A Grid-based Road Charging System Based on Spatio-Temporal Grid Reservation for Cooperative Automated Driving

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Abstract

The era of automated, connected, and electric vehicles is emerging. Extensive worldwide research efforts over the last two decades have resulted in sufficiently reliable, affordable, and popular products. Although zero-emission vehicles have the potential to become the primary mode of transportation and provide several benefits for future transportation, there are certain challenges associated with this technology, including a lack of compatibility with the current highway toll collection system and the potential for a continuous decrease in gasoline tax revenues. 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. As well, fuel taxes are still a primary funding source for the development and maintenance of transportation infrastructure. Such a tax is collected as a flat fee from the importer or producer of the taxable fuel product. Fuel efficiency improvements and the adoption of zero-emission vehicles result in a continuous decrease in gasoline tax revenues.

This study proposes a novel distance-based alternative method to replace current gasoline tax collection systems as well as provides a software architectural platform that enables connected automated vehicles to reserve a grid-based alternative method to replace current highway toll collection systems. We utilize driving information gathered via communication mechanisms installed in connected automated vehicles to develop a dynamic map platform that collects gasoline tax based on reserving spatio-temporal grids. As well, in this platform, a planned travel route is reserved in advance by a connected automated vehicle in a platoon 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 a designated road tax charge is assigned.

The performance evaluation is evaluated based on several parameters, such as performance evaluation, load testing for response time, revenue generation, annual ownership cost comparison, as well as travel time and platoon measurement. We investigate how the annual cost of ownership changes for each type of vehicle for both methods and analyzed the annual generating gasoline tax revenue for model years 2022 and 2030.

The results reveal that the proposed system 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. Consequently, 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. As well, we found that in model year 2022, the annual gasoline tax differences for conventional vehicles and hybrid vehicles were almost the same, a BEV $76 increase utilizing the proposed method. Furthermore, in model year 2030, using the proposed method, the annual gasoline tax differences for conventional vehicles are $20, hybrid vehicles are $43, and BEVs are $76. However, the proposed method is based on micro travel distance charges, which generates gasoline tax revenue by 5.7 percent for model year 2022 and 21.8 percent for model year 2030 as compared to the conventional method.

Consequently, the proposed method is capable of providing sustainability and guaranteeing long-term alternative gasoline tax revenue and adequately collecting toll tax from the CAV vehicle in a platoon. As well, the proposed method's travel time improvements will reduce congestion by more effectively exploiting road capacity as well as enhance the number of platoons by providing non-stoppable travel for autonomous vehicles platoon.

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CHAPTER – 1

Introduction

Autonomous driving is almost a reality that is expected to reduce the number of driving fatalities as a result of replacing human drivers with self-driving and autopilot technology [1]. According to the results of the 2015 World Economic Forum (WEF) survey of cities around the world, nearly 60% of consumers are willing to commute in self-driving vehicles [2]. Based on Bloomberg's Electric Vehicle Outlook, the annual publication for the world of electric vehicles, it is predicted that by 2040, AVs (autonomous vehicles) will account for 50% of all vehicle sales, 30% of vehicle ownership, and 40% of all vehicle commutes [3]. In order to advance innovation and maintain global market competitiveness, the automobile industry invested approximately 103 billion dollars in R&D in 2020 [4]. With optimistic announcements made by some organizations and successful testing and launching of autonomous vehicles by Tesla, Google, Waymo, Toyota, Honda, and others, commercialization and greater adoption of autonomous vehicles are accelerating [5].

In the intelligent transportation system, connected automated vehicles (CAVs) are a promising concept that have the capabilities for improving traffic efficiency, driving safety, reducing fuel consumption, and vehicle emissions. The reliability and safety of autonomous vehicle (CAV) systems are constantly increasing, with the ultimate goal of integrating them into transportation systems. However, this integration raises a number of challenges that must be properly considered, as we focused on the two major issues of gasoline tax revenue decreases and highway toll collection challenges with the future

CAV platoons. The revolutions of electrification, automation, and sharing create new challenges for major gasoline tax revenue sources to maintain the transportation infrastructure. As well as under certain conditions, the CAV platoon's advantage cannot be properly developed, especially when stopping for electronic toll collection (ETC) to pay the toll fee using the highway. First, we will discuss in detail the decreasing gasoline tax revenue and the challenges arising for maintaining the future transportation infrastructure.

There are several studies and publications that have highlighted the shortfalls in gasoline tax revenue, particularly when high fuel-efficiency vehicles are adopted. Based on the OECD/ITF (International Transport Form) report, they predicted that when more zero-emission cars are adopted, gasoline tax revenue will decrease by 56% between 2017 and 2050. This is mainly due to improvements in fuel efficiency and the adoption of zero-emission vehicles with respect to the increase in demand for vehicles [6]. As well, the United States Environmental Protection Agency (EPA) reports that vehicle fuel consumption efficiency will improve from 35 to 54.5 mpg based on corporate average fuel economy standards (CAFE) for model years 2017 to 2025 [7].

Several studies and publications have highlighted the shortfalls in gasoline tax revenue, particularly when high fuel-efficiency vehicles are adopted. Alan Jenn et al. studied the revenue generation for the state of Colorado in the United States and warned that annual gasoline tax revenue will decline by 2025 due to the adoption of zero-emission vehicles [8]. Japan’s gasoline tax supports the development and maintenance of its transportation infrastructure. According to the national tax agency (NTA), gasoline tax revenue continuously decreased from 2010–2020 [9]. As a result, fuel tax revenue is decreasing as fuel efficiency improves and zero-emission vehicles are adopted as the short summary is illustrated in Figure 1.

Figure 1. Shows the causse behind the decline of gasoline tax revenue.

To find a solution for obtaining sustainable gasoline tax revenues, various researchers are investigating a flat annual fee, a vehicle's manufacturer's retail price, and vehicle mile travel methods. Many of the proposed methods have drawbacks and cannot address the emerging challenges. Certain research studies show that vehicle mile travel is a promising alternative method to replace the current flat-fee gasoline taxation methods. Since the VMT tax is a relatively new concept and still in the experimental stage, less is known about its methodology of implementation in the era of future mobility, actual impact on driving behaviors, tax revenues, and tax burden.

The University of Iowa's public policy center conducted a 2-year field study to evaluate the technical feasibility and user acceptance of mileage-based charging systems for vehicles through such physical operations as installing on-board units (OBUs) and interviews and questionnaire surveys of various stakeholders. In this research, technical feasibility problems included on-board unit installation, tax calculation accuracy, and fee evasion. As well, the questionnaire survey results show that when using the system, 71% of the participants preferred auditability and maximum privacy protection [10].

The most significant component for people's acceptance of the new system is determining an acceptable tax price for each vehicle type via the VMT method, which is one of the barriers to overcome [11]. Since all studies suggest a flat fee per mile, it raises further equality problems and challenges the willingness to adopt the new tax system. Furthermore, in terms of fuel consumption and road occupancy, there are various types of vehicles. A flat fee levied as a tax on all types of vehicles is provoking equity concerns regarding willingness to change to the new system. Each type of vehicle consumes a different amount of fuel for traveling 100 km and has various types of fuel efficiency, such as cars, buses, trucks, hybrid vehicles, electric vehicles, hydrogen vehicles, solar energy vehicles, etc. Furthermore, as each vehicle occupies a distinct section of the road, it is not appropriate to compare the road damage of a small passenger vehicle to that of a truck, which is an equity concern regarding the road maintenance fees charged for each type of vehicle.

When modeling the effects of a VMT tax or any other alternative method, it is essential to consider how drivers will respond to dynamic changes in the tax structure and driving prices for each type of vehicle. However, since the vehicles have different fuel consumption, various types of length and weight, and different usages, In all studies, they found that drivers preferred auditability and maximum privacy protection to understand their daily usage. Furthermore, because each state has different tax regulations, an intelligent system that levies charges for different states when a vehicle travels between states is required. Moreover, when vehicles travel between two states, the boundary may not always be exactly one mile (km) to accurately calculate the fuel tax or road tax for a vehicle. Therefore, a system is needed that could be able to calculate the two-state different types of fuel tax charges and charge based on a minimum travel distance, as all travel distances could not be exactly one km or one mile.

As mentioned earlier, VMT is at an early stage because there is no adequate mechanism being investigated as a replacement for the gasoline tax, such as a collection mechanism, a dynamic pricing system, reducing administrative costs, preventing payment evasion, maintaining privacy, or vehicle onboard equipment installation. However, utilizing the tollgate on all roads is one of the options to collect gasoline tax, but the system has many drawbacks, including violation processing, high operational cost, fixed infrastructure device dependency, and a large amount of electronic equipment that must be installed in every vehicle and on the road infrastructure. To summarize, In the current situation, the collection of gasoline taxes is dependent on permanent fixed infrastructure devices, and for the future, a huge number of electronic devices must be installed in both vehicles and on all roads. Moreover, the deployment of tollgates on all roads is unfeasible due to the significant operational expenses associated with utilizing the equipment for accurately collecting road-pricing tax based on the vehicle mile travel method. Therefore, the proposed method provides a sustainable new mechanism for collecting gasoline tax as well as addressing many of the aforementioned challenges. In Chapter 3, we address the above concerns and describe our novel micro-road-pricing method based on reserving spatio-temporal grids.

The second part of this study is to discuss highway toll collection in the era of CAV platoons. CAV platoons have the potential to improve vehicle safety, efficiency, mileage, and travel time while decreasing traffic congestion, pollution, and passenger stress [12]. There are several advantages to autonomous vehicles, such as improved transportation services, social impacts, environmental friendliness, and economic benefits. Reports have shown that autonomous vehicles can save society approximately $800 billion each year. The reduction in car crash-related costs, the reduced strain on the healthcare system, more efficient transportation, better fuel savings, and more can all contribute to the overall societal cost savings. With this ability to communicate in real time, cars would be able to travel efficiently at optimized distances from each other. They'd also determine the best route for you to take to eliminate bumper-to-bumper traffic jams. Those with a disability or the elderly would be able to get into a self-driving car without putting others at risk. Cities with limited public transit coverage would also benefit from self-driving cars. Self-driving cars can easily reach areas where infrastructure is lacking. Moreover, CAV 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 [13] as illustrated in Figure 2.

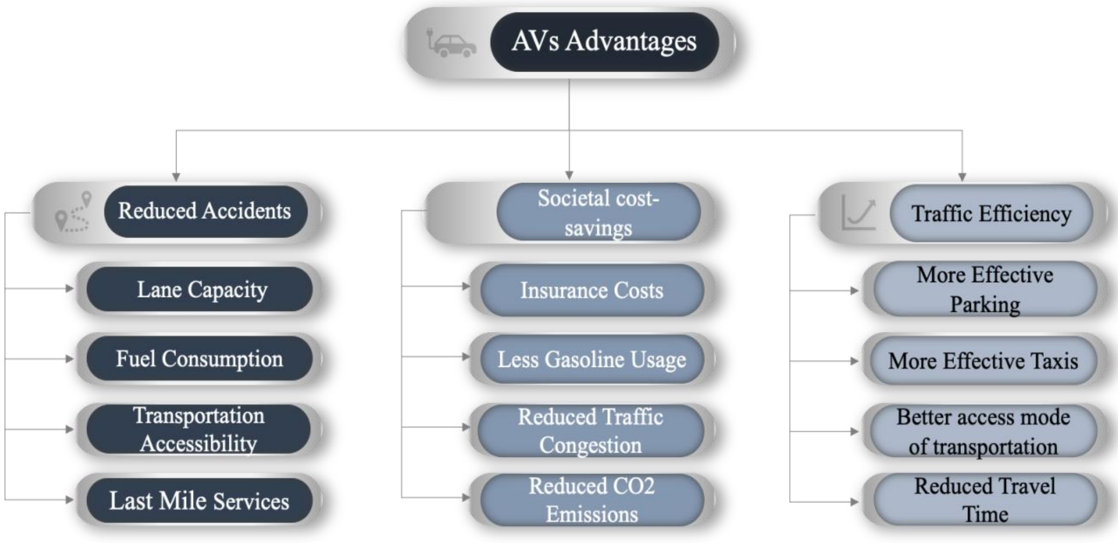

Figure 2. Shows the automated vehicle advantages.

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 [14]. CAV platoons have the potential to improve vehicle safety, efficiency, mileage, and travel time while decreasing traffic congestion, pollution, and passenger stress [15], [16]. 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 [17]. Consequently, it is not feasible to address the challenges arising from the current toll collection system for the CAV 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. One of the most significant obstacles is what is known as "mixed traffic." While conventional cars will not be replaced by fully automated vehicles overnight, humans and autonomous vehicles will have to coexist on the roads for some time. The consequences of this new traffic environment are difficult to forecast such as Technological error unpredictable traffic pattern, Unforeseen cost and consequences, Security issue, Job losses, and Moral machine dilemma as described in Figure 3.

The reliability and safety of autonomous vehicle (CAV) systems are constantly increasing, with the ultimate goal of integrating them into transportation systems. However, this integration raises a number of challenges that must be properly considered. Here's an obvious but significant drawback about self-driving cars: They rely heavily on technology. If self-driving vehicle technology is prone to malfunction and errors. We think that the machines are reliable and predictable. However, studies have found that both human drivers and self-driving cars can exhibit unpredictable behavior. We simply don't know all of their potential effects yet. There could be unexpected changes to the law in terms of making personal injury claims and securing compensation if a self-driving car hits a person. To have automated cars talk and coordinate with each other, they may be sharing the same network protocol. If a large number of cars share the same network, there is a possibility of a hack. Even a minor hack can cause significant damage on congested roads by causing collisions and gridlock traffic. Those in the trucking industry, bus drivers, and taxi drivers will all need to find new employment. Fast food delivery and Uber drivers would also find themselves replaced by automated cars. and lack of ability to make judgments between multiple unfavorable outcomes. Example. veering to the left and striking a pedestrian.

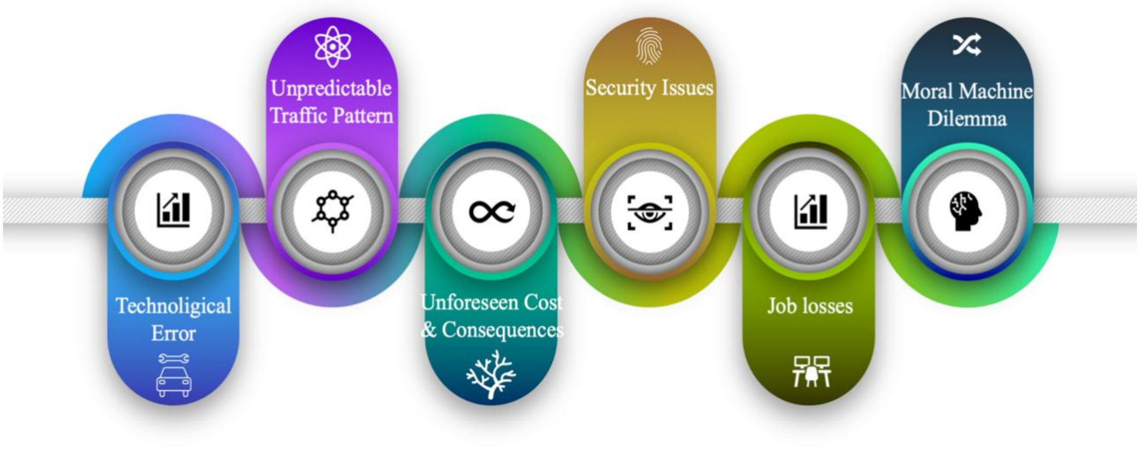

Figure 3. Illustrate the AV current and future challenges

As we mentioned earlier, the AVs integration is unpredictable, and interestingly, there are two more future challenges arising. such as gasoline tax revenue decreases and highway toll collection challenges with the future CAV platoons. We concentrated on these two aspects in our study as described in Figure 4.

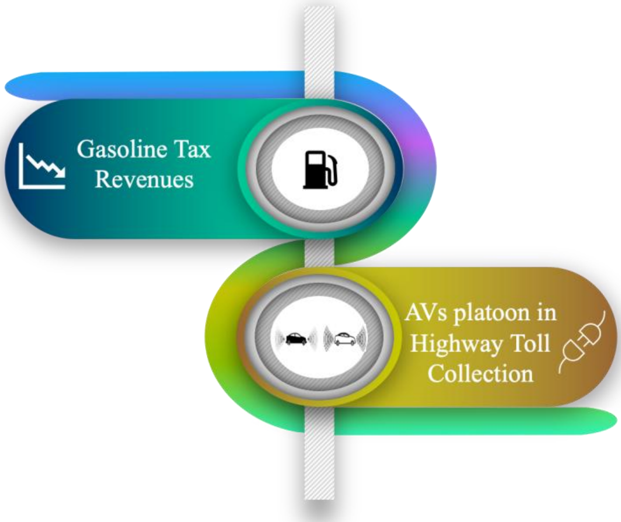

Figure 4. Described two more future challenges of AV integration.

Therefore, new technology must be researched for reliable application and ease of use in smart mobility. as well as to address the challenges of future mobility and lay the groundwork for conventional driving and autonomous vehicles to coexist on the roads.

Dynamic platoons [18] are classified into two types: real-time platoons [19] and opportunistic platoons [20]. 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 grid-based charging 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.

The performance evaluation result revealed that platform is capable of collecting gasoline tax revenue from connected automated vehicles as well as providing a novel framework for highway toll collection from the connected automated vehicle (CAV) platoon.

1.1 Objectives

The objective of this study is to provide a framework for a platform that functions as a network operating center to collect gasoline tax revenue as well as highway toll collection from the CAV and CAV vehicles in a platoon. We propose that the vehicle's driving information be transmitted through communication methods installed in connected automated vehicles by harnessing the concept of road pricing and combining it with the management of driving schedule information. The CAV vehicle reserves a geographical space (several meters) and time (several seconds) to collect gasoline tax from CAV vehicle as well as highway toll fees from the CAV vehicle in a platoon.

The gasoline tax is collected from CAV vehicles based on a dynamic, distance-based (grid-based) designated charging method as an alternative tax system to replace the current flat-fee gasoline tax collection method. Certainly, connected automated vehicles in a platoon can reserve the spatio-temporal sections by forming a planned travel route in advance and traveling according to the reservation information. The platform will provide a freeway mechanism for collecting toll fees without stopping or reducing speed for tollgates, thereby improving travel time and the number of generated platoons on the highway.

1.2 Thesis Contributions

In summary, the thesis contributions are as follow:

- The adoption of zero-emission vehicles has escalated, leading to a reduction in fuel tax revenue. It is critical to develop a system capable of collecting the gasoline tax in the zero-emission vehicle era.
- The tax issue is critical for vehicle owners in general, and an increase in the gasoline tax would present a new challenge to their willingness to transition to the new tax system. Therefore, a system is needed that does not change much in their ownership cost. Thus, based on the proposed design, a comparison of the tax charge system with the current method does not change much in the ownership cost of the vehicle.
- Tax charge accuracy is essential in terms of individual payments as well as total tax revenue for the government. Therefore, a system that accurately collects the gasoline tax with high accuracy is needed. The proposed method's performance evaluation result shows that the proposed method is able to collect gasoline tax with high accuracy and no data package losses.
- According to numerous studies, auditability and privacy are the two most important factors influencing willingness to change to the new gasoline method. As a result, we develop a system that provides auditability while also protecting the owner's privacy, with only specific data considered to be stored to protect the user's privacy.
- 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 improving 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.

CHAPTER - 2

Background Information

2.1 Connected Automated Vehicle Technology

Automated vehicles are sophisticated networks that collect data and communicate with their surrounding environment with high accuracy, which are expected to reduce traffic fatalities by replacing human drivers with self-driving technology using autopilot [21]. Automated vehicles utilize lidar, radar, and high-resolution cameras that operate as an independent in-vehicle unit to detect such nearby objects as road markings, infrastructure, automobiles, bicycles, and pedestrians [22]. To enable automated driving, the fundamental principle of automated vehicles is to travel from point A to B by navigating a state space. A state space is commonly described as an occupancy grid, which shows where vehicles are located in the environment [23]. In addition, such motion-planning techniques as graph search, sampling, interpolating, and numerical optimization generate optimal path planning based on collected data to travel from a starting point to a destination [24].

Currently, automated vehicles utilize advanced driving assistance systems (ADAS) that improve safety, comfort, travel time, and energy consumption [25]. Technologies like adaptive cruise control, automatic emergency braking, intelligent speed adaptation, lane keeping assist, lane departure warning, and lane change assist are the main assistance technologies that address longitudinal and lateral comfort, safety, and security [26]. Currently, ambiguous obstacle detection at high speeds over long distances is one of the most difficult technical challenges. Cameras can't see through fog, lidar can't interpret a driver's intentions, and detecting a human in the dark by machine learning is also challenging, although communications from vehicle to vehicle or vehicle to anything can convey information [27], [28]. If AVs act independently, then efficient and safe mobility will not be feasible. Instead, to achieve a cooperative environment, which is globally known as a connected automated vehicle (CAV), further connectivity is needed to advance safety [29].

A connected vehicle is a collection of applications, services, and technologies that enable the creation of such vehicular communications systems as vehicle- to-anything V2X, which includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication [30]. These vehicular communication technologies permit external support for computing tasks that mitigate traffic collisions and blind-spot detection by simultaneously exchanging such real-time state information as location, speed, acceleration, and direction among vehicles within a particular range [31]. In a smart travel system, communication and choosing an appropriate networking system are essential for response time in the reservations mechanism. However, depending on the application, two types of technologies are extensively utilized in vehicular networking communication: dedicated short-range communications (DSRC) IEEE 802.11p and cellular networks as third generation long-term evolution (2 - 3 GLTE). Both DSRC and cellular net- works are currently collecting ETC highway tolls and providing weather, con- struction congestion awareness information, and parking assistance [32]. It is easy to collect real-time data and provide a response for reservations as well as detailed travel and tax information.

CAV technology improves the overall traffic flow and safety on freeways using heuristic algorithms and optimal control strategies that were developed for ramp-metering to regulate the flow of vehicles merging onto freeways to decrease traffic congestion and increase safety [33]. For safe and efficient autonomous control of traffic through intersections, coordination methods are used so that vehicles cross intersections (or merge) without rear-end or lateral collisions in the merging zone. Centralized [34] and decentralized [35] control algorithms or intersection managers coordinate the reservation or crossing schedules based on the received requests and information to improve traffic capacity. Since vehicular networking technology is developing so rapidly, connected vehicles will soon be integrated with 5G technology to optimize their cooperative efficiency, including the internet of things and heterogeneous access of networks [36]. These technological advancements, paired with the applicability of new methodology in automated vehicles, increase the feasibility of accurately implementing dynamic map systems for road reservation mechanisms based on the distance-based charging method.

2.2 Dynamic map

One of the most significant technologies for the development of high-level automated driving vehicles is the dynamic map. Dynamic mapping is a cartographic concept that is used to show dynamic spatial occurrences or to convey spatial information in a dynamic manner. Local Dynamic Map (LDM) enables integrated management of the map and navigation systems. It offers a structure for layering data based on its properties and managing the data utilized in cooperative ITS systems.

Dynamic maps are comprised of both high-precision digital maps and ITS anticipative information, which contain functions for recognition, decision, and operation. To accomplish high-level self-position projection, sophisticated recognition requires maps and ITS information, as well as on-board sensors. They are composed of four layers. The lowest layer is a three-dimensional digital map that includes a lane-level road map with road geometry and topological data. Layer 1 is a semi-static information layer that displays planned phenomena such as signals, while Layer 2 is a semi-dynamic information layer that displays actual phenomena such as congestion and other traffic situations. The top layer contains dynamic information that depicts real-time changes and is derived from ITS predicted data from CAV vehicle sensor information.

The DynaMap is an enhancement of the LDM architecture, which was introduced by Netten et al. [34]. They realized that past LDM work had been car-centric, so they concentrated on roadside ITS stations. Netten et al. proposed a new architecture that consists of data sources, a world model, world objects, and data sinks. The world object associator generates world objects based on streaming input from various data sources, such as V2X messages and sensor measurements. The world model is similar to an ontology in that it describes all of the objects' relationships, including their hierarchical relationships and a running history of data items. They also clarify that each item has a reference point that is linked to a spatial topology [37].

The "open local dynamic map" was developed by Koenders et al. The emphasis is that the LDM cannot permanently store all objects and their data items. As a result, they implemented a "basic" streaming filtering mechanism, removing items that were too far away from the ITS station. They created their own relational schema, which included tables for regions, objects, and roads, as well as a geographic topology. They also supplied the LDM with new functionalities such as map matching and a security layer [38].

Shimada et al. developed and tested SAFESPOT's original (RDBMS-centric) method in a sophisticated collision detection application scenario. A traffic simulation application was utilized to produce V2X messages for varying numbers of cars for the evaluation [39].

A graph-based context model of an ego vehicle's static and dynamic surroundings was proposed by Ulbrich et al. [45]. They designed an ontology for context representation, which contains classes for actions, traffic items, and circumstances. The ontology is a component of an "overall" context model that consists of three interconnected layers: (a) a geometric layer, (b) a topological layer, and (c) a semantic layer. In addition to the context model, the authors provided a method for aggregating information to enrich the model. They also presented a quantitative assessment of the technique in the context of their Stadt pilot project [40].

The cooperative perception strategy for improving vehicle environmental awareness is described by Zoghby et al. [48]. They extended each vehicle's own LDM with a Dynamic Public Map (DPM) extension based on Dynamic Distributed Maps (DDM) that are transferred across cars. They proposed a method for computing the DPM that included a discounting phase with confidence evaluation, (ii) a prediction step with spatial and temporal alignment, and (iii) a fusion step using an existing association algorithm. A detailed experimental assessment revealed that the DPM increases the detection and categorization of nearby cars [41]. Zhao et al. proposed the "colored spatiotemporal Petri nets" [47], which are meant to mimic traffic control cyber-physical systems. These nets are an orthogonal technique that might be expanded to stream the LDM [42].

In each part of the fourth layer of LDM, there are several researchers studied for the development of LDM, but we focus on the usage and functionality of the LDM in the ITS System. The functionality of LDM in the ITS application is as follows: warning response, emergency vehicle warning, across-traffic turn collision risk warning, merging traffic turn collision risk warning, intersection collision warning, and cooperative forward collision warning.

The LDM utilization for in ITS for assistance is, slow vehicle indication, cooperative merging assistance, lane change maneuvers, and emergency electronic brake lights. As well as, for infrastructure-based assistance, there are the following: wrong-way driving warning (infrastructure-based), stationary vehicle accident, stationary vehicle problem, traffic condition warning, and signal violation warning, as illustrated in Figure 5.

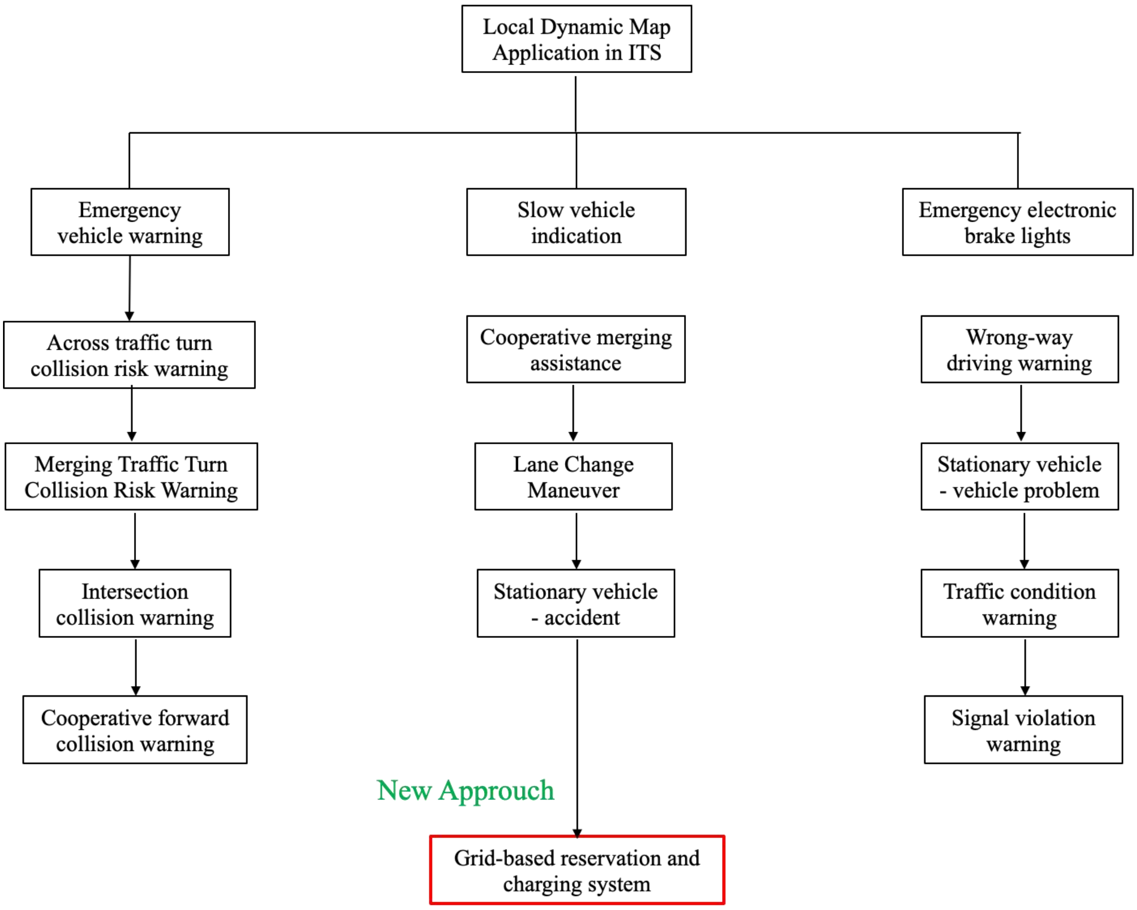

Figure 5. Shows the local dynamic map application in ITS systems.

We used the LDM functionality in different directions, such as grid-based reservation and charging systems for gasoline tax collection and highway toll tax collection from the CAV and CAV vehicles in a platoon, as discussed in detail in the following chapters.

2.3 Real time data

To implement the distance-based charging system, collecting real-time traffic data, vehicle networking, and communication are the essential factors for implementing the new system. Moreover, to understand the distance traveled with high accuracy for each vehicle type, it is important to collect real-time data for all the vehicles. As well as, to develop an effective real-time traffic management and information systems, high-quality real-time traffic information is required.

The ITS data and information transmission components enable the communication of obtained information to management centers for processing, as well as the distribution of information and/or management and control measures to travelers and infrastructure. This method data collection methods have over time changed and it is progressed from cables to optical fibers then to wireless networks (e.g., 3G/4G, WIFI, etc.) and with cloud platforms. By employing advanced communication technology, mechanisms for broadcasting information and control/management approaches have progressed from classic traffic signs and radio broadcasting to dynamic message signs [43], mobile applications [44], and in-vehicle information [45].

For further evaluation of current traffic conditions, data-collection components collect all observable information from the transportation system, such as traffic flow at a specific point on the road network, average travel time for a specific road section, number of passengers boarding a transit line, and so on. To collect this basic traffic information, such as traffic volume and spot speed, inductive loop detectors [46], [47], which detect the presence of vehicles based on the induced current in the loop with passing vehicles, and pneumatic tubes [48], which detect the presence of vehicles based on pressure changes in the tube, have traditionally been used. However, due to their high implementation costs and influence on traffic, these solutions are becoming less popular, particularly in crowded locations.

When the sensing and imaging processing technology developed, video cameras and radio-frequency identification (RFID) scanners are increasingly being considered for use in traffic data collection. The cameras could be installed at various points around the network to collect traffic videos. The videos are then analyzed using specifically designed image processing software (e.g., Autoscope) to determine information such as traffic flow, speed, vehicle types, etc. [49], [50]. In this regard, automatic license plate recognition [51], [52] is one crucial area of research, as the recognition and matching of license plates can provide additional information such as selected travel paths and travel times. On the other hand, radio-frequency identification (RFID) data can commonly be obtained at locations that accept contactless payment (e.g., Autotoll and Octopus systems in Hong Kong) or for freight transport. Through the matching of unique RFID tags, different traffic-related information, such as path choice and travel time, can be extracted [53], [54].

As smartphones and advanced communication technologies become more widespread, global positioning system (GPS) data [55], [56], media access control (MAC) addresses from Bluetooth and WiFi components [57], [58], and mobile phone data [59], [60] are becoming available for the analysis of traffic conditions or even travel behavior. In comparison to the previous data sources, these new sorts of data are more at the individual level, as such devices are generally personalized and capable of continuous tracking (e.g., GPS and mobile phone data). More sophisticated and/or behavioral-related analysis might be performed using such variables.

Recently automated vehicles enabled new approaches to vehicle-to-vehicle V2V communication, vehicle-to-infrastructure V2I communication, and vehicle-to-anything V2X communication for flexible control and management of transportation systems in real time to improve overall system performance.

ITS data analysis components aim to provide various information and management/control mechanisms based on traffic data obtained from the various sources as mentioned earlier (e.g., inductive loop detectors, GPS, etc.). To analyze traffic conditions and provide the appropriate response, predetermined and pre-calibrated models, such as traffic equilibrium models [61], [62], flow models [63], [64], and different models for signalized crossings [65], [66], have generally been used. Recent advances in processing capabilities, along with the requirement for more comprehensive evaluation, have resulted in the creation of micro-simulation and agent-based models in data analysis components [67], [68]. Though since new data sources have been introduced, these models have been expanded to effectively employ the new data to increase the accuracy and detail of evaluations [69].

To implement the distance-based charging system, collecting real-time traffic data, vehicle networking, and communication are the essential factors for implementing the new system. Moreover, to understand the distance traveled with high accuracy for each vehicle type, it is important to collect real-time data for all the vehicles. To impose the new gasoline tax system on those who try to manipulate the total distance traveled to avoid the tax. It is essential to collect real-time data on vehicles, and the vehicles reserve the route for driving. Human drivers may not strictly observe these traffic rules, but automated vehicles would easily do it. However, the new distance-based charging system could be implemented in any type of ordinary vehicle by installing a low-cost device equipped with GPS localization and a cellular-like communication (e.g., 4G) system. Al- though, because the future vehicle will be an automated and intelligent vehicle, and the new system will collect gasoline tax from zero-emission vehicles, we will consider an automated vehicle for this study. The vehicle’s driving information is collected through communication methods installed in connected automated vehicles, which can cooperate to fulfill the essential factors to implement the proposed method.

2.4 Road pricing

Road pricing implies that motorists pay directly for driving on a specific highway or in a specific area. The primary objectives include traffic congestion management, revenue generation from transportation-related emission reductions, social welfare maximization, and rewarding the use of public transportation or traffic mode change, which are frequently used to influence the decision about road pricing. Transportation practitioners generally agree that road pricing is a potentially effective method to improve the quality of transportation service, particularly in terms of reducing traffic congestion [70, [71].

At present, road pricing refers to a fee determined for the use of a road, such as distance or time-based fees [72], toll roads, congestion charges [73], and taxes intended to discourage certain types of cars, such as fuel propellants or polluting automobiles [74]. In this paper we propose a radical new approach to replace the present gasoline tax collecting method, which reserves (virtual) spatio-temporal sections of the road in real time for road pricing. This idea refers to the reservation of a geographical space (several meters) and time (several seconds) as well as levying a designated charge on the space-time/grid unit for each type of vehicle. Although human drivers would struggle to precisely observe such complicated traffic rules to reserve space-time grids on the road and manage gasoline tax-related issues, automated vehicles can manage them simply. However, by installing a low-cost device equipped with GPS localization and a cellular-like communication (e.g., 4G) system in any type of ordinary vehicle, the new micro-road pricing system could be implemented with an additional cost as the short summary is illustrated in the Figure 6.

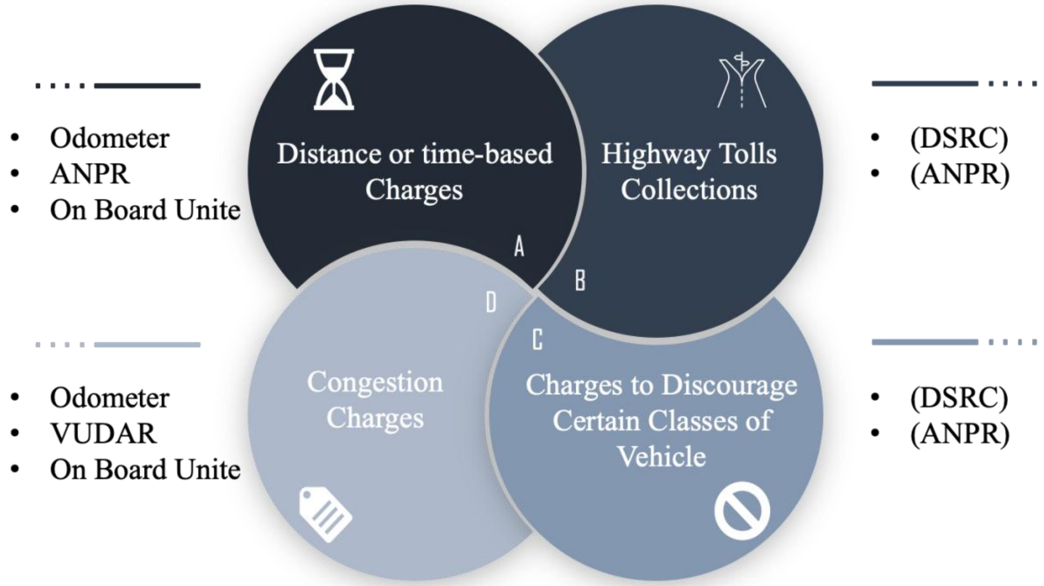

Figure 6. Shows the short summary of road pricing method used for different usage in transportation.

2.5 Connected Automated Vehicle Platoons

Cooperative Adaptive Cruise Control (CACC) is a vehicle technology that brings promise of greater road capacities and improved energy efficiency without investing on the road infrastructure, such as additional lanes or ramp metering controllers. Vehicles equipped with this technology are henceforth termed Connected Automated Vehicles, or CAVs for short. These vehicles monitor their speeds and gaps relative to their lead vehicles, and automatically adjust their motions in response. Moreover, CAVs can communicate with others of their kind nearby in real time and at high frequencies. With this communication, vehicle accelerations, lane-change maneuvers and other driving decisions can be shared across vehicles without the perception errors and reaction times associated with human drivers. These characteristics was studied by Shladover et al which enable smaller vehicle headways that improve higher road capacity than were previously feasible [75]. As well as Altinisik et al. study the lower air drag, which improves energy efficiency [76]. Note that the present research focuses on freeway setting to study the traffic impact of CAVs forming platoons without interruptions, such as signalized intersections.

The second part of the study is highway toll collection in the era of CAV platoons. The CAV platoons have the potential to improve vehicle safety, efficiency, and mileage, while improving travel time and decreasing traffic congestion, pollution, and passenger stress as short summary is described in Figure 7.

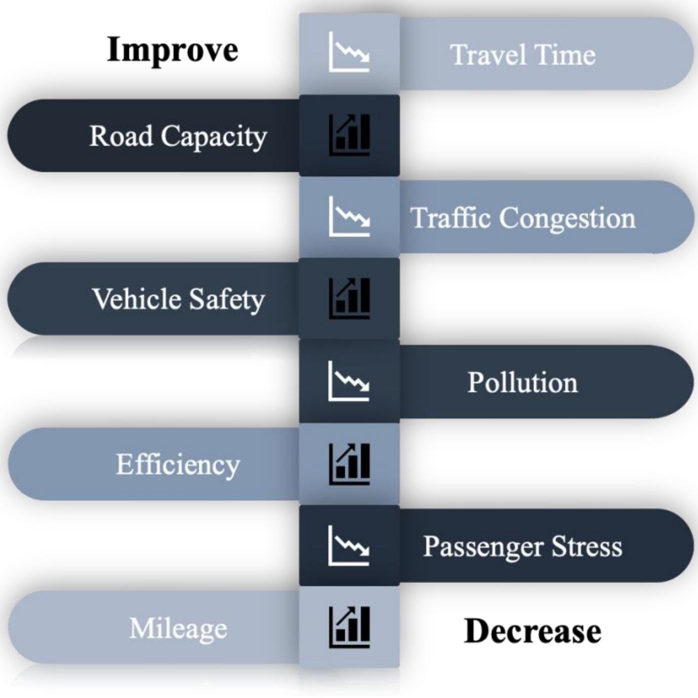

Figure 7. Show the CAV platoon advantages.

Platoon structure could have two effects on traffic. First, it can increase the number of CAVs in a platoon by lowering the headways, which improves traffic capacity [77]. Second, it may cause more lane changes on the road, thus disrupting traffic flow, which is studied by Chen and Ahn [78].

Dynamic platoons are classified into two types. The first is a real-time platoon, while the second is an opportunistic platoon [79]. The term "opportunistic platoon" refers to vehicles that are at a specific distance of each other and share similar interests or characteristics, forming a temporary platoon without previous arrangement. The opportunistic platoon formation approach is difficult to understand. It necessitates not just vehicle collaboration in terms of maneuver, but also robust formation procedures.

Besselink et al. [80] provide an overview of the cyber-physical regulation of road freight traffic. They further investigate the possibilities and prerequisites for building an opportunistic platoon. Sokolov et al. investigated platoon formation optimization by centralized routing and departure time coordination, as well as an actual simulation result and an optimization model [81]. Since platooning technology is not widely used, the potential benefits of an opportunistic platoon have yet to be found. As a result, significant consideration is necessary. Zeng et al. presented a combined communication and control method for wireless autonomous vehicular platoon systems, taking into account both communication latency and control system stability [82].

Alam et al. emphasized the importance of heavy-duty vehicle platooning in increasing global commerce safety and efficiency. They also investigated at how changing weather conditions affected fuel savings, controller operation, and affectivity [83]. Gong et al. developed a novel car-following control technique for a platoon of connected and autonomous cars going on a straight highway, as well as dual-based distributed algorithms to compute optimal solutions with proven convergence [84]. Following that, they provided a series of research articles on how to optimize AVP with human-driven vehicles in the actual world [85].

Overall, first it is clear that if the platoon stops or reduces the speed in the toll gate the real benefit of the platoon could not be archived. As well, none of the methods can be considered 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.

2.6 Related researches

2.6.1 Gasoline Tax Collection

Fuel tax is still collected as a flat-fee from all types of vehicles based on their fuel consumption as a specific percentage of the fuel price. Currently, no alternative system has been implemented for collecting gasoline tax based on vehicle miles traveled or any other method.

Alan Jean et al. investigate a flat annual registration fee and the study suggests a flat annual registration fee of 0.6% of the vehicle's manufacturer's retail price (MSRP). Furthermore, they estimated a 22-cent per mile fee to overcome the decrease in revenue for the USA. McMullen et al. (2010) find that a VMT tax (set at 1.2 cents per mile) that replaces a 24-cents-per-gallon gasoline tax would be slightly more regressive than the fuel tax [86]. Robitaille et al. compare a $0.015 VMT tax with a $ 0.10 federal gasoline tax increase and conclude that the former leads to a larger decrease in consumer surplus and a loss of social welfare.

In 2013, the first pilot project for a mileage-based revenue system was implemented in Oregon, USA. They installed the GPS tracking device on voluntary vehicles (limited to 5000 automobiles and light-duty commercial vehicles in the initial phase) at a cost of $250 per vehicle. Each vehicle was charged a tax of 1.5 cents per mile on their traveled distance on public roads. Participants in the scheme got monthly invoices for their road-use costs and had the state fuel tax repaid when they bought gasoline at Oregon stations. As a result, it is a complicated system for both users and authorities to implement on a large scale and with less accuracy for assigning gasoline tax charges. Furthermore, it is difficult to distinguish between travel in the different provinces or states and calculate the tax revenue for each type of vehicle in many provinces or states.

The University of Iowa's public policy center conducted a 2-year field study to evaluate the technical feasibility and user acceptance of mileage-based charging systems. In this research, technical feasibility problems included on-board unit installation, tax calculation accuracy, and fee evasion. They were able to track approximately 92.5 percent of all traveled miles using GPS and onboard vehicle devices. The remaining driven miles were estimated from the car's odometer using an interpolation technique, which will have an impact on revenue collection by not registering and calculating driven miles for each vehicle type. The second part of the study results shows that 71% of the participants preferred auditability and maximum privacy protection when using the system.

Several studies have examined its distributional implications and equity concerns. Zhang et al. estimate that Oregon's flat VMT tax would not lead to significant changes in the tax burden and taxpayers' welfare in either the short or long term [87]. Weatherford (2011) finds that a VMT tax, set at 0.98 cents per mile, would shift the tax burden from low-income to high-income households, from rural to urban households, and from retired to younger households with children [88]. The VMT tax would benefit rural households more than their urban counterparts because the vehicles owned by rural households are on average less fuel-efficient. Robitaille et al. compare a $ 0.015 VMT tax with a $ 0.10 federal gasoline tax increase and conclude that the former leads to a larger decrease in consumer surplus and a loss of social welfare [89].

Alan Jenn et al. studied the revenue generation for the state of Colorado in the United States, estimating that total annual revenue generation would decrease by about $200 million by 2025 as a result of EV adoption in our base case, but in projections with larger adoption of alternative vehicles, it could lead to revenue generation reductions as large as $900 million by 2025. A flat annual registration fee at 0.6% of the vehicle's manufacturer suggested retail price (MSRP) or 22 cent per mile fee as an alternative method to enhance the gasoline revenue. Since there are various types of vehicles, each with different sizes, fuel economy, and axel loads, both the MSRP and the per mile price may not be viable.

Rebecca Lewis and Benjamin Y. Clark investigate the revenue loss attributed to new mobility and evaluate revenue sources to fund transportation. They studied five Oregon cities, describing how transportation is currently funded and estimating revenue loss in a scenario of electrification, automation, and sharing using empirical analysis of local government budget data. They suggest that governments should seek out ways to find more stable revenues (VMT-based revenues) and move away from less stable revenues (motor fuel) [90]. Yiwei Wang and Qing Miao simulate the vehicle usage, tax burdens, and total tax revenues generated under a possible nationwide revenue-neutral flat VMT tax [91]. Caplan (2009) estimates a VMT tax (set at 0.3 cents per mile for cars and 1 cent per mile for light trucks) would decrease annual pollution emissions by 7% -

11%, suggesting a significant environmental benefit [92] as the short summary of studied proposed method is illustrated in Figure 8.

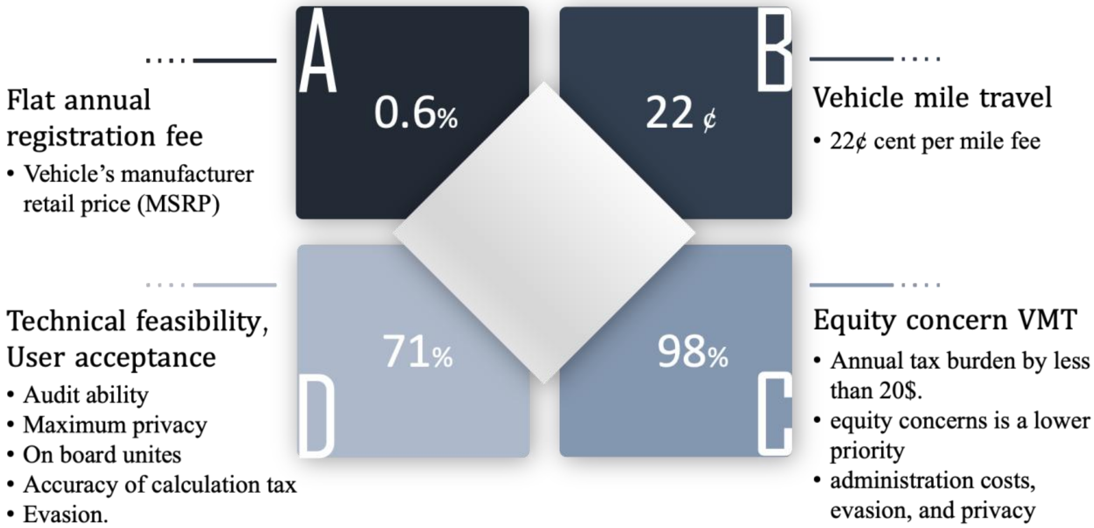

Figure 8. Shows the alternative methods for replacing the current gasoline tax system.

These challenges are different for each method using different technology, such as, Equipment costs, Operating cost, User inconvenience, Price Adjustability, Accuracy, and User Auditability. The vehicle mile travel method using Odometer technology Equipment costs low, Operating cost low, User inconvenience low to medium, Price Adjustability low, Accuracy medium, and User Auditability low. And using all the technology for vehicle mile travel method have it is own pross and cons.

VMT is at an early stage because there is no adequate mechanism being investigated as a replacement for the gasoline tax. There are several challenges to be addressed, such as a collection mechanism, a dynamic pricing system, reducing administrative costs, preventing payment evasion, maintaining privacy, or vehicle onboard equipment installation. Utilizing the tollgate on all roads is one of the options to collect gasoline tax, but the system has many drawbacks, including violation processing, high operational cost, fixed infrastructure device dependency, and a large amount of electronic equipment that must be installed in every vehicle and on the road infrastructure, which needs an appropriate mechanism to be investigated to address the challenges as the short summary is described in Figure 9.

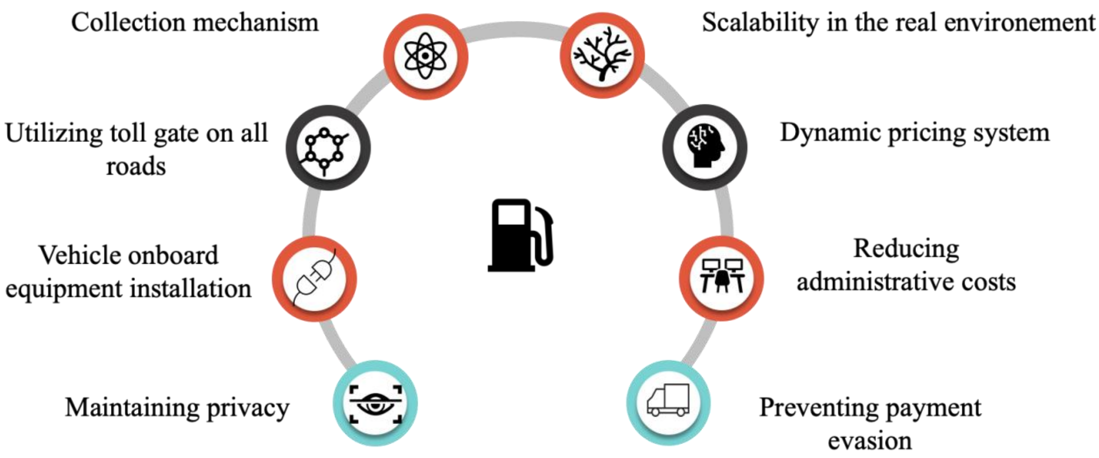

Figure 9. Described lake of Vehicle mile travel method.

2.6.2 Highway Toll Collection from Automated vehicle Platoon

Toll collection is a phenomenon used to reimburse infrastructure investments by those who use the infrastructure [93]. 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 [94] as the total literature review for highway toll collection is illustrated in Figure 10.

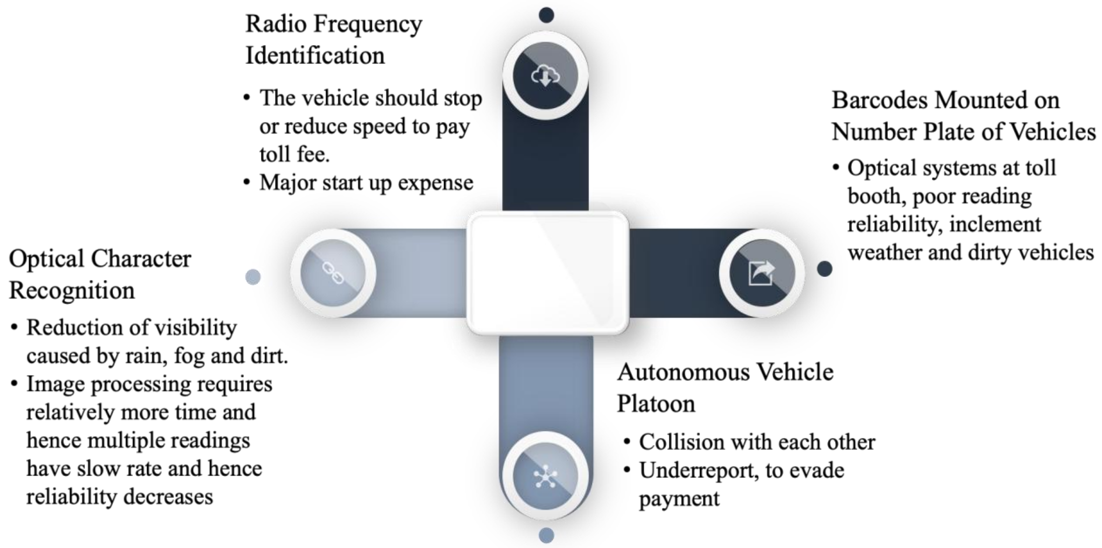

Figure 10. Shows the short summary of current method used for toll collection.

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) gate [95]. 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) [96]. 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 [97]. 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 have 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) [98], [99], 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 [100]. Despite having the advantage of being simpler than other technologies, it has several dis-advantages 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 [101].

The second technology is the RFID-based ETC system [102], 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 trans-action 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 play an important role in the reliability and high accuracy of these systems.

The third important technology is ANPR [103]. 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 [104]. 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 [105] 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) [106]. In 1998, the European Union proposed using the Global Navigation Satellite System (GNSS) to tax vehicles depending on the distance traveled (Brussels, 1998) [107].

This preliminary effort generated more concepts and variations of GPS-based road pricing. Lee, Jeng, Tseng, and Wang and Xu [108] 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 [109]. Ren and Xu proposed another node matching-based approach [110]. Dias, Matos, and Oliveira presented a smartphone-based toll collection system that could be used for both traditional ETC and contemporary GNSS tolling [111]. The GPS-technique [112] consists of world-wide 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 [113]. 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.

CHAPTER - 3

A Promising Distance-Based Gasoline Tax Charging System Based on Spatio-Temporal Grid Reservation in the Era of Zero-Emission Vehicles

3.1 Structure and System Model

This section presents the overall structure of the proposed system, which reserves (virtual) spatio-temporal sections of a road as grid/msec units in real time.

3.1.1 Overview of Proposed Method

In this study, a configuration system platform was established that consists of a network operating center/server, a viewer/user, and a billing center. An automated vehicle assumes the role of a vehicles or user to transmit position and driving in-formation collected from various sensors to the server. Each connected automated vehicle reserves a scheduled travel route and time on a dynamic map and travels based on the reserved information. When the automated vehicle starts to drive, it sends the desired departure time, vehicle ID, origin, and destination information to the server. The network operating center/server communicates with the connected vehicles and generates a database based on the collected information.

Since a dynamic map contains a spatio-temporal grid, by dividing time and space into equal grids, spatio-temporal grids can be reserved on the road in real time. It computes a dynamic travel distance by grid/millisecond unit and assigns a designated charge for each independent cell or grid, which is converted from the fuel consumption of each type of vehicle. The network operating center provides detailed information about the travel distance and related costs to the vehicle users. If the user does not pay the charges online, the billing center creates a monthly charge invoice and sends it to the vehicle owner. The viewer displays the dynamic map generated by the server and provides detailed travel and tax information to the vehicle user via an API. When the vehicle starts driving, it sends the user's information and requests to the network operating center to reserve the grid in the route as shown in number (1) of Figure 11. After that, when the server receives the request, it first checks the dynamic map for occupancy and decides for the reservation of the grid (2), and then responds to the vehicle with grid and route reservations as well as tax charges (3). When the vehicle arrives at the destination (4), the server sends the overall detailed travel and payment information (5). Additionally, it saves designated data (6). If the vehicle doesn't pay the tax charges, it will send the monthly bill to the vehicle owner (7) as illustrated in Figure 11.

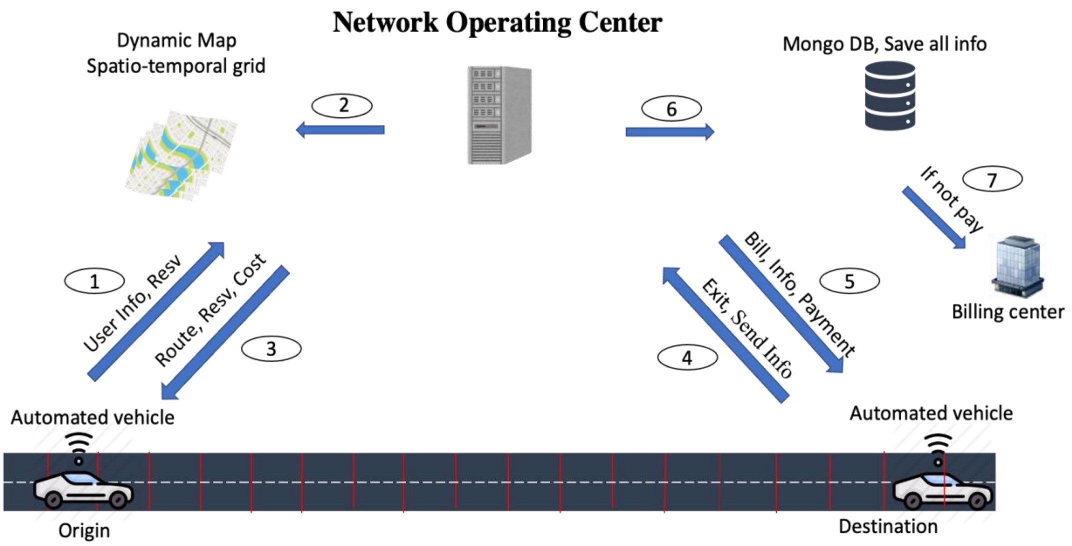

Figure 11. Sequence diagram of grid-based charging system.

A dynamic map is a platform that collects probe data such as vehicle position and speed information from various sensors in connected vehicles. The main criteria of real-time data collection and display, such as car reflection on the map, transmission, registration of vehicle information, and static map information, will be fulfilled by implementing the dynamic map platform, as studied by Netten, L. Kester et al [114]. Due to the above advantages of the dynamic map platform, we created a web-based dynamic map to implement the proposed system. In Figure 12, the overview of the structure's architecture that reserves a grid-based charging method is illustrated.

3.1.2 Overview of Dynamic Map Application

We created a server environment in Node.js and a web application framework called Express to implement a dynamic spatio-temporal section on roads in a real-time grid/millisecond unit-charging system.

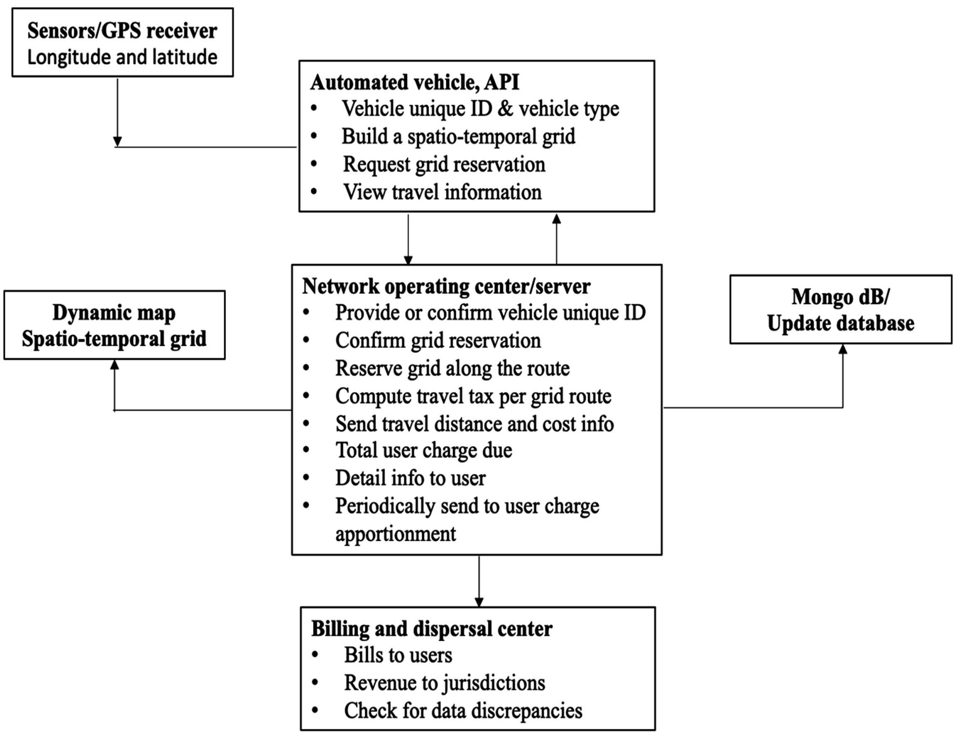

Figure 12. Structure architecture of reserving grid-based charging method.

We developed spatio-temporal grids with MongoDB, a document-oriented database like the Relational Database Management System (RDBMS) that supports a nested document structure. A spatio-temporal grid resembles a collection of grids or cells created by equally dividing time into one millisecond intervals and space into latitude and longitude and expressed in a nested document structure. We created a one-kilometer straight road environment by equally dividing a space into a spa-tio-temporal grid and making independent cells.

The grid cell mechanism is shown in Figure 13. The white arrow represents the vehicle's traveling path, the gray cells indicate the reserved cells on the travel route, and the other cells indicate unreserved cells. Since we concentrate on cooperative autonomous vehicles, a vehicle must travel precisely during the reserved time and be able to communicate with its surrounding environment. Thus, the connected automated vehicle sends vehicle information to the server, such as the desired departure time, origin, and destination position.

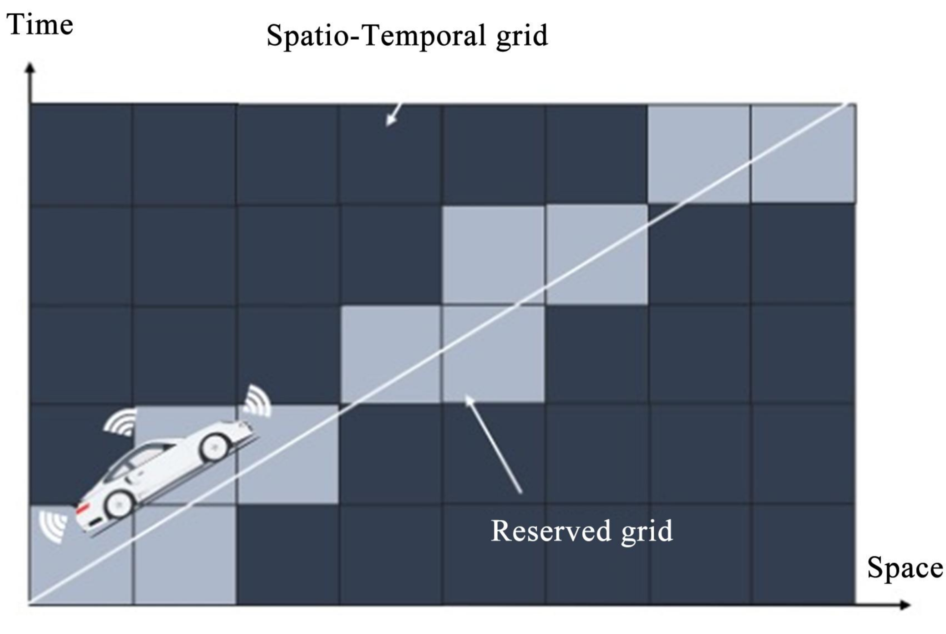

Figure 13. The reservation method of the spatio-temporal grid on a route.

For the first time, if the system registers a new vehicle, the network operating center/server provides a unique ID number to each vehicle and verifies it on the dynamic map to reserve the requested space-time grid to respond to the vehicle. If the grid is occupied, then the server notifies the vehicle to pause (shown in red cell) and call back the request for reservation, as described in Figure 14. The server generates a database based on the information collected from all the vehicles; when a vehicle sends a request to reserve a grid, the server reserves the requested grid along the travel route.

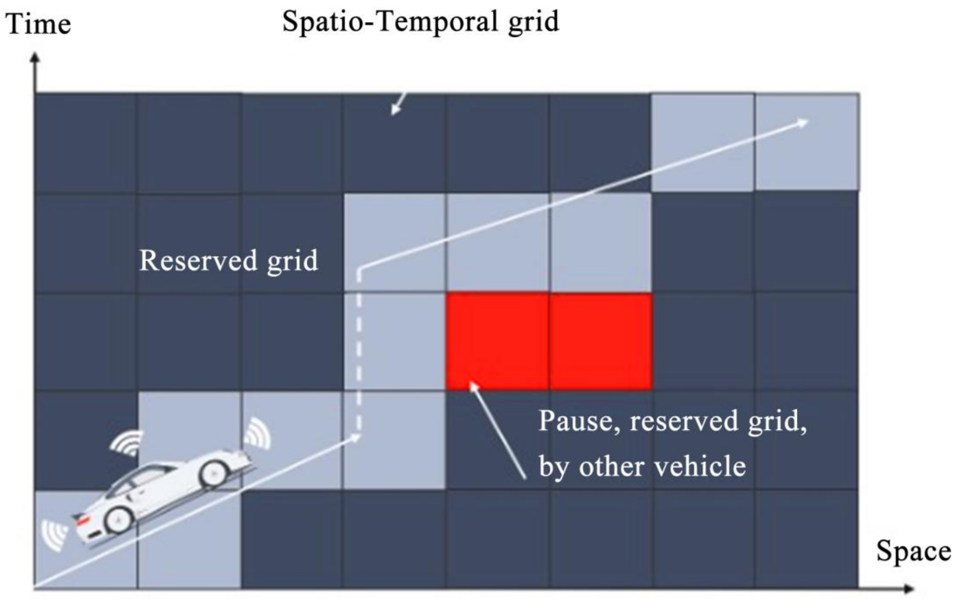

Figure 14. The mechanism of reservation of the spatio-temporal grid if the grid is reserved by another vehicle.

3.1.3 Method of Assigning Cost to the Grid

As previously mentioned, the space is divided into equal grids, and designated charges are allocated as the cost of each grid. When a vehicle submits a request to reserve the grid, the server assigns a designated tax charge to the grid for each type of vehicle and continuously calculates the tax costs for the travel route shown in Figure 15. Afterward, it records the vehicle information in MongoDB based on the vehicle's unique ID, date, time, travel distance, and calculated total tax charges for each type of vehicle. The billing center in turn creates monthly invoices and sends them to the vehicle's user if she does not use ETC or a credit card.

```
'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 },
'0_2': { rcvID: 0, price: 0 },
'1_2': { rcvID: 0, price: 0 },
'3_2': { rcvID: 0, price: 0 },
'4_2': { rcvID: 0, price: 0 },
```

Figure 15. Description example of spatio-temporal grid and assigning charges.

The assigned designated grid charge unit rate is converted from the fuel consumption efficiency of each type of vehicle to the grid/L from the CAFE standard. Based on the JAMA 2020 report [115], the fuel consumption efficiency rate for model year 2020 is 20.3 km/L, as estimated from the average fuel consumption of urban, rural, and express highways. The fuel consumption efficiency rate is converted into km/L and then grid/L units, multiplied by the 20% gasoline price, and assigned to each grid in the server's grid-based charging system. Following that, to create a grid/millisecond charge tax unit, the gasoline price is assumed to be constant at 1.5 $/L, where the government's gasoline tax revenue is 20% of the gasoline price per liter for each vehicle type, which is a combination of 10% local and 10% national tax revenues assumed for this study as shown in Figure 16.

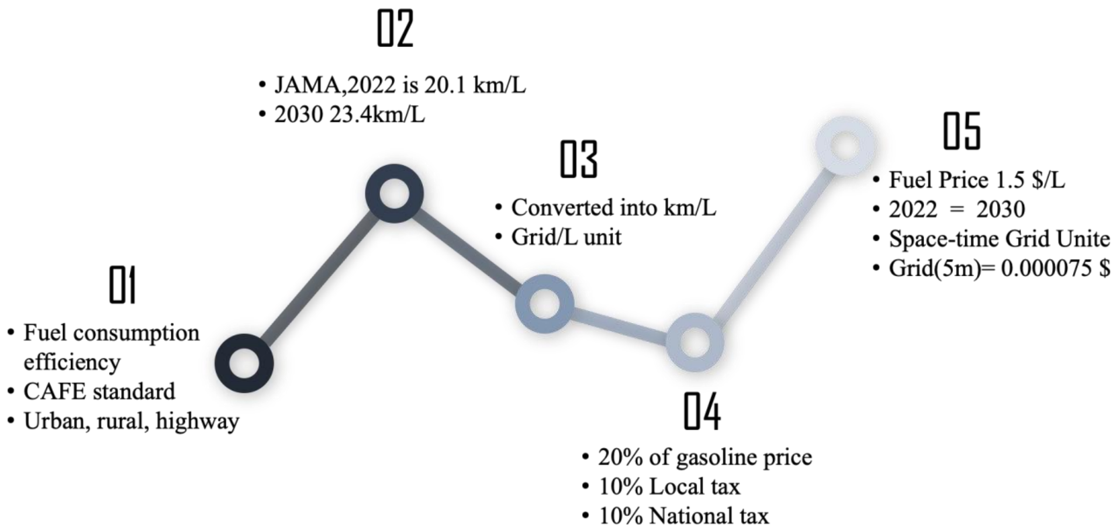

Figure 16. Described method of assigning cost to the grid.

Additionally, the average fuel efficiency rate for each type of vehicle was created using different vehicle types, makers, and model years. Vehicles were classified into ten different categories, based on average fuel consumption from a combination of urban, rural, and express highways. The grid length could be any size, such as five meters, ten meters, or the length of various types of vehicles. 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 is approximately 4.6, 14, and 12 meters, respectively. For this study, we as-sumed the grid length to be five meters, which means 200 grids is one kilometer.

In this study, we only considered conventional gasoline cars and assumed that electric vehicles pay gasoline tax based on the travel distance in the proposed method, just like passenger cars. The tax charges are calculated based on this assumption and determined for both conventional gasoline cars and electric vehicles as illustrated in Table 1. A grid/millisecond (5m/millisecond) unit tax charge could also be created and expanded to every type of vehicle based on the same method for assigning de-signed tax charges in the proposed system. Thus, revenues can be captured from vehicles that do not use fossil fuels, such as electric cars or other zero-emission vehicles, for all vehicle categories.

Table 1. Conversion of fuel efficiency rate to grid (5 m/millisecond) for each vehicle type.

Vehicle types	Fuel economy rate km/L, 2020	Fuel economy rate L/1km	Space–time grid L/grid	Fuel price $/L, 2020	Fuel tax 20% $/L	Grid/msec unit price
Gasoline car	17.3 km/L	0.058 L/km	0.00029 L/G	1.25 $/L	0.25 $	0.0000725 $
Hybrid car	20.3 km/L	20.3 km/L	0.00025 L/G	1.25 $/L	0.25 $	0.0000625 $
Electric car	20.3 km/L	20.3 km/L	0.00025 L/G	1.25 $/L	0.25 $	0.0000625 $

3.2 Implementation

This section describes the implementation of our proposed method for reservations in a spatio-temporal grid-charging system.

3.2.1 Implementation Environment

The implementation environment of the proposed system is shown in Table 2. The server environment is Node.js, and the web application framework is Express. NodeJS is a JavaScript runtime execution environment for web servers that handle the back end of web development. Express is a minimal and flexible Node.js web application framework that provides a robust set of functionalities for web and mobile applications. This framework has the advantage of simplifying the description of numerous procedures for developing a web application with a variety of HTTP utility methods as well as the ability to establish a comprehensive API quickly and simply. The server was started on a Mac computer to ensure the proposed system's performance, and both HTTP requests and responses were validated in the local environment.

Table 2. Implementation environment for the proposed system.

Environment	Model
OS	Mac OS Mojave 10.14.6
CPU	2.4 GHz Intel Core i5
Memory	8 GB
Python 3	COM interface
Server environment	Node.js + Express
Database	MongoDB version 4.0.4
PTV VISSIM 11	Traffic environment simulation
Load Test	Apache JMeter

3.2.2 Application Programming Interface (API)

Figure 17 describes the flow chart of the reservation and cost assignment to the road or a grid. The network operating system/server enables vehicle users to apply for grid reservations to facilitate their driving. Thus, the server provides APIs to the automated vehicle users to make reservations on space-time grids using the POST method to reserve a travel route. The POST method transmits the vehicle's unique ID, scheduled departure time, origin's latitude and longitude, and destination position in the request body. After the server receives a request, it first queries the spatio-temporal grid database for an empty spatio-temporal grid in the travel route, then responds to the requested vehicle with grid and route reservations and calculates the route's cost. When the automated vehicle starts driving and continuously sends requests for grid reservations, the server dynamically reserves the grids and travel routes as illustrated in Figure 17.

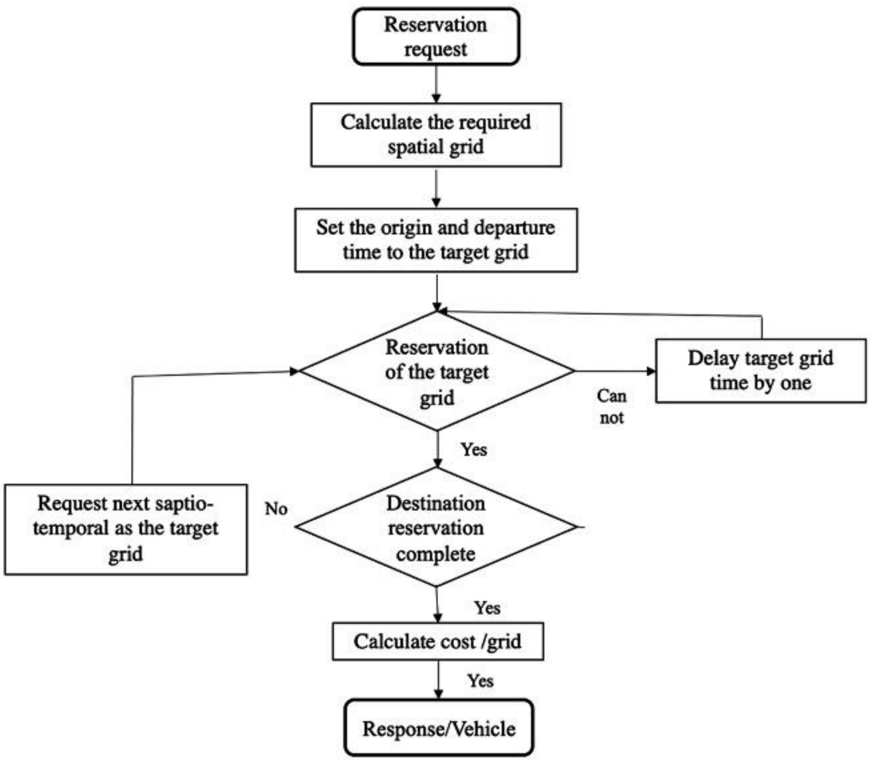

Figure 17. Flow chart of grid reservation and assigning cost processing of network operating server.

3.2.3 Spatio-Temporal Grid

MongoDB, which implements the spatio-temporal grid, is a document-oriented database, such as the Relational Database Management System (RDBMS) and is also open-source software. MongoDB does not save data in a table structure; it stores it in a JavaScript Object Notation (JSON) file format. JavaScript Object Notation (JSON) is a widely used open file and data interchange format which stores information in an organized and easy-to-access manner. The other beneficial quality is that it transmits data consisting of attribute-value pairs and array data types, which can be easily changed. Since the transportation infrastructure increases and decreases frequently, the space-time grid's data structure must also be frequently changed. Consequently, MongoDB is a schema-less database that is more flexible in terms of modifying the data structure after executing a system operation and enables a nested structure to store data. Thus, we manage our proposed system's spatio-temporal grid with MongoDB.

In this study, time is described in ISO Date type, which is divided into 1-millisecond intervals, and space is expressed in a nested document structure as latitude and longitude. A road's north-south direction (latitude) and east-west direction (longitude) are determined and controlled at regular intervals. When the vehicle reaches its destination, the server provides the user through the API with such detailed information as vehicle ID, travel time, travel distance, travel tax charges, and total tax charges as well safe data in Mongo DB as demonstrated in Figure 18.

```
_id: ObjectId("60618430cee348f8bcd7ad35")
totalDistance: 1000
totalCost: 0.0125
totalGridNum: 5
vehicleType: "passengerCar"
sid: 20
endTime: 2021-03-29T07:39:29.198+00:00
startTime: 2021-03-29T07:39:28.231+00:00
v destination: Object
    lng: 135.70342
    lat: 34.79827
v origin: Object
    lng: 135.70961
    lat: 34.80568
```


Figure 18. Description example of storing data in MongoDB.

3.3 Performance Evaluation

3.3.1 Evaluation Environment

To evaluate the proposed method, we use three evaluation methods such as performance evaluation of the system, response time for the communication, and car ownership cost for both the grid-based charging system and flat-fee method.

We use three evaluation methods to evaluate the proposed method: system performance evaluation, communication response time, revenue generation for gasoline tax, and annulled ownership cost for both the grid-based charging system and the current flat-fee method. Travel time measurements for platoons and the number of generated platoons for three different scenarios as illustrated in Figure 19.

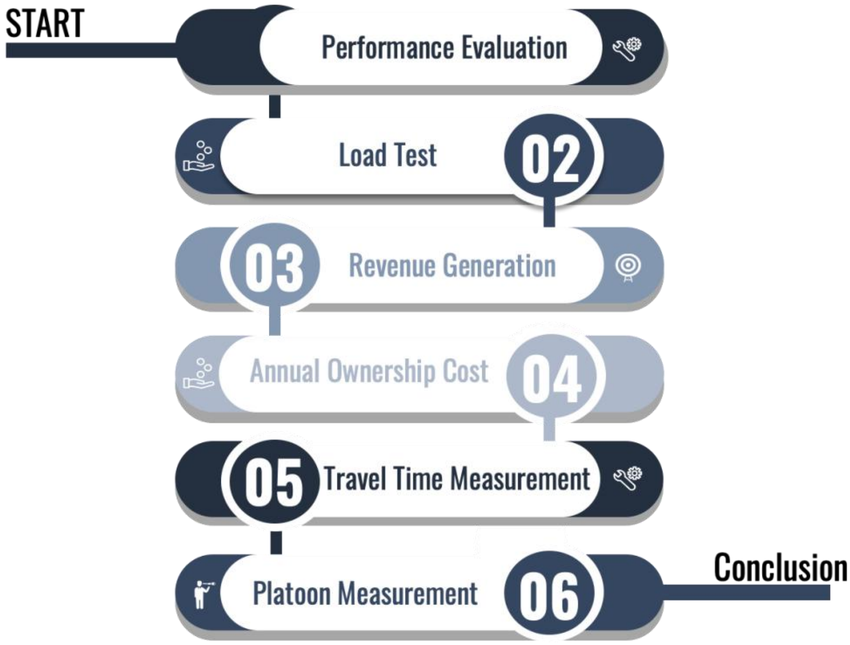

Figure 19. Shows the performance evaluation

First, we created a traffic environment in PTV VISSIM (Verkehr In Stadten-SIMulations Model) software. which is a microscopic multi-model traffic flow simulation software which can model a variety of types of traffic environments. Thus, we use it to model the traffic environment for the flow of passenger cars and electric cars. As well as the PTV VISSIM COM (Component Object Model) interface, which defines a hierarchical model in which the functions and parameters of the simulator allow you to externally design a model for any intelligence transportation system.

Second, we use PTV VISSIM 11, which supports the COM interface and can read script files written in any programming language. We developed a script file in the COM interface in Python that provides an environment for cooperative automated vehicles that communicate with the networking operator center/server. Thus, to execute the functions of the connected and automated vehicles, they send package data such as vehicle ID, origin position, and destination position to request a grid reservation through URLs to the server for each type of vehicle, as illustrated in Figure 20.

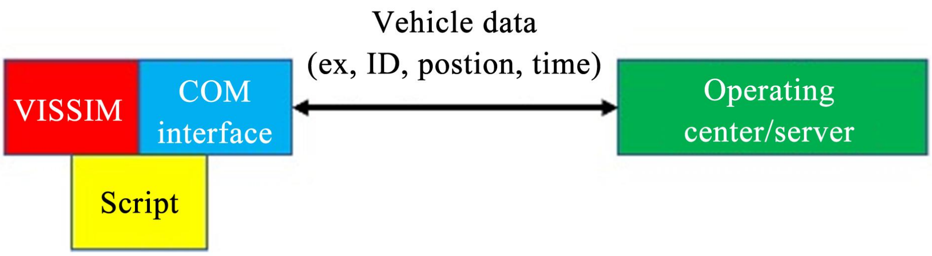

Figure 20. Demonstrate the environment developed for automated vehicles transmitting data to the network operating center.

To implement the traffic environment as mentioned above we create a one-kilometer road with two-lane and 3.5-meter-wide. The number of vehicles on the road ranged from 100 to 500 vehicles per hour as a different vehicle input for simulation, and the vehicle speed limit was set to 60-kilometer meter/hour. Based on current global electric vehicle sales worldwide [116], the percentage of electric vehicles and passenger cars is assumed to be 2.6% and 97.4%, respectively, and the simulation measurement times were set to one hour as all the simulation parameters are illustrated in Table 3.

Table 3. Simulation parameters for VISSIM.

Parameters	***Setting***
Speed limit	60 km/h
Number of vehicles (Sample)	500 veh/hr
Passenger vehicles: 2020–2030	97.4% – 80% = 487 – 400 vehicle
Electric vehicles: 2020–2030	2.6% – 20% = 13– 100 vehicle
Lane width	3.5 m
Measurement time	1 hour
Number of measurements	10 times
Measurement section	1000 m
TTC (time-to-collision)	5.0 s

The measurement time is one hour, the number of measurements is ten times, and time to collision (TTC) is considered five seconds. To achieve the required 60 km/hr speed on one kilometer of road, we calibrated the software based on changes in the vehicle behavior and driving behavior parameters. Figure 21 shows the PTV VISSIM execution screen for the proposed method, where red and green cars represent conventional gasoline cars and electric cars.

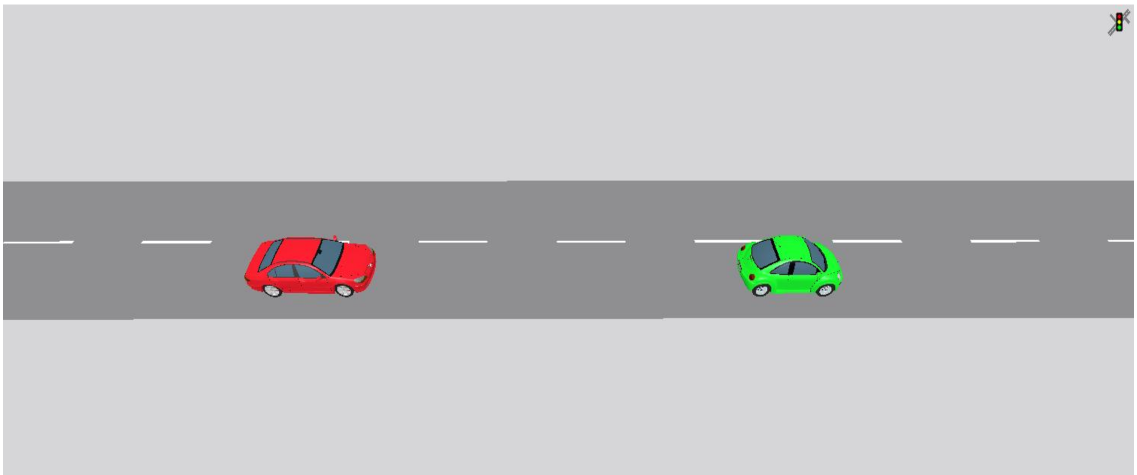

Figure 21. Execution screen of VISSIM simulation for proposed method.

3.3.2 Flow of Reservation and Assigning Cost to Grid

When an automated vehicle makes a grid reservation, perhaps other vehicles are simultaneously making reservations, which can cause inconsistencies and confusion. To avoid such issues, the server must process a vehicle's grid reservation requests on a first-come, first-served basis. Thus, Node.js provides non-blocking I/O asynchronous processing methods, which can process multiple requests with a single thread. Furthermore, to reserve a grid for each vehicle based on requests at a specific time, if the grid is already reserved by another vehicle, regaining access to the database is essential to process it once again.

Therefore, a callback processing mechanism must be appropriately established. If the processing time is constant for requests and responses from the database, no inconsistency or overlapping will occur due to another vehicle's request for route reservations. This method of operation is faster than locking the database. In addition, when the server responds to a vehicle's grid reservation and the vehicle drives it successfully, the server assigns the charges to a grid that is driven on and saved in the MongoDB based on the vehicle's unique ID. When the server reserves the grid, it assigns the unique ID of the requested vehicle to the spatio-temporal grid, which is highlighted in red as illustrated in Figure 22. When the server reserves the grid, it assigns 1 as occupied and (0) zerodemonstrate as unreserve grid.


```
_id: ObjectId("6061842e3ee61e4990d1a6a6")
time: 2021-03-29T07:39:28.597+00:00
space: Object
    2_0: 0
    2_1: 0
    2_2: 0
    2_3: 0
    2_4: 1
    0_2: 0
    1_2: 0
    3_2: 0
    4_2: 0
station: ObjectId("6061842ecee348f8bcd7ad01")
```


Figure 22. Description example of spatio-temporal grid reservation.

3.3.3 Load Test

We conducted load tests to analyze the system's response time using Apache JMeter, an open-source Java application that tests load, functional behavior, and application performance. The response time is the period between when the cooperative autonomous vehicle sends a request and receives a response from the server. An HTTP request protocol is utilized that contains the vehicle ID, desired departure time, origin, and destination positions, which are contained as 5-space grids in the X direction and 5-space grids in the Y direction.

We assumed that a cooperative automated vehicle could drive at 1 grid/millisecond and the desired departure time is identical for all the requests. The starting point is (0, 2) or (2, 0), and the destination is (2, 4) or (4, 2). The load test begins with the server in an unreserved state, and the results are obtained three times for such numerous requests as 1, 10, 15, and 50 in a loop. The load test results in Table 4 include average, maximum, and standard deviation of response times for each number of requests.

Table 4. Measurement of required times for requests and responses.

Number of requests	Response Time		
	Mean	Max	SD
1	41	41	0
10	33	46	7
15	36	58	11
50	43	48	10

3.3.4 Confirmation of Package Data, Accuracy, and Privacy

To clarify whether the proposed method is operating accurately, PTV VISSIM 11 provides an environment for cooperative automated vehicles that communicate with the networking operator center/server. In addition, PTV VISSIM supports the Component Object Model interface (COM), 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 functions of the connected and automated vehicles to send package data such as vehicle ID, origin position, and destination position through URLs to the server for each type of vehicle.

First, we validated the required speed of 60 km/hr on the road in VISSIM based on changes in the vehicle behavior and driving behavior parameters. Subsequently, we ran the simulation and input various numbers of cars, such as 100 - 500, and checked the number of vehicles assigned from VISSIM to the network operating 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 re-serves grids and routes for all 100 vehicles, accurately calculates the travel distance, applies the designated charges, and saves the information in its database. We repeated the same approach for different vehicle inputs and verified that our proposed method's performance was accurate.

We created a one-km straight road in VISSIM and confirmed the distance traveled and tax charges for each vehicle in the database as 1000 meters and $0.0125 for Prius vehicles. Detailed information was provided to the vehicle owner at the end of each travel trip to verify and ensure the ability to minutely audit both travel and tax information. The gasoline tax revenue charged to all vehicles is verified in the (MongoDB) database to validate that all vehicles were charged and to collect the tax from each vehicle as shown in Figure 22. 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 is considered to prevent tracking travel information issues as shown in Figure 23.


```
_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 23. Description example of invoice to billing center.

3.4 Simulation to Compare Gasoline Tax Revenue Collection for Flat-Fee and Proposed Grid-Based Charging Method

3.4.1 Proposed Method

To determine the proposed method's effectiveness, we evaluated and compared the gasoline tax revenue for a vehicle using the current conventional flat-fee method with the grid-based gasoline tax charging method. The grid-based charging method is to pay the gasoline tax fee based on the distance you traveled, which is considered a minimum of a grid (5 meters/millisecond), and the proposed system can be able to charge gasoline tax on a grid basis for all vehicle types. The revenue is calculated for 500 vehicles sample and for one km of travel road for both methods in model years 2022 and 2030. PTV VISSIM 11 is a microscopic multi-modal traffic flow simulator that models various traffic environments and visualizes traffic phenomena with 3D graphics. We used it to simulate a real traffic environment for the proposed method as well as, provide an environment for the cooperative automated vehicles. Since PTV VISSIM 11 also supports the Component Object Model (COM) interface to read script files written in any programming language and can transmit data from VISSIM to the server. We developed a script file in Python 3 that performed the roles of the connected and automated vehicles to transmit package data to the server through URL for each type of vehicle, including vehicle ID, origin position, and destination position.

The simulation environment for the proposed method is identical to the one described in the evaluation environment section. As the new gasoline tax charges are illustrated in section D of the proposed method structure and system model, we considered three types of vehicles for our simulation. The conventional gasoline cars such as gasoline-powered cars, hybrids (gasoline and battery electric), and full-battery electric vehicles (BEV). The average fuel consumption is considered for each type of vehicle for the JAMA 2021 report. Since full electric vehicles do not use fuel, we considered them the same as hybrid vehicles.

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. First, we ensured that if 100 vehicles make grid reservation requests from VISSIM, the server reserves the grids and routes for all 100 vehicles. Second, ensure that for various types of vehicles, the designated charges are applied accurately based on the driven distance, such as, a vehicle being charged $0.125 for one kilometer of travel, as an example is shown in Figure 22.

Moreover, to confirm that there was no data package loss, the database was checked to ensure that all the information was saved in the database without any data package loss. As demonstrated in detail in section (D) of the proposed method structure and system model, the unit rate of the designated grid charge unit rate is assigned $0.0000725 in the network operating center/server. The first scenario in the proposed method is gasoline tax revenue for the 2022-year model. In PTV VISSIM, the percentage of cars in 500 vehicles for model year 2022 is set at 64.2 percent, 35 percent, and 0.8 for conventional passenger gasoline vehicles (combination of Conventional and Clean diesel vehicles), hybrids, and electric vehicles (combination of Plug-in hybrid, Electric, and Fuel cell vehicles), respectively [117]. The plug-in hybrid electric vehicle is considered the same as the BEV for this study. Following the above settings and parameters, the simulation ran for one hour, and overall, 500 vehicles communicated with the network operating center/server and were charged based on their designated grid charge unit. The total revenue for these 500 vehicles was confirmed in the MongoDB database, and the overall result is illustrated in Table 5.

Table 5. Shows analyzed parameters in the proposed method for model year 2022.

Vehicle Types	parameters for model year 2022			
	Grid-time unite, Grid/L (5 meter/L)	20% Tax of gasoline price $	Veh types % in 500 Veh Sample	Total Revenue, Vehicle types $
Passenger car	0.00029 * 200	0.25	64.2% = 321	4.65
Hybrid car	0.00029 * 200	0.25	35% = 174	2.523
Electric car	0.00029 * 200	0.25	0.8% = 4	0.058
Total	0.058	0.25	500	7.23

The second scenario in the proposed method is for model year 2030 and is identical to the first scenario. The change point is the percentage of cars in the 500-vehicle sample, which is 50 percent of conventional passenger gasoline cars, 30 percent of hybrid vehicles, and 20 percent of electric vehicles, to represent the forecasted percentage for model year 2030 [117]. The simulation ran for one hour, and the revenue collection was confirmed in the database, as illustrated in Table 6. It is assumed that for model year 2030, all vehicles will be charged gasoline tax by the proposed method. Therefore, since electric vehicles are charged based on a grid-based charging system, the collected tax results in a revenue increase of up to 21.8 percent, as illustrated in Table 6 and Figure 41.

Table 6. Shows analyzed parameters in the proposed method for model year 2030.

Vehicle Types	parameters for model year 2030			
	Grid–time unite, Grid/L (5 meter/L)	20% Tax of gasoline price $	Veh types % in 500 Veh Sample	Total Revenue, Vehicle types $
Passenger car	0.00029 * 200	0.25	50% = 250	3.62
Hybrid car	0.00029 * 200	0.25	30 % = 150	2.175
Electric car	0.00029 * 200	0.25	20% = 100	1.45
Total	0.058	0.25	500	7.25

3.4.2 Flat Fee Method

The flat-fee method is calculated for 500 vehicles for one kilometer using the formula Equation (1). The fuel price is assumed to be constant at $1.25 for both model years 2022 and 2030. In Equation (1), R represents revenue in dollars, VKMT represents vehicle kilometer traveled; for this study, one kilometer is considered; L/KM represents fuel economy in kilometer per liter; C represents the fuel tax, which is 20%, a combination of 10% local tax revenue and 10% national tax revenue; and N represents the number of vehicles driven in one kilometer.

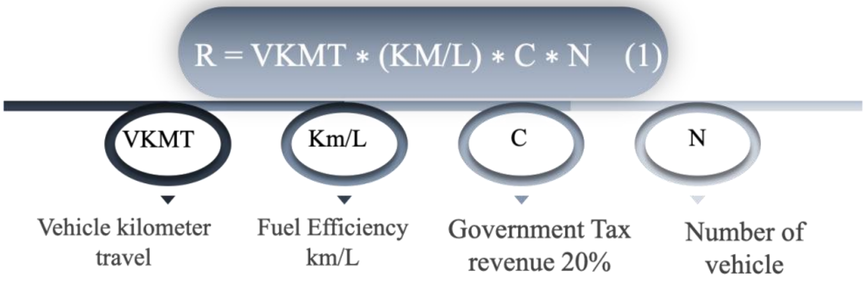

Figure 24. shows the method of calculating the gasoline tax for flat fee method.

In the third scenario for model year 2020, the fuel price is $1.25 per liter and the 20% tax (C) on the fuel price is 0.25. In a 500-vehicle sample, conventional gasoline vehicles, hybrids, and electric vehicles received 64.2 percent, 35 percent, and 0.8 percent, respectively, for model year 2022. The VKMT is one kilometer since we are calculating revenue for one kilometer. Furthermore, fuel economy for conventional gasoline vehicles is 17.2 km/L and hybrids are 20.3 km/L, which is converted to liters/km for model years 2022 [117].

Since, in the current condition, electric vehicles are not paying the gasoline tax, the electricity cost is considered instead of the gasoline tax. The average efficiency of the Nissan Leaf is 164 Watthour/km, which is 0.061 kW per kilometer. The average price of one kilowatt in Japan is $0.19, and we assumed that the electricity tax is also 20%. In a 500-vehicle sample, the BEV percent is considered 0.8 percent to represent the current BEV and PHEV for model year 2022. Based on the above-mentioned parameters, the gasoline tax revenue is calculated using Equation (1) as illustrated in Figure 24. for model year 2022 as demonstrated in Table 7.

Table 7. Shows analyzed parameters in the Flat-fee method for model year 2022.

Vehicle Types	Parameters for model year 2022			
	Litter/Kilometer (L/km) or KW/km	20% Tax of gasoline price $	Veh types % in 500 Veh Sample	Total Revenue, Vehicle types $
Passenger car	0.058	0.25	64.2% = 321	4.65
Hybrid car	0.05	0.25	35% = 174	2.175
Electric car	0.061 kw/km	0.004, Elec price	0.8% = 4	0.001
Total	0.079	0.25	496	6.825

The fourth scenario is for model year 2030. The fuel price is assumed to be constant and the unit price of (C) is the same as 0.25 as well as the vehicle traveled distance is one kilometer. In a 500-vehicle sample, conventional gasoline vehicles are expected to account for 50%, hybrid vehicles for 30%, and electric vehicles for 20%. Furthermore, the average fuel efficiency for model year 2030 is 25.4 km/L is forecasted, which is converted to L/km as 0.04 liters/km [117].

The average efficiency of the Nissan Leaf is assumed to be the same at 164 Wh/km, which is 0.061 kW per km for this study. The average price of one kilowatt is $0.19. Electricity tax is assumed to be 20% in Japan. As of model year 2030, the percentage of BEVs is expected to be 20%. Based on the above parameters, the gasoline tax revenue is calculated using Equation (1) for model year 2030 as illustrated in Table 8. As the number of electric vehicles in the global market grows and fuel efficiency improves, revenue will decrease continually.

Table 8. Shows analyzed parameters in the flat-fee method for model year 2030.

Vehicle Types	Parameters for model year 2030			
	Litter/Kilometer (L/km) or KW/km	20% Tax of gasoline price $	Veh types % in 500 Veh Sample	Total Revenue, Vehicle types $
Passenger car	0.058	0.25	50% = 250	3.62
Hybrid car	0.04	0.25	30 % = 150	1.5
Electric car	0.061 kw/km	0.004, Elec price	20% = 100	0.025
Total	0.05	0.25	400	5.145

3.5 Car Ownership Comparison for Grid-Based Charging and Flat-Fee Method

This total cost of ownership is the sum of all the expenditures associated with purchasing and operating a vehicle over a period of time. This cost includes not only the purchase and financing price of the vehicle but also maintenance costs, gasoline costs, insurance, and depreciation costs. Total car ownership can vary substantially across different countries. For this study, to specify the parameters and vehicle characteristics, we considered the annual cost of ownership in Japan.

In this study, the following representative vehicles are considered among all different types of vehicles, such as the Toyota Prius (HEV) for hybrid electric vehicles and the Nissan Leaf Battery Electric (BEV), as well as compared with conventional gasoline vehicles such as the Toyota Corolla for Japan. The typical comparison vehicles were chosen for their significant market share, model size, and representation of different vehicle types. The annual ownership cost for the vehicles mentioned is calculated using the following parameters: annual tax and fee; annual maintenance; insurance; gasoline and electricity costs; and average annual mileage.

The vehicle tax and fee systems have changed over the time period. Therefore, for this study, the total cost of ownership is considered only for the model year 2022. In Japan, three distinct taxes must be paid: an acquisition fee based on the vehicle's Manufacturer Suggested Retail Price; a weight tax every two years; and an annual tax [118]. The annual tax and fee in Japan are paid differently for each type of vehicle, such as an average for conventional gasoline vehicles of $1078, average for hybrid vehicles of $315, and an average for electric vehicles of $315 [119].

The average annual maintenance cost for each vehicle type is different for each type of vehicle. Electric vehicles were found to be less expensive due to lower brake wear and fewer moving parts. Annual taxes and fees are $358 per year for traditional gasoline vehicles, $323 for hybrid vehicles, and $276 for electric vehicles, as explained in detail in [120].

In the case of car ownership costs, the annual fuel cost is usually the largest operating cost; therefore, it is important to use representative real-world driving fuel consumption. The average gasoline cost for a conventional gasoline vehicle (corolla) is calculated to be $663. As well, the annual gasoline cost for hybrid vehicles is $562 considered [120].

The insurance is mainly dependent on the vehicle model, condition, insurance company, and other factors. The Prius is classed as an average vehicle for insurance purposes [120].Therefore, the average comprehensive insurance cover is considered to adequately represent insurance costs for all vehicle types. Therefore, for this study, we assumed full insurance at an average cost of $1512 in 2022 for a Prius vehicle to adequately represent insurance costs for all vehicle types. [121].

The average annual travel distance of LDVs is 9120.3 km [122]. The fuel price and the fuel economy for each type of vehicle are used to calculate the gasoline cost. The average fuel economy for conventional gasoline vehicles is 17.2 km per liter, while hybrid vehicles average 20.3 km/L for model year 2022, and electric vehicles are considered the same as hybrid vehicles for this study. In addition, for model year 2030, conventional gasoline vehicles have an average fuel economy of 20.1 km/L, hybrid vehicles have an average of 25.4 km/L, and electric vehicles are considered the same as hybrid vehicles. For models 2022-2030, the fuel price is assumed to be constant for both model years at $1.25 per liter.

Since BEV vehicles do not use gasoline, the electricity cost is considered for the Nissan Leaf. The average annual electricity cost is dependent on the increased efficiency of the electric drive powertrain during urban or rural driving. Annual fuel costs are usually cheaper for BEVs and PHEVs depending on the percentage of driving in fully electric mode. The average efficiency of the Nissan Leaf is 164 Wh/km, and it can travel 6.1 kilometers at one kilowatt [123]. As well, the average annual travel distance is considered the same as a hybrid vehicle, which is 9120.3 km, and the average price of one kilowatt in Japan is $0.19. Based on these parameters, the average annual cost of electricity is $284.

The annual gasoline tax (20%) is calculated for each type of vehicle based on the average annual travel distance of LDVs of 9120 km, the 20% fuel price of $1.25, and the fuel economy for each vehicle type for the current flat-fee method.

The annual ownership cost is calculated for conventional gasoline, hybrid, and battery electric vehicles and compared for both model years 2022 and 2030 as illustrated in Figure 25 and Figure 26.

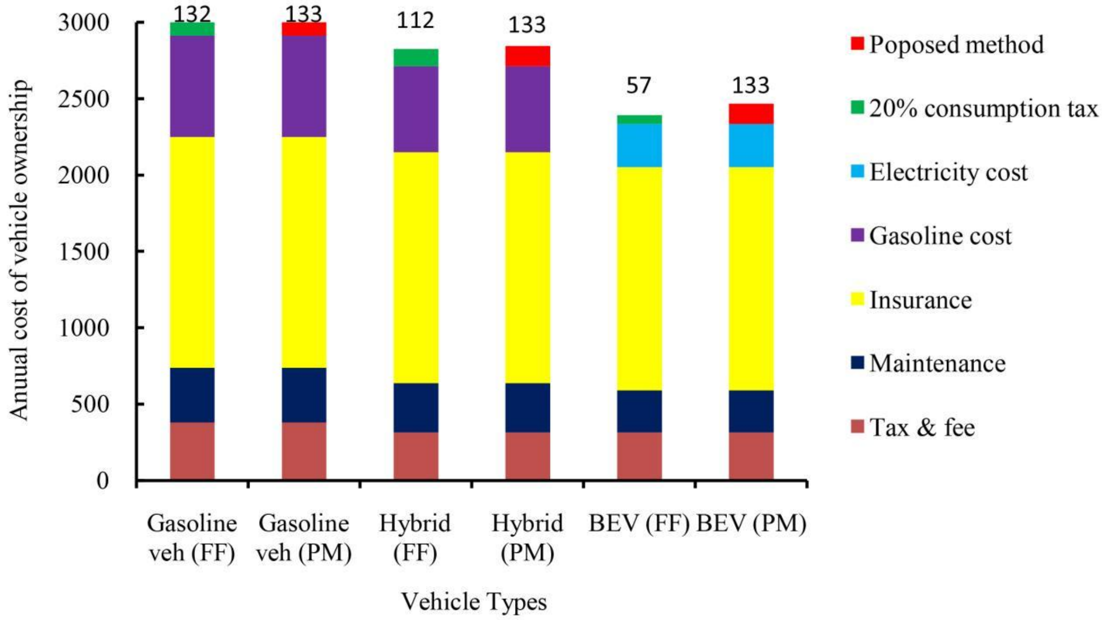

Figure 25. Annual usage cost of ownership in currant flat-fee and proposed method (PM) model year 2022.

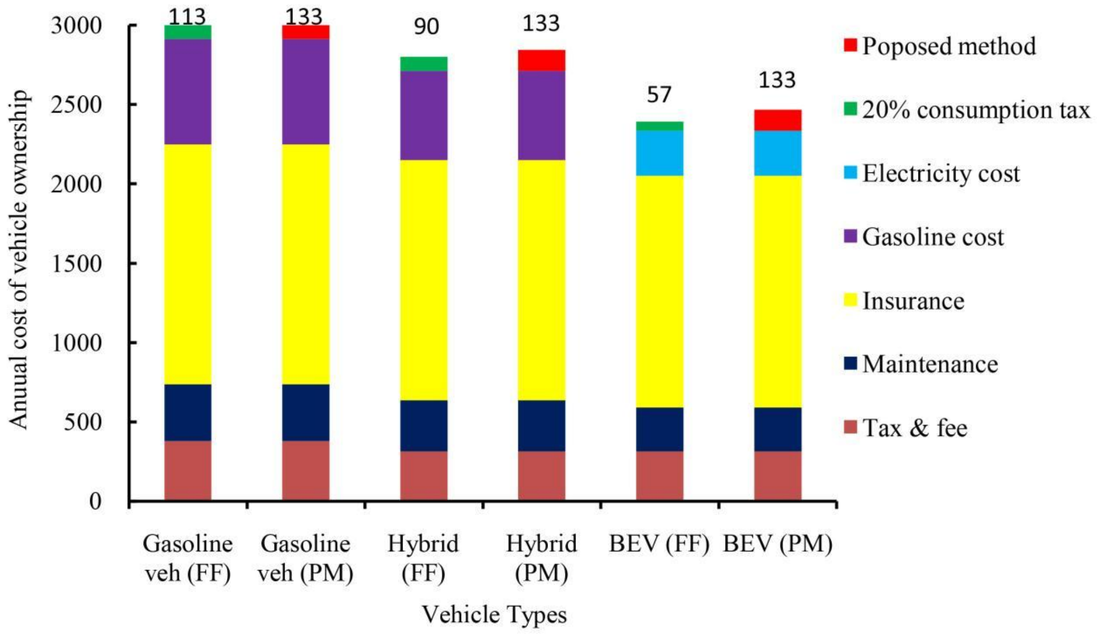

Figure 26. Annual usage cost of ownership in currant flat-fee (FF) and proposed method (PM) model year 2030.

CHAPTER - 4

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

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 novel gasoline tax collection method and highway toll-fee collection for CAV vehicles in platoons.

4.1 Overview of 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. [124], 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 MongoDB, 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 27.

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 27.

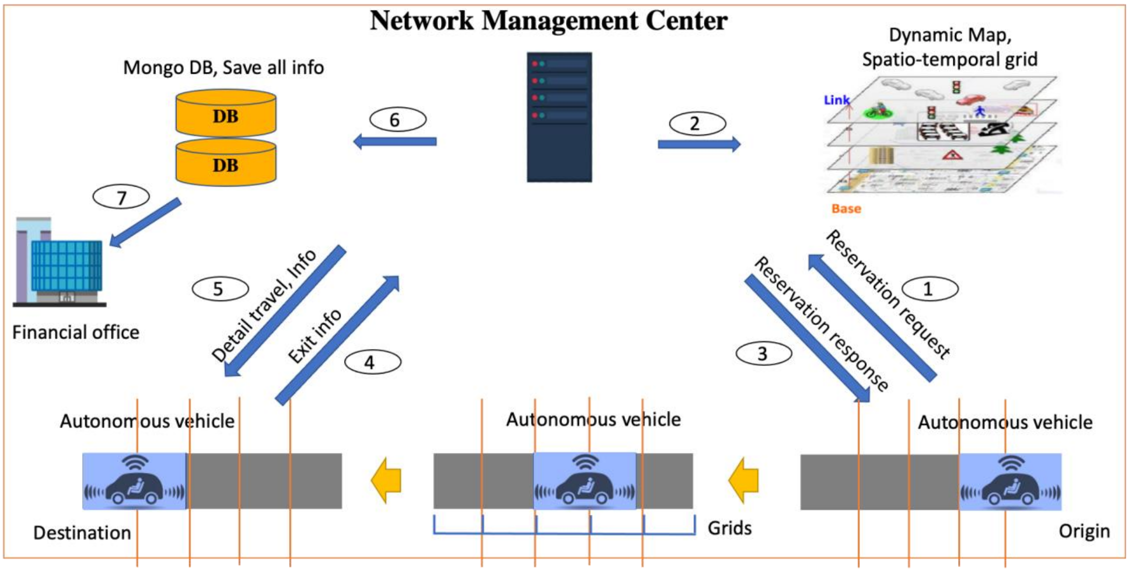

Figure 27. The proposed method sequence diagram

4.2 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 road environment is created by dividing a space equally into a spatio-temporal grid and defining independent cells. Figure 28 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.

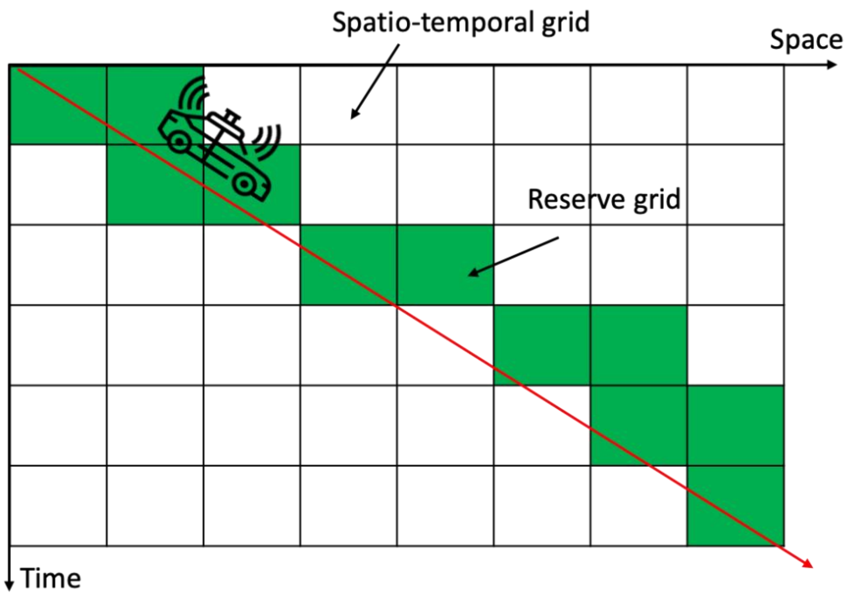

Figure 28. Structure architecture of reserving grid-based charging method.

To manage the reservation process accurately, the CAVs' 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 de-parture 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 29. The server creates a database 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.

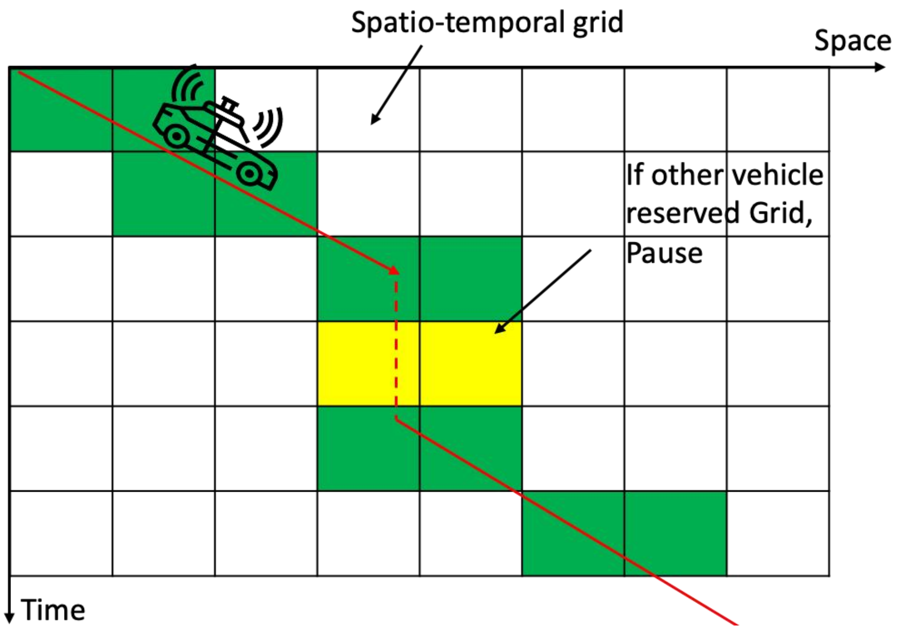

Figure 29. If the grid is reserved for another vehicle, pause, and call back method.

4.3 Road charging method

Road pricing is currently represented by fixed charges for road usage, such as time-based or distance-based charges, toll road congestion charges, and taxes on particular types of vehicles (such as polluting cars), 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.

4.4 Highway toll-fee charging mechanism based on the grid/millisecond

As shown in Figure 30, 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.

```
'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 30. Description example of spatio-temporal grid and assigning charges.

The designated grid-based charging toll fee is calculated based on the fuel 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. 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 31.

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.

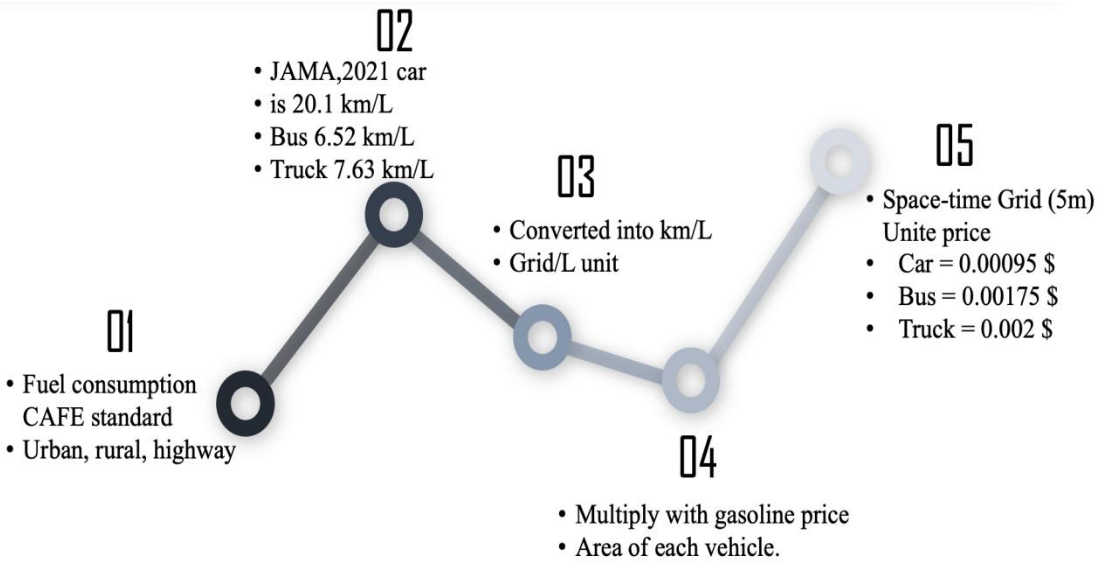

Figure 31. The toll fee conversion to grid (5 m)/millisecond for each vehicle type.

4.5 Proposed Method Implementation

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

4.5.1 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 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.

Table 9. 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	2.4GHz Intel Core i5
Memory	8 GB

4.5.2 Overview of API and Post Method

Figure 32 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 32.

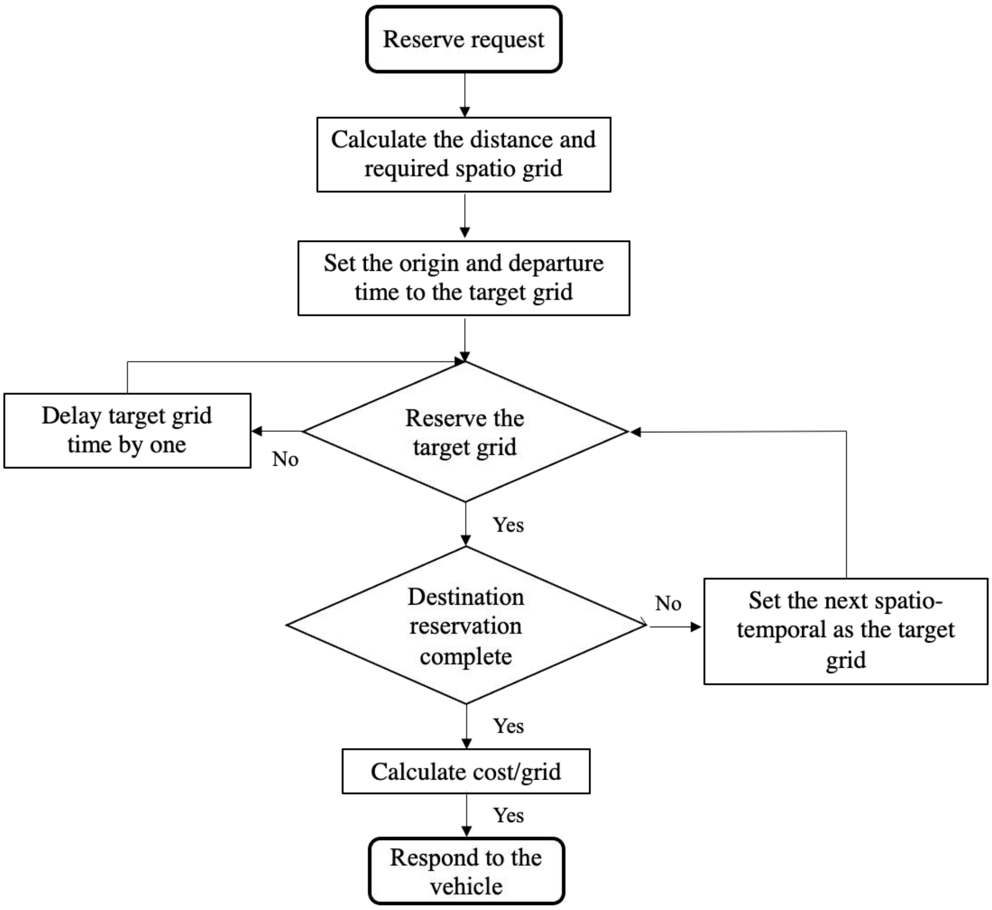

Figure 32. Flow chart of grid reservation and assigning cost processing of network management server.

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 33.

Figure 33. Description example of spatio-temporal grid reservation.

4.5.3 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 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 34 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.

4.5.4 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 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 34.

```
_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 34. Description example of storing data in MongoDB.

4.6 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.

4.6.1 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 35 shows the load test results, which include the average, maximum, and standard deviation of response times for each number of requests.

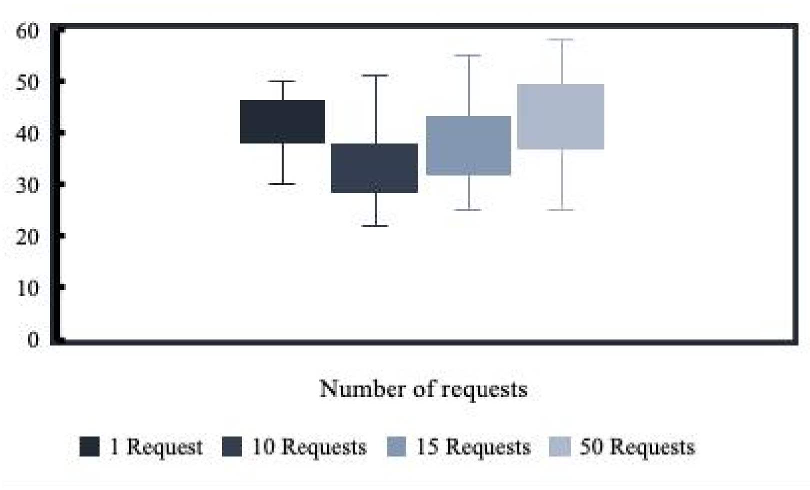

Figure 35. Measurement of required times for requests and responses.

4.6.2 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 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.

Table 10. 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

4.6.3 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 36.

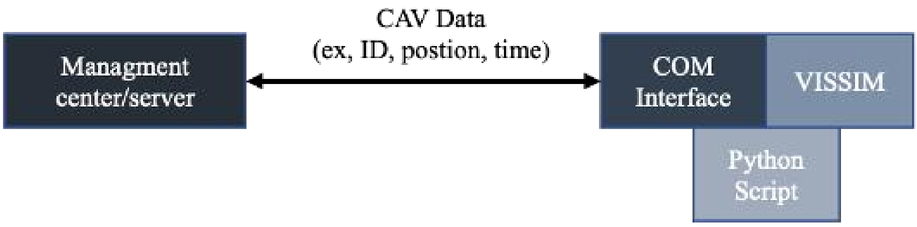

Figure 36. Configuration of PTV VISSIM 11.

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 37.


```
_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 37. Description example of invoice to billing center.

4.7 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 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.

4.7.1 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 [125]. 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 38. 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 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 [126].

Table 11. 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	2.8 m/ Sec^2

4.7.2 Simulation of travel time and number of platoons for proposed method

We create three scenarios, such as those for the proposed method, the ETC method, and the combination of freeway roads and ETC. The first scenario is the proposed method. If the platoon uses the proposed method, such as paying the highway toll collection by a grid-based charging system, for which a toll gate is not required, the platoon can reserve the grid and route in advance and pay the highway tax through the system. The average time of a vehicle traveling in a certain section which is one km for this study, is denoted as a travel time, which is measured by subtracting the starting time of the origin position from the destination position. in the Figure 38. The dark blue represents the platoon leader, and the light blue represents a platoon member. Following the mentioned parameter sittings, the simulation ran for one hour, and the travel time was obtained for various vehicle inputs, and travel time and platoon number were measured. The script file 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 sizes 2 type, 3, 4, and 5 are documented. Based on these parameters, we run the simulation and measure the travel time and number of platoons.

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 (Fig. 42). 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 (Fig 44).

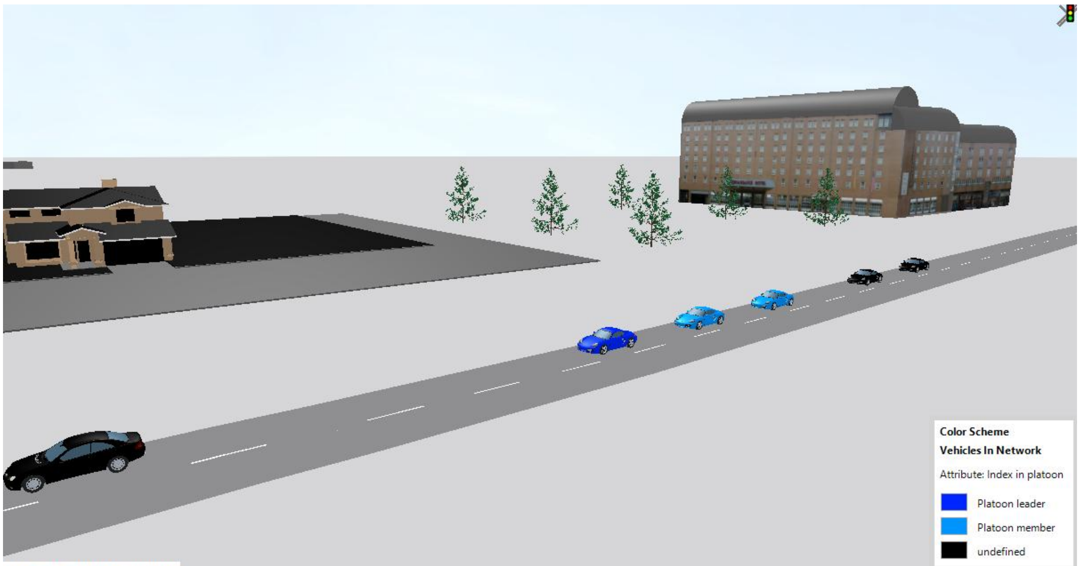

Figure 38. Execution screen of VISSIM simulation for toll collection for platoons in the proposed method.

4.7.3 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 39. 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 the 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.
- The default deceleration setting is 20 km/hr 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.

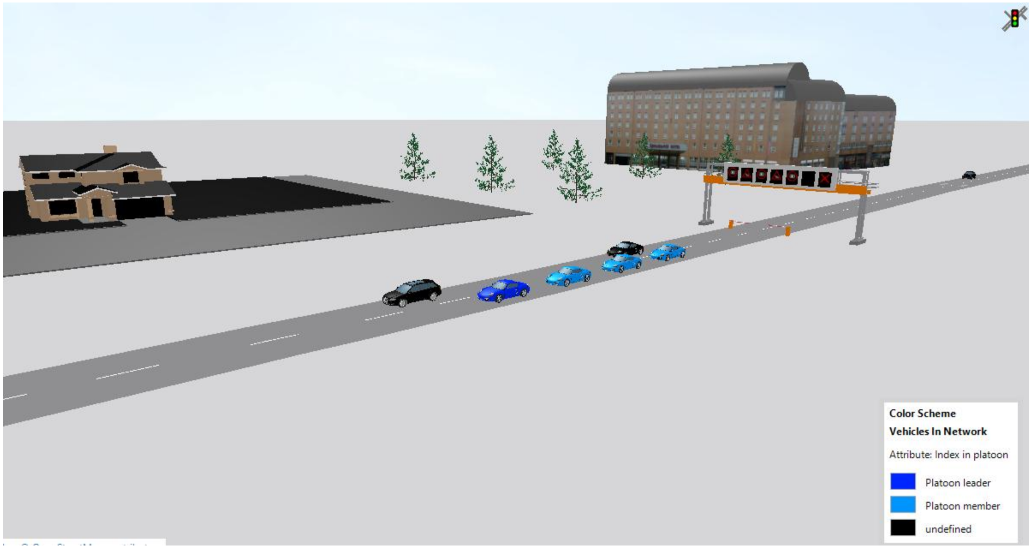

Figure 39. Execution screen of VISSIM simulation for toll collection for platoons in the proposed method.

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 compared to the proposed method (Fig. 42). 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 (Fig 43).

4.7.4 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 40. 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.

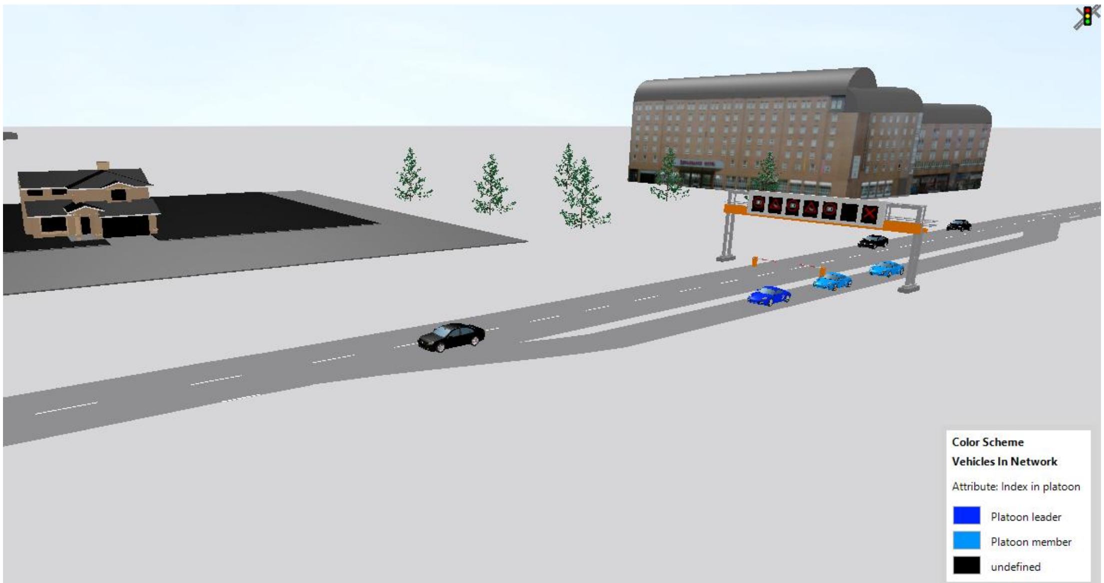

Figure 40. Execution screen of VISSIM simulation for toll collection of platoons in the ETC and freeway road lane.

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 (Fig. 42). 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 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 (Fig 43).

CHAPTER - 5

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 (Fig 35). 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.

We evaluate and compare the gasoline tax of a 500-vehicle sample for one kilometer as well as the annual ownership cost for both the proposed and current flat-fee methods. Table 5 and Table 6 demonstrate the grid-based charging system results, which show a 5.7 percent revenue increase for model year 2022 as well as 21.8 percent for model year 2030, as shown in Figure 41. Table 7 and Table 8, illustrate the gasoline tax revenue of 500 vehicle samples in one kilometer. The result shows that since the electric vehicles are not paying the gasoline tax as well as the hybrid vehicles are paying less tax, the total revenue decreased compared to model years 2022 and 2030.

The proposed software platform is capable of taking gasoline taxes from any type of Automated vehicle based on its fuel consumption. We considered only the abovementioned types of vehicles to compare them with conventional gasoline tax collection methods such as the flat fee method. For this study, the grid-based charge fee is considered to be constant, and it is converted based on conventional gasoline vehicle fuel consumption. which applies to hybrids and BEVs as well. Thus, it will bring equity in road tax for all types of vehicles that are using the road, as well as increase the revenue per kilometer.

To better understand the tax burden for each type of vehicle for both methods, we investigate how the annual cost of ownership changes for each type of vehicle for both methods. We found that in model year 2022 the annual gasoline tax differences for conventional vehicles and hybrid vehicles were almost the same, a BEV $76 increase utilizing the proposed method as illustrated in Figure 25. Furthermore, using the proposed method, the annual gasoline tax differences for conventional vehicles are $20, hybrid vehicles are $43, and BEVs are $76 in model year 2030, as illustrated in Figure 26. Since in the proposed method (PM), grid-based charging units are considered constant for conventional, hybrid, and BEV vehicles in both model years 2022 and 2030. Thus, the gasoline tax revenue will increase by 5.7% and 21.8% in 2020 and 2030, respectively, over that gained by the flat fee method (FFM).

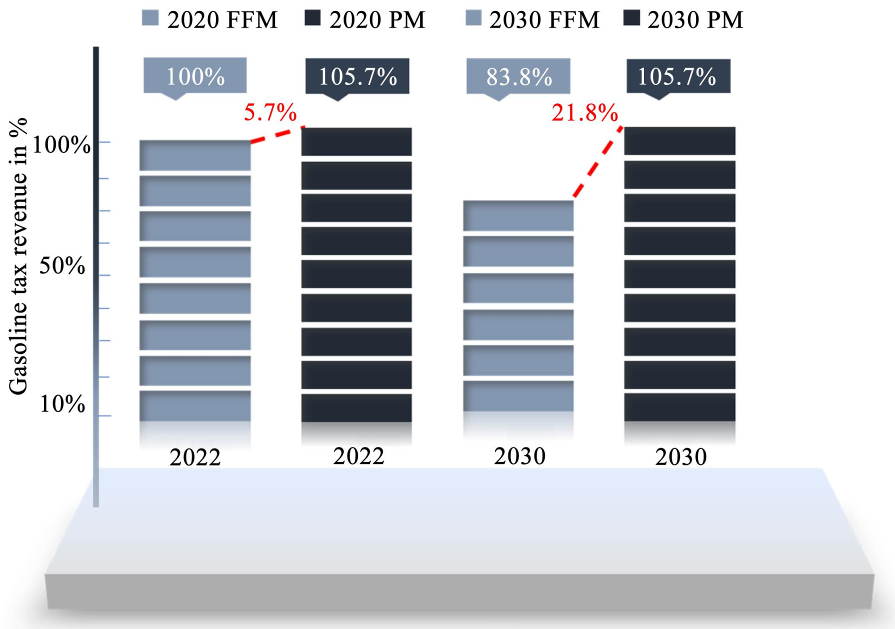

Figure 41. The comparison of total tax revenue for the proposed and flat-fee methods in model years 2022 and 2030.

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 toll 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 42 shows the average travel time for the three scenarios; as the number of vehicles increases, the travel time increases directly proportionally.

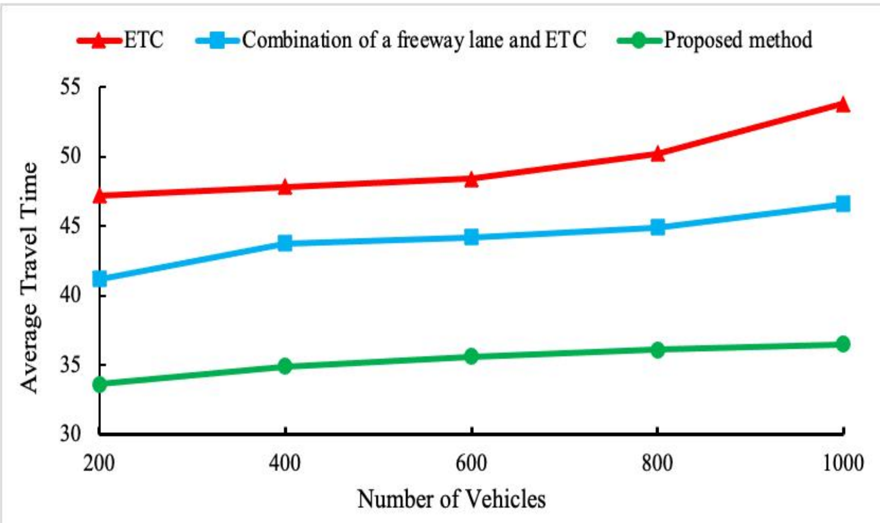

Figure 42. Average travel time for proposed, ETC, and Combination of ETC and free-way road lane.

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 43 and Figure 44.

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 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.

ETC Method	Combination Method	Proposed Method
Total Generated # Platoon = 29	Total Generated # Platoon = 21	Total Generated # Platoon = 16
Platoon size 2 = 16	Platoon size 2 = 14	Platoon size 2 = 12
Platoon Size 3 = 6	Platoon Size 3 = 4	Platoon Size 3 = 3
Platoon Size 4 = 4	Platoon Size 4 = 2	Platoon Size 4 = 1
Platoon Size 5 = 3	Platoon Size 5 = 1	Platoon Size 5 = 0

Figure 43. Shows the result of platoon measurements.

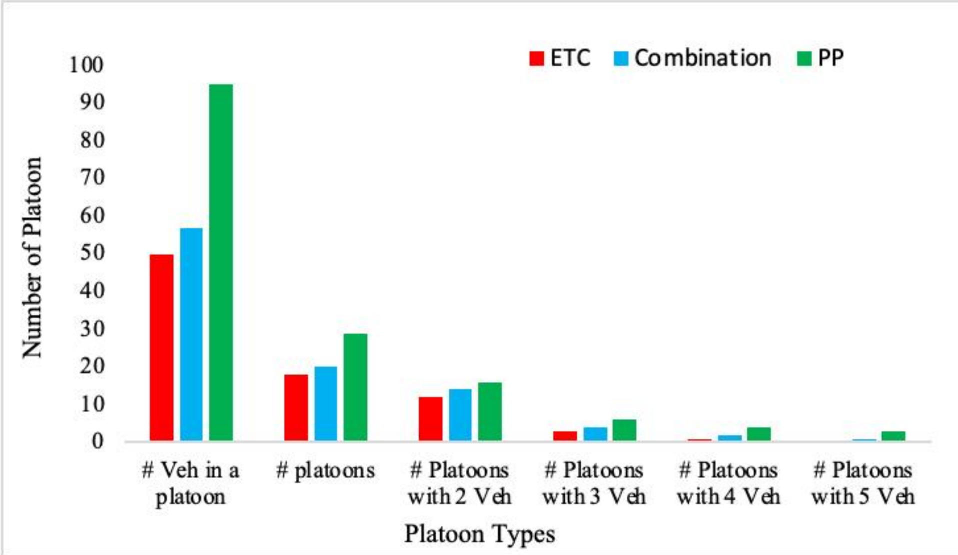

Figure 44. The comparison of the number of generated platoons for different types of platoons.

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.

CHAPTER - 6

Conclusion and Future Work.

The short summary of this study is illustrated in Figure 45. We investigated a novel grid-based toll charge collection mechanism as an alternative to the present ETC toll gate method for collecting toll 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, route, and collects toll tax from the CAV vehicle in a platoon. The load test result reveals that the response time was less than 48 milli-seconds for communication.

We tested and validated that our proposed method accurately generates revenue from all types of vehicles. Each time the vehicle travels, the vehicle user could audit in detail his travel and tax information to maintain privacy. The total gasoline tax revenue is supposed to increase by 5.7% and 21.8% in 2020 and 2030, respectively, over that gained by the flat fee method (FFM). Furthermore, the annual ownership cost difference between the proposed and flat-fee methods is not high. Therefore, the proposed method is capable of providing sustainability and guaranteeing long-term alternative gasoline tax revenue.

The evaluation results for highway toll collection from the CAV platoon 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 opportunistic platoons on the highway.

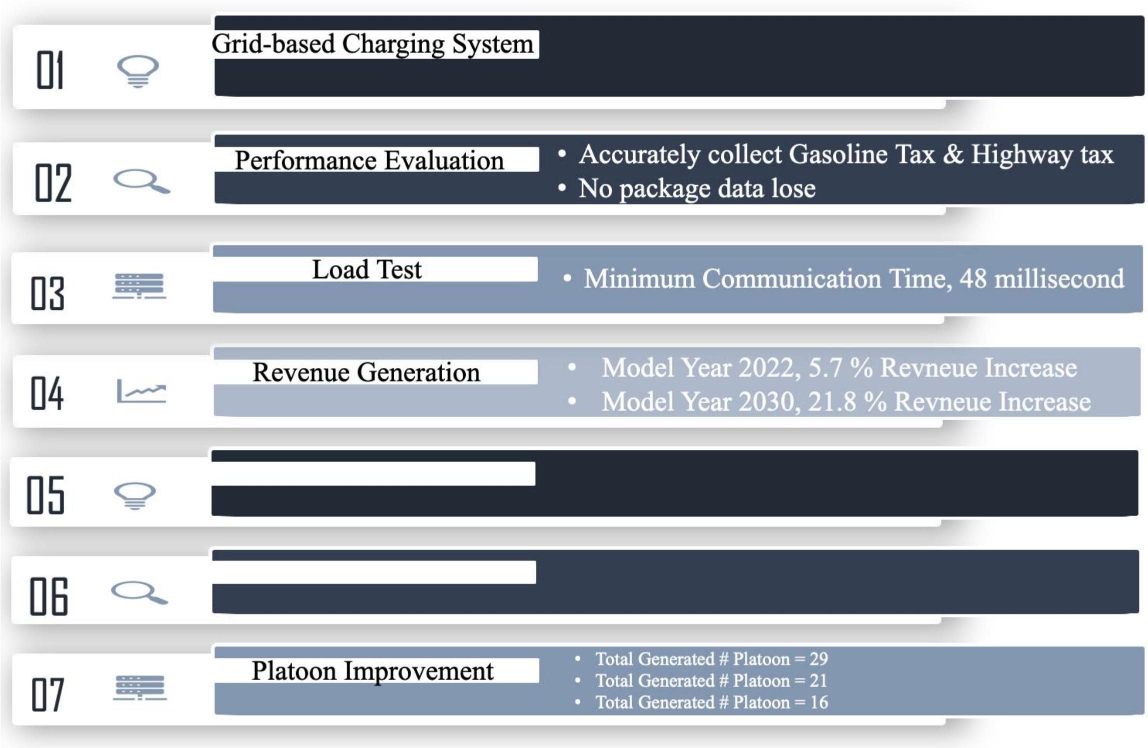

Figure 45. Shows the short summary of this study.

Since the proposed method is implemented based on reservation role, 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. which will reduce and manage traffic congestion as well as increase revenue for road usage. For the future work, since the new method is based on a reservation system that will provide assistance to emergency vehicles in traveling to their destinations on time. The revenue could be generated by collecting tax fees from emergency vehicles as well, which would increase the total revenue. As well, it is important to investigate further the scalability of the proposed method in terms of implementing it in a real environment. Because the proposed method's structure and architecture are developed in a dynamic map, how to prioritize emergency road lanes should be investigated further. In addition, to improve the safety of ramp meters on highways, it is possible to reserve the grid at the entry and exit of highways.

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