Micro-Road-Pricing for Highway Toll Collection with Reserving Spatio-Temporal Grid in the Era of Automated Vehicles

Babakarkhail Habibullah[1], Kenya Sato[2]

[1]Department of Information Science and Technology, Graduate School of Engineering, Doshisha University, Kyoto, Japan.

[2]Network Information System Laboratory, Doshisha University, Kyoto, Japan.

Abstract

This work proposes a novel micro-road pricing alternative method to replace the current highway toll collection method by providing a software architecture platform. In this platform, the automated vehicle reserves (virtual) spatio-temporal sections on the road in real-time for road pricing. Time and space are divided into grids and assigned a designated charge to a grid managed on a dynamic map. An automated vehicle reserves the planned travel route and time in advance and mediates based on the reservation information. The performance evaluation results show that the system reserves the requested grid, routes, and collects the highway tax charges with minimum communication time and no data package loss. At moderate traffic volumes on the highway, it reduces travel time more than conventional tollgate systems. Consequently, our proposed system's travel time improvements will reduce congestion by more effectively exploiting road capacity while generating highway toll tax collection from all types of vehicles.

Introduction

Toll fee collections are required for expansion, operating, and maintenance purposes of highways. Toll fees were traditionally collected manually at designated toll gates on highways, bridges, and tunnels using cash or cards [1]. Presently, the highway network has been established utilizing manual, semi-automatic, and automatic toll collecting systems [2]. Which has several drawbacks, including each vehicle having to stop or reduce speed to pay at a tollbooth, causing congestion and increasing travel time [3]. Therefore, the old toll collection systems can no longer meet the demands of expanding highways in today's high-tech mobility. Therefore, a modern system in the era of automated vehicles is needed to address current needs and challenges.

- A new method in the smart mobility era is required to collect toll tax and increase the usage capacity of highways.

Table 1. Summary of Road pricing Options and Comparsing

Type	Description	Equipment costs	Operating cost	User inconvenience	Price Adjustability	Aquracy	User Auditability
Pass	Drivers must perchase a ticket to enter tollgate	Low	Low	Medium	Low	Medium	Low
Toll booths	Drivers stop and pay at tollgate	High	High	High	Medium to high	Medium	Medium
Electronic tolling	An electronic system in each vehicle bills user as they pass a point in the road	High	Medium	Low	High	Low-Medium	Low-Medium
Optical vehicle recognition	An optical system bills vehicle users as they pass a point in road	High	Medium	Low	High	Medium	Low
GPS	GPS is used to track vehicle location. Data are automatically transmitted to a central computer that bills users.	High	Medium	Low	High	Medium-High	Low-Medium
Proposed Method	Network operating center is created which is consists of server, user, and billing center. Each vehicle reserve thr route and pay toll fee.	Medium	Low	Low	High	Medium-High	High

Methodology

1) PROPOSED METHOD STRUCTURE

- System configuration of the dynamic map platform is created which consists of the Network operating center/server, viewer or user, and billing center.

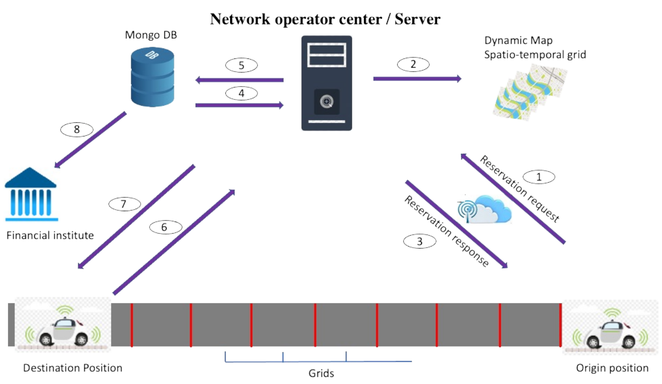


Figure 1. Sequence diagram of proposed method

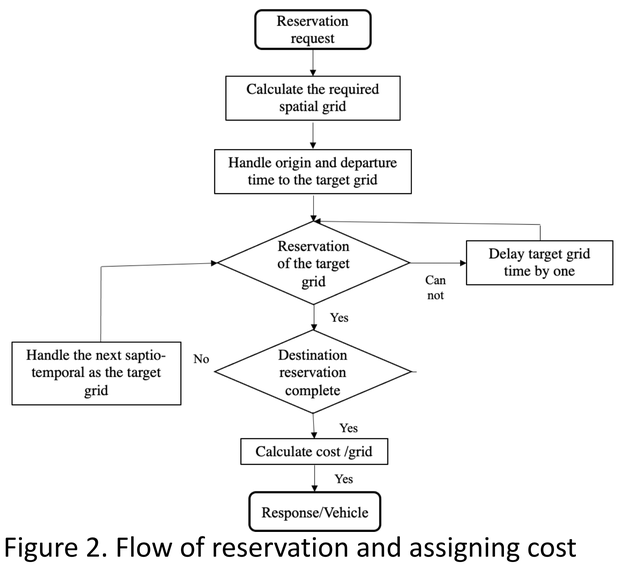


Figure 2. Flow of reservation and assigning cost to grid

- Time and space divided into grid and assigned designated charges.

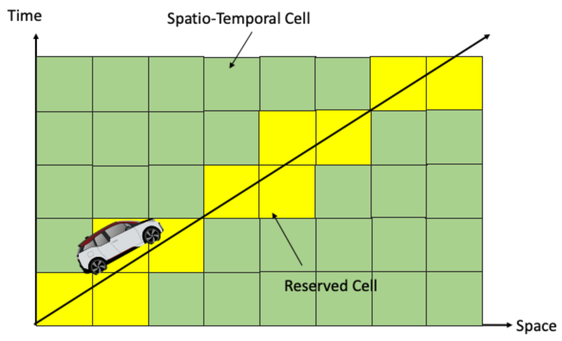


Figure 3. Spatio-temporal section, grid reservation.

- In case of cell to be reserved is occupied by another vehicle. Server responds to the vehicle to pause and call back the request.

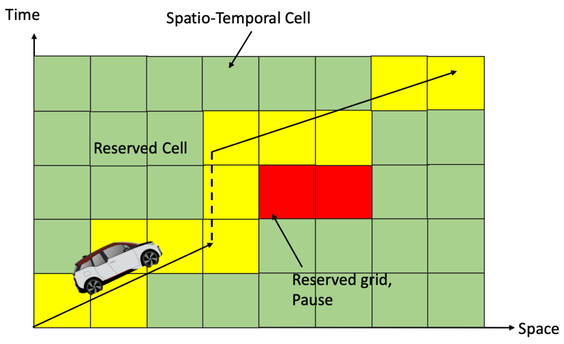


Figure 4. Grid reserved by another vehicle

2) SIMULATION

Table 2. Implementation environment

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	Real traffic environment simulation

Figure 5. Configuration of VISSIM with network operating center

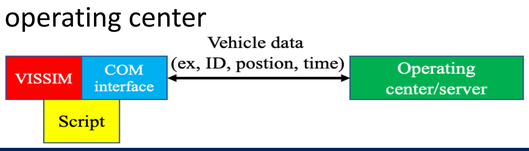


Figure 6. Execution screen of simulation for ERP1.

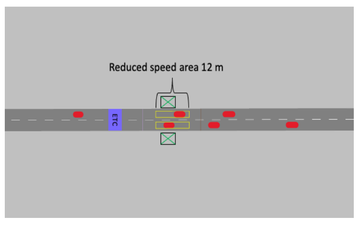
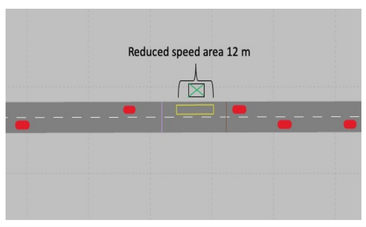


Figure 7. Execution screen of simulation for ERP2.



3) EVALUATION

- Create a one-km straight road environment in Vissim.
- Two scenarios, the current conventional method and the proposed method.
- Toll conversion for model years 2022 and 2023 based on fuel consumption to distance based.

Table 3. Simulation setting in VISSIM

Parameters	Setting
Speed limit	60 km/h
Number of Veh	100-500 Veh/h
Passenger Veh 2020-2025	98.4-94 % = 492-470 veh
Electric Veh 2020-2025	1.6-6 % = 8-30 veh
Lane width	3.5 m
Measurment time	1 hour
Number of measurment	10 time
Measurment section	1000 m
TTC	5.0 s

Table 4. Convert the gasoline tax charges rate to grid (5 m)/millisecond for two vehicle types.

No	Vehicle Type	Flat fee method, Veh fuel consumption Km/L	20 % tax of Gasolin price $	Each type veh % in 500 veh	Total revenue for each type of veh in $
1	Passenger car	0.05	0.25	98.4% = 492	6.15
2	Electric car	0	0	1.6% = 8	0
3	Total	0.05	0.25	492	6.15

Table 5. Convert the distance-based toll charges rate to grid (5 m)/millisecond for two vehicle types.

No	Vehicle Type	grid-time unite grid/L	20 % tax of Gasolin price $	Each type Veh % in 500 veh	Total revenue for each type of veh in $
1	Passenger car	0.00025*200	0.25	492	6.15
2	Electric car	0.00025*200	0.25	8	0.1
3	Total	0.05	0.25	500	6.25

A Simulation of travel time for the proposed method

PTV VISSIM supports the COM interface, used to utilize the environment for a cooperative automated vehicle that communicates with the networking operator center/server for reservation and toll collection.

B Comparison with conventional methods (ERP1 and ERP2)

- We assumed a tollgate along the road in a 500-m location
- With specific parameters and conditions.
- ETC payment method relies on dedicated short-range communication and electronic equipment in vehicles to maintain the collection of highway taxes or road user charges.

Results & Future Work

a) PROPOSED METHOD PERFORMANCE EVALTION RESULT

✔ Micro road pricing based on grid reservation system had been succesfuly established

- Each travel time vehicle owner have the ability to audit detailed travel information and toll tax information


```
_id: ObjectId("603c9371c11ff58dea0df450")
sid: 5
date: 2021-03-05T07:11:03.991+00:00
destination: Object
   lat: 34.82152
   lng: 135.67814
origin: Object
   lat: 34.81508
   lng: 135.67048
vehicleType: "100"
travel_distance: 1000.8789265294216
tax: Object
   gasTax: 0.2502197316323554
total_cost: 0.2502197316323554
```


- Requested spatio-temporal grid reservation


```
_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")
```


- Privacy have been maintaine


```
_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
```


b) TRAVEL TIME, PROPOSED AND ERP1 and ERP2 RESULTS

To mediate driving on a one-kilometer

- PM, an average of 64 seconds
- ERP1,an average 71.8 seconds
- ERP2, an average 66.5 seconds

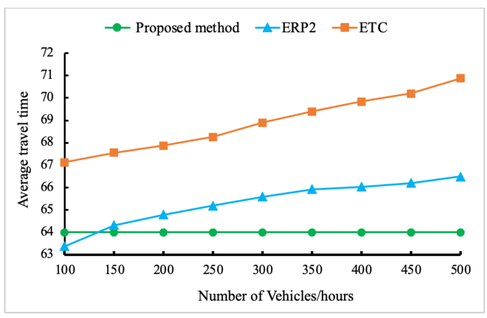


Fig. 8. Average travel time, proposed method, ERP2, ERP1.

Future work

- It is possible to reserve the route in a time frame according to the traffic demand by using a pricing-based control charging system over the traffic density to reduce traffic congestion.
- Since the new method is based on a reservation system, it 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.

Conclusion

- Using a software platform, the proposed micro road pricing system as an alternative method to replace the current highway toll collection method has been established.
- Space and time are divided into grids where the designated cost is assigned based on the fuel consumption values for each type of vehicle and managed on a dynamic map.
- At moderate traffic volumes on a highway, it reduces travel time more than conventional tollgate systems.

References

[I] S. Song, "On the Highway Toll Collection System", [J). Northern Traffic, vol.6, 2007, pp. 164-166.

[2] S Chen. "Jian Province Digital Highway Unified Data Center Planning and Design". Transportation Information Industry in China. vol.l, 2008, . 109-112.

[3] Z. Liu, L. Cheng. "The General Study of Electronic Toll Collection (ETC)", [J). Technology Innovation Newspaper, Vol.ll, 2008.