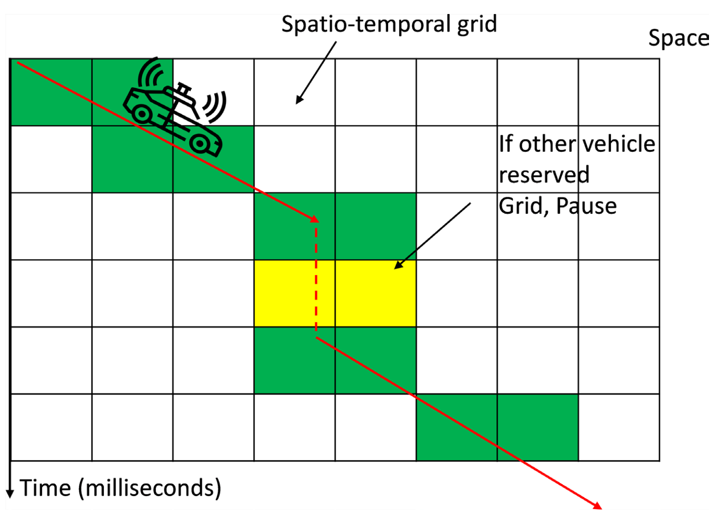

Figure 3. If the grid is reserved for another vehicle, pause, and call back method.

based on the data collected from all vehicles. When a vehicle requests a grid reservation, the server reserves the grid and route based on the real-time collected information.

2.3. Road Charging Method

Road pricing is currently represented by fixed charges for road usage, such as time-based or distance-based charges [30], toll road congestion charges [31], and taxes on particular types of vehicles (such as polluting cars) [32], which are collected via ETC or other methods. In this paper, we propose a new method for replacing the current toll tax collecting system by reserving a spatio-temporal section of road for real-time road charges in order to provide freeway tolls for the CAV platoon. The notion is to reserve geographic space (several meters) and time (several seconds) for each kind of vehicle and assign a toll-fee depending on fuel consumption to the spatio-temporal grid/seconds. While it is difficult for human drivers to precisely observe sophisticated traffic rules such as requesting a spatio-temporal grid on the road and managing toll payments in real-time, CAV platoon vehicles can do so effortlessly.

2.4. Highway Toll-Fee Charging Mechanism Based on the Grid/Millisecond

As shown in Figure 4, the grid-based charging system is developed by dividing the space into equal grids and assigning a designated toll fee to each vehicle type. When a CAV vehicle submits a reservation request, the network management center first confirms the grid occupancy and, if applicable, responds to the request. The server assigns the grid-based toll fee to each vehicle type as well, incessantly calculating the toll fee for the travel route. The collected information is recorded in MongoDB for the distance traveled, date, and calculated toll charges for each vehicle type.

The designated grid-based charging toll fee is calculated based on the fuel

```
'2_0': {rcvID: 0, price: 0 },
'2_1': {rcvID: 0, price: 0 },
'2_2': {rcvID: 0, price: 0 },
'2_3': {rcvID: 0, price: 0 },
'2_4': {rcvID: 0, price: 0 },
'2_5': {rcvID: 0, price: 0 },
'2_6': {rcvID: 0, price: 0 },
'0_2': {rcvID: 0, price: 0 },
'1_2': {rcvID: 0, price: 0 },
'3_2': {rcvID: 0, price: 0 },
'4_2': {rcvID: 0, price: 0 },
'5_2': {rcvID: 0, price: 0 },
'6_2': {rcvID: 0, price: 0 },
```

Figure 4. Description example of spatio-temporal grid and assigning charges.

efficiency of each vehicle type. First, the fuel consumption efficiency of each vehicle type is converted to km/L and then to grid/L based on the Corporate Average Fuel Economy (CAFE) standard. We use the Japan Automobile Manufacture Association (JAMA) 2021 report for fuel economy efficiency rate, which is estimated using the average fuel economy of urban, rural, and expressways. In the report, the fuel efficiency for passenger cars is 20.1 km/L, for buses 6.52 km/L, and for trucks 7.63 km/L [33]. The converted fuel consumption efficiency to grid/L units is multiplied by the 20 % gasoline price and the area of the passenger vehicle. The price of gasoline is considered to be $1.5 per liter; the 20 % is the combination of 10% local and 10% national tax revenues; and the area of any vehicle easily multiplies to create the grid-based charging fee. For this study, we only considered passenger cars, but we have created a grid-based charging toll fee for passenger cars, buses, and trucks as illustrated in **Figure 5**.

It is possible to charge each type of vehicle based on its size and length, such as the length of a car, truck, and bus, which is approximately 4.5, 14, and 12 meters, respectively. Therefore, the grid length could be any size, such as five meters, ten meters, or the length of various types of vehicles. For this study, we assumed the grid length to be five meters, which means 200 grids is one kilometer. We considered only passenger cars, which means 4 meters is the length of a CAV vehicle and one meter is the headway in a platoon to maintain the platoon headway distance for this study.

3. Proposed Method Implementation

This section presents the implementation of the grid and route reservation for toll collection based on a spatio-temporal charging system.

3.1. Execution Environment

Table 1 shows the execution environment for the proposed method. Where the server environment is Node.js, which is a JavaScript runtime environment for

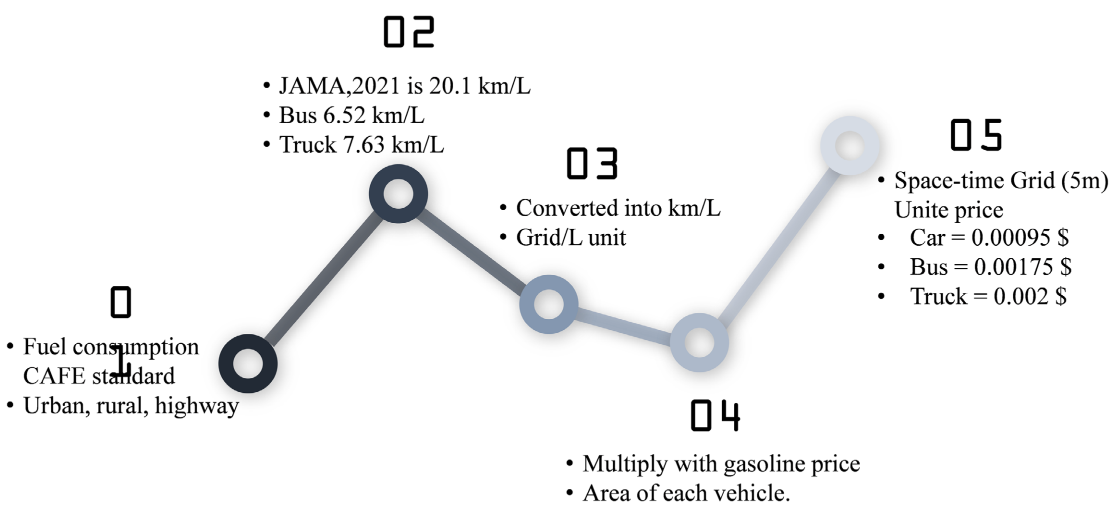

Figure 5. The toll fee conversion to grid (5 m)/millisecond for each vehicle type.

Table 1. Proposed method execution environment.

Environment	Model
Server Environment	Node.js + Express
Database	MongoDB version 4.0.4
PTV VISSIM 11	Traffic environment simulation
Platoon, Python 3	VISSIM, COM interface
Load Test	Apache JMeter
OS	MAC OS Monterey 12.2.1
CPU	2.4 GHz Intel Core i5
Memory	8 GB

web servers that handles the back end of web development. As well, Express is a minimal and flexible Node.js web application framework that provides a powerful set of features to utilize for web and mobile applications. The significance of this framework is that it provides a simple description of several processes for developing web applications utilizing various HTTP service protocols, as well as the ability to establish comprehensive APIs quickly and effectively. To ensure the proposed method's performance, the server is started on the MAC OS and verifies HTTP requests and responses on the local network.

3.2. Overview of API and Post Method

Figure 6 the flow chart below depicts the platform's grid reservation and toll-fee collection for the CAV vehicle. The server allows CAV vehicles to request grid and route reservations to facilitate their driving. As a result, the server provides an API (application programming interface) for CAV vehicles to make reservations in spatio-temporal networks by using the POST method to book the grid and travel route. The POST method sends the unique vehicle identification ID, the departure time, original position, and destination position in the request body. After the server receives the request, it first searches the spatio-temporal network database for the occupancy of the grid in the travel path and then responds with the requested grid reservation as illustrated in Figure 6.

When the CAV vehicle starts driving and sends grid reservation requests incessantly, the server dynamically maintains the grid reservation and travel route. In both cases, such as opportunistic platoon or static platoon, the CAV vehicle in the platoon will request the grid along the route and the server will dynamically reserve the grid without delay. When the server responds to the grid reservation, it assigns the unique ID of the CAV vehicle to the spatio-temporal grid, which is shown in red as illustrated in Figure 7.

3.3. Developing the Spatio-Temporal Grid Reservation

We utilize MongoDB to implement a spatiotemporal grid, which is open-source software and is a document-based database like a relational database management

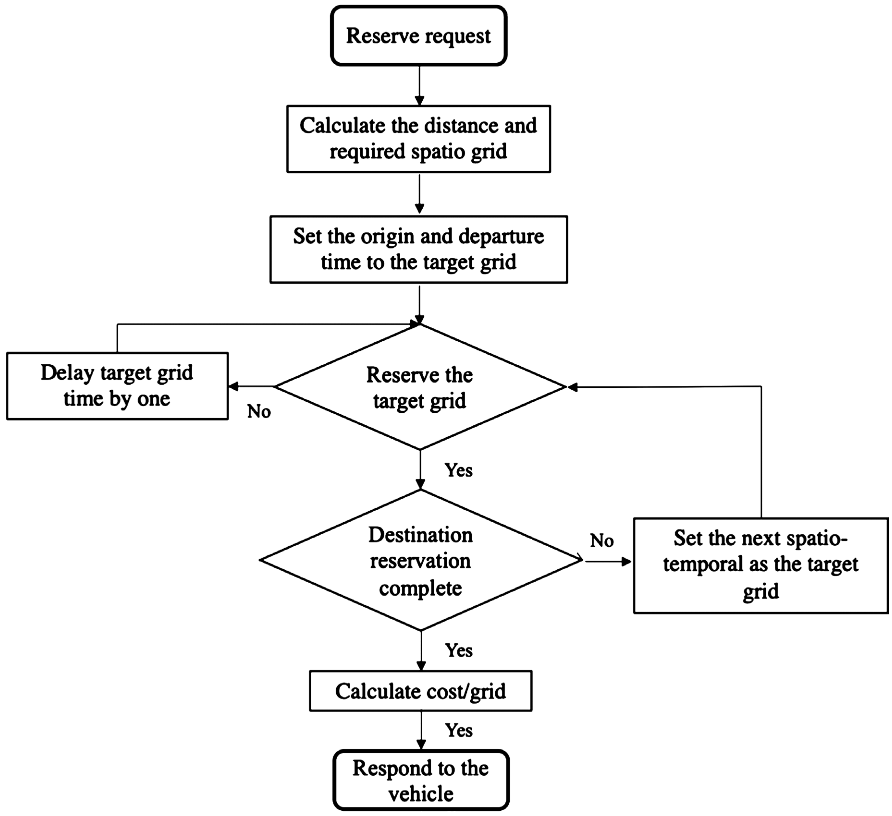

Figure 6. Flow chart of grid reservation and assigning cost processing of network management server.

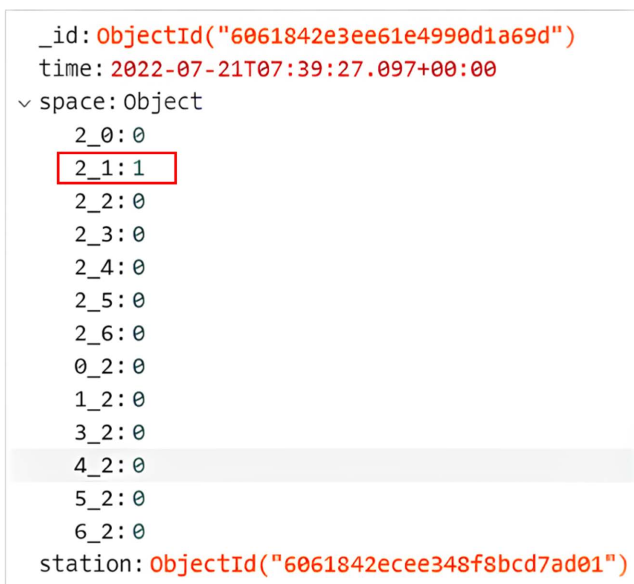

Figure 7. Description example of spatio-temporal grid reservation.

system (RDBMS). MongoDB doesn't store data in a table structure; it stores it in the JSON (JavaScript Object Notation) format. JavaScript Object Notation (JSON) is a widely used open-source and data exchange format for storing information in a structured and easy-to-access format. The transportation infrastructure is in frequent growth and changing rapidly, so the platform should also be easily capable of changing the data structure of the spatio-temporal grid. Therefore, MongoDB is a schema-less database that is more flexible in changing data structures after performing system operations and allows nested structures to store data. In addition, the times are described in ISO date types in 1-millisecond intervals, and spaces are represented in a nested document structure such as latitude and longitude. The north-south direction is considered to be the latitude and the east-west direction is considered to be the longitude of the road. Figure 8 shows an example of the data format used to save data in MongoDB. Since we only considered the CAV vehicle, which is predesign for real-time platoon and we assume that 4 meters is the length of a CAV vehicle, and one meters is the headway in a platoon. Based on the above assumption the grid length to be considered five meters, which means 200 grids is one kilometer and we develop the certain environment in Mongo DB to perform the evaluation.

3.4. Reservation Process and Assigning Toll-Fee to the Grid

When a CAV vehicle requests a reservation for the grid and route, it is possible that the other vehicles make reservations at the same time, which leads to inconsistency and disruption. To avoid such problems, the server should process vehicle reservation requests on a first-come, first-served basis. As a result, because Node.js provides asynchronous I/O processing techniques that can handle multiple requests with a single thread, we used it for this study. In addition, reserve the grid for the vehicle based on requests at a planned time. If the grid is already reserved for another vehicle, re-accessing the database is essential to process the reservation once again. Therefore, the callback processing method must be appropriately configured. There will be no contradiction or overlap due to other vehicles' requests for a route reservation if the processing time for requests and responses from the database is consistent. This method is faster than locking the


```
_id: ObjectId("606184afcee348f8bcd7b2d1")
totalDistance: 1000
totalCost: 0.0125
totalGridNum: 200
vehicleType: "passengerCar"
sid: 499
endTime: 2022-07-21T07:39:09.566+00:00
startTime: 2022-07-21T07:44:35.866+00:00
destination: Object
    lng: 135.69722
    lat: 34.84006
origin: Object
    lng: 135.70192
    lat: 34.84755
__v: 0
```


Figure 8. Description example of storing data in MongoDB.

database. Additionally, when the server responds to the vehicle and successfully reaches its destination, it automatically allocates the tax charges based on the unique ID of the CAV vehicle in the platoon and stores the data in MongoDB. Furthermore, the server provides the user with detailed travel information such as vehicle ID, travel time, travel distance, and total toll fee through the API as demonstrated in **Figure 8**.

4. Performance Effectiveness of the Proposed Method

To evaluate the proposed method, we use three evaluation factors, such as performance evaluation of the system, response time for communication, and comparison of the travel time and platoon generation improvement for both the grid-based charging system and conventional toll collection methods. The load tests are performed to measure the system's response time. The performance evaluation is conducted to confirm and validate the number of received package data, calculated distance, designated tax charges, saved data in Mongo DB, and the number of invoices submitted to the billing center. In the end, we evaluate and compare the travel times and numbers of different types of platoon generations for the three designated scenarios.

4.1. Load test

We performed load tests to measure the system's response time using Apache JMeter, an open-source Java software that evaluates the performance of client/server systems. The response time is the period of time between the cooperative autonomous vehicle sending the request and the server responding. In the POST method the vehicle ID, planned departure time, origin, and destination positions are all included in an HTTP request protocol as 6-space grids in the X and Y directions, respectively. We assumed that a CAV vehicle could travel at 1 grid/millisecond and the planned departure time is identical for all requests. The start position is (0, 2) or (2, 0), while the destination position is (2, 6) and (6, 2). The load experiment started with the server in an unreserved condition, and the results were recorded three times for various requests, such as 1, 10, 15, and 50 requests, or in a loop. **Figure 9** shows the load test results, which include the average, maximum, and standard deviation of response times for each number of requests.

4.2. Performance Evaluation Environment

To evaluate the performance of the proposed method, the traffic environment for simulation is created in VISSIM software for a one-kilometer, 3.5-m-wide road with two lanes. The vehicle types in the simulation are considered to be conventional vehicles and CAV vehicle platoons. The number of vehicles on the road ranged from 100 to 1000 vehicles per hour as a result of various vehicle inputs for simulation, and the vehicle's desired speed was set to 80 km/hr. Simulation periods are set to 3600 seconds. A simulation resolution of 10-time steps per

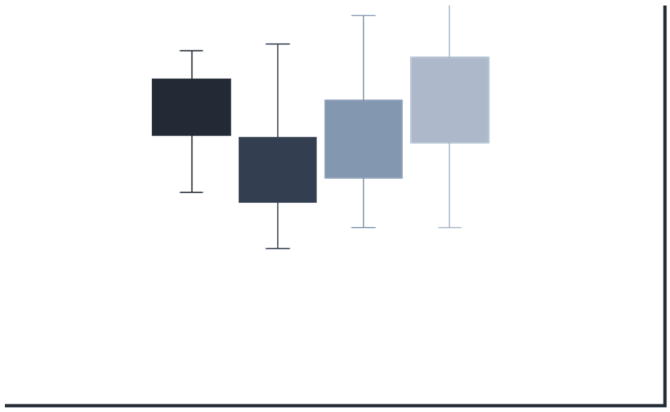

Figure 9. Measurement of required times for requests and responses.

Table 2. Simulation parameters for VISSIM.

Parameters	*Setting*
Measurement section	1000 m
Lane width	3.5 m
Number of measurements	10 times
Desire speed, All Vehicles	80 Km/hr
Platoon desire speed	>80 Km/hr
Measurement time	1 hour
Simulation resolution	10 times step/sec
TTC (time-to-collision)	5.0 s
Number of vehicles	100 - 1000 Veh/hr

simulation second is considered for this simulation. The number of measurements is 10-times, as illustrated in Table 2. The initial setup for the platoon leader's motion control is with external commands made through the COM interface. It consists of the launching of five vehicles, with a length of 1 meter each, a few seconds apart. The first one becomes the leader, and the followers obey the control model implemented for the approach of the preceding vehicles until they are almost one meter apart. Then, the three scenarios for the study are simulated for evaluating the travel time and the number of different types of platoons is monitored.

4.3. Confirmation of Package Data, Accuracy, and Privacy

To clarify whether our proposed method is operating accurately, PTV VISSIM 11 provided an environment for cooperative automated vehicles that communicate with the networking operator center/server. In addition, PTV VISSIM supports the Component Object Model (COM) interface, which can read script files written in any programming language and send data from VISSIM to the server. Thus, script files were developed in Python 3 to execute the function of the connected and automated vehicles to send such package data as vehicle ID, origin position, and destination position through URLs to the server for each type of vehicle as illustrated in **Figure 10**.

First, we validated the required speed of 80 km/hr on the road in VISSIM. Subsequently, we ran the simulation and input various numbers of cars, such as 100 - 1000, and checked the number of vehicles assigned from VISSIM to the network management/center database. We verified in the database all the assigned parameters, including the calculated distance, tax charges, and the number of invoices submitted to the billing center. If 100 vehicles make grid reservation requests from VISSIM, the server reserves grids and routes for all 100 vehicles, accurately calculates the travel distance, applies the designated tax charges, and saves the information in the database. We repeated the same approach for different vehicle inputs and verified that the proposed method's performance was accurate. We created a one-km road in VISSIM and confirmed the distance traveled and tax charges for each vehicle in the database as 1000 meters and $0.0125. Detailed information was provided to the CAV vehicle at the end of each travel time to verify and ensure the ability to minutely audit both travel and tax information. To protect user privacy, only the vehicle ID, travel distance, tax charges, and invoice number related information are disclosed to the billing center, and not all the location data are considered to prevent tracking travel information issues demonstrate in **Figure 11**.

5. Simulation for Travel Time and Platoon Measurement

We use PTV VISSIM (Verkehr in Stadten-SIMulations Model) software to evaluate the effectiveness of the proposed method. We evaluated and compared the

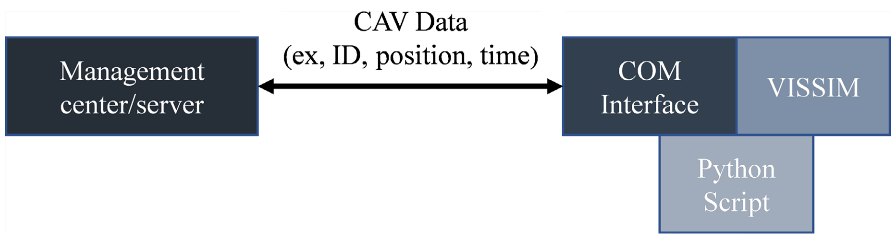

Figure 10. Configuration of PTV VISSIM 11.


```
_id: ObjectId("605b0d8d40c975cc70facc8c")
decisionTime: 2021-03-24T09:59:41.969+00:00
cost: 0.0125
number: 123
sid: 1
regAt: 2021-03-24T09:59:30.322+00:00
__v: 0
```


Figure 11. Description example of invoice to billing center.

travel times and number of different platoon generations for the three scenarios. The first scenario is for the proposed method; the second scenario is for the current conventional tollgate methods (ETC); and the third scenario is a combination of ETC with a free lane to provide service to the platoon. We used PTV VISSIM 11 to create a real traffic environment for the tollgate collection, a combination of ETC and freeway road lane, as well as provide an environment for the proposed method. PTV VISSIM 11 can connect to other applications through the Component Object Model COM interface, which allows users to access and manipulate certain VISSIM simulation object attributes from the outside software, such as platoon leaders, while the PTV VISSIM acts as the simulation engine for the platoon control as well as being able to read script files written in any programming language and having the ability to transmit data to the client-server architecture. We developed a script file in Python 3 that performed the roles of the connected automated vehicles to transmit package data to the server through URL for each type of vehicle, including vehicle ID, origin position, and destination position. All the platoon identification algorithms are implemented in a COM interface developed using the Python programming language.

5.1. Platoons Driving Behavior

To change the car following model to enable vehicles to create and maintain platoons with constant spacing, independently of their velocities. As such, the control of the vehicles was implemented in two major steps. First, the platoon leaders' parameters are controlled externally with the Python script file, which allows their change in run time, enabling platoon control through their leaders. For CAV driving behavior, a self-organizing CAV platooning concept model is developed using the PTV VISSIM application programming interface and integrated with the micro simulator using the COM interface. Second, the non-platoon vehicles are controlled by the internal user-defined attributes in PTV VISSIM. For controlling non-CAV driving behavior on freeways, the Wiedemann 99 models, which is the car-following model for car-following behavior, are used as default settings. The default parameters calibration for the (Wiedemann 99) Freeway Car Following Model is studied in detail in [34]. The default values for CC1 (headway time), safety distance reduction factor, and DLCD (desired lane change distance) are determined based on the previous study and compared with the VISSIM user guide report, and the default value is considered. The Wiedemann 99 car-following model uses the CC1 parameter as an input to calculate the required following distance of each vehicle from the leading vehicle. The minimum value is 0.7 and the maximum is 1.2 seconds, and the default value is 0.9 seconds. The safety distance reduction factor is the headway in the neighboring lane that a vehicle needs at a minimum to perform a lane change. The minimum value is from 0.0 to 0.8 seconds, and the default value is 0.6, as well as the default value of DLCD (desired lane change distance) is 200 meters.

The algorithm considers connected automated vehicles with communication capabilities of vehicles forming, maintaining platoons with constant spacing, and leaving a platoon. The first vehicle becomes the leader, and the followers obey the control model implemented for the approach of the preceding vehicles in the platoon. The platoon leader is shown in dark blue, the platoon members in light blue, and the non-platoon vehicle in the network is shown in black in **Figure 12**. The detailed parameters of the following driving behavior parameters that are used for platooning are presented in **Table 3**. The maximum number of vehicles in the platoon, including the leader vehicle, is considered to be 5. The movement of the entire platoon is determined by the movement of the leader. The maximum

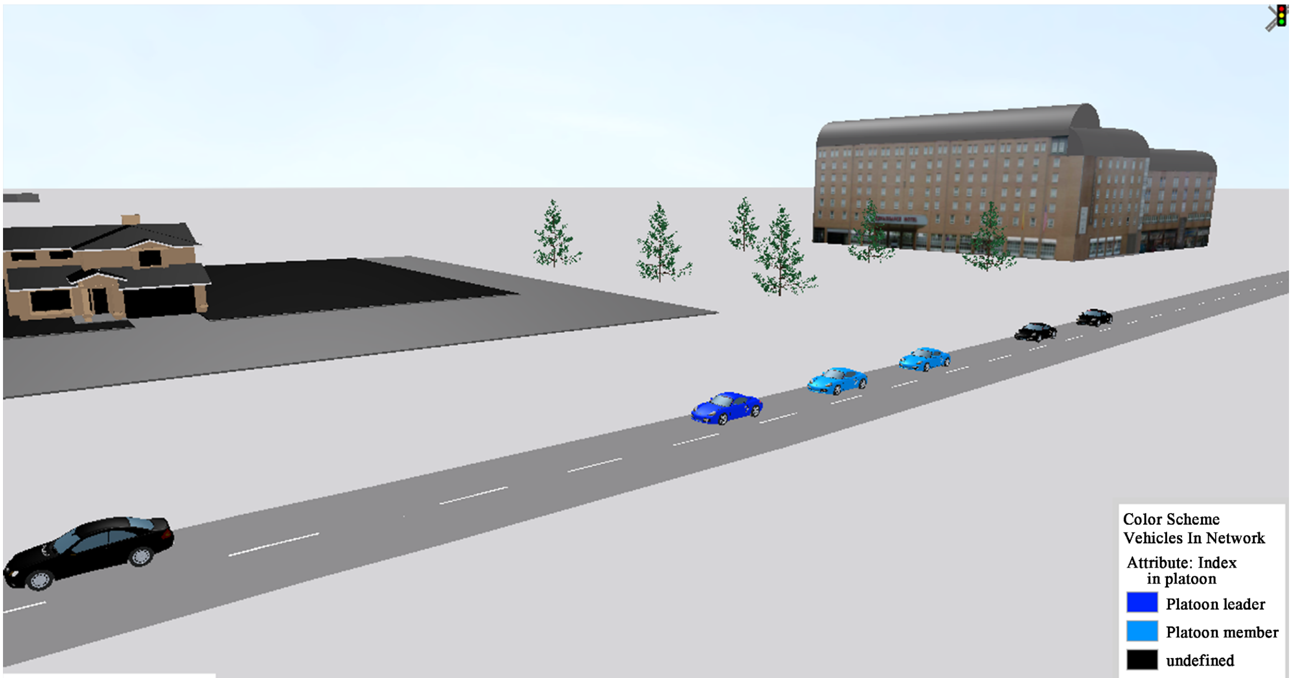

Figure 12. Execution screen of VISSIM simulation for toll collection for platoons in the proposed method.

Table 3. CAV platoon driving behavior parameters.

Model Parameters	*Connected Vehicle*
Maximum number of platoon vehicles	5 platoons
Maximum platoon approach distance	250 m
Desired speed	>80 km/hr
Platoon follow-up gap time	0.2 Seconds
Maximum acceleration	1 m/Sec^2
Desired deceleration	2 m/Sec^2
Maximum gap distance at standstill	1 m
Platoon clearance	1.5 m
Safe time headway	0.6 Sec
Maximum deceleration	−2.0 m/ Sec^2

platoon approaching distance to the last vehicle of a platoon, up to which a vehicle tries to become a trailing vehicle of a platoon, is 250 meters. All followers in a platoon get the same desired speed as their leader. The maximum desired speed of the platoon is 80 km/hr. The minimum clearance platooning is considered 1.5 meters, which is the gap acceptance criteria. It is spatially defined as the minimum required distance headway between the lead and following vehicles. The Platoon follow-up gap time is 0.20 seconds, as well as the safe time headway is 0.6 seconds. This paper provides a clear and comprehensive explanation of the external CAV control method [35].

5.2. Simulation of Travel Time and Number of Platoons for Proposed Method

The first scenario is for the proposed method. The simulation environment for the proposed method is identical to the one described in the evaluation environment section. Thus, the same procedure measured and compared the travel times for the proposed method. PTV VISSIM supports the COM interface and utilizes the environment for a cooperative automated vehicle that communicates with the networking management center/server. The CAV vehicle sends such package data as vehicle ID, origin position, and destination position through a URL to the server for each type of vehicle. First, we ensured that if 100 vehicles make grid reservation requests from VISSIM, the server reserves the grids and routes for all 100 vehicles, calculates travel distance, applies the designated charges, and saves the information in the database. The average time of a vehicle traveling in a certain section is denoted as a travel time, which is measured by subtracting the starting time of the origin position from the destination position.

In this study, the road length is set to one km, the departure time for all vehicles starts from zero, and the end time is measured from the destination position when the vehicle arrives at the 1000-m position. Following these sittings and parameters, the simulation ran for one hour, and the travel time was obtained for various vehicle inputs (**Table 2**). Since there is no use of toll plazas for payment, stop signs, or traffic rules that force vehicles to stop or reduce their velocity in the proposed method. The average travel time for one kilometer at the desired speed of 80 km/hr is recorded at 36.5 seconds. The script stores the result based on the user-defined-attributes for driving behavior and dynamically shows the result in a chart in VISSIM. In the proposed method, the platoon measurement is evaluated for a traffic volume of 1000 cars per hour, and the average values of a ten-time simulation are considered. The parameters include the total number of vehicles in generated platoons, the total number of platoons, and the number of generated platoons for each size. As for this study, the maximum number of vehicles in the platoon is 5. The measurements for the platoon size 2 type, 3, 4, and 5, are documented.

5.3. Simulation of Travel Time and Number of Platoons for ETC Toll Gate Method

The second scenario is the ETC method. To evaluate the travel time using the

ETC payment method, we assumed a tollgate along the road in a 500-m location with specific parameters and conditions as demonstrated in Figure 13. For this scenario, where the traffic environment and parameters are identical to the first scenario. Since the ETC payment method relies on dedicated short-range communication and electronic equipment in vehicles to maintain the collection of highway toll fees. We have added some traffic roles in the VISSIM, which the second scenario presumes to meet the following conditions:

- We assumed that all vehicles in simulation had an on-board device to use the ETC system.
- Both road lanes are only for ETC usage.
- The desired speed on the road is 80 km/hr.
- All vehicles, including the platoon, should reduce speed in the tollgate for toll fee payment and, after toll payment, rejoin the platoon.
- A 12-meter reduced speed area was created in the middle of the road in two lanes as a default configuration for the tollgate speed reduction area.
- The vehicle's desired speed distribution in the reduced speed area was 20 km/hr.
- 20 km/hr was the default deceleration setting at the beginning and at end of the reduced speed area.
- When a faster vehicle decelerates as it approaches the reduced speed area, its maximum deceleration is 6.56 m, which is the default setting value for the ETC method.

The simulation is run for various vehicle inputs using the above-mentioned assumptions and tollgate parameters for the ETC toll-collection system. The travel time is measured using the average values of a ten-time simulation and

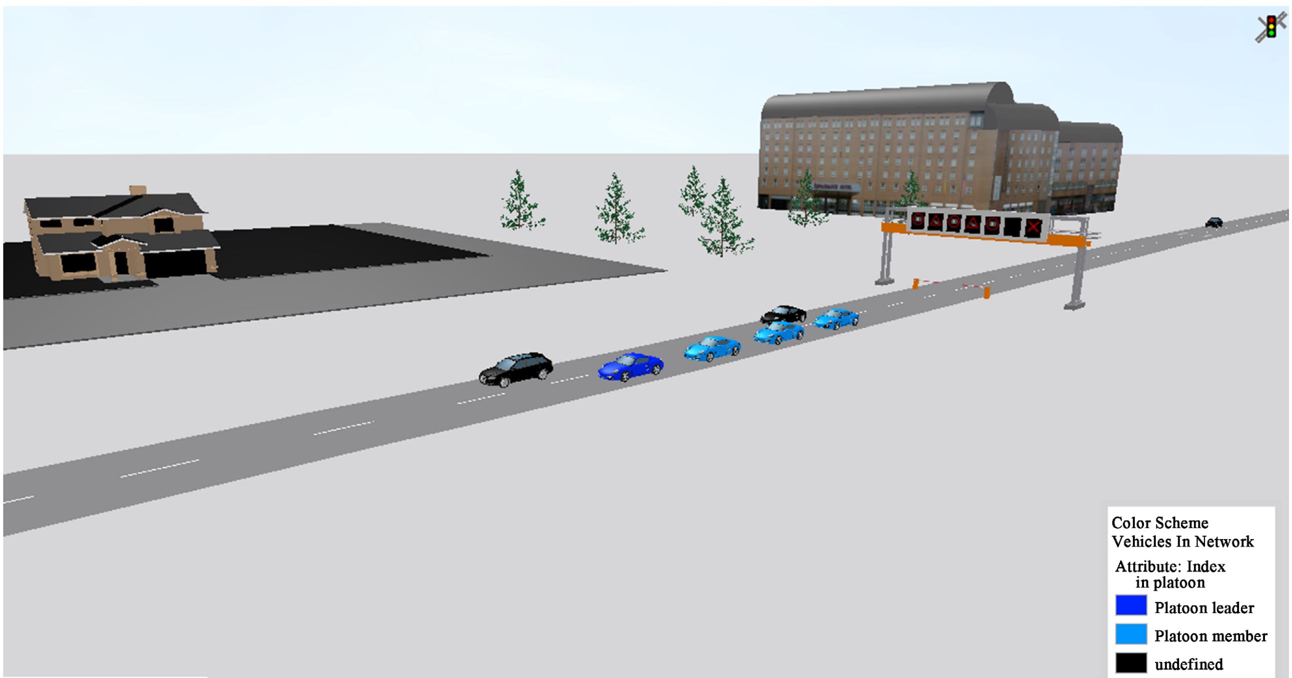

Figure 13. Execution screen of VISSIM simulation for toll collection for platoons in the ETC method.

compared to the proposed method. In the ETC method, the platoon measurement is evaluated for a traffic volume of 1000 cars per hour, and the average values of a ten-time simulation are considered. The parameters include the total number of vehicles in generated platoons, the total number of platoons, and the number of generated platoons for each size. As for this study, the maximum number of vehicles in the platoon is 5. The measurements for the platoon size 2 type, 3, 4, and 5, which are shown in the VISSIM are documented.

5.4. Simulation of Travel Time and Number of Platoons for Combination of ETC and Freeway Road Lane

The third scenario is a combination of ETC and freeway lane, which is a freeway road lane that is considered for the CAV platoon to avoid the tollgate. We determine that the platoon vehicle uses the freeway road lane, and the conventional vehicle can pass through the tollgate to pay the road charges using the ETC method as illustrated in Figure 14. The simulation parameters, general assumptions, and traffic environment in this scenario are identical to those in the second scenario. For the ETC system, as the conventional vehicles are using the ETC method, we have changed the settings of the vehicle travel route options for the platoon to travel through designated lanes.

Following the above assumptions and settings for the combination of ETC and freeway road lane methods. We performed a simulation for various vehicle inputs and measured the travel times, considering the averages of ten-time simulation results and comparing them with the proposed method (Figure 15). In the combination of ETC freeway road lane method, the platoon measurement is measured for a traffic volume of 1000 cars per hour, and the average values of a

Figure 14. Execution screen of VISSIM simulation for toll collection of platoons in the ETC and freeway road lane method.

ten-time simulation are considered. The parameters include the total number of vehicles in generated platoons, the total number of platoons, and the number of generated platoons for each size. As for this study, the maximum number of vehicles in the platoon is 5. The measurements for the platoon size 2 type, 3, 4, and 5, which are shown in the VISSIM are documented (**Figure 16**).

6. Result and Discussion

The proposed method is evaluated based on the load test, performance evaluation, simulation for travel time, and number of platoons generated in one kilometer.

The load test results showed that each vehicle could be processed with a maximum response time of less than 48 milliseconds. However, as the number of inquiries increased, the average response time reduced (**Figure 9**). The fundamental reason for this is that the proposed method uses non-blocking I/O for asynchronous processing. The response times are shortened by this method because, as the number of requests increases, the processing threads are also increased simultaneously. Inconsistencies in data storage happened twice when the number of processed requests reached 50. Inconsistencies might thus be prevented while operating in a real-world context by defining the number of requests to be processed for each thread on a server.

The proposed method's performance was successfully evaluated by verifying grid reservations and collecting toll taxes using the spatio-temporal grid-charging method, as illustrated in (**Figure 8**) and (**Figure 9**). To ensure that the proposed methos works accurately, the number of vehicles submitting the request are verify, such as if 500 vehicles submit requests, the server reserves grids, computes the travel distance, assigns toll tax charges, and sends invoices to the billing center for 500 vehicles. Furthermore, the distance traveled and tax charges for each vehicle were confirmed in the server database as 1000 meters and 0.0125 dollars for CAV in a platoon, respectively. We repeated the same procedure to validate the performance of various vehicle inputs and verified that the proposed method functioned accurately.

The simulation results for the proposed, ETC, and the combination of freeway road lane and ETC methods revealed that the travel times were significantly improved for the proposed method compared to the ETC method and the combination of freeway road lane and ETC method, respectively.

In the proposed method, since the toll tax is paid through an automated online platform, the CAV vehicles don't need to stop or reduce their velocity. The simulation results revealed that for the proposed method scenario, when the traffic volume was 1000 vehicles per hour, driving on a one-kilometer road takes an average of 36.5 seconds without the need to reduce velocity or stop for payment. Thus, the travel time improves compared to the conventional methods.

In the combination of freeway road lane and ETC method, since the CAV platoon will not go through the ETC gate for payment but instead use the designated freeway road lane and pay the toll tax through the online platform, there is no need to unchain the platoon or reduce speed and rejoin the platoon. But the non-CAV vehicles, which use the ETC method for payment, will use the ETC toll gate. That will affect the road capacity and increase the overall travel time on the road. Therefore, using the combination of freeway road lane and ETC methods to mediate driving on a one-kilometer route takes an average of more than 46.6 seconds for 1000 vehicles compared to the proposed method. Accordingly, the CAV platoon travel time will improve, which will affect the average travel time for all vehicles and improve the road capacity compared to the ETC method.

In the ETC method, since all vehicles, including the CAV platoon, should stop or reduce their velocity, the travel time increases for all vehicles, including CAV vehicles. When the CAV platoons arrive at the ETC barrier, the platoon should be unchained at the time of toll payment, reduce the speed, and pay the tool tax. After that, CAV vehicles should rejoin the platoon once again, which increases the travel time drastically. Therefore, using the ETC methods to mediate driving on a one-kilometer route, it takes an average of more than 53.8 seconds for 1000 vehicles. **Figure 15** shows the average travel time for the three scenarios; as the number of vehicles increases, the travel time increases directly proportionally.

The simulation results for the proposed, ETC, and the combination of freeway road lane and ETC methods demonstrated that the number of CAV platoons was significantly improved for the proposed method compared to the combination and ETC methods, respectively, as illustrated in **Figure 16**.

Since the toll tax is paid through an automated online platform in the proposed method, the CAV vehicles don't need to unchain, reduce their velocity, and rejoin the platoon once again, so the total number of generated platoons is

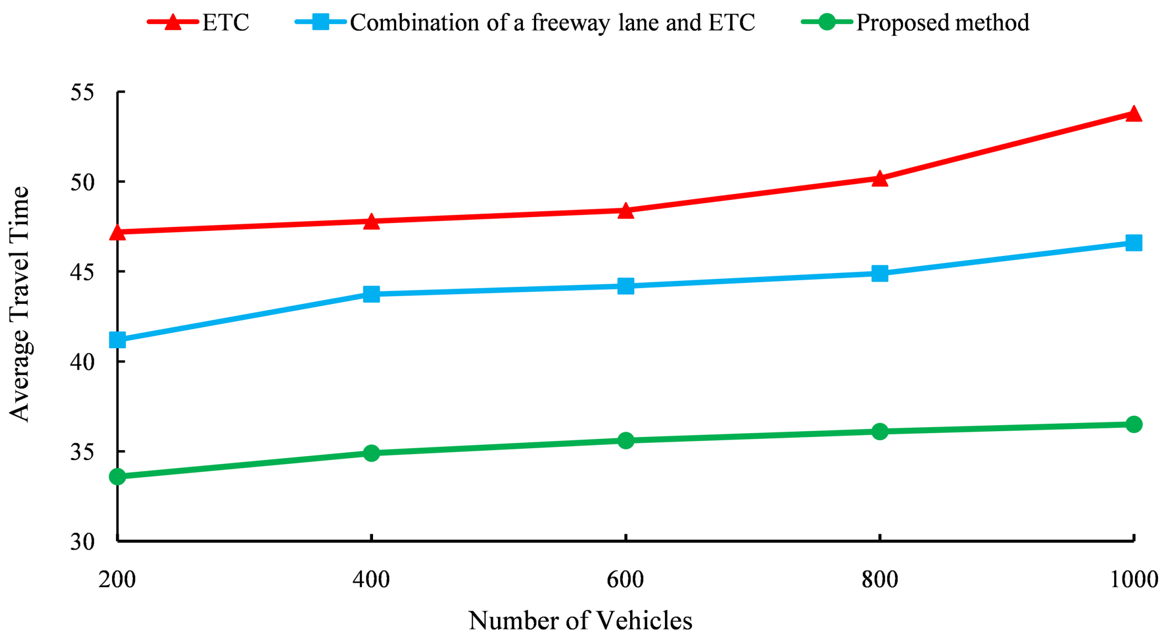

Figure 15. Average travel time for proposed, ETC, and combination of ETC and freeway road lane.

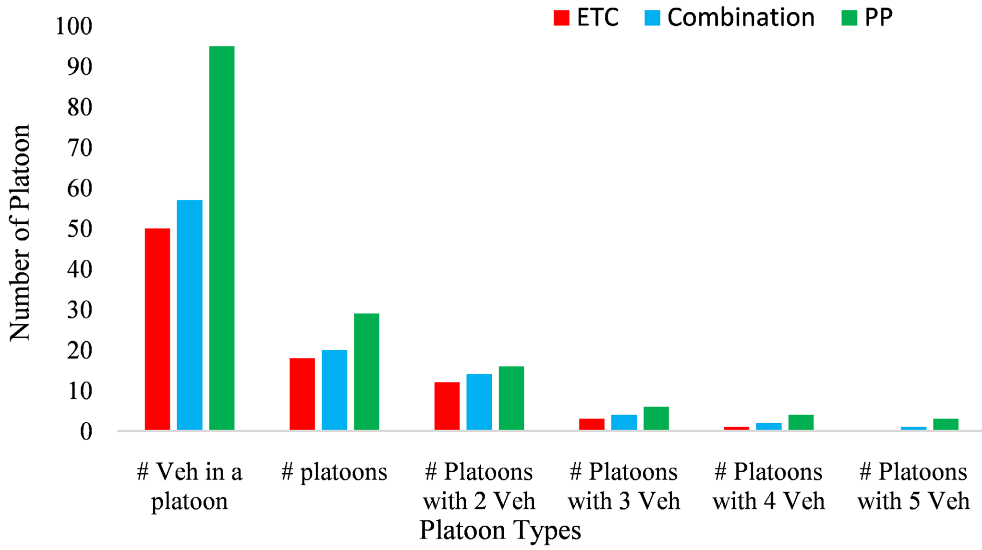

Figure 16. The comparison of the number of generated platoons for different types of platoons.

improved. The simulation results revealed that for the proposed method scenario, when the traffic volume was 1000 vehicles per hour, the generated total number of vehicles in platoons was 95 vehicles. The total generated number of platoons is 29. For the size 2 type platoon, the number of generated platoons is 16. For the size 3 type platoon, the number of generated platoons is six. For the size 4 type platoon, the number of generated platoons is four, and for the size 5 type platoon, the number of generated platoons is three.

In the combination of freeway road lane and ETC method, since the CAV platoon will not go through the ETC gate for payment but instead use the designated freeway lane and pay the toll tax through the online platform, there is no need to unchain the platoon or reduce speed and again rejoin the platoon. But the non-CAV vehicles, which use the ETC method for payment, will use the ETC toll gate, which will affect the CAV speed and many vehicles may not be able to join the platoon. Therefore, the total number of vehicles in the generated platoons is reduced to 57 vehicles, which is less than compared to the proposed method. The total generated number of platoons is 20. For the size 2 type platoon, the number of generated platoons is 14. For the size 3 type platoon, the number of generated platoons is four. For the size 4 type platoon, the number of generated platoons is two, and for the size 5 type platoon, the number of generated platoons is one.

In the ETC method, since all vehicles, including the CAV platoon, should stop or reduce their velocity, the travel time increases and the speed is reduced for all vehicles, including CAV vehicles. When the CAV platoons arrive at the ETC barrier, the platoon should be unchained at the time of toll payment, reduce the speed, pay the toll tax, and rejoin the platoon once again. This phenomenon is reducing the speed drastically, so many vehicles may not be able to join the platoon effectively and affect the total number of generated platoons. Therefore, the total number of vehicles in the generated platoons is reduced to 50 vehicles, which is less than compared to the proposed method. The total generated number of platoons is 18. For the size 2 type platoon, the number of generated platoons is 12. For the size 3 type platoon, the number of generated platoons is three. For the size 4 type platoon, the number of generated platoons is one, and for the size 5 type platoon, the number of generated platoons is zero.

To summarize, we confirmed that the system can safely collect toll tax revenue for CAV vehicles based on a grid-based charging method without errors or data package losses for the distance traveled. Our proposed method enhances travel times without reducing velocity or stopping for highway payments. Thus, it allows many vehicles to be driven on the road, resulting in a more efficient use of road capacity as well as the proposed method improving the total generated platoon.

7. Conclusion

We investigated a novel grid-based toll charge collection mechanism as an alternative to the present ETC toll gate method for collecting tool tax from CAV platoons. We developed a system using vehicle-driving information obtained via communication methods installed in CAV vehicles. We developed a spatio-temporal grid using the dynamic map platform by dividing space-time into equal grids and applying designated tax charges for each vehicle type based on their fuel consumption. The performance evaluation result shows that the proposed method adequately reserved grids and accurately collected toll taxes based on spatio-temporal grids with minimum data package loss for connected automated vehicles. We tested and validated the number of vehicles requested for reservation. The proposed method accurately reserves the grid, routes, and collects toll tax from the CAV vehicle in a platoon. The load test result reveals that the response time was less than 48 milliseconds for communication. The evaluation results indicate that the proposed method enhanced travel time efficiency in moderate traffic volume better than a conventional tollgate system on the highway. Such travel time improvements will reduce congestion by more effectively using the road capacity and increasing the level of service for CAV platoons, as well as increasing the number of generated platoons on the highway. Since we introduced a grid-based reservations charging system using monetary transactions to charge for highway tolls, routes can be reserved in a time frame based on traffic demands with a pricing-based control-charging system over traffic density to reduce and manage smart traffic congestion.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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