Highway Reservation System: Models, Simulations, and Implementation Discussions

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ABSTRACT

Learning from the success of reservation systems in industries including airlines and hotel, a highway reservation concept has been considered by transportation engineers. In the reservation system, people are not allowed to access the highways whenever and wherever they want, instead they need to reserve a spot in advance to use some highway segments within a certain amount of time. This dissertation includes a feasibility study of the highway reservation system and its findings, the evaluation of benefits, the implementation challenges, the supporting technology, and a consideration of time of value and social equity issues. The dissertation contains four papers about different aspects of the highway reservation system from chapter 2 to chapter 5, and a discussion of implementation challenges in chapter 6.

Chapter 2 is a mathematical optimization model that finds the reservation (trip scheduling) plan that minimizes the total system cost. This paper endorses the concept of imposing a capacity constraint to the highway usage by the reservation system. Chapter 3 adopted a microscopic traffic simulator (VISSIM) to conduct a proof-of-concept study, and investigated the potential benefits. The reservation scenario outperformed the baseline in terms of Vehicle-Hours-Traveled and emissions. Chapter 4 explored an auction-based implementation of the highway reservation system, using an agent-based simulation technique. Chapter 5 deals with the communication reliability of the Connected Vehicles technology, as the whole reservation system will be built on reliable Vehicle-2-Infrastructure, Infrastructure-2-Vehicle, and Vehicle-2-Vehicle communications.

This is the first systematic and comprehensive study of highway reservation system, laying a solid foundation for more detailed research over different aspects and a potential implementation.

CONTENTS

CHAPTER 1

INTRODUCTION

Motivation

Urban road networks are severely congested with economic development, resulting in increased travel times, air pollution, noise, and traffic crashes. As shown by the National Congestion Measures between 1982 and 2011, provided by the 2012 Urban Mobility Report [1], congestion has increased substantially over the 30 years, and is “recovering” from the economic recession during 2009. The delay per commuter in 2011 is 38 hours, which is equivalent to 5 days of vacation per year. Adding more capacity by providing more road lanes and more public transportation is the most fundamental congestion solution in most growing urban regions to satisfy the increasing travel demand. However, road capacity almost always increases in a slower rate than the demand growth. As shown by the Road Growth and Mobility Level Exhibit [1] (**Figure 1**), 56 in 101 study areas have travel demand growth 30% faster than supply, and only 17 areas have a less than 10% gap between demand and supply growth. Furthermore, accidents or work zones may create bottlenecks on the road and seriously downgrade the road capacity. It is not economically justified and hardly possible to satisfy the increasing peak hour demand. An economical way is leveling the time fluctuation of traffic demand in order to decrease the imbalance between road capacity and traffic demand during the peak-hours.

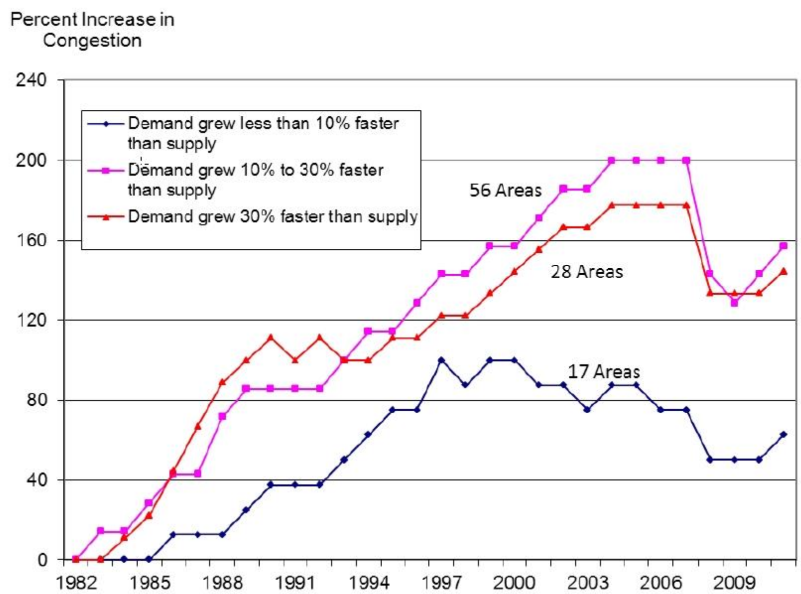

Figure 1 Road Growth and Mobility Level Exhibit

The highway system has been operated as a queuing system from the day it emerged, in which drivers enter the road based on a First-Come-First-Serve (FCFS) rule. On the other hand, reservation has been deployed in many service systems such as hospital, hotel, and airline, in which customers share resources. According to a study conducted by McGinley et al. [2], at the profitable point of a service system, if the waiting time is large or the blocking probability is high, a reservation time could help reduce the waiting time. The highway system satisfies both of these two conditions. Highway system has variable demand over time and limited supply. Adding new capacity is quite expensive, but the marginal cost is negligible. Thus as a service system, highway system could potentially benefit from being operated by reservations. That's why this study brings the highway reservation concept. It discusses the basic ideas of the proposed highway reservation system and potential implementation issues, develops an analytical optimization model to find the potential benefits, and applies an agent-based simulation technique to test the system.

Brief Idea of Highway Reservation System

The philosophy of the proposed highway reservation system is that the commuters are willing to change the trip plan, say leaving home one or two hours earlier, to avoid the peak hour congestions on the highway. From economist's view [3], it means the travel time has higher cost than the same amount of time spent at home or workplace. This assumption is realistic as people can work or entertain at home or workplace, while being jammed on highway is not an enjoyable experience.

The basic idea of the highway reservation is that all road users need to reserve certain road segments for certain amount of time in advance. The reservation center determines a predefined control speed and a capacity constraint. The users know that all the vehicles will be operated to travel at the predefined control speed. Then they can decide which time interval they need to reserve based on their desired arrival time and the predefined control speed. A reservation center is in charge of dealing with all these trip bookings. It needs to decide whether to accept or reject a booking request, based on certain rules, such as FCFS, or Higher-Pay-Earlier-Serve. The reservation center may provide the rejected users with alternative options. The rejected users can also ignore the suggestions, but instead submit a new request based on his/her schedule flexibility. The capacity constraint guarantees that there will never be oversaturated flows on the roads, and thus the users with valid permission will travel at the predefined control speed.

Highway resource does not have clearly defined boundaries, like seats on an airplane. To solve this problem, the highway capacity is sliced in two dimensions: spatial and temporal. By space, the highway is separated by on- and off-ramps into multiple segments. By time, the capacity of each segment is sliced into equal-sized time intervals, like five minutes. The total amount of vehicles allowed into a segment in an interval should not exceed the capacity of that interval. Note that these vehicles might include those from an upstream segment. That means the vehicles on the reserved highway segments need to travel at the predefined control speed, since any delay will accumulate and jeopardize all the following reserved trips. Thus a speed maintaining algorithm is need for the proper functioning of the reservation system.

The proposed highway reservation will designate some lanes on the highway as "reserved lanes." The number of reserved lanes may be decided by the demand level, or user participation rate. At least one lane should be general-purpose and open to public. On a two-lane freeway, it means reserving the left lane, and the opted-out users can use the right lane. The vehicles on the general purpose lane can make on-the-fly reservations for immediate access to the reserved lane. The predefined control speed of the reserved lane should vary by weather, road geometry condition, and demand level. Since slightly reducing the operational speed can increase the throughout, the predefined control speed could be set to be lower, such as 50 mph during peak hour. Doing this brings two benefits: higher throughput, and easier lane change from general-purpose lane to the reserved lane, as the reserved lane could be much faster than the general-purpose lane.

The highway reservation system is different from the current traffic management strategies in that it does not monitor and control traffic at the aggregate level, but it operates individual vehicles. It is based on real time Vehicle-to-Vehicle, Vehicle-to-Infrastructure and Infrastructure-to-Vehicle communications, which enable reservation message collection and centralized operations on individual vehicles. For example, speed advisories will be sent from the reservation center to the vehicles through Infrastructure-to-Vehicle channel. Lane changing assistance system needs real time Vehicle-to-Vehicle communication to direct the upstream cars on the reserved lane to decelerate, to create a gap for a car to merge in from the general-purpose lane.

Introduction of the Four Papers in the Dissertation

Chapter 2 is a mathematical optimization model that finds the reservation (trip scheduling) plan that minimizes the total system cost. The system cost is a combination of travel time cost and early/late arrival cost. The model used a Vickrey's bottleneck model to propagate the trips through the traffic network. Although there is no constraint over the maximum number of vehicles allowed into a highway segment within a time interval, there were no oversaturated flows on any links in the optimal result, and the peak hour demand spread over a long time window. This finding endorses the concept the highway reservation that imposes a capacity constraint to the highway usage. Also in the case studies, the total system cost of the reservation system reduced by 19% and 24% comparing with the corresponding user equilibrium trip scheduling.

Chapter 3 adopted a microscopic traffic simulator (VISSIM) to conduct a proof-of-concept study, and investigated the potential benefits. In the baseline, the departure time of the users randomly distributed within one hour and they all tried to use the highway. In the reservation scenario, these users had the same departure time but made reservations for that departure time. These reservation requests were submitted in a random sequence and handled based on a First-Come-First-Serve (FCFS) rule. The reservation scenario outperformed the baseline in terms of Vehicle-Hours-Traveled and emissions. When travel demand is 30% higher than capacity, the total delay time is 58.6% less and CO_2 emissions is 18.3% less in the reservation scenario.

Both Chapter 2 and Chapter 3 are based on some assumptions of the users' characteristics and behaviors. Chapter 3's reservation system is free to use and the requests are handled based on a FCFS rule. Since the commuters will be the major users and they know their desired time interval ahead of time, they will be likely to submit the request as early as possible, or right after the system opens. Being late by a few milliseconds in that rush could mean losing an interval, which is clearly not how the reservation system should work. Chapter 2 is based on the assumption of all the users having the same value of time and 100% compliance rate with the scheduled trip plan, which do not hold in real life. So Chapter 4 explored an auction-based implementation of the highway reservation system, using an agent-based simulation technique. The FCFS rule becomes Higher-Bid-Earlier-Serve, and people with higher value of time would normally bid higher. All the limitations mentioned above are solved by the auction-based rule. It can transfer more consumer surplus to the reserved lane operator to help them generate more revenue. The users consider it as buying "insurance" of a congestion-free traffic.

Chapter 5 deals with the communication reliability of the Connected Vehicles technology, as the whole reservation system will be built on reliable Vehicle-2-Infrastructure, Infrastructure-2-Vehicle, and Vehicle-2-Vehicle communications. Previous research efforts focused on the Connected Vehicle technology applications typically assume perfect communications. However, a few studies pointed out that the wireless communications experience packet drops, which might lead to a serious downgrade of the real-time Connected Vehicle applications. Chapter 5 is the calibration of an NCTUns simulator to replicate the real world vehicular communication environments using field test data. Physical layer parameters (e.g., data rate and transmission power) and channel models are calibrated. The calibrated simulator provides a tool to evaluate the Connected Vehicle applications under unreliable communications.

CHAPTER 1 REFERENCES

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CHAPTER 2

ANALYTICAL MODELING OF A HIGHWAY RESERVATION SYSTEM: AN INTEGRATED TRAFFIC MANAGEMENT APPROACH

ANALYTICAL MODELING OF A HIGHWAY RESERVATION SYSTEM: AN INTEGRATED TRAFFIC MANAGEMENT APPROACH

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ABSTRACT

Inspired by the success of reservation systems in industries such as airlines and hotel and the vehicular communications supporting Connected Vehicle technology, transportation researchers have demonstrated potential benefits of a highway reservation concept. Under the highway reservation system, travelers need to reserve in advance for the right of using some highway segments during a predetermined amount of time. For a given link at a given time, the total number of open slots would be limited. If some time intervals have been fully booked, the users can choose a different but suitable time.

This paper presents a mathematical optimization formulation to solve the best trip scheduling plan for roadway reservation system for a traffic network with a given OD demand matrix. Vickrey's bottleneck model is used to estimate the link travel time. The system cost is quantified by the total monetary costs of travel time, early arrival time, and late arrival time. In the two numerical case studies, by assuming 100% compliance of the users to the reservation system's scheduling, the system cost was 24.1% and 21.7% lower than those of the two corresponding user equilibrium solutions. The major contribution of this paper to the research community is the formulation of the reservation system optimization algorithm and a demonstration of it improving system performance.

KEYWORDS

Highway reservation system, Rescheduling cost, Value of time, Optimization, Vickrey's bottleneck model

INTRODUCTION AND BACKGROUND

Metropolitan transportation road networks are typically congested due to concentrated travel activities and consequently faced with increased travel times, air pollution, noise, and traffic crashes. As shown by the National Congestion Measures between 1982 and 2011, provided by the 2012 Urban Mobility Report [1], congestion has increased substantially over the 30 years. The delay per commuter in 2011 was 38 hours, equivalent to 5 days of vacation per year. Adding more supply by providing more road lanes and more public transportation is the most fundamental congestion solution in most growing urban regions to satisfy the increasing travel demand. However, transportation system supply almost always increases in a slower rate than the demand growth. As shown by the Road Growth and Mobility Level Exhibit [1], 56 in 101 study areas have travel demand growth 30% faster than supply, and only 17 areas have a less than 10% gap between demand and supply growth. Even if the supply growth perfectly matches with travel demand, new problems would occur as reduction in congestion induces departure time shifts into peak-hour [2]. In addition, crashes or work zones may create bottlenecks on the highway and seriously downgrade the highway maximum throughput. While the Intelligent Transportation Systems helped mitigating the congestion impact by providing solutions to efficient use of highway systems, transportation system can benefit from a new innovative approach to address congestion problem.

The mismatch between demand and supply could potentially be solved by leveling off the traffic demand fluctuations by adopting a highway reservation concept [3, 4]. Travelers in such a reservation system need to book in advance for the right of using the highway segments during their desired time. If some time slots have been fully booked, additional travelers need to book an alternative time or route. A major difference between reserving airline seats and highway slots is that an airline seat is a well-defined object that is clearly identifiable, but a highway slot is difficult to define in practice. The travelers need to be shown the “edges” of a slot in time and space, and to be indicated of admittance into the system as well as being notified of violations. While existing transportation system is not likely to handle highway reservation system due to lack of real-time communications and computation power, the connected vehicle technology would make the highway reservation idea feasible.

A proof-of-concept simulation study was conducted to investigate the potential benefits of the highway reservation system [4]. If fully booked, the booking center recommends time intervals near the requested one, and the travelers choose which one to accept according to a predefined maximum amount. This algorithm was applied to a carefully designed microscopic simulation testbed, and the reservation scenario outperformed the baseline in terms of total delay time and emissions. However, this scheduling algorithm provides no guarantee of system level optimization of the reservation plans.

In this paper, an analytical scheduling algorithm, based on nonlinear optimization, is developed to solve the optimal trip plans. The remainder of the paper is organized as follows: LITERATURE REVIEW briefly discusses previous studies and concepts on highway reservation and departure time choice problem. HIGHWAY RESERVATION SYSTEM CONCEPT describes the concepts of the reservation system. LINK BOTTLENECK MODEL explains how the Vickrey’s bottleneck traffic flow model works. OPTIMIZATION MODEL describes the system objective and solution approach.

At last, NUMERICAL EXAMPLES shows how two case studies are solved by the proposed method as well as discussions, followed by CONCLUSIONS AND FUTURE RESEARCH.

LITERATURE REVIEW

Highway Reservation Studies

The concept of road reservation or trip-booking is mentioned in the literature as early as 1990s, but extensive modeling efforts have not been done till the recent 5 years. Some researchers conducted surveys to explore travelers' acceptance of the reservation system and its effectiveness [5, 6]. Akahane and Kuware [5] found if the participation compliance rate is 90%, a 15-minute adjustment of the departure time could eliminate congestion over single bottleneck. Kim and Kang [6] found that 73.4% of the respondents would participate in or accept if an expressway reservation system is implemented during South Korea's national holiday.

Wong [7], Iftode and Gerla et al. [8-10] pioneered the discussions of the basic functions, advantages and difficulties of a highway booking system. Wong suggested slicing the highway capacity into time intervals on which trip bookings are based. Iftode and Gerla et al. [8-10] proposed the coexistence of reserved lanes with general-purpose lanes, so that opted-out or rejected users can always use the general-purpose lanes. A merging/diverging assistance system is needed because of the lane separations.

Koolstra [11] was the first that brought the scheduling cost into the highway reservation system. They evaluated the queuing and scheduling costs with single bottleneck and heterogeneous travelers. They found all queuing costs can be eliminated without increasing the average rescheduling costs. Their study also supported that a freeway reservation might be more effective in practice than road pricing. And reservation system with variable booking fees is an option to incorporate the benefits of congestion pricing. McGinley et al. [12] showed, from the standpoint of queuing theory, that a reservation system is necessary to avoid waiting, when the average waiting time is large at the optimal point of operation. De Feijter et al. [13] stated that the objective of trip-booking is improving reliability and predictability of travel times, and his simulation experiments showed exactly so.

Edara and Teodorovic [3] took the lead in conducting extensive modeling work of reservation system by proposing a Highway Allocation System (HAS) and Highway Reservation System (HRS). HAS selects trips from received booking requests to maximize the total Passenger-Miles-Traveled over a period. HRS works in an on-line mode to decide whether a request should be accepted or rejected. Edara and Teodorovic [14] showed that HAS produced 35% to 45% more Passenger-Miles than the two ramp-metering algorithms. However, some shortcomings exist in their study. Using passenger-miles-traveled as objective is open to question. The HAS does not explicitly consider the scheduling cost.

Different from the idea of sliced highway capacity by time [7], Liu [15] proposed a token-based reservation idea. Each road segment has a set of tokens, and the number of tokens is the product of the segment length and critical density, or the total number of vehicles on the link at the maximum throughput. A reservation request is accepted only if at least one token on the requested segment is available, and the requested time slot does not overlap with any of the existing reserved time slots on this token. Greenshield's linear speed-density model is used in Liu's study, thus the optimal density is a half of jam density, and optimal speed is a half of free flow speed. Liu's work is a meaningful exploration of different ways of modeling the reservation system. The problem is that the amount of time needed for a trip on a token is difficult to determine, and the second shortcoming is the lack of a way to avoid too many tokens having overlapped time reserved, which means short-time excessive demand and congestion. These shortcomings might limit the application of this token-based reservation system.

In summary, most of the previous highway reservation studies have focused on the concepts or the modeling it over a single bottleneck. System optimal approach has been considered by Edara [3], but with inappropriate objective function. This paper adopted Wong's concept of slicing the capacity by time and relaxed the shortcoming of Edara's model [3] by using Vickrey's link bottle neck model [16] instead of micro-simulation, and modeling the rescheduling cost explicitly.

Departure Time Choice Studies

The highway reservation system works by rescheduling the travelers' departure time as well as route choice to avoid oversaturated traffic flows. Thus, the departure time choice modeling methods are useful for this study. The most commonly used travel time model is Vickrey's bottleneck link model [16]. This has been used in numerous departure time studies [17-20]. Hendrickson and Kocur [17] analyzed the users' departure time decisions in a single bottleneck under three different settings. Arnott et al. [18] studied user equilibrium, system optimum and various toll regimes for a network with parallel routes between one OD pair. Huang and Lam [19] solved a user equilibrium with route and departure time choices. Other than Vickrey's model, Mahmassani and Herman [21] used

Greenshield's traffic flow relationship in an ideal arterial to represent congestion effects. This model works only for routes with single uninterrupted link, as it is difficult to calculate the exact exit flow rate.

Some other studies developed discrete choice models based on survey data to see what factors can affect travelers' departure time choices [2, 22, 23]. Small's work [22] is the very first econometric study of the trip scheduling behaviors at the individual level. The discrete logit model of the commuters' work trip scheduling provides useful information of time values, the relative magnitude of them is consistent with Hendrickson and Plank [2]: late arrivals at work have the highest value of time, early arrivals have the lowest, and the value of wait time on the road is between them. Noland and Small [23] analyzed the effect of uncertain travel times on the commuting departure time choice. They found that travel time uncertainty can account for a large proportion of the morning commute cost.

Wie et al [24], Friesz and Mookherjee [25], and Chow [20] analyzed theoretically the dynamic traffic assignment problem with departure time choice. Wie et al. formulated the user equilibrium and system optimum conditions and compared the two using a numerical example. Chow [20] discussed the effect of choosing different traffic model and time discretization on the quality of the assignment result, found that the necessary condition for system optimum with deterministic queuing model is having the inflow equal to the bottleneck capacity for all routes and all departure time intervals in use. This finding will be compared with the results of the two numerical examples of this study.

Under system optimum, travelers with different departure time might have different total cost, and they have incentive to adjust departure time and arrive at user equilibrium. Some researchers [2, 16, 17] suggest using time dependent tolls to help balance the unequal total cost, so that different departure time will generate the same cost. With the optimization model's results provided in this paper, the exact time dependent toll pattern can also be identified. This toll idea works under two conditions: the exact travel demand pattern is known, and all the travelers are homogeneous. However, neither of the two is satisfied in practice.

HIGHWAY RESERVATION SYSTEM CONCEPT

According to two economic studies of commuters' traveling behavior [2, 22], late arrivals at work have the highest value of time, early arrivals have the lowest, and the value of wait time on the road is between them. That means, if there is anticipated congestion, the commuters have the incentive to depart earlier (also arrive earlier) to avoid the congestion. Highway reservation system provides a reliable mechanism for them to do so. Another big advantage of highway reservation system is reducing the travel time uncertainty, as "travel time uncertainty can account for a large proportion of the morning commute cost" [23]. These economic studies lay the foundation for the highway reservation system.

The proposed highway reservation system works by redistributing the peak hour travel demand earlier or later to non-peak hours. Its validity depends on how the users respond. Some of them may have flexible schedule and are willing to accept any rescheduling, while some of them may not cooperate. The users' attitude depends on a lot of factors, such as work schedule flexibility, experience with the reservation system, etc.

In this paper, it is assumed that the highway users will fully corporate with the booking center, meaning they accept any rescheduling, and will travel by the planned schedule.

To provide a proper “edge” of the reservation token to the user, highway system is divided into multiple links by on- and off-ramps, and time is discretized into intervals with link capacity sliced [7]. A reservation slot is defined as the combination of several consecutive links and time intervals. For example, a user can reserve a 3 mile-long segment (may have multiple links) between time 8:30 am and 8:33 am. Certain tolerance could be defined by the local traffic conditions to accommodate inaccurate travel time estimate. For example, ± 10 minutes tolerance could be used if the local traffic is unpredictable. This segment’s operational speed is set to be 60 mph. That’s why travel time is 3 minutes. Such accurate arrival time and speed control would be feasible by transmitting speed and lane-change advisories messages from the operation center with Connected Vehicle technology. If only parts of the freeway lanes are reserved, users might need special assistance to change from slower general-purpose lane to faster reserved lane. This can be done by sending a merging request through Connected Vehicle device to the surrounding vehicles, and the following vehicles on the reserved lane will brake to create a safe gap.

Compared with HOV lane strategy, reservation system produces higher utilization of the highway capacity when the demand level is low, as there might not be enough vehicles to occupy the HOV lane. HOT strategy might be able to lower the tolls to make better use of the highway, but the elasticity of the demand to the toll is unknown. Sometimes it could be too late to increase the tolls to avoid congestion if the travel demand bumps up. All these problems do not exist in the reservation system. In a sense, it makes the traffic information transparent to both demand and supply side beforehand.

LINK BOTTLENECK MODEL

Vickrey's Model [16] is a deterministic queuing model that considers each link to be free flowing with a constant travel time, and a bottleneck at the beginning or the end of the link with fixed capacity. Delays will occur when the traffic inflow continuously exceeds the capacity of the bottleneck for a substantial period. If there is no queue, the outflow rate is equal to the inflow rate, and the travelers have no delay. This model assumes relatively stable inflows, without considering stochastic variations, that's why it is deterministic. Its queue is assumed to be vertical (virtual) so that it does take physical space and has no spill-back issues. After entering the bottleneck, vehicles travel through the link by a constant "typical" speed, which depends on the "maximum allowed flow rate". This flow rate should be lower than real capacity for some safety and emergency margin. Vickrey's queue model is selected in this study because 1) the maximum flow rate can be considered explicitly and 2) it is easy to calculate the exit flow time and rate, and propagate the exit flow into the successor links.

The queue length evolves as shown in **EQUATION 1** [19]. When $\lambda_a(k)$ is higher than μ_a, the capacity of link a, the queue length increases from $q_a(k-1)$ to $q_a(k)$, and if $\lambda_a(k)$ is lower than μ_a, the queue length decreases. The queue length can never be negative.

$$q_a(k) = \max[q_a(k-1) + \Delta t(\lambda_a(k) - \mu_a), 0]$$

EQUATION 1

$q_a(k)$: Queue length on link a at the end of time interval k

Δt: Length of the time interval

$\lambda_a(k)$: Inflow rate of the k^{th} time interval

μ_a: Capacity of the link segment a

t_0: Travel time under "typical" speed

$\Delta t * \lambda_a(k)$ is the number of vehicle arrived at link a in time interval k. The exit time of these vehicles from link a and the associated exit flow rate depend on the current queue length and the relative magnitude of $\lambda_a(k)$ and μ_a. Thus there are four different situations in calculating the exit flow rate and time, as shown below. Note that the link index and time interval indexes are omitted for simplicity in the following expressions.

1) $\boldsymbol{q = 0}$ and $\boldsymbol{\lambda > \mu}$

There is no initial queue at the beginning of interval k and the inflow rate is higher than the outflow capacity. Extra vehicles will be queued. As shown in **FIGURE 1**, it takes the link $\lambda/\mu * \Delta t$ time to dissipate vehicle arrivals in interval k. The average delay of these vehicles is $(\lambda/\mu * \Delta t - \Delta t)/2$.

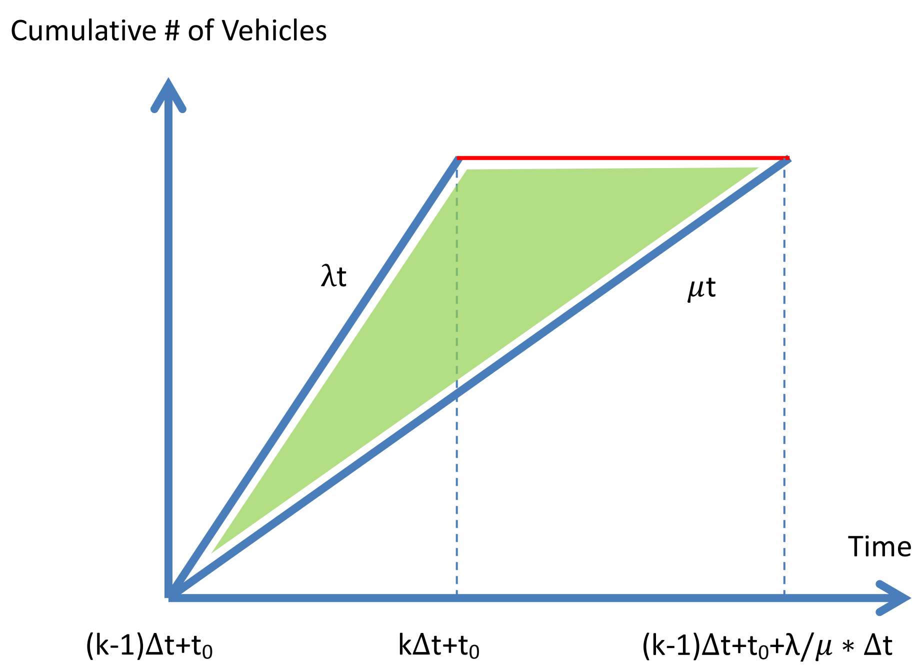


FIGURE 1 Queuing Link Model when q=0 and λ > μ

2) $\boldsymbol{q = 0}$ **and** $\boldsymbol{\lambda \leq \mu}$

In this case, there is no initial queue and the inflow rate is lower than the outflow capacity. There will be no queue and no delay. The arrived vehicles will simply depart after t_0 time.

3) $\boldsymbol{q > 0}$ **and** $\boldsymbol{\lambda > (\mu - q/\Delta t)}$

There is initial queue on this link and the inflow rate is higher than $(\mu - q/\Delta t)$. The λ threshold that separates case 3 and 4 is $(\mu - q/\Delta t)$ instead of μ, because at this inflow rate, the newly arrived vehicles in interval k disappears right at time $k\Delta t+t_0$. At time $(k-1)\Delta t+t_0+q/\mu$, the existing queue, left from previous time intervals, disappears. Then the k^{th} interval vehicles start exiting, and finish at time $(k-1)\Delta t+t_0+\lambda/\mu * \Delta t+q/\mu$. The outflow time range is longer than a time interval. The average delay is $(\lambda/\mu-1)\, \Delta t/2+q/\mu$.

4) $q > 0$ and $\lambda \leq (\mu - q/\Delta t)$

There is existing queue at the beginning of interval k and the inflow rate is less than $(\mu - q/\Delta t)$. As shown in **FIGURE 4**, the new arrivals dissipate the link before time $k\Delta t + t_0$. When the queued vehicles are exiting, the outflow rate is μ, and becomes λ after the existing queue clears. Thus the outflow line is a piecewise linear function. The average delay of the vehicle arrivals in interval k is q^2/(2$\mu(\mu - \lambda)$ Δt).

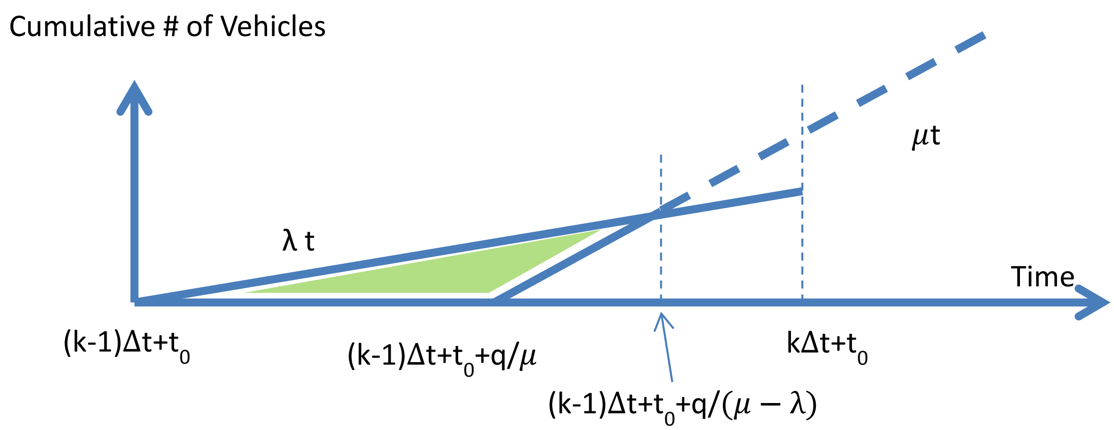


FIGURE 2 Queuing Link Model when q>0 and $\lambda \leq (\mu - q/\Delta t)$

TABLE 1 Notations in the Link Bottleneck Model and Successive-Update Approach

i	Integer	Index of origin, a member of {1, 2, … O}
j	Integer	Index of destination, a member of {1, 2, … D}
k	Integer	Index of time interval, a member of {1, 2… K}

r	Integer	Index of a route in R_{ij}, a member of {1, 2, … R_{ij}}
l	Integer	Index of a desired arrival time, a member of {1, 2, … DAT}
a	Integer	Index of a link, a member of {1, 2, … A}
m	Integer	The maximum number of links of all the routes
n	Integer	Each link has a number of routes that start from it. n is the largest number.
O	Integer	Total number of origins
D	Integer	Total number of destinations
K	Integer	Total number of time intervals
R_{ij}	Integer	Total number of routes between OD (i, j). R_{ij} is a subset of R
R	Integer	Total number of routes between all the ODs pairs
DAT	Integer	Total number of desired arrival times
A	Integer	Total number of links in the network
w_1	Double	Value of time for the early arrival
w_2	Double	Value of time for the late arrival
w_3	Double	Value of time for travel time
V_{ijkrl}	Integer	Number of vehicles between OD (i, j) with desired arrival time DAT_l that travel on route R_r (R_r is one of the routes in R) and start in the k^{th} interval. **This is the decision variable of the model.**
C_{ijkrl}	Double	Average cost of the vehicles V_{ijkrl}

AAT_{ijkrl}	Double	Actual arrival time of the vehicles V_{ijkrl}
ROUTES	R by m matrix	Each row represents a route's links.
$Demand_{ijl}$	Integer	The number of trips between OD (i, j) with desired arrival time DAT_l
INPUT	R by K by DAT matrix	Each cell (r, k, l) means the number of trips on route r with desired arrival time l and depart in time interval k.
ARRIVALTIME	R by K by 2 matrix	Cell (r, k, 1) and (r, k, 2) mean arrival time range of the trips in INPUT (r, k), or the trips on route r that depart in interval k.
TRAVELTIME	R by K matrix	Cell (r, k) means the average travel time of the trips in INPUT (r, k), or the trips on route r that depart in interval k.
LINKSINITIAL-ROUTES	A by n	Each row a represents the routes that start from link a. The row has zeros if no routes start from it.
$QUQUE_a$	1 by 2K vector	Queue length at the end of each time interval on link a
$INFLOW_a$	R by 2K matrix	If a is the first link of some routes, the corresponding rows of $INFLOW_a$ are initialized by that travel demand. Other rows remain empty.
$OUTFLOW_a$	R by 2K matrix	Initialized as empty.
$DEPART_a$	2K by 2 matrix	Cell (k, 1) and (k, 2) means the exit flow time range

		of the vehicles that entered link a in interval k.
LINKS	A by 2 matrix	Cell (a, 1) is the typical travel time on link a. Cell (a, 2) is the bottleneck capacity of link a.
TotalTravelTime	Double	The total travel time of all the vehicles.
TotalEarlyArrival	Double	The total early arrival time of all the vehicles
TotalLateArrival	Double	The total late arrival time of all the vehicles

OPTIMIZATION MODEL

System Objective

The objective of the reservation system is minimizing the total cost of its users, a weighted sum of early arrival cost, late arrival cost, and travel time cost (**EQUATION 2**). The decision variable is V_{ijkrl}: the number of trips between OD (i, j) with desired arrival time DAT_l using route r that start the trip from the kth time interval. The C_{ijkrl} is calculated by the Successive-Update approach mentioned in the next section of the paper, and there is explicit expression for it. So the objective function in **EQUATION 2** is just for illustration purposes. In implementation, there is no index of i, j, and r, since an overall route index can identify all the possible routes. That's why the decision variable dimension is $R \times K \times DAT$, instead of $O*D*K*R_{ij}*DAT$. C_{ijkrl} is the total cost of the trips that belong to V_{ijkrl}, including early/late schedule cost and travel time cost. These decision variables have to satisfy the OD demand constraint and non-negative constraint. The vehicles are propagated through the traffic network by using a successive-update method, as discussed in the following section.

$$Min \quad \sum_{i=1}^{O}\sum_{j=1}^{D}\sum_{k=1}^{K}\sum_{r=1}^{R_{ij}}\sum_{l=1}^{DAT} V_{ijkrl} C_{ijkrl}$$

$$C_{ijkrl} = w_1 * \max(DAT_l - AAT_{ijkrl}, 0) + w_2 * \max(AAT_{ijkrl} - DAT_l, 0) + w_3 * TravelTime_{ijkrl}$$

Subject To:

$$\sum_{k=1}^{K}\sum_{r=1}^{P_{ij}} V_{ijlkr} = Demand_{ijl} \quad \text{for all } i, j \text{ and } l$$

$$V_{ijlkr} > 0 \text{ and integer} \qquad \text{for all } i, j, k, r \text{ and } l$$

EQUATION 2 System Objective and Constraints

Successive-Update Approach

The link bottleneck model can calculate exit time and rate from each link. The exited vehicles enter the successor link, together with vehicles from other routes that also use the successor link. The successive-update approach uses an INFLOW vector and OUTFLOW vector to keep the flow information for each link, and updates them in each time step, until all the vehicles have reached their destination. The routes between each OD pair are predetermined either manually or by a route-searching algorithm, and stored in ROUTES, an R by m matrix, where R is the total number of routes. m is the maximum number of links in a route. All the routes are numbered by the row ID in ROUTES, no matter which OD pair they connect. The initial traffic assignment is stored in INPUT, an R by K by DAT matrix. Note that we assume the users' desired arrival time is not continuous but belongs to a set of discrete time points, as they are determined by morning commuters' work start time, which is not continuous most of the time.

$INFLOW_a$ and $OUTFLOW_a$ record the flow propagation process for link a. They are 2K by R matrices. 2K is used because the propagation process runs for 2K time intervals, in case some trips cannot finish at the end of Kth interval. For the links that are the beginning of any route, their INFLOW matrices are initialized using INPUT. For example, if link b is the first link of route r, $INFLOW_b(r, k)$ is initialized by summing up INPUT(r, k, 1:DAT). During the traffic propagation process, in each time step k, sum($INFLOW_a$(1:R, k)) vehicles enter link a, and $OUTFLOW_a$ is updated according to the calculated exit flow time and rate. To maintain flow conservation, at the end of each time step, $INFLOW_a$(r, 1:2K) of all the links are updated by taking in vehicles from the predecessor links' OUTFLOW. A $QUEUE_a$ vector records the queue length of link a in all the time intervals. A $DEPART_a$ vector records the flow exit time of link a. The time interval is set to be shorter than the shortest travel time of all the links, so that the outflow of the links will never affect the successor's inflow in the same time interval. When the propagation process is finished, the DEPART vectors have the exit time of the trips from each link. By tracking down the DEPART vectors of the links on route r, we obtain the arrival time at the final destination of the vehicles using route r. With the final arrival time, the system objective is calculated. The successive-update approach is shown by a pseudo code in **FIGURE 3**.

Given: INPUT, ROUTES, LINKS, INFLOW_a's
For k=1:2K
    For a=1:A
        $\lambda_a(\text{k}) = \sum_{r=1}^{R} \text{INFLOW}_a(r,k)$
        $q_a(k-1) = QUEUE_a(k-1)$ ($QUEUE_a(0)$ is always 0)
        Take $\lambda_a(\text{k})$, μ_a, and $q_a(k-1)$, calculate $q_a(k)$ by **EQUATION 1**, set $QUEUE_a(k) = q_a(k)$
        Check $q_a(k-1)$, $\lambda_a(\text{k})$, and $\mu_a = LINKS(a,2)$, with $t_0 = LINKS(a,1)$, find the appropriate bottleneck function, and calculate the outflow time range (O_1, O_2) and the $OutFlowRate$ for later uses
        O_1I=Floor(O_1)+1 O_2I=Floor(O_2)+1
        $DEPART_a(k,1) = O_1$
        $DEPART_a(k,2) = O_2$
        For k^*=O_1I: O_2I
            $OUTFLOW_a(\text{r},k^*) = OUTFLOW_a(\text{r},k^*) + OutFlowRate^* * \delta t^* * \frac{\text{INFLOW}_a(r,k)}{\sum_{r=1}^{R_a} \text{INFLOW}_a(r,k)}$
            δt^* is the time length in the interval k^* that has outflow from $\lambda_a(k)$
        End
    End
    For r=1:R
        Predecessor=ROUTES(r, j)
        Successor=ROUTES(r, j+1)
        If(Predecessor~=0 && Successor~=0)
            $\text{INFLOW}_{\text{Successor}}$(:, r)=$\text{OUTFLOW}_{\text{Predecessor}}$(:, r)
        End
    End
End
For r=1:R
    NumLinksOnRoute=the number of links on route r
    For k=1:K
        Track down along the links on route r, to find the destination arrival time of the trips in the kth interval on route r, denoted by (Early, Late).
        ARRIVALTIME(r, k, 1)=Early (in time intervals)
        ARRIVALTIME(r, k, 2)=Late (in time intervals)
        TRAVELTIME(r, k)=(Early+Late)/2-k
    End
End
For r=1:R
    TotalTravelTime=TotalTravelTime+sum(INPUT(r).*TRAVELTIME(r))
    For k=1: K
        For d=1:DAT
            TotalEarlyArrival=TotalEarlyArrival+EarlyArrivalTime of INPUT(r, k, d)
            TotalLateArrival=TotalLateArrival+LateArrivalTime of INPUT(r, k, d)
        End
    End
End
Output: TotalTravelTime, TotalEarlyArrival, TotalLateArrival
Obj=w1*TotalEarlyArrival+w2*TotalLateArrival+w3*TotalTravelTime

FIGURE 3 Pseudo Code of the Successive-Update Method

Solving the Optimization Problem

This study adopted the Active Set Method (ASM) [26] that is based on sequential quadratic programming and Interior Point Method (IPM) [26], which is an analytical technique based on the calculation of the Karush-Kuhn-Tucker conditions. Since there is no close-form formula, the two algorithms use finite-difference equation to find the search direction. Given an initial solution, both algorithms begin the iterative process to search for the next solution. The initial solution assumes that the demand is evenly distributed in all the routes and all the time intervals. The results of IPM turned out to be better than ASM for both the two case studies, so only IPM results were displayed in the paper.

NUMERICAL EXAMPLES

This paper uses the two numerical examples used in Huang's study [19]. Huang solved the user equilibrium route and departure time choice problem using the Vickrey's bottleneck model. So using the same examples makes it consistent to compare the performance of the highway reservation system with user equilibrium solution.

A Two-Route Network

There are two routes between an OD pair and both are reserved. Morning commuters travel from Origin to Destination with desired arrival time (DAT) 9 am. The time value of these commuters is \$6.4/h for travel time, \$3.9/h for early arrivals, and \$15.21/h for late arrivals [19, 22]. Route 1 capacity is 8000 veh/h, and route 2 is 3000 veh/h. The typical travel time is 0.2 hours and 0.3 hours correspondingly. The analysis time range is from 6 am to 10 am and time interval is 2 minutes.

This problem was solved using “fmincon” function with ASM and IPM algorithms in Matlab and run on a Dell desktop (Optiplex 960 with Intel Core2 CPU 3.33GHz and 4G Memory). The function with IPM stopped after 200 iterations in 11 minutes when the step size is smaller than the step size tolerance. **FIGURE 4** shows the two routes’ inflow rates. Route 1 inflow remains zero till the 34th interval and becomes zero again at the 98th interval. Route 2 inflow remains zero till the 35th interval, and becomes zero again at the 93rd interval. Since the “typical” travel time is 6 intervals (0.2 hr) on route 1 and 9 intervals (0.3 hr) on route 2, vehicles departing at the 84th interval on route 1 and 81st interval on route 2 have the lowest cost on the corresponding route, as they arrive right at DAT. As the departure time changes earlier or later, the costs increase linearly by the amount of change.

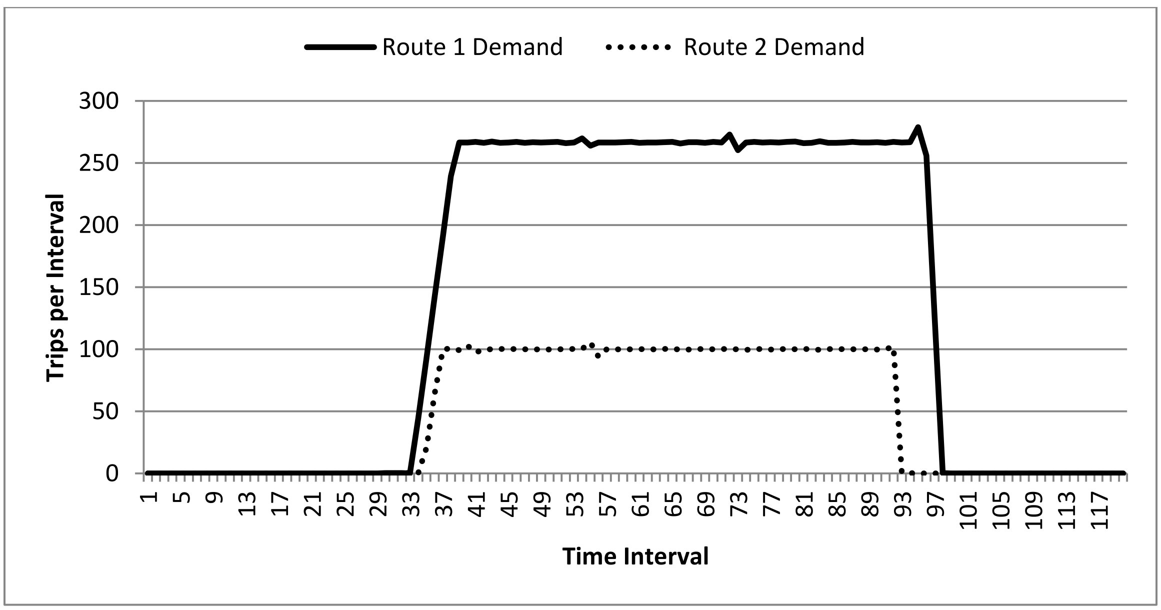


FIGURE 4 Optimization Solution of the Two-Route Network

17, 566 vehicles arrived at the destination earlier than DAT, and the average early arrival time is 0.8 hr. 4,434 vehicles arrived at the destination later than DAT, and the average late arrival time is 0.2 hr. The average cost of all the 22,000 vehicles is $4.55. Huang's user equilibrium average cost is slightly higher than 6$ [19]. If taking the user equilibrium as the base case condition, reached ideally by the drivers' self-selection behavior, we see a 24.1% reduction of total travel cost in the reservation system.

A Grid Network

This grid network, as shown in **FIGURE 5**, includes nine nodes, 12 links and two OD pairs (from A to C and from B to C). All the typical travel time and capacity of the links are shown in the figure. The trip demands from A to C and from B to C are 20,000 and 10,000 veh, respectively. All the other settings are the same with the previous example. The network is symmetric as well as the input data, so there are only three unique routes: 1 or 6, 2 or 3 or 4 or 5, and 7 or 8. The program treated all the routes independently, and symmetric outputs are indeed found.

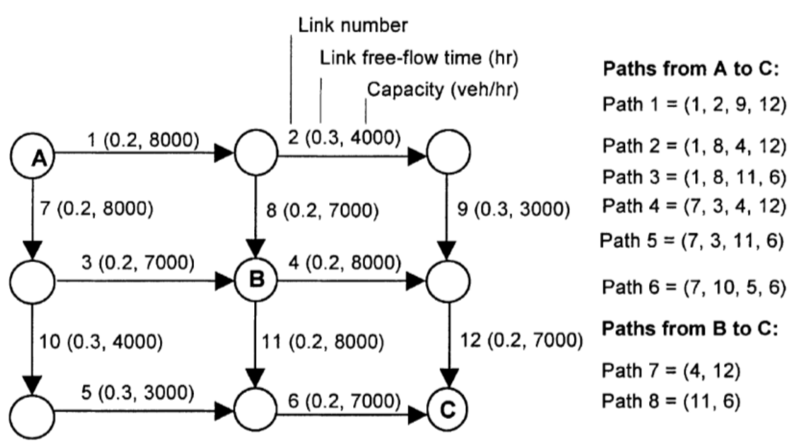
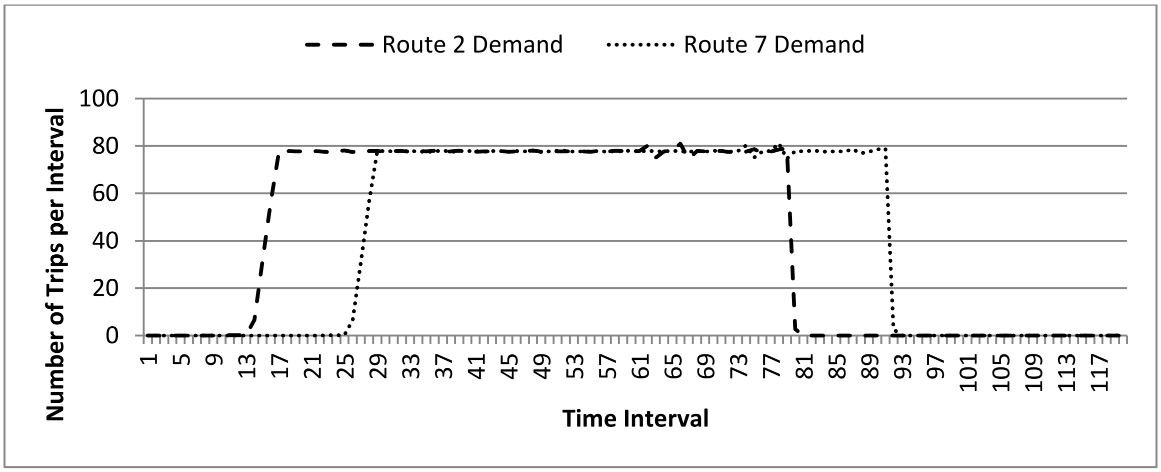


FIGURE 5 Grid Network

This problem was solved using the same method in the previous example. Using IPM, the optimality condition was satisfied after one hour run. **FIGURE 6 A** shows the inflow rate of the three unique routes. There are no trips on route 1 (6), because route 1 (6) have longer travel time than route 2 (3, 4, 5), and all of them share bottleneck link 6 and 12. Let's see how the reservation system works by looking at the earliest user, John, on route 2. As shown in **FIGURE 6 A**, John departs origin A at the 15th interval and arrives at C after 24 intervals. He arrives 102 minutes earlier than 9 am. If John switches to route 1, and departs at the 60th interval, he will arrive right at 9am and his travel time would be 30 intervals. By switching from route 2 to 1, he spends 6 intervals (12 min) more travel time, but saves 102 minutes' early arrival cost. Using the predefined time value, in total he saves 6 dollars. Without the reservation system, he will be more than happy to do so. However, route 1 shares link 12 with another three routes 2, 4 and 7, and link 12 has reached capacity. If John switches to route 1, he will create queues on link 12 and the travel time of a lot of other people will be higher. The optimization algorithm does the trade-off and finds it optimal not to use route 1 and 2 at all. This is strong evidence of how the reservation system can help realize the system optimum condition with route and departure time choices. This model also has the potential of identifying critical links and under-utilized links.

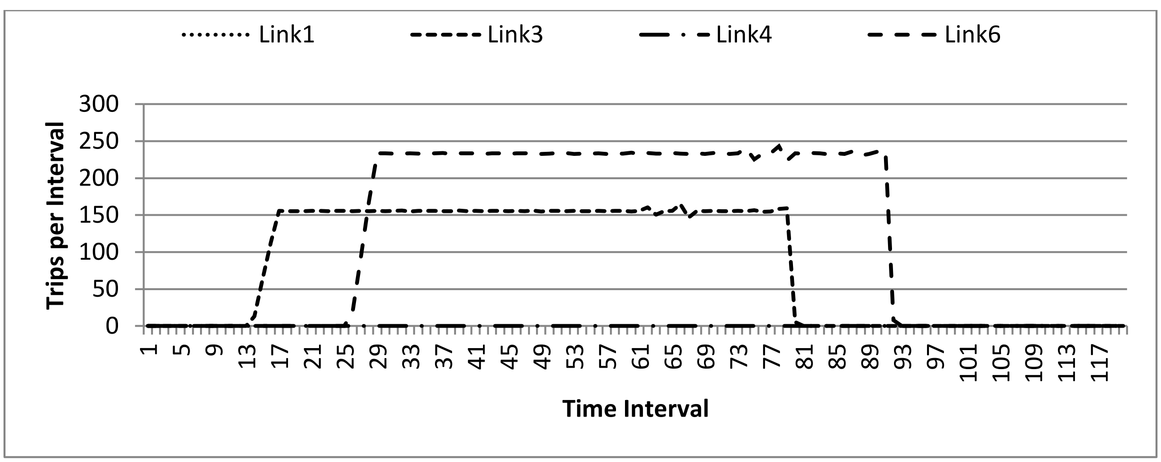
FIGURE 6 B shows the traffic flow rates of six unique links. It is noted that links 2 (10) and 5 (9) have no traffic at all, and link 6 (12) has reached capacity. This is easy to understand since all the trips ending in zone C need to use either link 6 or link 12. All the other links have some traffic but not saturated. This is evidence that links 6 and 12 are the bottlenecks in this grid network.

A total of 23,920 vehicles arrive earlier than 9 am, and the average early arrival time is 0.853 hr. A total of 6,080 vehicles arrive later than 9 am, and the average late arrival time is 0.219 hr. The average cost of all the vehicles between A and C is about 7.9 dollars, and 8.03 dollars between B and C. Although BC distance is shorter than AC, the BC traveler average cost is higher than AC travelers, because some of the trips on route 7 (between B and C) arrive late (the late arrival value of time is much higher than early arrival and travel time value of time) (**FIGURE 6 A**). Huang's user equilibrium average cost is about 11 dollars between A and C, and 7 dollars between B and C [19].



*Route 1 has no traffic.

A Optimized Traffic Flow of Three Unique Routes



*Link 2 and 5 has no traffic.

B Optimized Traffic Flow of Six Unique Links

FIGURE 6 Optimized Reservation Plan of the Grid Network Problem

Discussions

A critical component of the roadway reservation system is the constraint that limits the total number of trips allowed into a link in certain time. However, the optimization model presented in this paper does not have these constraints, since the goal of the paper is justifying the idea of imposing such a constraint, by optimizing the highway resource allocation plan. The results support this concept. In the converging state of both the two numerical examples, none of the links are operated at oversaturated level, or none of the highway links are congested. The flow rate remains constant during a fairly long period. This finding is consistent with Chow [20]: the necessary condition for system optimum is having the inflow equal to the bottleneck capacity. In addition, the optimization model also finds the best scheduling plan for all the users from a systematic perspective.

Since all the links are operated under the predefined control speed (60mph in the case studies), as long as two vehicles use the same route, they have the same travel time, no matter when they travel. Clearly, the users that arrive right at their DAT have the lowest cost. In the optimization process, the users are assigned the departure time intervals by the model. In real life, people would like to take cost to get that interval. If the reservation center is first-come-first-serve basis, we would expect that the users would call in right after the reservation system is open. That might bring some problems to the communication channel of the booking system. The authors are considering using a bidding system, by having the users bid for their desired time intervals and routes. Certain amount of people on top are accepted and granted the reservation tickets. Its application in the reservation system would be further analyzed in the future research.

CONCLUSIONS AND FUTURE RESEARCH

This paper shows an innovative highway reservation system as a travel management strategy, and models it with a mathematical optimization model. This model is capable of finding the best scheduling plan that the reservation system could make for optimal system performance. In the optimal result, traffic volume of all the links is at or under the capacity, lending support of bringing capacity constraint into the reservation system. In two case studies, by applying reservation system over a highway network, the total system cost reduces by 20% to 25%, comparing with a user-equilibrium traffic assignment. These two numerical examples show the proposed approach is well capable of solving the reservation optimization problem.

The optimization model works under two assumptions: all the travelers are homogeneous in terms of travel time values, and they are fully compliant with the reservation system's scheduling plan. So the future research should include using an agent-based simulation technique that considers the users' different time value and compliance level. An auction system will be able to solve the compliance level problem: people who pay higher have higher priority. The Vickrey's model used in this paper is deterministic in nature, while the traffic dynamic is stochastic, especially in maximum throughput. Thus the agent-based simulation should be able to consider a more realistic stochastic model. The speed harmonization and traffic flow smoothness based on Connected Vehicle technology will also help increase the traffic flow stability at the maximum throughput.

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CHAPTER 3

PROOF-OF-CONCEPT STUDY FOR A ROADWAY RESERVATION SYSTEM: AN INTEGRATED TRAFFIC MANAGEMENT APPROACH

PROOF-OF-CONCEPT STUDY FOR A ROADWAY RESERVATION SYSTEM: AN INTEGRATED TRAFFIC MANAGEMENT APPROACH

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ABSTRACT

Learning from the success of reservation systems in industries including airlines and hotel, a roadway reservation concept has been considered by transportation engineers. Traditionally, vehicles are allowed to use freeways on a first-come-first-serve basis. In the proposed roadway reservation system, vehicles need to reserve a spot on the freeway in advance, which allows them to use some segments of the freeway within a certain amount of time. By controlling the number of tickets issued by the roadway reservation system, this concept can maintain a certain level of service on the freeway. Emerging Vehicle-2-Infrastructure and Vehicle-2-Vehicle communication technologies make the roadway reservation concept feasible.

In this study, a proof-of-concept test is conducted to investigate the potential benefits of the roadway reservation system. A VISSIM traffic network with a 20-mile long two-lane freeway and some arterials serves as the simulation test-bed. The reservation algorithm is applied to a carefully designed baseline, and the results of the reservation scenario and baseline are compared. The reservation scenario turns out to outperform the baseline in terms of total delay time and emissions. When travel demand is 30% higher than capacity, the total delay time is 58.6% less and CO_2 emissions is 18.3% less in the reservation scenario than the baseline. Although some practical issues are not considered in this proof-of-concept study, the proposed roadway reservation system outperforms the baseline so much, which provides strong evidences that the proposed reservation system shows promising future and deserves more attention including feasibility test for implementation.

INTRODUCTION

Surface transportation is being operated as a queuing system in which congestion is inevitable when too many vehicles attempt to use the same road at the same time. Other systems with limited resources, on the contrary, allow users to make reservations ahead of time, and eliminate oversaturated conditions. Such systems include hotels, hospitals, airlines, and passenger trains. Then, a question arises, “Why did the surface transportation never adopt such a reservation system?” It is in part due to the costs and technical challenges of maintaining such a system for a big urban transportation network. For example, a reliable and efficient real time communication capability is needed to handle the enroute vehicle reservation requests. Emerging Connected Vehicles (CV) technology [1] is likely to provide the necessary communication medium. For example, a driver can send a request through a CV device in the vehicle instead of using telephone or Internet. The issued digital-ticket is stored in the device and can be detected by the Roadside Equipment without having to stop or even slow down the vehicle. The supporting functionalities of the reservation system, such as lane entrance assistance, lane-exit assistance, and enforcement system can be realized with the help of CV technology. Advances in computing power make it feasible the development of hierarchical distributed computer systems, where a central computer shares operations with on-board vehicle microchips. As a result, the technical barriers are diminishing.

The basic idea of the roadway reservation is that all road users need to book in advance. As noted, reservation system is very common in other transportation industries such as passenger railroad (Amtrak) and airlines. Compared with a first-come-first-serve queuing system, reservation system reduces the waiting time significantly. Successful examples of industries with reservation systems have the following characteristics [2]: 1) variable demand over time, 2) perishable assets, 3) limited supply, 4) market segmentation, 5) adding new capacity is expensive, and 6) marginal cost is negligible. A closer look at surface road system indicates that it has all these characteristics. It is well known that transportation flow changes over time, so the demand is variable. The inventory of spots on the highway is perishable, because all the not used spots during some time interval are definitely lost. Highway has limited supply (not exceeding capacity) and expansion is not possible in a short time period. Once a traffic network is built, the marginal cost of adding a vehicle into the system is negligible. There is also market segmentation in surface transportation, for example, vehicle with different occupancy rates, vehicles with different trip distances, etc. All these characteristics are necessary conditions of a reservation system. As indicated by Veeraraghavan's study, a sufficient condition to implement a reservation system is long mean waiting time of customers [3]. The average annual delay per auto commuter in the 101 urban areas in the US is 38 hours in 2010 and 2011 [4]. Veeraraghavan et al. [3] identified the necessary and sufficient conditions of building a reservation system for the highways.

This study aims at testing the validity of the roadway reservation system concept through manipulating the vehicles' behavior in micro-simulation software. It is the first systematic simulation work on the assessment of a roadway reservation system. A baseline traffic network in VISSIM is elaborated by abstracting from a real urban road network, and the vehicles on it maneuver properly. Then the proposed reservation algorithm is applied on it to see how much benefits it can bring, in terms of total delay time and environmental effects. The comparisons are conducted under varying travel demand levels. This study is called proof-of-concept because a few idealizations and simplifications are made.

The remainder of this paper is organized as follows. A short review of previous work on the roadway reservation concept is given. Then, a brief description of the roadway reservation concept is proposed, followed by the simulation model configurations. The experiment process is discussed with the result analysis. A plan of future work on this topic follows at the end.

LITERATURE REVIEW

The concept of road reservation or trip-booking is mentioned in the literature as early as 1990s, but extensive modeling works have not been done till the recent 5 years, when emerging technologies make this concept realizable. Akahane and Kuware [5] used a Stated-Preference survey to evaluate the user acceptance and effectiveness of a road reservation system on an inter-city motorway in the Tokyo Metropolitan area, to mitigate holiday congestions. They concluded that the system seemed promising. In another survey published in 2011, Kim and Kang [6] tested how willing the respondents were to change their departure time during the national holidays and their acceptance of an expressway reservation system in South Korea. They found that 73.4% of the respondents would participate in the expressway reservation system if implemented, and concluded that the public were ready to adjust their travel behaviors. Note these two surveys were both conducted in Asian countries, thus the story might be different in US. Wong [7] provided the functions, advantages and difficulties of an advance booking for highway use. The conclusion is that the highway booking system is in its infancy but has great potential and is worth being exploited in the future. Iftode and Gerla et al. described a

Lane Reservation System for Highways in several position papers [8-10] and its five subsystems, including reservation system, lane entrance system, lane exit system, enforcement system and exception handling system. They also presented possible strategies under each subsystem and the technologies needed to realize them. Veeraraghavan's paper [11] compared the general reservation system versus a queuing system and her findings lent support theoretically to applying the reservation concept in highway.

The studies mentioned above are either about surveys or discussing some roadway reservation concepts. Some other studies started exploring and did some modeling or analytical work. De Feijter [12] stated that the objective of trip-booking is improving reliability and predictability of travel times. His simulation experiments, which were based on a simple freeway link, showed that trip booking reduces waiting time and thus results in more reliable travel time. Edara and Teodorovic [2] proposed a Highway Space Inventory Control System with two parts: Highway Allocation System (HAS) and Highway Reservation System (HRS). HAS is an off-line module that uses Genetic Algorithm to maximize the total Passenger-Miles-Traveled over a period for a defined length of the highway. The spots on the highway are allocated to different combinations of vehicle type, departure time and OD pairs. On the other hand, as the future demand cannot be accurately estimated, HRS is needed to work in an on-line mode to decide whether a request should be accepted or rejected. This study tried to borrow concepts from the reservation system in other transportation modes, such as airline, to use in surface transportation. It uses past reservation cumulative data (fixed demand) to find the optimal allocation using HAS. With the optimal allocation results, HRS trains a neural network to deal with the requests in real time manner. This system works well if the future demand is similar to the past, but the performance may not be so good if the demand pattern changes significantly. The most important contribution of HAS is its ability of doing market segmentation, such as giving priority to long distance or high-occupancy vehicles. This ability can be obtained by setting different prices for the tickets. Edara and Teodorovic [13] compared the performance of the HAS with some other traffic management strategies, such as pre-timed ramp-metering and an isolated ramp-metering algorithm called ALINEA. The simulation results show that HAS produces 35% to 45% more Passenger-Miles than the two ramp-metering algorithms. It can be concluded that HAS makes more sufficient use of the highway resource, in terms of Passenger-Miles.

Roadway reservation system is one of traffic management strategies (TMS). TMS includes ramp-metering, High-Occupancy-Vehicle (HOV) lane, congestion pricing, etc. Ramp-metering changes the on-ramp metering rate depending on the traffic conditions in the vicinity of the ramp to ensure mainline traffic flows well without causing queued vehicles on the ramp causing spillback at the adjacent arterial network. HOV lane is a separate lane for high occupancy vehicles that often require dedicated infrastructure (e.g., separate lane) and works typically well for areas where ride sharing is possible. Similar to HOV lane, congestion pricing also has limited applicable area. All the three strategies provide some benefits over existing transportation systems that rely on a simple queuing system. It is noted that the roadway reservation system is one of the most profound and comprehensive strategies because it collects very detailed demand information from the users who opted-in. These include the departure time, desired routes and vehicle type for each trip. In addition, the fact that onboard unit (OBU) equipped vehicles and roadside unit (RSU) can communicate each other via CV technology allows the roadway reservation system feasible.

ROADWAY RESEARVATION CONCEPT

Two major differences between roadway and other transportation modes which have reservation systems are 1) the supply of roadway cannot be very easily split into many segments, such as seats in airline industry, on which reservations are made and 2) roadway system is public property with maximizing social welfare instead of revenue as its primary goal. To deal with the first problem, the time period is divided into smaller time intervals (e.g., 5 minutes in this study), and the highway network is split into a series of connected links. As such, each 5 minutes' capacity of one link is treated as a reservation unit, comparable to a flight in the airline industry. The second problem has been considered with in a previous research. Edara and Teodorovic [2] developed a Highway Allocation System (HAS) algorithm to allocate the highway resource among different kinds of demands to optimize the passenger-miles-traveled. The proposed reservation system in this study used a first-come-first-serve algorithm to deal with the booking requests. When the number of accepted requests exceeds capacity, further requests will be rejected.

Iftode and Gerla [8-10] mentioned in a few of their position papers a framework for the reservation system: 1) Reservation system, 2) Lane entrance system, 3) Lane exit assurance system, 4) Enforcement system and 5) Exception handling system. These components are briefly discussed in the following section.

Highway Reservation System

In Ravi, Smaldone and Iftode's paper [10], three different reservation policies are mentioned. In policy 1, the user specifies the date, time and section of highway and the system offers a number of slots. Policy 2 favors frequent drivers by setting lower prices or assigning a higher proportion of the highway to them. Policy 3 includes on-the-fly reservations directly on the highway, in addition to making advance bookings. Here on-the-fly reservations mean requests from vehicles on the normal lanes to immediately enter the reserved lane. On the contrary, pre-trip reservations mean requests made in advance of the reservation time. This paper deals both pre-trip reservations and on-the-fly reservations. The pre-trip reservations are handled in a similar way to the Policy 1 mentioned above. The users specify departure time, origin and destination, and the system decides a freeway route for them and decides whether to accept this request. If a request is rejected, the user has to travel through arterial routes. The on-the-fly reservations have different definition from that in Ravi, Smaldone and Iftode's paper [10], because all the two lanes of the freeway are reserved in this study, and the on-the-fly requests have to come from arterials instead of freeway. The request-sending time of these vehicles is treated as departure time by the reservation system, and there is a certain amount of time between the request-sending time and actual arrival time at the on-ramp. The rejected on-the-fly vehicles will need to reroute to an arterial path.

Lane Entrance and Exit Assistance System

Lane entrance and exit assistance system is needed if some of the lanes are managed by the reservation system (called high-speed lanes, usually the inner most lane) but other lanes are normal, because the merging and diverging of the ticketed vehicles will disrupt both high-speed lanes and normal lanes, especially when the normal lanes are congested. In that case, lane entrance and exit assistance system is pivotal in dealing with the on-the-fly vehicles. In the proof-of-concept reservation algorithm, all the two lanes of the highway are high-speed lanes, so vehicles do not need lane entrance and exit assistance.

Exception Handling and Enforcement System

Possible exceptions include emergency vehicles, early and late arrivals, no shows, accidents, unauthorized vehicles, etc. Emergency vehicles, such as ambulances and fire trucks, have the priority to enter the reserved freeway without any reservations. Thus, a small amount of capacity is reserved for them. The early and late arrivals are not big problem in this study, firstly because these early and late arrivals offset each other (the arterials are not congested in the test-bed settings), and secondly, they are accommodated by the reserved capacity for emergency vehicles. Unauthorized vehicles and no-shows must be punished for proper functioning of the system. They can be detected by a monitoring system, which could be based on V2I communications. Unauthorized vehicles on the high-speed lanes will be issued a penalty ticket. No-shows may or may not be punished, depending on how the system is designed. In this proof-of-concept study, it was assumed there are neither unauthorized vehicles nor no-shows. However, these can be relatively easily accommodated in the simulation study.

SIMULATION DESCRIPTION

In this section, how the roadway reservation system proposed is realized in a simulation environment is presented. A microscopic traffic simulator, VISSIM, is selected as the primary simulation tool, because 1) VISSIM provides COM interface enabling users to control the behavior of each vehicle in real-time and 2) authors utilized a COM-based simulation test-bed in a previous relevant research dealing with a route guidance system [14]. Trip chain file is an input file needed by VISSIM. It contains information like vehicle ID, vehicle type, departure time, origin zone, destination zone, activity time, etc. In this study, trip chain file is used to store information of all the pre-trip vehicles. The reservation algorithm which deals with pre-trip requests is emulated by changing vehicles' type in the trip chain file. Baseline trip chain file have all the vehicles typed 100, while ticketed vehicles in the reservation scenario have their type changed to "101", and rejected vehicles' type is changed to "102". Note that this study only considers the vehicles that intend to travel through the roadway reservation system (i.e., freeway). And all these vehicles are placed into the trip chain file.

The reservation system works in a "distributed" manner. Pre-trip reservations are pre-processed by changing the vehicle types in the trip chain file (Step 4 Generate the trip chain file for reservation scenario), while the on-the-fly reservations are handled by a function embedded in a control system, which will be mentioned in Step 5 Program the central control system. The baseline network is abstracted from a real network. It is very carefully designed and elaborated to be realistic, so that the comparison between reservation scenario and baseline is fair. The steps to configure the VISSIM simulation model are given in the following sections.

Step 1 Build the network

The road network in VISSIM, as shown in **FIGURE 1**, is abstracted from a real traffic network in Buffalo, New York. The freeway in the center, I-290, has four interchanges and three links, as shown by L1, L2 and L3. North road and Sheridan drive are two major arterials that serve as alternative routes. The western area in the map (number 1 to 10) is mainly residential while the eastern (number 11 to 14) is mainly commercial and school. So the morning peak hour traffic is from west to east. Zones #1 to #5 are designated origin zones for pre-trip vehicles. Zones # 6 to #10 are designated origin zones for on-the-fly vehicles. Zones #11 to #14 are designated destination zones for both pre-trip and on-the-fly traffic.

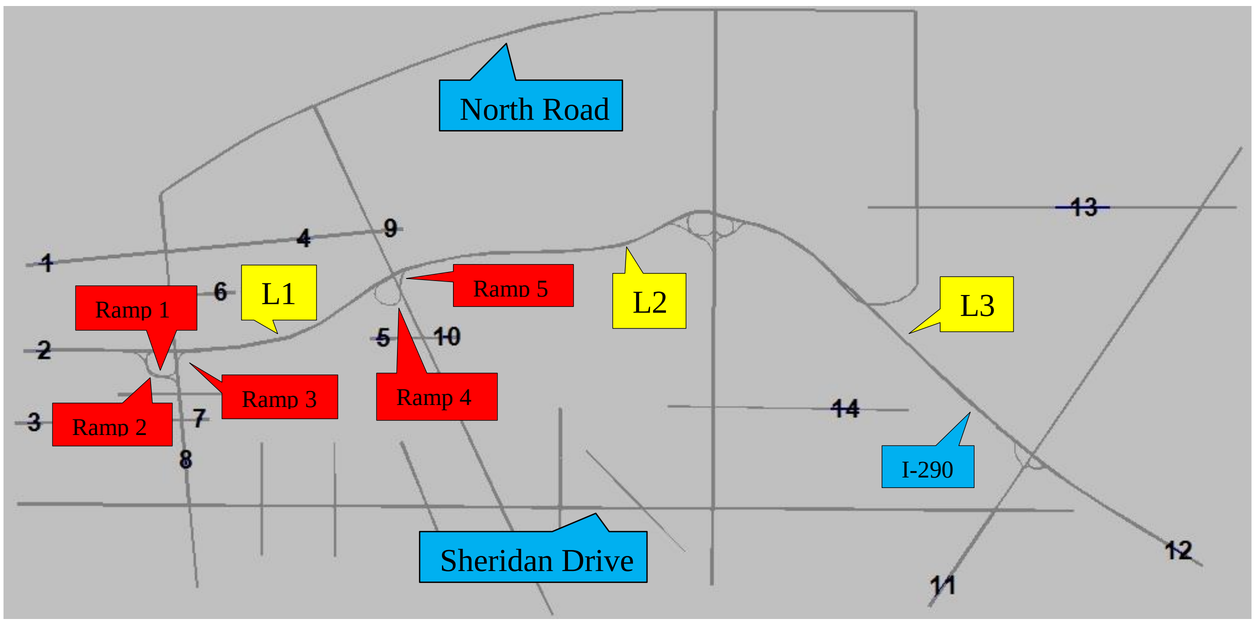


FIGURE 1 Road network and parking lots

Step 2 Test runs to obtain parameter values

Three kinds of parameters are needed for the simulation work: freeway capacity, travel time from each origin to the on-ramp, and travel time on each freeway link. These values are not known and need to come from actual tests in VISSIM. The capacity decides how many slots can be reserved. Travel time from each origin to the on-ramp is important for calculating the on-ramp (first freeway link) arrival time. Travel time on each freeway link is used to calculate the vehicle’s arrival time at the following freeway links. The tests showed that the capacity of the two-lane freeway in VISSIM is around 2200 passenger-car per hour per lane (pcphpl). In terms of travel time, the average value of multiple runs is adopted, shown in **TABLE 1**. Note that these travel times are tested under different travel demand levels, and they do not vary very much, because neither the freeway nor the arterials from origins to the on-ramps are congested in the reservation scenarios. That's why the simple average values are used in **TABLE 1**. In the real world implementation of the roadway reservation system, these travel time values can be obtained from vehicles equipped with the CV technology devices.

TABLE 1 Travel Time on Free Links and from Origins to On-ramps

Road Name	Travel time (s)
Link 1	64
Link 2	95
Link 3	103
Origin 1 to ramp 1	125
Origin 2 to ramp 2	23
Origin 3 to ramp 3	103
Origin 4 to ramp 4	71
Origin 5 to ramp 5	50

Step 3 Generate the trip chain file for the baseline

This step generates a trip chain file for the baseline. The trip chain file is produced based on OD matrix. The SIMULATION EXPERIMENTS section discusses how the OD matrices used in this study were developed. A Matlab code reads in an OD matrix and produces trips accordingly. For each trip, it generates a VID (vehicle ID), vehicle type, origin zone, departure time, destination zone, and request-making sequence number. VID is a unique ID for each vehicle. Vehicle type is initially assigned as 100 for all the baseline vehicles. Origin and destination zones are based on the OD matrix. Departure time is a random number between 1 second and 3600 seconds, so that the pre-trip vehicles' departure time distributes evenly over the one-hour reservation time. Note that departure time is the time the vehicle leaves its parking lot (or zone). The initial trip requests are generated by the sequence of origins and destinations through two nested loops. Then these requests are resorted randomly to emulate the actual request-making sequence. The resorting is necessary because without it the reservation system will always deal with the trips between OD (1, 11) earlier than the trips between OD (1, 12), which is unrealistic.

Step 4 Generate the trip chain file for reservation scenario

This step is part 1 of the "distributed" reservation system, which deals with pre-trip vehicles in the trip chain file. A Matlab code reads in the baseline trip chain file and treats each record as a booking request in order. Then a freeway route is found for each trip based on its origin and destination, and its arrival time at the on-ramp and at all the other freeway links is calculated. The reason for doing this is that the time interval of a vehicle on each link needs to be known to count this vehicle into that link's traffic volume. During any time interval, the traffic on a link consists of vehicles belonging to trip allocations in the current interval and vehicles belonging to trip allocations during earlier intervals that are currently traveling on the link. Note that the travel time estimations are based on the pre-estimated travel time in **TABLE 1**, and real-time congestions are not considered. Then, the code checks the capacity of all these links in the corresponding time interval. If the number of accepted trips is less than capacity on all the links, this new request will be approved, and the database is updated which records the number of reserved slots on each link in each time interval. If else, it will be rejected. When all the trip reservation requests have been handled, the system will output a new trip chain file for reservation scenario. The flow chart of handling the pre-trip reservations is shown in **FIGURE 2**.

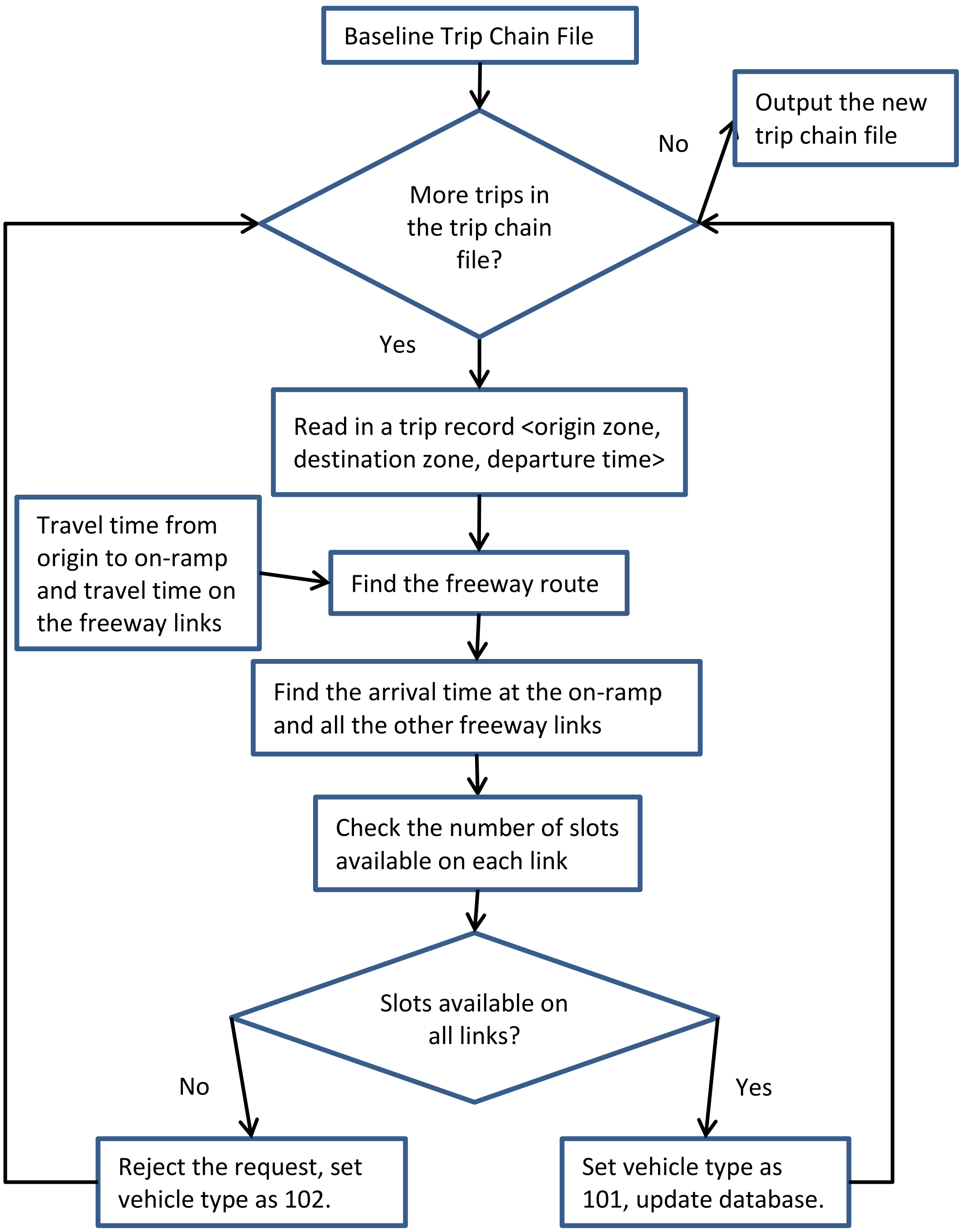


FIGURE 2 Flow chart of handling the pre-trip reservations

Step 5 Program the central control system

The VISSIM simulations are controlled by a C# code controls through COM interface. The control system reads in trip records from the trip chain file and assigns it a freeway or an arterial route, depending on its ticket status. At the beginning of the simulation, VISSIM reads in all the trips from the trip chain file and places them into the corresponding parking lots (i.e., origin zones). The control system loops through all the vehicles and assign it a route. It will be freeway route if the vehicle type is “101” or “100”, and arterial route if the vehicle type is “102.” Both the freeway and arterial route for each OD pair is unique in this traffic network. They are selected based on shortest travel time.

Part 2 of the “distributed” reservation system is embedded in this control system to deal with on-the-fly reservations. Once every 5 simulation minutes, a few vehicles are inserted in the traffic network. Each vehicle is put into a randomly generated origin zone in number 6, 7, 8, 9 or 10. Their destination zone is also randomly generated in number 11, 12, 13, or 14. The departure time is when each vehicle departs from the origin zone. With these origin and destination zones information, this booking request is sent to the central control system. Part 2 of the reservation system is very similar to part 1, but it works during the simulation instead of pre-processing. Part 2 estimates on-the-fly vehicles’ arrival time at the on-ramp and all the other links. These requests are not accepted unless capacity allows on all the links: the same process as shown in **FIGURE 2**. In this study, the number of on-the-fly vehicles generated every 5 minutes is 24. This number is selected so that the total number of on-the-fly vehicles ($24 \times 12 = 288$) is much more than the reserved capacity for them (60 pcphpl). As a result, on-the-fly vehicles have much less possibility than pre-trip vehicles of being accepted, or pre-trip vehicles are favored by the system.

Note that in the baseline, Ramp 5 is a bottleneck. This is easy to understand, as all the freeway routes go through link L2 and Ramp 5 is the last entrance ramp before L2. Ramp 5, as well as the arterial link before Ramp 5, is jammed with vehicles during baseline simulations. In the default VISSIM settings, these vehicles wait there till they get on-ramp, and the waiting time is always excessive. Thus it is unfair to compare such a baseline with reservation scenario. In the real world, most drivers will immediately reroute if they see a jammed on-ramp. To make the baseline more realistic, a rerouting algorithm is added to the baseline. The central control system checks the number of vehicles on Ramp 5 every 30 simulation seconds, if the number exceeds a threshold (10 vehicles in this study which is based on the ramp storage capacity), all the vehicles on the left lane and a certain percentage of the vehicles on the right lane of connecting arterial are rerouted. The rerouting percentage of right lane is included in the sensitivity analysis in the SIMULATION EXPERIMENTS section. Note that the threshold, 10 vehicles, is 60% of the ramp storage capacity, and is a strong signal for the drivers that there are congestions on the freeway.

Step 6 Select the measurement parameters

Measurements of effectiveness include vehicle-miles-travelled (VMT) of all the vehicles, vehicle-hours-travelled (VHT) of all the vehicles and CO_2 emissions. CO_2 emissions is examined by employing VT-Micro model, a microscopic emissions and fuel consumption model developed by Virginia Tech. VT-Micro model is a two-regime regression model, estimated with emissions and fuel consumption records obtained from 60 instrumented vehicles under various speed and acceleration/deceleration combinations. Thus, coupled with a microscopic simulator such as VISSIM, it can estimate vehicular emissions by capturing each vehicle's instantaneous speed and acceleration rate at every simulation interval. In this paper, VT-Micro model was transformed to a dynamic linked library (DLL) as a VISSIM's external API module enabling the real-time measurements of CO_2 emissions.

SIMULATION EXPERIMENTS

Multiple simulation experiments are conducted to test the potential benefits of the reservation system over baseline. Some parameters can influence the results, but the authors are not sure of their exact values. So sensitivity analysis is conducted on these parameters, including travel demand level, the reserved capacity percentage for emergency vehicles, and the rerouting percentage of the right lane in front of Ramp 5 in the baseline. Their meanings are mentioned in the previous sections. Each parameter has three levels. Travel demand is set to be 30% less than capacity, equal to capacity, and 30% more than capacity. Note that the travel demand includes both pre-trip and on-the-fly vehicles, and capacity is the measured capacity from VISSIM simulation runs (2200 pcphpl in this study). Pre-trip OD matrices of the three levels of travel demand are shown in **TABLE 2**. The percentage of reserved capacity for emergency vehicles varied 15%, 10%, and 5% of the capacity. The rerouting percentage of right lane in front of Ramp 5 in baseline can be 30%, 50%, and 70%. A total of 27 ($3\times3\times3$) sets of simulations need to run. In each set, both baseline and reservation scenario are repeated for 5 times with different simulation seeds. So a total of 324 simulation runs should be needed. But for baseline the reserved capacity does not need to vary and for reservation scenario the rerouting percentage does not need to vary. Thus, a total of 108 (i.e., 324/3) simulation runs were actually conducted.

The simulations are run for 4500 seconds so that all the vehicles can finish their trips. The first 600 seconds is warm-up period, which means all the data collections begin to be conducted from the 600th second. Each simulation takes from 3 to 7 minutes, depending on the travel demand level.

TABLE 2 OD Matrices

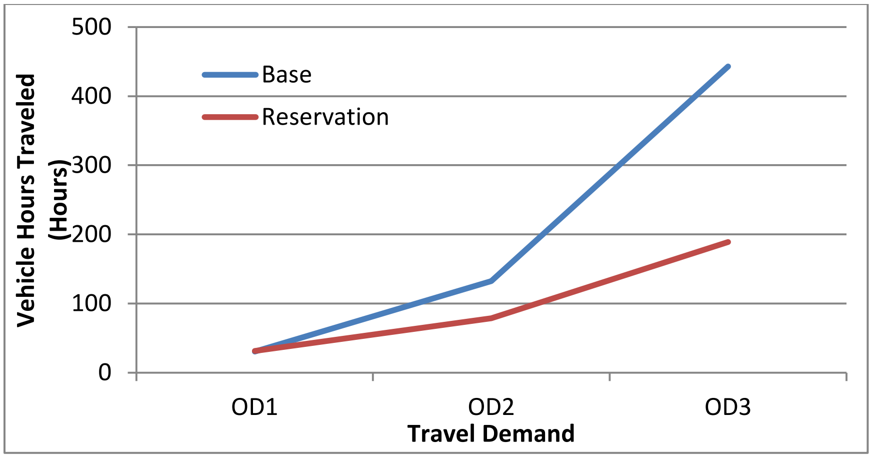
OD1	11	12	13	14	Sum
1	130	130	130	130	520
2	178	178	178	178	712
3	130	130	130	130	520
4	130	130	130	130	520
5	130	130	130	130	520
Sum	698	698	698	698	2792
OD2	11	12	13	14	Sum
1	198	198	198	198	392
2	236	236	236	236	944
3	198	198	198	198	392
4	198	198	198	198	392
5	198	198	198	198	392
Sum	1028	1028	1028	1028	4112
OD3	11	12	13	14	Sum
1	265	265	265	265	1060
2	298	298	298	298	1192
3	265	265	265	265	1060
4	265	265	265	265	1060
5	265	265	265	265	1060
Sum	1358	1358	1358	1358	5432

ANALYSIS OF RESULTS

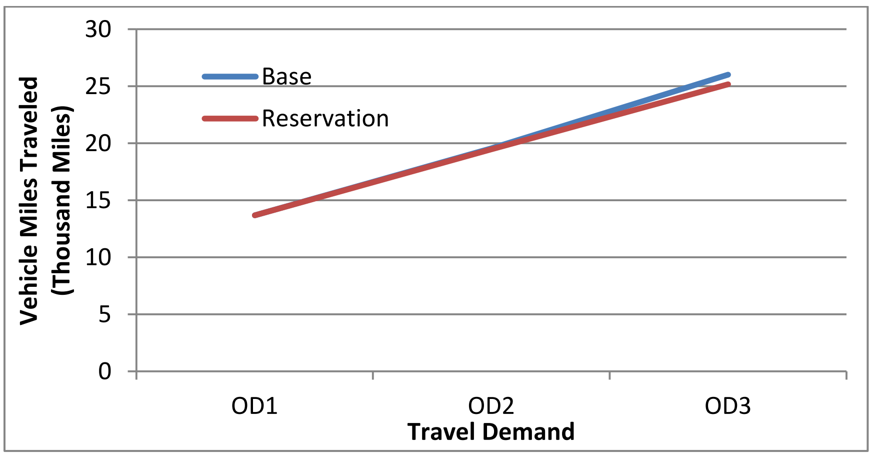
The VHT of these simulations is shown in **FIGURE 3 (a)**. When traffic demand is 30% less than the capacity, the total delay time of the baseline and the reservation scenario has no significant difference. Then as traffic demand increases, the VHT of the baseline shows much larger than those of the reservation scenarios. The huge reduction of the VHT in the reservation scenarios proves the validity of the roadway reservation concept.

The VMT does not vary much from the baseline to the reserved scenarios as shown in **FIGURE 3 (b)**. But, VMT of the reservation scenario is still a little bit less than the baseline. There are two possible reasons. The first one is that most arterial routes are longer than corresponding freeway routes. The second reason is that in the baseline, the rerouted vehicles in front of Ramp 5 traveled longer distance than not rerouting, because rerouting means travelling north to make U-turn.

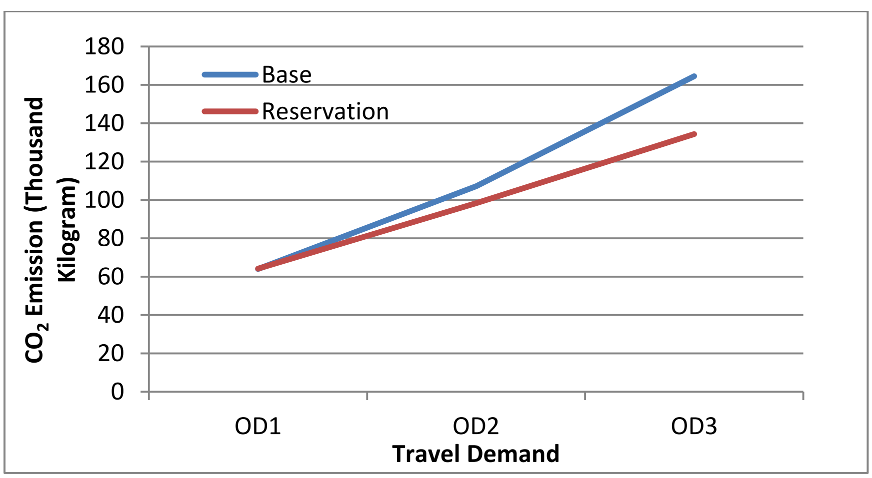
The environmental effects of the proposed roadway reservation system are demonstrated by CO_2 emissions. As shown in **FIGURE 3 (c)**, CO_2 emissions reduced in the reservation scenario. When demand is 30% higher than capacity, the CO_2 emissions decreased by 18.3%, while the VMT only decreased by 3.3%. This is strong evidence that the reduction in the CO_2 emissions is mostly a result of the less waiting time and less idling in the reservation scenario.



(a) VHT



(b) VMT



(c) CO_2

FIGURE 3 VHT, VMT and CO_2 Emissions

The influence of the rerouting percentage in baseline seems to be not clear, as shown in **TABLE 3**. The VHT has minor variations in OD1, when the freeway is not congested. In OD2, the rerouting seems to make VHT bigger, but smaller in OD3. A possible explanation is as follows. The freeway can actually accommodate the OD2 travel demand, but some fluctuations of the traffic flow make Ramp 5 congested. If not rerouted, the vehicles in front of Ramp 5 wait for very short time before moving into Ramp 5. If rerouted, the extra time traveling through arterial routes is longer than the waiting time if not rerouted. As a result, rerouting increases the total VHT. Things are difference in OD3, because travel demand is much larger than capacity. The waiting time if not rerouted is much longer than the extra time of taking arterial route if rerouted. That's why the rerouting reduces the total VHT in OD3. This rerouting emulates drivers' spontaneous behavior when they see congested on-ramps, which might not lead to a systematic optimization. A systematic reservation strategy would perform much better than these spontaneous behaviors.

TABLE 3 VHT of Different Rerouting Levels in Baseline

VHT		No Rerouting	30% Rerouting	50% Rerouting	70% Rerouting
OD1	Average	336.7	336.8	337.5	337.0
	Std. Error	0.8	0.8	1.3	0.7
OD2	Average	555.3	580.2	562.4	574.5
	Std. Error	22.5	11.9	16.5	23.1
OD3	Average	1213.6	1065.3	1065.7	1038.3
	Std. Error	25.9	18.0	13.6	43.8

Sensitivity analysis of the influence of the reserved capacity for emergency vehicles on VHT is conducted. As mentioned in the SIMULATION EXPERIMENTS section, the capacity reserved for emergency vehicles varies from 15% to 5%. As shown in **TABLE 4**, VHT has very small variations under different reserved capacity percentages in OD1, because travel demand is much less than the capacity. In OD 2 and OD 3, the change of VHT does not have very obvious pattern. In OD 3, VHT reduces from Capacity1 to Capacity 2, but then increase a little bit in Capacity 3. Using more accurately-estimated travel time would improve the quality of the reservation system, in which is feasible under CV technology.

TABLE 4 VHT of Different Reserved Capacity Levels in Reservation Scenario

VHT		Capacity 1 (15% of capacity)	Capacity 2 (10% of capacity)	Capacity 3 (5% of capacity)
OD1	Average	338.6	337.9	336.6
	Std. Error	1.6	0.6	0.4
OD2	Average	518.9	517.7	535.8
	Std. Error	3.5	1.2	9.0
OD3	Average	848.5	764.7	775.2
	Std. Error	24.5	9.3	22.0

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This study proposed a roadway reservation system concept and tested its feasibility though simulations using a VISSIM microscopic traffic simulator. The two lanes of the freeway in the road network are controlled by the reservation system during a morning peak hour from 7:00 am to 8:00 am. Pre-trip vehicles have their requests handled before the simulation run, and on-the-fly vehicles have their requests handled during the simulation. The reservation system controls the total number of tickets issued to the vehicles so that the traffic volume does not exceed the capacity, thus traffic breakdowns are avoided as much as possible. As a result, the vehicles with tickets do not need to experience congestion and/or wait at congested freeways. The results show that as traffic demand increases, the reservation scenario further outperforms the baseline in terms of Vehicles-Hours-Traveled and CO_2 emissions. When the travel demand on freeway is 30% higher than the capacity, the total VHT reduced 24.6% from the baseline, and the CO_2 emissions reduced by 18.3%. Although this proof-of-concept study has some weaknesses, such as the inaccurate travel time estimation and some practical challenges such as no considerations were given to an enforcement system and early and late arrivals of the vehicles on-ramp, the proposed roadway reservation system significantly outperformed the baseline. The roadway reservation system deserves more detailed modeling work and further research.

This proof-of-concept study made some simplifications for a quick assessment on the system's effectiveness. The promising results lead to a strong need of further work to improve the system. In the future work, this roadway reservation system should be further refined. The estimated travel times on the freeway links as well as from origins to the on-ramps should consider the influence of network congestion, for example how to handle the massive late arrivals caused by arterial congestions. The system should provide the users more route options to choose from. If the high-speed lane is separated from general purpose lanes, a lane-entrance and lane-exit system should be built and the on-the-fly reservations should handle them in a different manner.

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CHAPTER 4

AUCTION-BASED HIGHWAY RESERVATION SYSTEM AN AGENT-BASED SIMULATION STUDY

AUCTION-BASED HIGHWAY RESERVATION SYSTEM
AN AGENT-BASED SIMULATION STUDY

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ABSTRACT

Based on previous studies of a highway reservation system, this paper proposed an auction-based implementation of it. In the auction, the users can bid for the right of using a route during certain time interval. This paper models the auction system with an agent-based simulation technique, using MATSim. The simulation converges after around 130 iterations, when the number of users using the reserved highway and the total collected revenue become stable. The auction would help the toll road operators generate more revenue by transferring more consumer surplus to them. The users are using the reservation system as insurance of free-flow travel and on-time arrival. When the overall demand changes, the collected revenue ranges from 5 to 11 dollars per user, and from 0.7 to 1.5 dollars per mile. The auction-based highway reservation shows great potential as a new traffic management system.

INTRODUCTION AND BACKGROUND

Adding more transportation supply by providing additional infrastructure or expanding current roads has been one of the most fundamental congestion mitigation solutions in most growing urban regions. However, due to budget constraints and lack of available lands, roadway supply almost always increases at a slower rate than the traffic demand growth. The 2012 Urban Mobility Report [1] shows that only 17 areas have a less than 10% gap between demand and supply growth, while the gap is higher than 30% in 56 of the 101 study areas. In addition, increasing roadway supply might not be able to alleviate peak-hour congestion since reduction in congestion might induce departure time shifts into peak-hour [2]. Researchers have shifted their focus into travel demand management addition to improving traffic operation efficiency. One of the emerging innovative demand management approaches is "highway reservation." The idea behind it is slicing the highway resource into pieces by time and space and allowing people to reserve them in advance so that oversaturation traffic flow does not appear. The highway reservation system operates in a similar way with airplanes and passenger trains: allowing the users to reserve the resources in advance through buying tickets. When the resource of certain time in a future day has been fully reserved, additional users need to switch the departure time or choose other travel mode. Such a reservation system forbids too many users using the resource at the same time. Different from the airline and train seats, which have clear boundaries, highway resource does not have a clear edge. Thus, it is sliced both in time, into time intervals, and space, by links separated with on- and off- ramps.

A few studies [3-6] demonstrated the promising performance of the proposed highway reservation system without explicitly considering realistic queuing behaviors and travel times. For example, our previous study [6] minimized the total system cost by allocating the sliced highway slots to the users. In the two case studies, the optimized system costs were at least 20% lower than corresponding user equilibrium conditions. However, two assumptions of the model do not hold in real life: homogeneous users in terms of value of time and all of them comply with the scheduled trip plan. In real world, some of the time intervals are more desirable than others, thus people would be likely to pay to secure them. Based on this idea, this paper proposes an auction-based approach to implement the highway reservation system and simulates it with a multi-agent-based model.

Here is how it works. The reservation system operates the highway in a metropolitan area. The travelers notify the reservation center their desired highway segments and on-ramp time, and put a bid for it. Based on the bids sequence, these users' requests are handled: either accept or reject, based on the highway availability. The center determines the amount of slots available to the public, most likely based on maximum throughput level, for example, by subtracting some amount from the estimated maximum throughput level. The estimated maximum throughput changes by weather, work zones, accidents, or other abnormal conditions. The user with the highest bid has his/her request handled first. If part or all of the segments of a requested route are fully reserved, that request would be rejected, and the user either submit a new request with different on-ramp time and/or route, or use a parallel alternative arterial. If unforeseen or emergency events (e.g., incidents, etc.) result in a reduction of the maximum throughput, the users would be notified with suggested schedule changes to choose from.

The purpose of this paper is to explore the feasibility of the auction-based highway reservation system. The case study network includes a reserved highway route and a parallel arterial. The highway is controlled by the reservation from 6am to 10am, or the morning peak hour, while the parallel arterial is open to access. The remainder of the paper is organized as follows: LITERATURE REVIEW briefly discusses previous studies and concepts on highway reservation and other auction-based traffic management, followed a description of the auction-based reservation architecture. CASE STUDY describes the traffic network structure and travel demand in OD matrix. DESCRIPTION OF THE AUCTION-BASED HIGHWAY RESERVATION SIMULATION MODEL section illustrates in detail the logic of the agents in the simulation framework. CONCLUSIONS AND RECOMMENDATIONS section highlights the findings from the simulation, and discussions.

LITERATURE REVIEW

The concept of road reservation or trip-booking is mentioned in the literature as early as 1990s [3-5]. Wong [3], and Iftode et al. [4, 5] discussed basic functions, advantages and difficulties of a highway booking system. Extensive modelling efforts have not been done till the recent 5 years. McGinley et al. [7] showed that a reservation system is necessary to avoid waiting when the mean waiting time is large at the optimal point of operation. Studying the reservation system on a single bottleneck with heterogeneous users, Koolstra [8] found all queuing costs can be eliminated without increasing the mean rescheduling costs. Another finding is that a freeway reservation might be more effective in practice than road pricing. De Feijter et al. [9] showed that trip booking can improve reliability and predictability of travel times. Since travel time uncertainty can account for a large proportion of the morning commute cost [10], the improvement of travel time reliability could be a huge benefit of the reservation system. Edara and Teodorovic [11] conducted extensive modelling work of reservation system, proposing a Highway Allocation System (HAS) and Highway Reservation System (HRS). The goal of HAS is maximizing the total Passenger-Miles-Traveled over a period by selecting trips from received booking requests. HRS assumes an incoming booking request flow and makes on-line decision if to accept or reject a request. A major problem with HAS is using Passenger-Miles-Traveled as objective, as it is biased towards longer distance trips. HAS fails to consider explicitly the departure time adjustment, which is the core role of reservation system.

Due to the fact that highway does not have separable seats like airplanes, researchers proposed different methods to discretize the highway resource. The most common one is slicing highway capacity by links and time interval [3-5, 12]. Liu [13] used a different approach: a token-based reservation idea from computer science domain. Each road segment has a set of tokens. A vehicle has to be affiliated with a token to travel on that segment. When it arrives at the next road segment, there should be a token on that segment available for this car. Tokens can be reused by multiple vehicles, as long as the requested time slots on the token do not overlap. The total number of tokens is the product of the segment length and optimal traffic density, which is determined by Greenshield’s model. Thus the optimal density is a half of jam density, and optimal speed is a half of free flow speed. A critical problem with this approach is that the amount of time a car occupies a token is hard to determine, since the travel time depends on the traffic volume, which is not known until all the requests have been processed. The second problem is how to avoid too many tokens being reserved for a short time range, because that would lead to oversaturated traffic in that time.

Adler et al. and Iwanowski are the first researchers that considered using market-based or negotiation-based approaches for cooperative roadway usage. Adler et al. [14, 15] proposed a principled negotiation process, between agents representing network managers and drivers equipped with route guidance systems. The goal of the negotiation is an efficient distribution of network capacity over time and space, while maintaining individual user's preference (route, departure/arrival time) as much as possible. However, according to the case studies in the paper [14], the percentage of drivers who took the negotiated path ranged between 10% and 20%: a small proportion of the drivers reached a common end with the network manager. Iwanowski et al. [16] discussed the concepts of several market-based approaches for road traffic coordination. In the auction-based traffic control system, all rights to use road segments are distributed by auctions, and the auctions are continued periodically. All the biddings are handled by vehicle/driver unit, which represents the driver's individual interests and strategies. The vehicle/driver unit uses an automated software unit to participate in an electronic trading process, to bid for the right of using certain road segments. The advantage of auction-based mechanism is the independence of a prior set-up of traffic models and analysis. Our paper has adopted this auction-based mechanism into the reservation system.

Using a redistribution mechanism to realize a money flow among participants has been discussed by researchers to solve the social equity issue related to toll roads. In the auction-based approach discussed by Iwanowski [16], the collected tolls are credited to all the participants uniformly. However a more delicate redistribution algorithm should be considered since some participants might sacrifice more and deserve more refund. In the exchange-based trading approach [16], participants directly exchange the roadway using rights, like stocks. Adler and Cetin [17] extended Arnott's work by redistributing the toll collected from a more desirable route to users on a less desirable route, and created a user equilibrium assignment.

Multi-agent based modelling techniques have been used by numerous studies in transportation. Halle and Chaib-draa [18] applied it in modelling a collaborative platooning system. Galland et al. [19] used agent-based model to model individuals' carpooling mobility behaviour. Wahle et al. [20] modelled the impact of real-time information in a two-route scenario using an agent-based simulation, and explored the impact of using different types of information. MATSim is an open-source software that provides a framework to implement large-scale agent-based transportation simulations [21]. It has been applied by numerous researchers in traffic impact analysis, road/congestion pricing analysis, carpooling, freight modelling, environment effect evaluations, and evacuation plans [22-27]. Agent-based simulation is rather effective when a process includes numerous heterogeneous participants interacting with each other in a decentralized way. The auction-based reservation system is exactly such a system.

DESCRIPTION OF THE AUCTION-BASED HIGHWAY RESERVATION SIMULATION MODEL

Motivation

Why reservation? Our previous study [6] proposed an optimization model to allocate the highway slots to users so that the total system cost is minimal. It is found that the system cost is 20% to 25% lower than corresponding user-equilibrium traffic assignment. An important finding is that in the optimized trip schedule, the volumes over all the road links are lower than the capacity. This finding supports bringing capacity constraint into the reservation system. Optimization model is a centralized way of allocating the spaces to the people, based on a hidden assumption of 100% compliance. This is not the case in real life. That's why we need to model the users' behaviors through agent-based simulation in a decentralized way.

Why not First-Come-First-Serve? A First-Come-First-Serve policy works in many reservation-scheduling services. People with strong preferences over some time slots will typically be the early-birds. However, things become different when congestion becomes so bad that everyone becomes early-bird. That literally moves the congestion away from the highway but into the cyber or telephone. That's why First-Come-First-Serve policy is not a feasible one.

What's the advantage over time-varying toll? As discussed above, people have preferences over different routes and time, and they are willing to pay something to satisfy these preferences. Time-varying and distance-varying toll basically implies charging different amount of money depending on congestion level and the distance travelled, such as I-495 High-Occupancy-Toll (HOT) system. The beauty of the auction system is that price is directly determined by the users through competition, thus more consumer surplus transferred to the operator. Through the proposed reservation system, the users can decide ahead of time how much they would pay and when they travel. But the time-varying toll may have some delay in controlling demand. If traffic "bumps-up," the HOT lanes could still break down.

Agents

There are two types of agents in the reservation system. Traffic Management Center Agent (TMCA) is responsible for making full use of the highway system, i.e. maximizing the throughput, efficiency, and reducing safety issues. Driver Agent (DA) represents individual driver's interest and preference. They can be software unit that does the bidding and routing automatically. The DAs notify the TMCA their preferred route and on-ramp time slot, and put a bid for it. Then, all the conflicting requests (i.e., routes that share some highway segments at the same time) are sorted by the bid, from high to low, and handled by the TMCA. When part or all of the requested highway links are not available (meaning being reserved by someone else with higher bid), that request will be rejected, and the TMCA will move on to the next. For a DA that submits multiple requests, one request being approved will automatically remove the rest of them out of the queue. The requested time is based on the on-ramp time interval, and the users are responsible for arriving at the on-ramp by the requested time.

The maximum amount of vehicles per unite time allowed into a highway link is restricted by the TMCA. Generally, it makes sense to deduct a buffering amount from the capacity, since traffic flow easily breaks down near capacity level. Also some room should be left for emergency vehicles and on-the-fly reservations. In this paper, with 60 mph predefined control speed, the maximum amount allowed is set to be 1800 vehicles/hour/lane. This is 400 vehicles/hour/lane lower than the suggested capacity value of the Highway Capacity Manual [28] when free flow speed is 70 mph. Inclement weather and crashes could lead to a drop of the maximum throughput, thus an emergency-response system is needed to deal with the unexpected events by rerouting the users already on the highway, and the upcoming users. For example, the user could receive a message saying “You can choose to leave the highway at the next exit and receive a 100% refund. If you can remain on the highway, you might be late for as long as 20 minutes due to the crash and lane closure.” The system can fine-tune the refund amount and delay warning to adjust the number of users leaving the highway, so that the amount of users choosing to stay is still under the capacity level.

For each reservation request (a route/time combination), the TMCA needs to estimate when this vehicle will arrive at each of the highway links, to determine if the capacity constraint of those links have been violated. Under predefined control speed of 60 mph, the arrival time at the links can be estimated with high accuracy. The predefined control speed should be changed in real implementation per different situations, such as weather, road geometry, pavement quality, etc. Once the predefined control speed is determined, it should be maintained, through speed-control and merging-assistance systems. That’s not the focus of this paper, but existing Cooperative Adaptive Cruise Control and platooning control strategies are helpful for this task [18, 29, 30].

The above-mentioned request-making and handling are supposed to happen way before the actual traveling time. In some cases, people cannot always make trip plans ahead of time, thus the TMCA is also open to on-the-fly reservations. Since by then the succeeding bids would have been known, the on-the-fly requests will be charged a rate higher than the average successful bids over the same route/time choice, or similar ones. The higher rate is to compensate the risk of causing traffic breakdowns on the reserved links. The penalty could be 50% or even more, depending on the demand and operational needs.

The route scheduling, request making, and bidding processes mentioned above are fairly complicated, in the foreseen future, they are more likely to be handled by automatic smartphone apps or embedded systems in cars, instead of by human beings. The smart APPs take orders from the user, such as destination, desired arrival time or departure time, travel mode, maximum acceptable bidding amount, indifference level of the above mentioned goals, and do the route scheduling and bidding for the users. TMCA could also do more. For example, instead of simply rejecting a request, it can consider the indifference level of on-ramp time and make other route/time suggestions. In that case, there could be more interactions between the TMCA and the DAs.

Travelers' Strategy

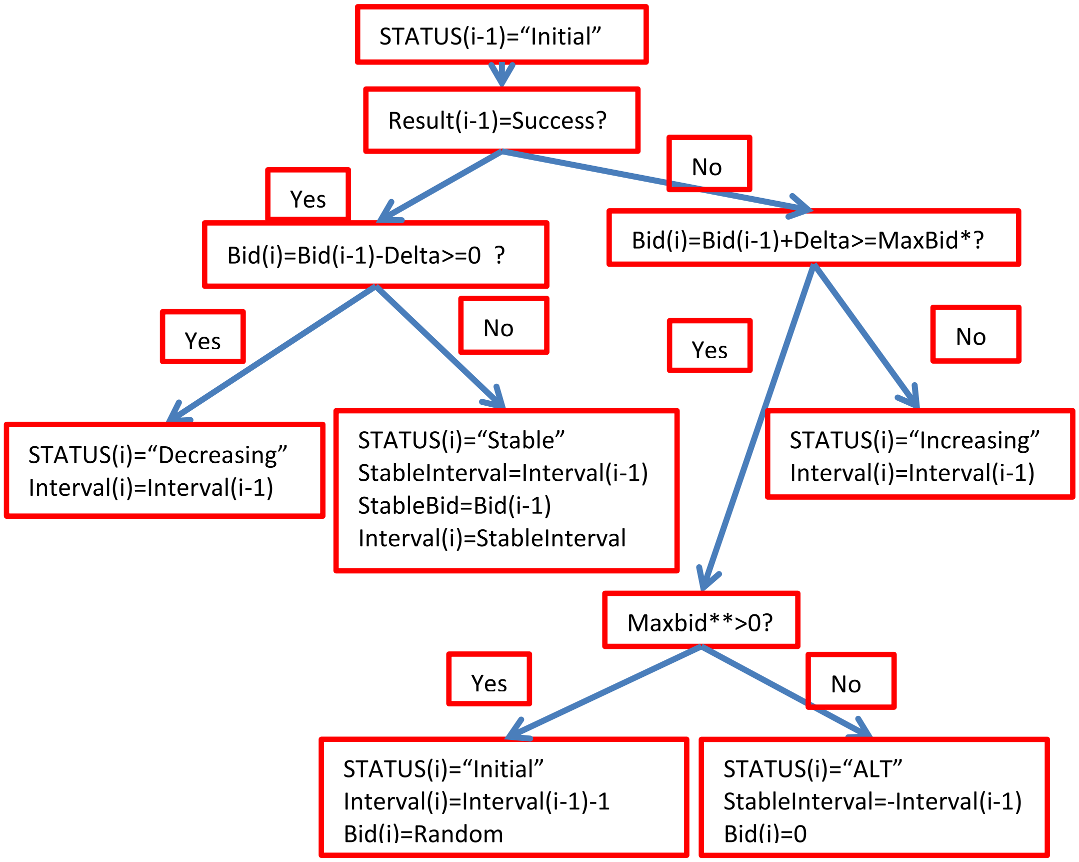
These morning commuters have two route choices: highway, or the arterial. Since the arterial is open to traffic and has much lower capacity than the highway, the arterial travel time is generally much longer. The DAs follow a simple logic when making a selection between the two: use the highway only if the total cost of using the reservation system is lower than the cost of using the arterial. The cost of using the highway is composed of three parts: cost of travel time, cost of early arrival time at work, and bid cost. The cost of early arrival time could be zero since a user might arrive right on time. For arterial users, the cost includes cost of travel time, cost of early or late arrival, and cost of travel time variability. The arterial travel time variability is modelled [1], by adding twice the standard deviation of travel time to the mean travel time.

In this study, the DA's logic is more like a blind search: it starts from the most desired time interval, by which the traveler can arrive at the workplace right on time, and moves to an earlier interval if they cannot win it. When a DA finds the total cost of using reservation system higher than using arterial, it will go and travel through the arterial. In the first iteration, a DA bids for the most desirable time interval, with a randomly-generated price. If succeeded, the DA will try to lower the bid in the next iteration, since the user thinks s/he might be overpaying for it. This "decreasing" process of the bid will continue until the DA fails. In that case, the last successful bid would be taken as the optimal strategy. This logic is shown in **FIGURE 2**. The optimal strategy might still lose, since other people may come with higher bid. In that case, the DA will try to increase the bid till success (an "increasing" process), as shown in **FIGURE 3**.

Five different states are used to represent the users' status in the simulation: "Initial" means a user just starts to bid for an interval. "Decreasing" means the user is able to win an interval and is trying lower bids. "Increasing" means the user cannot win an interval under current bid and is trying to bid higher. "Stable" means the user has found the optimal bid and will keep on using it. "ALT" means a user finds it more beneficial to use the arterial instead of the reserved highway.

Initial

"Initial" state means the DA is deciding whether to increase or decrease the bid, depending on last bid successful or not (**FIGURE 1**). If last bid succeeds, and the bid can be further reduced by Delta (not becoming negative), the DA will enter "decreasing" process. If the bid becomes negative when subtracted by Delta, it probably means that interval is in low demand and the DA might win with zero bid. In this case, the DA will change the state to "stable", and record the interval and bid of last iteration into the profile for future uses. The Delta value is not fixed. If it is too low, the simulation takes too long to converge. If Delta is too big, it might lead to unnecessary oscillations of the whole bid system. In this paper Delta is set to 7% of the average arterial cost, and the simulation works fine. If last bid fails, this DA will enter “increasing” process, and needs to increase the bid by Delta. However, if increasing the bid by Delta makes the total reservation system cost higher than arterial cost, the DA will move to an earlier interval and set the state as “Initial”. If the time cost of the earlier interval is even higher than the current arterial cost (MaxBid**<0), the DA will use the arterial and set the state as “ALT”. This is a blind and greedy search, since the DA tries different intervals step by step, and stops when it finds a satisfactory strategy, instead of going over multiple intervals and selecting the lowest-cost one. This is a reasonable assumption of the users’ behaviors, when the winning bids information of other people information is not disclosed to all the participants.



MaxBid=ArterialCost(i-1)-TimeCost(Interval(i-1))*

*MaxBid**=ArterialCost(i-1)-TimeCost(Interval(i-1)-1)*

Interval(i): the time interval that the user bided in iteration i

Interval(i-1)-1: the interval before iteration (i-1)'s interval

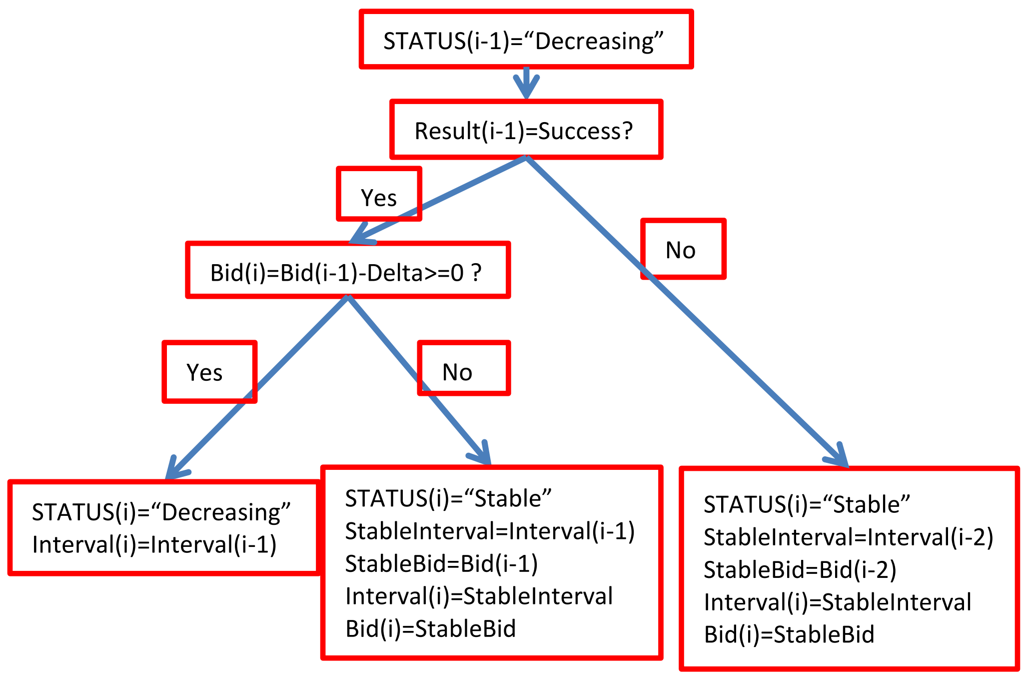
Result(i): the result of iteration i

Bid(i): the bid of iteration i

FIGURE 1 Decision Making Flowchart when Status is "Initial"

Decreasing

A DA in the "Decreasing" state suspects s/he is paying too much for an interval and is testing if s/he can win with lower bids (**FIGURE 2**). The time interval and the last successful bid before a failure is taken as optimal strategy and stored in the profile for future uses.

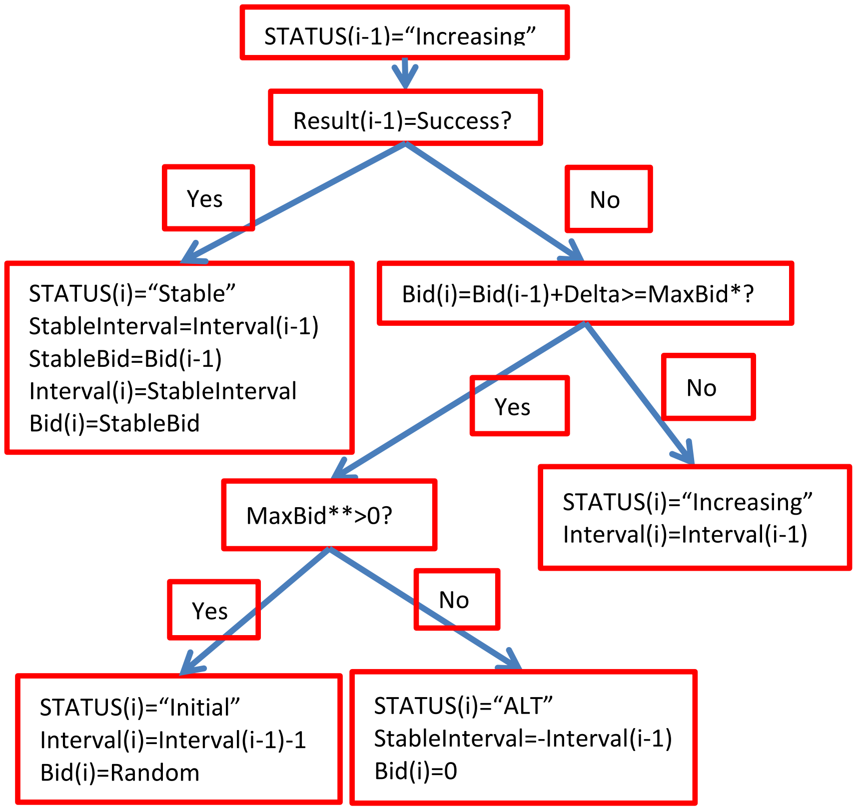


*: Please refer to **FIGURE 1** for notations

FIGURE 2 Decision Making Flowchart when Status is "Decreasing"

Increasing

A DA continues increasing the bid until s/he succeeds, as long as the total reservation cost does not exceed the arterial cost, and then set the state as "Stable" (**FIGURE 3**). If the DA has reached the up-ceiling bid amount, it either moves to an earlier interval and sets the state as "Initial", or uses arterial, if the time cost of the earlier interval is even higher than current arterial cost, just like the logic in "Initial" state.



*: Please refer to **FIGURE 1** for notations

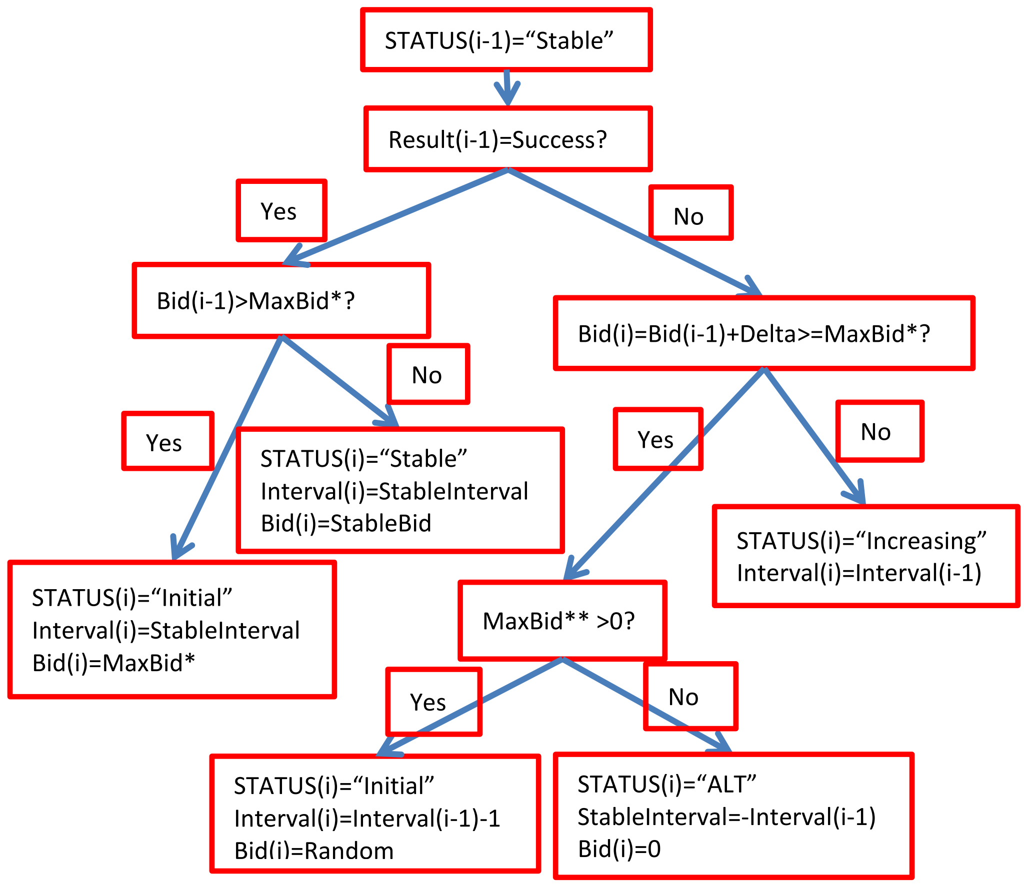
FIGURE 3 Decision Making Flowchart when Status is "Increasing"

Stable

If a DA loses a bid in the "Stable" state, it will follow the same logic with the "Initial" and "Increasing" states. If the up-ceiling bid is reached, the DA either moves to earlier interval and sets the state as "Initial", or uses arterial, if the time cost of the earlier interval is even higher than current arterial cost (***:** Please refer to **FIGURE 1** for notations

FIGURE 4). Also the "Stable" DAs keep an eye on the arterial cost, and if the cost of using reservation system is found to be higher than the arterial cost, the DA will reduce the bid correspondingly (***:** Please refer to **FIGURE 1** for notations

FIGURE 4).



*: Please refer to **FIGURE 1** for notations

FIGURE 4 Decision Making Flowchart when Status is "Stable"

ALT

In the "ALT" state, a DA will use arterial without trying to bid in the reservation system. With 5% chance, the "ALT" DAs give reservation system another try. The rest 95% and all the DAs rejected by the reservation system will have to use the arterial, and choose a departure time. The departure time choice is critical to the simulation. Here is the logic we used. If a DA happened to travel through the arterial in the previous iteration, s/he will determine the departure time by a simple rule: desired arrival time minus the previous arterial travel time. If this user's arterial experience is a few iterations before, it is considered as outdated, since the arterial travel time changes dramatically by iteration. In this case, the departure time is adjusted based on the average arrival time of arterial users with the same OD pair and DAT from the last iteration. A tolerance time window is assumed to be from being 10 minutes early to being 4 minutes late. If the previous iteration's average arrival time falls within this window, no adjustment is made to the departure time in this iteration. If not, early arrivals will trigger the departure time being later, and vice versa. The actual departure time intervals are uniformly distributed in five consecutive intervals (± 2.5 intervals) around the adjusted interval, to avoid it being oversaturated.

Time Value

The value of travel time is assumed to follow a lognormal distribution with mean value 15.56$/hr and standard deviation 4.78$/hr, according to a report [31]. The value of early arrival at workplace is assumed to follow a lognormal distribution with mean value 9.44$/hr and standard deviation 2.9$/hr. The late arrival value of time is also lognormal with mean 38.28$/hr and standard deviation 7.54$/hr. The value of early and late arrival is derived from the value of travel time based on the ratios from Small's study [32]. For the same person, travel time value is at least 30% higher than early arrival time value, and late arrival time value is at least 30% higher than travel time value. If these two criteria are not satisfied, a user's value of time is re-drew from the corresponding distributions.

CASE STUDY

We idealized the Interstate 66 (I-66) and parallel US-29 in Virginia between Centreville and Interstate 495 (I-495) as the simulation testbed (**FIGURE 5** and **FIGURE 6**). This is a major commuting corridor for people that work in Washington DC/Arlington/Tysons Corner area and live in Fairfax/Centreville/Chantilly area. I-66 can be split into 6 links along this route by on- and off-ramps. US-29 is a parallel arterial along the I-66 route. **FIGURE 5** shows the map of the network with all the nodes, links and connectors. **FIGURE 6** is an abstract view just showing the zones. I-66, the highway (green links), is managed by the reservation system, and US-29, the arterial (red links), is open to all traffic. All the highway and arterial links are two miles long. The maximum allowed hourly volume on the highway is 7200 vehicles/hour (four lanes), and 2000 vehicles/hour on the arterial. The predefined control speed of the highway is 60 mph. The speed of the arterial is set to be 20 mph, which is relatively low in order to compensate the miss of traffic signals in the testbed. The time interval is 2 minutes in this study.

Black numbers are links IDs.

Red numbers in circles are node IDs.

FIGURE 5 Simulation Testbed: an Idealized Highway and Arterial System

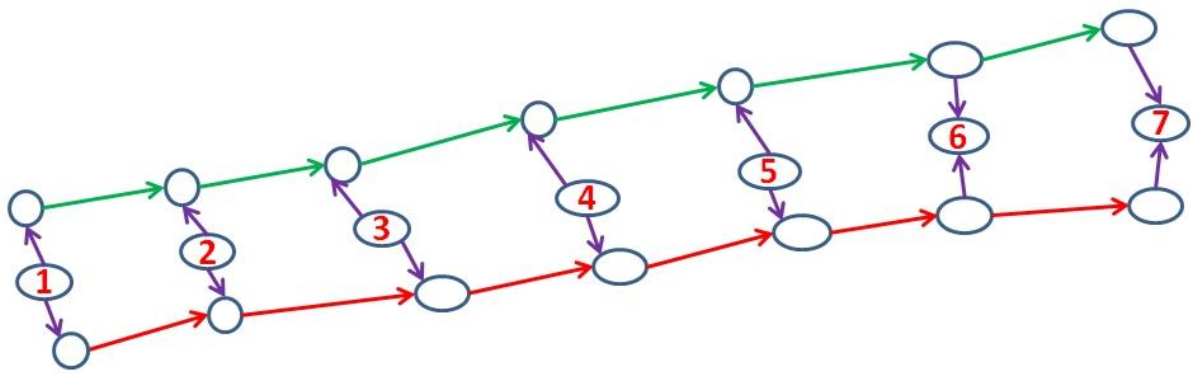


FIGURE 6 Simulation Testbed Abstract Graph

A total of 23,000 people are assumed to travel on this network on a daily basis. The OD matrix is shown in **TABLE 1**. Trips that need single highway link are not considered, since they are too short and people would be more likely to use local roads. The desired arrival time of all the 23,000 people or agents are randomly assigned: 10% 8:00am, 20% 8:30am, 50% 9:00am, and 20% 9:30am.

TABLE 1 OD Matrix

OD	**3**	**4**	**5**	**6**	**7**
1	920	1840	1840	1840	1840
2		920	1840	1840	1840
3			920	1840	1840
4				920	1840
5					920

The authors developed a program to feed MATSim with individual travelers' departure time, have MATSim do the network loading, and take the arrival time of individual travelers from MATSim as input to the simulation of the auction. To be more specific for readers knowing MATSim, we did not use MATSim's replanning module, instead we used the auction system to generate the trip plans and feed them to MATSim's network-loading module.

RESULTS AND DISCUSSIONS

Converging process

In the beginning of the simulation, all the users try to reserve their most desired time interval, and these intervals are short in supply. As a result of the capacity constraint, only small number of users with the highest bids win, and the others are rejected. That's why the number of accepted users is low at the beginning shown in **FIGURE 7**. Since a lot of people are rejected and use the arterial, the arterial is severely congested, generating extremely high travel cost. Thus these users bid very high. That's why we see the total collected revenue increases quickly in the beginning of the simulation as shown in **FIGURE 7**. As time goes on, people begin to bid earlier time intervals and win, and fewer people use the arterial, relieving the arterial congestion, and lowering the bids. So the total revenue decreases. When the number of people actually accepted into the reserved highway and the total collected revenue become stable at around 130th iteration, the simulation converges, as shown in **FIGURE 7**. The converging revenue is 154,000 dollars, and the converging number of highway users is 19,170. The auction system creates a filter: lower-time-value users are filtered to earlier intervals. **FIGURE 8** illustrates that for the users with the same OD and same DAT, those winning later intervals have higher value of travel time in general.

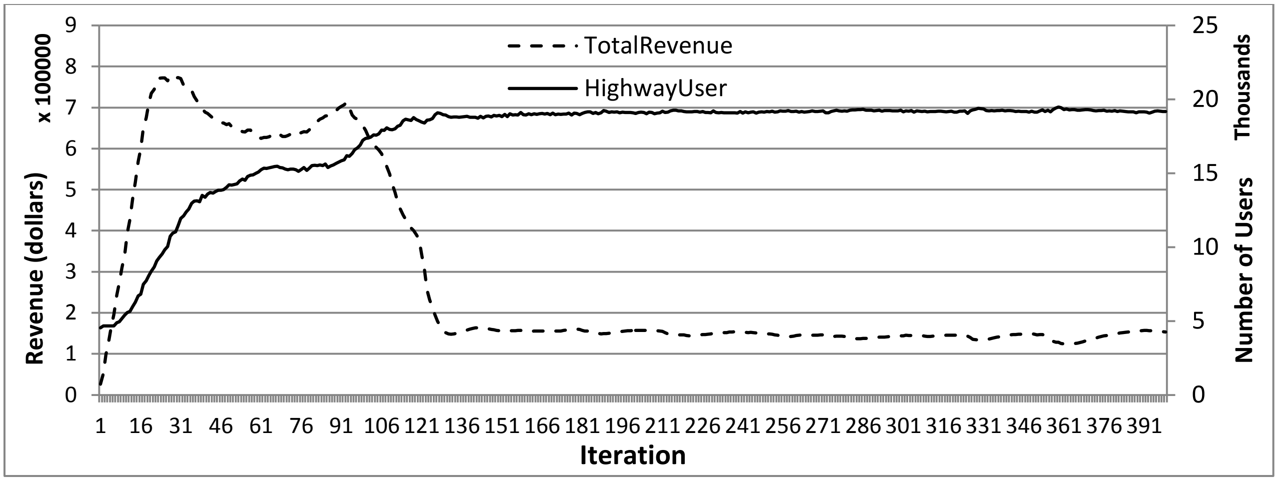


FIGURE 7 Total Number of Accepted Users and Total Revenue by Iteration

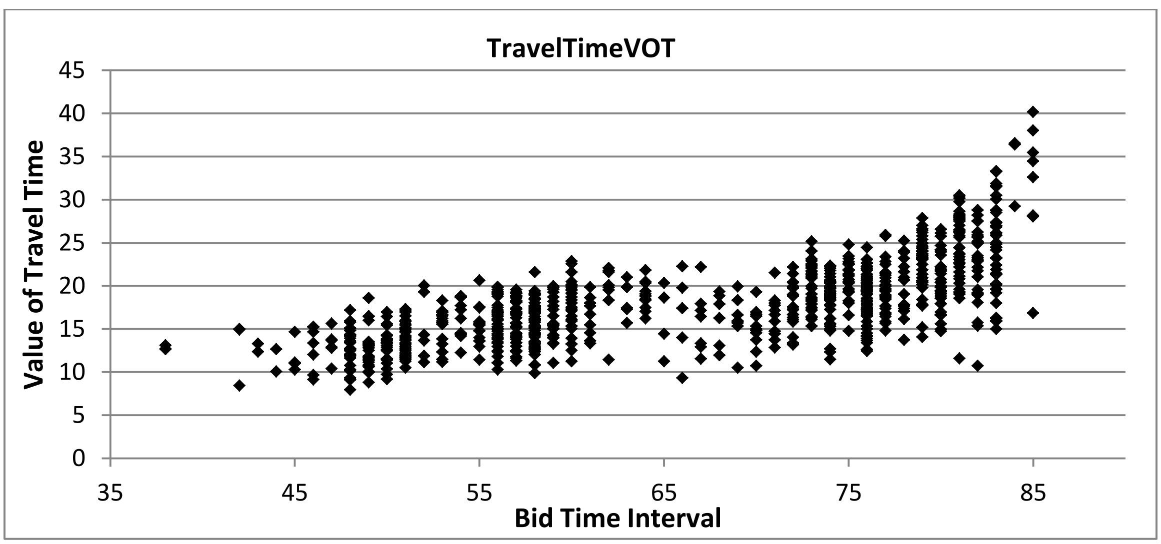


FIGURE 8 Value of Travel Time by Bid Interval: Users with DAT 9:00am between OD (2, 6)

FIGURE 9 shows how the number of people in the states “ALT”, “Initial” and “Stable” change by iteration. After 150 iterations, the number of users in the three states becomes fairly stable with minor fluctuations. The fluctuation comes from the arterial travel time variability, since “Stable” users keep an eye on the arterial travel time and will reduce the bid and change the state to “Initial” if they find themselves overpaying (shown by the left-most box in ***:** Please refer to **FIGURE 1** for notations

FIGURE 4). Whenever arterial travel time drops, the number of “Stable” users decreases, and the number of “Initial” users increases. Note that after convergence, the number of highway users (**FIGURE 7**) is much more stable than the number of users in the three states in **FIGURE 9**, since the reserved highway users could come from any of the “Initial”, “Stable”, “Decreasing” and “Increasing” states.

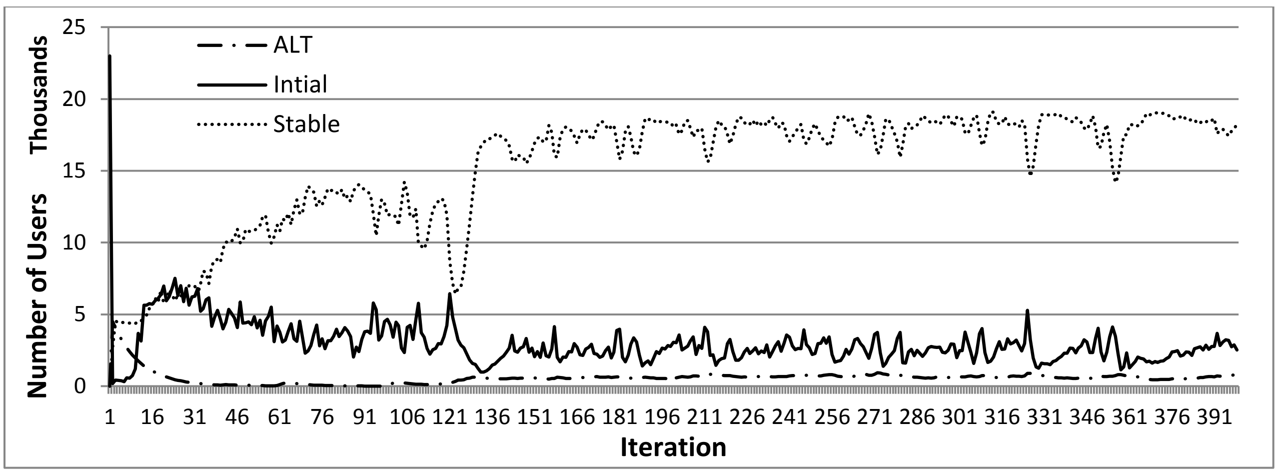


FIGURE 9 Number of Users in “ALT”, “Stable”, “Initial”, and “Stable” States by Iteration

Bidding Cost Analysis

The total collected revenue at converging is 154,000 dollars per day, 8.0 dollars per person, or 1.07 dollars per mile. Since the users decide how much to bid based on the comparison with arterial, they pay more when the total demand level becomes higher. **TABLE 2** shows the sensitivity analysis of changing the demand level from 17K to 29K (note that demand level is adjusted by shrinking or expanding the OD matrix in **TABLE 1**). As the demand grows, the bid cost per user and the average collected revenue per mile increases. Note that other than this sensitivity analysis, all the discussions in this paper are based on overall demand level 23K.

TABLE 2 Sensitivity Analysis of Overall Demand

Demand	17K	20K	23K	26K	29K
Reservation User (%)	85.6	84.9	83.4	81.3	81.3
Total Revenue ($)	74K	112K	154K	171K	265K
Average trip length (mi)	7.4	7.4	7.5	7.5	7.5
Revenue per User ($)	5.05	6.62	8.01	8.11	11.25
Revenue per Mile ($)	0.68	0.89	1.07	1.08	1.51

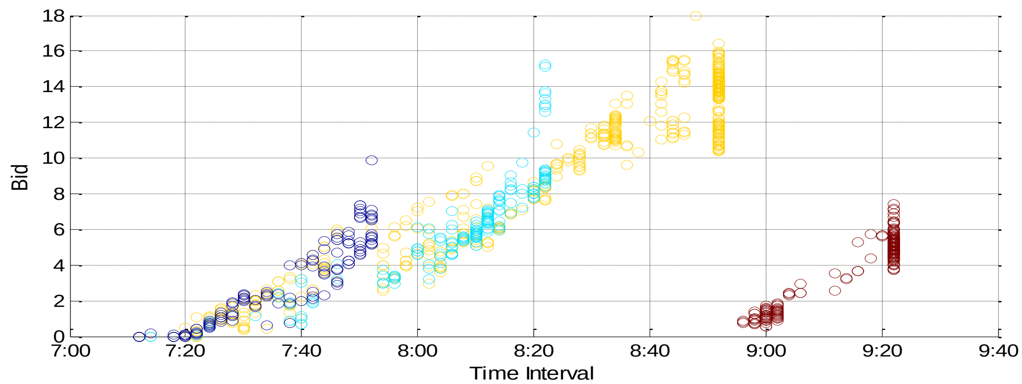
The bid amount a user is willing to bid depends on how much time s/he can save by switching from the arterial to the reserved highway. Generally, as the trip length is longer and as the arterial becomes more congested, the user bids higher. But it also depends on the demand level over a period. Given a traffic network, OD matrix, travelers' value of time, and their desired arrival time, the agent-based simulation tool tells how much are people bidding for certain routes and time intervals. **FIGURE 10** shows the bid of three OD pairs: (1, 4), (1, 7) and (3, 6). Below are the four findings from these plots.

1) The bid increases by time for people with the same DAT. In the simulation setting, the users want to arrive at the workplace right on time instead of being early or being late, thus later time intervals are more attractive as long as they are not late. That's why people generally pay higher for later intervals.

2) For the users from the same OD pair, their bids for a particular interval are close, no matter what DAT they have. This is easy to understand, since the TMA does not know these people's DAT. All it does is sorting the requests by bid and handle them from high to low. Due to the existence of the "decreasing" process in the people's decision-making, they all end up paying very similar prices.

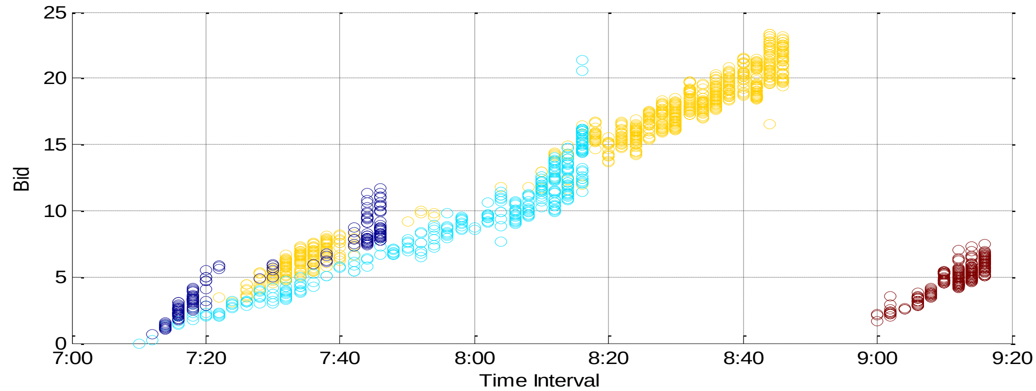
3) For the same interval, the bid of the users from OD (1, 7) is similar to the users from OD (3, 6), but higher than the bids of people from OD (1, 4). For example, for the 8:40 interval, OD (1, 7) and OD (3, 6) users pay 20 dollars, while the OD (1, 4) users pay 13 dollars. This has something to do with the OD structure. As shown in **TABLE 1**, the links (both highway and arterial) between zone 3 and zone 5 are used by 80% of the users: the most among all the links. Thus, these links are the bottleneck. OD (1, 7) and OD (3, 6) use both of the two bottlenecks, while OD (1, 4) users use only one of them, that's why OD (1, 7) and OD (3, 6) users pay higher than OD (1, 4) people. OD (1, 7) and OD (3, 6) users pay similar bids although OD (1, 7) trip distance is twice longer than OD (3, 6), because the bottlenecks are the determining factor of price.

4) The bid of users with DAT 9:30 am is much lower than the other people. 50% of the users have DAT 9:00 am, and these users use time interval as early as 7:20. Since these people bid higher, all the users with DAT 8:30 and 8:00 have bid as high to win. However, the users with DAT 10:00 am are relatively independent, as they can use the highway between 9:00 am and 9:30 am. When the majority want to get to work before 9:00 am, being able to go half an hour later can save a lot of travel time, or money in this case.



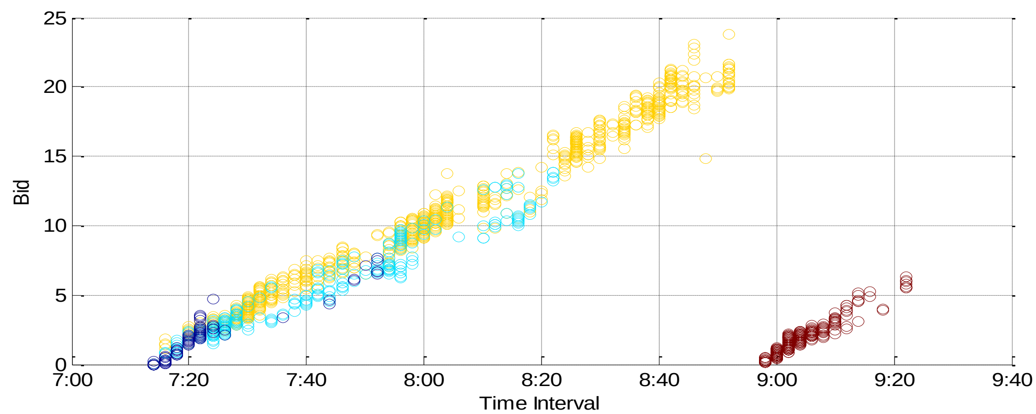
Blue: DAT 8:00am Cyan: DAT 8:30am Yellow: DAT 9:00am Red: DAT 9:30am

a) Bid Cost of People from OD (1, 4)



Blue: DAT 8:00am Cyan: DAT 8:30am Yellow: DAT 9:00am Red: DAT 9:30am

b) Bid Cost of People from OD (1, 7)



Blue: DAT 8:00am Cyan: DAT 8:30am Yellow: DAT 9:00am Red: DAT 9:30am

c) Bid Cost of People from OD (3, 6)

FIGURE 10 Bid Cost Plots

Comparing with MATSim Traffic Assignment

To see how much benefits the auction-based reservation system can bring to this highway/arterial network, we compared the total travel time of the reservation system with MATSim's dynamic traffic assignment module. The MATSim module works in different way with the reservation system, as explained below.

MATSim uses complete all day activity plans as search space to maximize a fitness function, as shown in **EQUATION 1** [22]. Using all day plans means the activity durations can be shortened or extended and it will affect the fitness function. However, the highway reservation system in this study is based on the morning commuting trips from home to work, without changing the activity durations. We used exactly the same desired arrival time for all the people in the MATSim DTA system. One parameter in the DTA module named "MutationRange" determines the range of the departure time adjustment. It is the single most parameter that changes the dynamic assignment result. So we changed the MutationRange from 600s to 3600s and listed the corresponding simulation results in **TABLE 3**. As shown, in most cases the VHT of MATSim DTA is much higher than the reservation system. When the MutationRange is 3600s, the VHT of the MATSim DTA module is lower than the reservation system, but with some users' arrival time as late as 12:30pm, which is unacceptable and unrealistic. When the actual arrival time is not so late (10:40am when the MutationRange is 600s), the VHT is almost twice as much as the reservation system. Thus, the reservation system achieves very short VHT with the departure time range only 2 hours and 34 minutes, much better performance than the MATSim DTA module.

$$F = \sum_{i=1}^{n} U_{\mathrm{act}}(\mathrm{type}_i, \mathrm{start}_i, \mathrm{dur}_i) + \sum_{i=2}^{n} U_{\mathrm{trav}}(\mathrm{loc}_{i-1}, \mathrm{loc}_i)$$

EQUATION 1 MATSim Fitness Function

TABLE 3 Comparison between the Reservation System and MATSim DTA

		MATSim DAT (MutationRange changes)					
	Reserv.	600s	900s	1200s	Default	1800s	3600s
# Highway Users	17933	20213	20185	20100	20127	20358	21950
# Arterial Users	5067	2787	2815	2900	2783	2642	1050
VHT	5770	10424	9670	9221	8127	7973	5271
Departure Time	6:50am 9:24am	7:50am 10:10am	7:50am 10:20am	7:50am 10:50am	7:50am 11:10am	7:50am 11:20am	7:30am 12:30pm
Departure Time Range	2hr 34min	2hr 20 min	2hr 30min	3hr	3hr 20min	3hr 30min	5hr

Catfish Effect

In each iteration, a small proportion of users in the state “ALT” give the reservation system a shot. This is a reasonable assumption, and these people play the role of “catfish.” With the “decreasing” process, if there is no new users coming to bid a time interval, the existing users of that interval will come up to a “trust” to put very low bids. Now some arterial users bid in the reservation system again, and mostly likely they bid with the highest price they can afford or slightly lower. In this case, the existing users have to bid high enough to retain the slots, and the “trust” would not last long even if it exists. Like sardines, who have to keep swimming to avoid being eaten by the catfish, the reservation system users have to bid high enough to avoiding being kicked out by the returning arterial users.

Longer or shorter trips are favored?

At first glance, shorter trips are more easily accepted by the reservation system, since they need fewer links available. On the other hand, longer-trip travelers bid higher, since they save more time by switching from the arterial to the reserved highway. From this perspective, the longer trips are favored by the reservation system. The truth is that the bottlenecks matter. In **FIGURE 10**, both OD (1, 7) and OD (3, 6) users need the bottleneck (links between zone 3 and 5), thus they pay almost the same for the same interval, although OD (1, 7) trips are 12 miles long while OD (3, 6) are 6 miles long. Comparing OD (3, 6) and OD (1, 4), they have the same distance, but OD (3, 6) users pay much higher than OD (1, 4), because OD (3, 6) need more bottleneck links.

Social Equity

The auction-based reservation gives wealthy people more leverage of using the highway, since they can afford higher bids. Thus, it might bring a social equity concern. Current traffic demand management strategies, such as HOT or other congestion pricing techniques, all have the same problem. The auction-based system is advantageous since it also makes it easier to conquer the social equity issue with two potential ways. The first is redistributing the collected bid back to the all the participants, evenly or proportion to the distance [16, 17]. In this case, the users rejected by the system receive some refund to compensate the losing chances of using the reserved highway, so it is with the users who have to use very early time intervals. Another way is having the users bid with some "reservation coins," instead of directly using money. They are allocated a certain amount of "reservation coins" at the beginning, and can trade them at a free market. In this case, some people can make some profit by selling the coins. This paper will not dig too much into the social equity issue, and leaves it to future studies.

CONCLUSIONS AND RECOMMENDATIONS

This study shows the agent-based simulation of an auction-based highway reservation system. At converging, the number of users in the reserved highway and the total collected revenue become stable. In comparison to the state-of-the-art research work, this study has a number of advantages. 1) The VHT at converging is around 40% lower than the MATSim Dynamic Assignment result, under similar departure time range, since the queues and delays are avoided with the capacity constraint imposed by the reservation system. 2) The highway reservation concept provides the users a chance of buying insurance for a protection of their travel, against highway congestions, and for a guarantee of free-flow travel. The premium is determined by the users themselves through auctions, different from normal High-Occupancy-Toll lane, in which the operator sets the tolls and updates them based on system performance. 3) The auction system is more like a personal tolling system that finds the maximum amount a user is willing to pay. Or it transfers more consumer surplus to the operators, since high-time-value and risk-averse travelers pay higher. Under the given demand level, the converging revenue is around 8 dollars per user, and 1.1 dollars per mile.

The simulation provides a solution to a complex problem, and it consumes a lot of computing resources. The simulation time is proportional to the total number of users, the number of routes, and departure time interval options. For a larger scale simulation, there would be more users and routes, while the number of departure time intervals remains the same. For one user, the number of available routes is limited even for a metropolitan traffic network, since the focus is the highway and its alternative routes. We are caustically optimistic about the computational requirements of the model due to technology advancements. Like all models with user behaviors, the simulation tool requires a large amount of detailed and accurate input data, including the agents' time values and decision-making logic.

There are three directions of future studies for the auction-based simulation. The first one is an emergency-response system, say how to change the users' reservation plans or even persuade some of them to cancel the reservation, when some or all the links cannot reach the designed speed or volume. The second one is modelling a High-Occupancy-Toll over the same testbed, and comparing the revenue with the auction system. Another direction is cracking the social equity issues, by redistributing the collected revenue back to all the users or using tradable reservation coins to bid instead of money.

The field implementation of such a reservation system also faces some challenges. For example a real-time communications channel between the drivers and the control center is required for the bidding and speed control. A smooth transition between the reserved lanes and general-purpose lanes is another challenge, since the former could be much faster than the latter, thus special assistance is needed to safeguard a lane-change from congested general-purpose lanes to the fast reserved lanes. The highway reservation system is a gold-mine for researchers, with these implementation challenges.

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CHAPTER 5

CALIBRATING COMMUNICATION SIMULATOR FOR CONNECTED VEHICLE APPLICATIONS

CALIBRATING COMMUNICATION SIMULATOR FOR CONNECTED VEHICLE APPLICATIONS

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ABSTRACT

Research efforts focused on the Connected Vehicle (CV) technology applications typically assume perfect communications among the vehicles and between the vehicles and the roadside equipment. However, a few studies, including this one, pointed out that the wireless communications experience packet drops, which might lead to a serious downgrade of the safety critical CV applications. Thus the wireless communication simulators used to emulate the communications performance need to be properly calibrated to replicate the real world vehicular communication environments. This study calibrated an NCTUns simulator for the Dedicated Short Range Communications (DSRC) of CV technology using the DSRC field test data executed on an instrumented intersection at the Turner Fairbank Highway Research Center. Physical layer parameters (e.g., data rate and transmission power) as well as channel models are calibrated. The calibration applied a Latin Hypercube Sampling technique to generate multiple combinations of parameter sets. The calibrated NCTUns simulator produced much more realistic outputs than the uncalibrated one. Then it was applied to a signalized intersection in a case study to further investigate the packet drops of DSRC-based CV communications. The results indicated that there were significant packet drops requiring further research before implementing safety critical CV applications.

INTRODUCTION

Intelligent Transportation System (ITS) intends to establish safe and reliable surface transportation systems by using sensing technologies including vehicle sensors, speed radars, traffic cameras, and radio frequency identification technology. A new technology named Connected Vehicle (CV) for transportation was initiated when the Federal Communication Commission allocated 75 MHz of licensed spectrum to use for Dedicated Short Range Communication (DSRC) in the US [1]. By enabling Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) wireless communications, this technology is expected to produce much more benefits than existing ITS technologies by providing accurate real time information of individual vehicles, such as trip OD, real-time position, speed and acceleration, from the opted-in vehicles. Given the provided rich data, a lot of emerging transportation services and applications mainly focusing on safety and mobility are being investigated. An example is Cooperative Intersection Collision Avoidance System (CICAS) [2], a V2I cooperative system designed to address intersection crash problems such as unprotected left turn movements. Other state-of-the-art applications include traffic monitoring [3, 4], ramp metering [5], route guidance [6], traffic signal control [7-12], freeway safety [13, 14], Vehicle-Infrastructure-Integration implementation issues [15-17], and public transit applications [18]. These studies showed promising results.

The studies mentioned above did not consider the practical issues of wireless communications, such as packet drops and communication delays. Instead, they assumed perfect and real-time information sharing among the vehicles and the Roadside Equipment (RSE). However, that is not the case in the real world. Due to the complexity, unpredictability and wide variety of vehicular environments, the DSRC communication environments are affected by a lot of factors including separation distance, vehicle speeds, the number of vehicles within the communication range, physical obstacles (e.g., building, barriers, or foliage), and even temperature [19]. Under such imperfect and unpredictable vehicular networking environments, both V2V and V2I communications could produce serious communication latencies and packet drops, leading to a degradation of the CV applications' performance. For example, Shladover and Tan [20] analyzed the vehicle positioning accuracy needed for effective cooperative collision warning based on vehicular communications. The communication latencies and packet drops can lead to higher variance of the positioning accuracy. As a result, a reliable tool that can evaluate the DSRC quality under unpredictable propagation channels would serve as the enabling foundation for robust, practical, and efficient design of CV applications.

The purpose of this research is to calibrate a wireless communication simulation tool which handles the DSRC communication standards, such as IEEE 802.11p [21], IEEE 1609 [22], and SAE J2735 [23], by using empirical packet drop rate (PDR) data obtained from an actual CV testbed in Northern Virginia operated by FHWA. To this end, this research selected NCTUns (Wang & Lin, 2008) as the simulation tool from many existing commercial/non-commercial communication-network simulators such as NS-2 [24], OPNET [25], GlomoSim [26], NCTUns [27], because NCTUns, at the time of this study, does implement most of the DSRC protocol layers without modifying the source code.

The rest of the paper is organized as follows. Literature review summarizes the previous studies on building vehicular wireless communication models. Then the DSRC field test conducted in TFHRC is described with data analysis. The methodology section presents the process to calibrate and validate the NCTUns simulator's parameter set. Then a case study shows the simulator's effectiveness for multiple vehicles by applying it to a signalized intersection. Finally, findings and future research suggestions are discussed.

LITERATURE REVIEW

Researchers have tried to use both theoretical and statistical communications models in the wireless access vehicular environment (WAVE). Theoretical models can accurately realize specific propagation channels, but some simplicity assumptions are needed due to the high complexity and unpredictability of signal channels. Statistical channel models have a few adjustable inherent parameters to better fit different environments. Some studies analyzed field experiments data of DSRC under multiple driving environments, and revealed some basic characteristics. A short review of theoretical modeling efforts is given first and followed by a detailed introduction of statistical channel modeling studies.

Theoretical vehicular communication modeling is discussed in numerous research efforts [29-40]. Tabatabaei et al. [38] refined traditional propagation model parameters to consider characteristics of vehicular environments. For non-line-of-sight (NLOS) component, the model considered reflection distance and roadside obstacles for slow-fading and a phase factor for fast-fading. For line-of-sight (LOS) component, they considered single and double reflections from roadside buildings and the distribution of vehicles within a street segment to adjust the reflection coefficient. Boban et al. [39] proposed a model that considered vehicles as three-dimensional obstacles and took into account their impact on the LOS obstruction, received signal power, and the PDR. Boban et al.'s research showed the feasibility of modeling the vehicles as obstacles in existing simulators. The CORNER model used by the Vehicular Lab at UCLA [40] includes three LOS scenarios. The model works well in city centers with grid traffic network, where it is feasible to estimate the LOS condition by a reverse geocoding based on road topology. Its application in other environments might be limited, and this model is incapable of considering the effects of moving vehicles on the communication quality. Generally speaking, theoretical models are based on certain simplifying assumptions of the vehicular environment, such as single and double reflections of roadside buildings. That's why the theoretical models have limited applications, due fast-changing vehicular environments.

Statistical channel models include large-scale propagation model (slow-fading) and small-scale fading model (fast-fading). In slow-fading, the amplitude and phase change imposed by the channel can be considered as roughly constant over the period of use. Three major large-scale models are free-space model (FSM), two-ray ground model (TGM) and free-space shadowing models (FSSM) [19]. FSM and TGM are deterministic in nature with distance as the main affecting factor. FSSM considers shadowing effect into FSM by including a Gaussian random factor. In the regime of fast-fading, the amplitude and phase change is considered to vary considerably over the period of use. Fast-fading model includes three commonly used Rayleigh, Rician and Nakagami models [19]. Rayleigh fading model is suitable for NLOS urban area where numerous multiple reflective paths exist. Rician fading model is suitable for a dominant LOS condition. Nakagami fading model is a practically useful for small-scale fading [6]. Each of these fading models has some characteristic input parameters. A lot of studies have investigated the selection of fading models for a specific environment and have calibrated the models' input parameters [41-45]. The following part summarizes the findings of key calibration work and discusses their gains and shortcomings.

Taliwal et al. [41] used Nakagami model in an open space and a typical highway with moderate traffic and calibrated the parameters from empirical data. It showed that the Nakagami average power parameter Ω falls off as the inverse-square of the sender-receiver separation distance up to about 160 meters and as the inverse-fourth of the distance more than 160 meters. This means the fast-fading is close to FSM under 160 meters and TGM beyond 160 meters for both open space and moderate highway environment. The calibrated Nakagami fading parameter m lies between 1 and 4 for open space area and between 0.5 and 1 for the highway. It shows that highway environment is more serious in fading than open space possibly because of obstacle impacts of vehicles on highway and Doppler effects caused by higher vehicle speed. Yin et al. [42] also calibrated Nakagami model using empirical data. The analysis revealed that fast-fading follows Rician model within 100 meters and Rayleigh model beyond 100 meters. Cheng et al. [43] calibrated a large-scale propagation model and Nakagami model using two sets of continuous WAVE experiments in suburban driving environments. The distance between two vehicles equipped with a transmitter or a receiver ranged from 2 to 600 meters. The finding was very similar to [42]: fading is more severe than Rayleigh at large distance and is Rician at small distances. Miloslavov et al. [45] used data from Detroit-area Michigan Vehicle Infrastructure Integration (VII) testbed to calibrate the channel model for WAVE/DSRC. It considered two large-scale models: TGM and FSSM, and

Nakagami model for small-scale fading. Similar to [43], the calibrated Nakagami m value is 1.0 when distance is large than 150 meters, and 1.5 within 150 meters.

In summary, the research mentioned above all used Nakagami model in small-scale fading effects and showed the communication performance as a function of distance [41-45], but did not take into account the impacts of other environmental factors such as vehicle speed. Yin's paper [42] used the received signal strength as the indicator of communication quality but latencies and packet drop rates are more directly related to the performance of CV based applications. Miloslavov's study [45] has some shortcomings: when comparing TGM with FSSM, they set other parameters to the commonly used in most simulation studies. However, those factors such as propagation distance and reflection coefficient are indeed affected by vehicular environments, as shown in Hosseini Tabatabaei et al.'s study [38]. Another shortcoming of Miloslavov's paper is a lack of model validation.

Compared to the previous research efforts reviewed in this section, our research overcomes the limitations by (i) using PDR (instead of signal strength) as a fitness indicator, (ii) using a Latin Hypercube Sampling (LHS) technique that helps better covering the whole sample space and (iii) validating the calibrated parameters via additional field observed data not used in calibration.

OVERALL CALIBRATION FRAMEWORK

Calibration means finding an optimal parameter combination that produces the best fit with field test data. It is similar to finding the maximal or minimal value of a function with multiple independent variables, while the only difference is that the "function" here is a simulator with no explicit mathematical expression. Thus it is difficult to identify the shape of the whole response surface given the large number of independent variables (12 in this case). So a Latin Hypercube Sampling (LHS) technique [46] was used to sample the parameter combinations. LHS is a form of stratified sampling that can be applied to multiple variables, and is commonly used to reduce the number of runs necessary for a Monte Carlo simulation to achieve a reasonably accurate random distribution. Compared with pure random sampling, LHS has the advantage of generating a set of samples that more precisely reflect the shape of a sampled distribution, and is pointed out to perform better than random sampling [47, 48]. The following steps show how LHS works.

1) LHS divides the range of each factor into n>1 mutually exclusive and exhaustive intervals of equal probability, and randomly selects one value for this factor (x1) from each interval without replacement. So a total of n values are sampled.
2) LHS pairs the n values of factor x1 with the n values of factor x2 randomly without replacement. Each level of a factor appears exactly once in each pair.
3) LHS combines these n pairs with the values of other factors.

DSRC FIELD TEST AND DATA ANALYSIS

Data Collection and Processing

The actual communications data were collected at the Cooperative Vehicle Highway Testbed of the Saxton Transportation Operations Laboratory located in TFHRC in McLean, Virginia, on Friday, August 19, 2011 for approximately 40 minutes (i.e., from 5:15 pm to 5:53 pm). The testbed is an instrumented intersection equipped with a RSE nearby (**Figure 1**). In the controlled traffic, a vehicle equipped with Onboard Equipment (OBE) traveled between point A and point B. The distance between the OBE and the

RSE ranged from 5 meters to 240 meters. The OBE broadcasted a Here-I-AM (HIA) message at every 100 milliseconds interval and the RSE sent an A la Carte Message (ACM) back to the OBE. The OBE-equipped vehicle had a GPS device which could detect and record its real-time position and speed at each time stamp when the messages were sent and received at the OBE. The messages were captured by "data sniffers" connected to both the RSE and the OBE. Following are the collected data by the sniffers and the GPS device:

- OBE trajectory: Each record of this file was a time-stamped latitude/longitude position of the OBE. The GPS locations were transformed to Universal Transverse Mercator coordinates and then transformed to coordinates relative to the RSE location.
- OBE communication log data: This binary type log data recorded the time stamps at which the OBE sent messages and actual packet data to the RSE. The log data was converted to readable text data by a commercial network sniffer program, namely WireShark [49]
- RSE communication log file: The structure of the RSE log file is the same as the OBE log file. It was analyzed in a similar way with OBE log data.

Figure 1 Turner Fairbank Highway Research Center Test Bed

Since all the messages transmitted between OBE and RSE were unique and could be identified easily, by checking the messages in the OBE and the RSE log data, one can tell whether a packet transmission was successful. For instance, if a packet was identified in both the OBE and RSE log file, the packet was successfully transmitted; the time between OBE sending a message and RSE receiving the same message is treated as the packet transmission latency. The OBE GPS location data were also captured when the messages were sent out and received at the RSE. It is noted that the test bed in TFHRC utilizes both differential GPS and geo-referenced grids on the test bed highway to improve the accuracy of GPS measurement up to 0.5 meters. The data were collected for around 6 minutes. 2.5 minutes data were used for simulator calibration, and the other 2.5 minutes data were used for validation. The OBE was over 210 meters away from the RSE during the rest 1 minute, that’s why data of that minute was not used.

Data Analysis and Findings

The PDR Root Mean Square Error (RMSE) between field data and simulation results was used as the measure of effectiveness in this study. The transmissions were aggregated by distance, i.e., all transmissions that happened within a specific distance bin were treated as one group/bin and produced a PDR. The PDR, average vehicle speed and the number of transmissions in each distance bin are shown in **Figure 2**. The simulated PDR measurement is compared with that field observed PDR to calculate the RMSE.

PDR gradually increases as the OBE moves further away from the RSE (**Figure 2**). When distance is larger than 120 meters, PDR can be as big as 0.65 with huge variations from the overall trend. This finding demonstrates the complexity of vehicular environments and lends support to the necessity of calibrating a simulator to model the fading effects. The overall trend of increasing PDR by distance can be described by large-scale fading model and the variations can be described by small-scale fading model.

As shown in **Figure 2**, the number of received messages remains stable in most of the distance bins except for two areas: one very close to RSE and the other near point B (**Figure 1**). As the messages were transmitted every 100 milliseconds, the number of messages transmitted in a distance bin depends on how fast the vehicle travels in that distance bin. The vehicle needed to turn near point B, and stop for traffic signal near RSE. That's why the number of messages is higher near point B and RSE area.

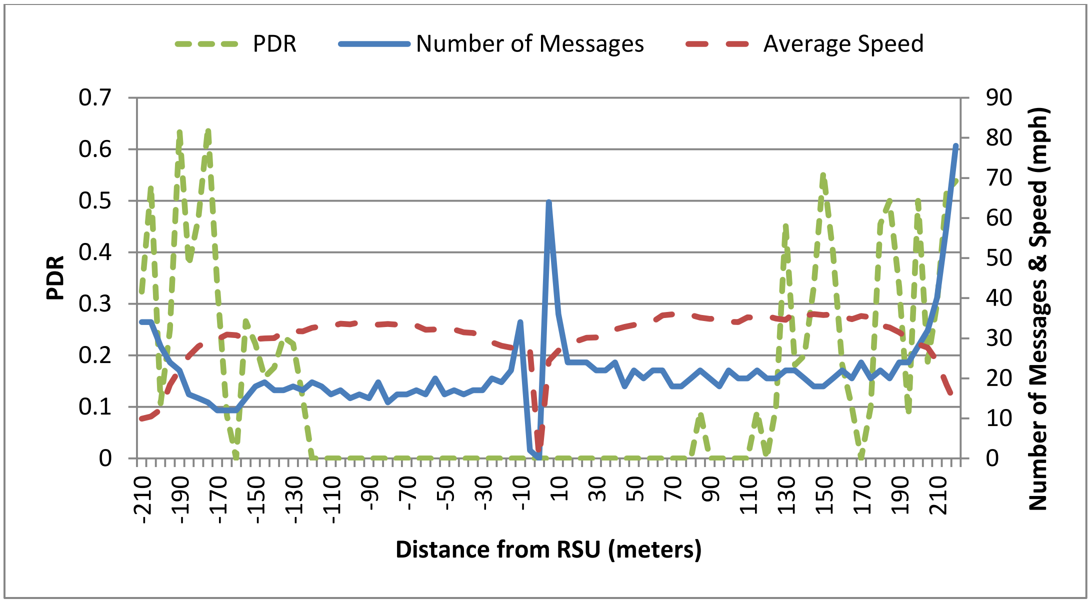


Figure 2 Packet Drop Rate, Average Vehicle Speed, and the Number of Messages by Distance

THE CALIBRATION PARAMETERS

As mentioned, NCTUns was selected because it was the only one that implements most of the DSRC protocol layers [27] at the time of this study. Original NCTUns was enhanced to include Nakagami fading model and SAE J2735-based message disseminations [50, 51]. SAE J2735 defines standard messages sets for DSRC-based communications. A detailed list of the calibration parameters and their default values are shown in **Table 1**.

Table 1 Parameter Values of the Best 10 Scenarios and the Calibrated Set

ID	Data Rate (Mbps)	TP*	LSF*	PLE*	System loss	SSF*	M1	M2	M3	D1	D2	RMSE
1	27	19	TGM	2.2	1.3	Na*	1.24	1.16	0.67	59	123	0.091
2	12	21	FSM	1.6	1	Na*	1.72	0.95	0.63	57	109	0.094
3	6	16	TGM	2.4	2.3	Ra*	2.16	1.15	0.7	51	113	0.099
4	18	21	TGM	2.6	2.6	Na*	1.96	1.07	0.67	58	134	0.100
5	6	16	TGM	2.7	2.4	Ra*	1.62	0.83	0.66	66	109	0.101
6	18	18	FSSM	2	1.4	No*	2.06	0.94	0.68	57	136	0.101
7	18	19	TGM	2.6	1.4	Na*	1.79	1.19	0.78	54	127	0.101
8	18	21	FSM	2	1.4	Na*	2.25	1.11	0.63	69	134	0.102
9	18	16	TGM	2.7	2.8	Ra*	2.04	0.9	0.65	70	117	0.105
10	18	17	TGM	3	3	Ra*	1.68	1.02	0.74	51	123	0.105
Final	27	19	TGM	2.2	1.3	Na*	1.85	1.1	0.7	59	123	0.092

TP Transmitter Power*

LSF: Large-Scale Fading*

PLE: Path Loss Exponent*

SSF: Small-Scale Fading*

Na: Nakagami*

Ra: Rayleigh*

No: None*

The default parameter values come from the initial settings of NCTUns. NCTUns has no default value for Rician K factor because Rician is a small-scale fading while there is no default small-scale fading model. It is also noted that Original NCTUns does not support Nakagami fading model, so there are no default values for it.

Two physical layer parameters, namely, data rate and transmitter power, are selected for the calibration parameter set. Since actual data rate and transmitter power are affected by numerous external factors (e.g., humidity, Doppler effects, etc.) and dynamically changing, it is challenging to precisely capture the actual values through the DSRC devices in the field test. Thus, it is necessary to properly calibrate them. The range of data rate is from 6 to 27 Mbps. Transmitter power determines the signal strength. The wireless communication fading effects are the combination of two sub effects: large-scale fading and small-scale fading. As shown in

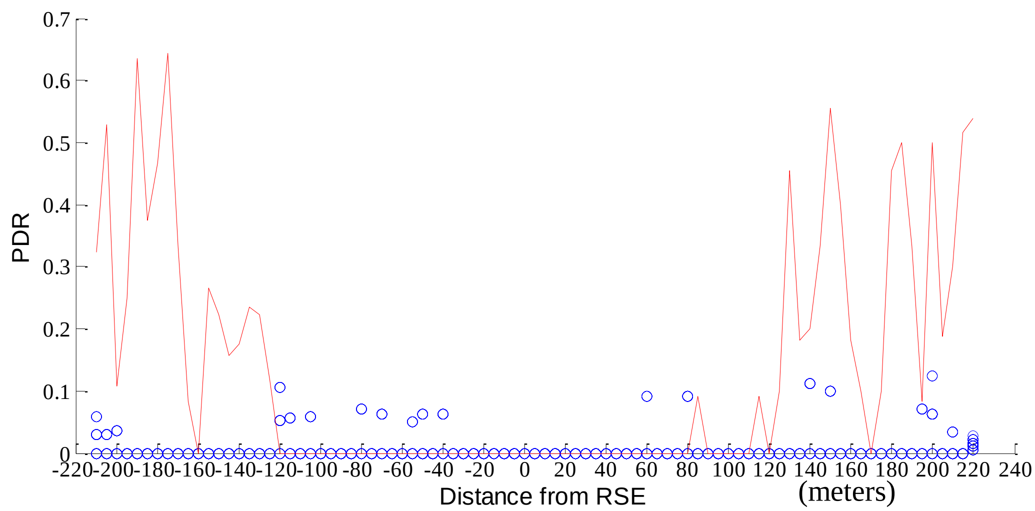
Table 2, the large-scale fading model has three options in NCTUns: FSM, TGM, and FSSM. FSM has a characteristic input called system loss exponent. FSSM has two inputs: system loss and path loss exponent. Small-scale fading model has four options: None, Rayleigh, Rician, and Nakagami. Rician model has a K factor as its characteristic input. Nakagami model has a characteristic m value. Previous research efforts [41-45] showed that Nakagami model fits empirical data very well, but its m value tends to vary with distance. Yin and Cheng [42, 43] revealed that small-scale fading is Rician at short distances and becomes Rayleigh or more severe at long distances. Miloslavov et al. [45] suggested m value as 1.0 when distance is larger than 150 meters, and 1.5 within 150 meters. To consider the effects of varying m value more effectively, three distance bins (0~D1, D1~D2, D2~infinity) and single m value for each bin (M1, M2, M3) were specified. The conclusions of the studies mentioned above are considered to specify the ranges of the five variables. Note that ideally speaking, continuous-changing m value would be best, but that’s very difficult to realize in NCTUns. As a compromise, three discrete m values were used.

Table 2 NCTuns Calibration Parameters Set

ID	Parameter Name	Factor/Level	Default
1	Data Rate	6,12,18,27 Mbps	6
2	Transmitter Power	6~30 dBm	28.8
3	Large-Scale fading model	Free-space model (FSM) Two-ray ground model(TGM) Free-space shadowing model(FSSM)	TGM
4	Path Loss exponent (for FSSM)	1.5 ~ 3.0	2.0
5	System loss (for FSM & FSSM)	1.0 ~ 3.0	1.0
6	Small-Scale Fading Model	None Rayleigh fading Model Rician fading model Nakagami fading model	None
7	Rician K Factor	6,10,20,30 dBm	--
8	Nakagami M1	1.2~2.4	--
9	Nakagami M2	0.8~1.2	--
10	Nakagami M3	0.6~0.8	--
11	Nakagami D1	50~70 meters	--
12	Nakagami D2	100~140 meters	--

The simulator with the default parameter settings was run for 50 times and the resulting PDR with field observed PDR are shown in **Figure 3**. The average RMSE of the

50 simulation runs is 0.225. As shown, the NCTUns simulator with default parameters produced almost flawless communications, which are not compatible with the field observed data.



Line: Field Test PDR Dots: Simulated PDR

Figure 3 Packet Drop Rate by Distance (Default Parameter, Calibration Data)

CALIBRATION OF THE SIMULATOR

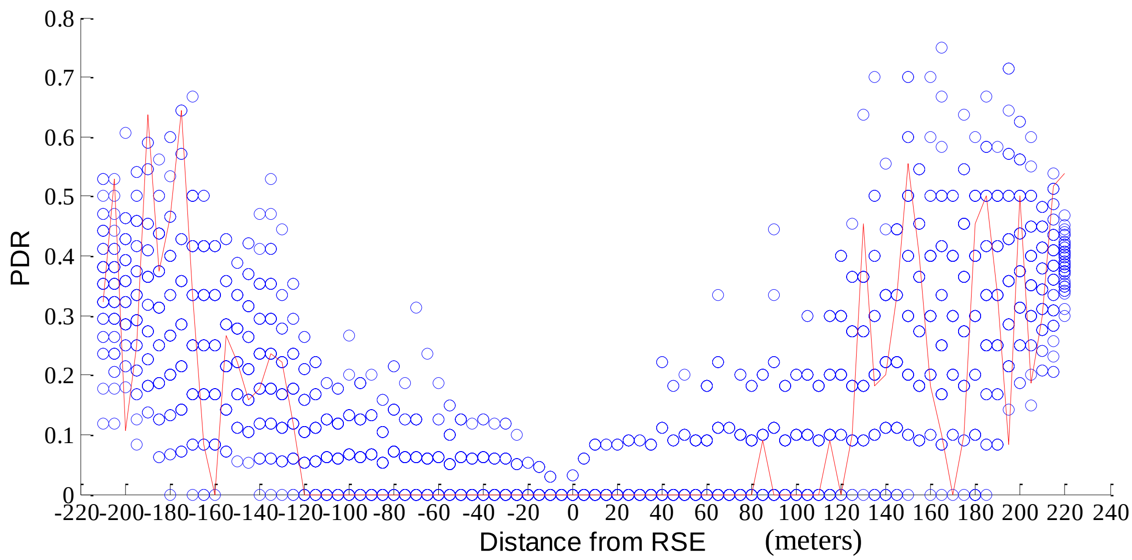
In LHS, there is no strict mathematical relationship between the number of samples and the number of factors. But obviously, more samples can cover the sample space better, as long as the simulation time is acceptable. In this study, a total of 700 scenarios are sampled. It is a fairly large number, but the total run time (70 hours) is acceptable. In each scenario run, the 2.5 minutes vehicle trajectory file was fed into NCTUns, and NCTUns simulated whether each transmission was successful or not. During the 2.5 minutes, a total of 1500 (2.5 minutes $\times$ 60 seconds/minute $\times$ 10 communications/second

= 1500) transmissions was made. The transmissions were aggregated by distance to calculate PDRs and then RMSE.

ANOVA analysis is applied to see how the three nominal parameters (data rate, large-scale fading model and small-scale fading model) affect RMSE. The p value of data rate is 0.9, implying that there is no significant difference. The p value of large-scale fading model is almost zero, indicating significant difference. The FSSM model has RMSE values larger than TGM and FSM. But there is no significant difference between TGM and FSM. ANOVA analysis of small-scale fading model implies that Rayleigh and Nakagami models generate lower RMSE values.

The first 10 scenarios with the smallest RMSE have their parameter values shown in **Table 1**. The calibrated parameter set is selected from these ten. 7 of the 10 have TGM large scale fading model, so TGM is selected for large scale fading. The 10 scenarios have 5 Nakagami models and 4 Rayleigh models for small scale fading. Previous studies also showed better performance of Nakagami, thus Nakagami is selected as small scale fading. The other parameter values are mainly based on scenario #1, except M1, because M1 value of scenario #1 is the smallest among all these 10 scenarios. The average M1 value of these ten is used as calibrated value. The final calibrated parameter set is shown in the row "final" in **Table 1**.

The simulation with the calibrated parameter set was run for 50 times. The resulting PDR together with the field test PDR is shown in **Figure 4**. The simulated PDR points cover most of the field observed PDR line. Comparing with **Figure 3**, the calibrated parameter set performs much better than the default parameter set in replicating the DSRC PDRs. The RMSE of the simulation results using the calibrated parameter set is 0.145, a 35.6% reduction compared with the RMSE of default parameters, 0.225.



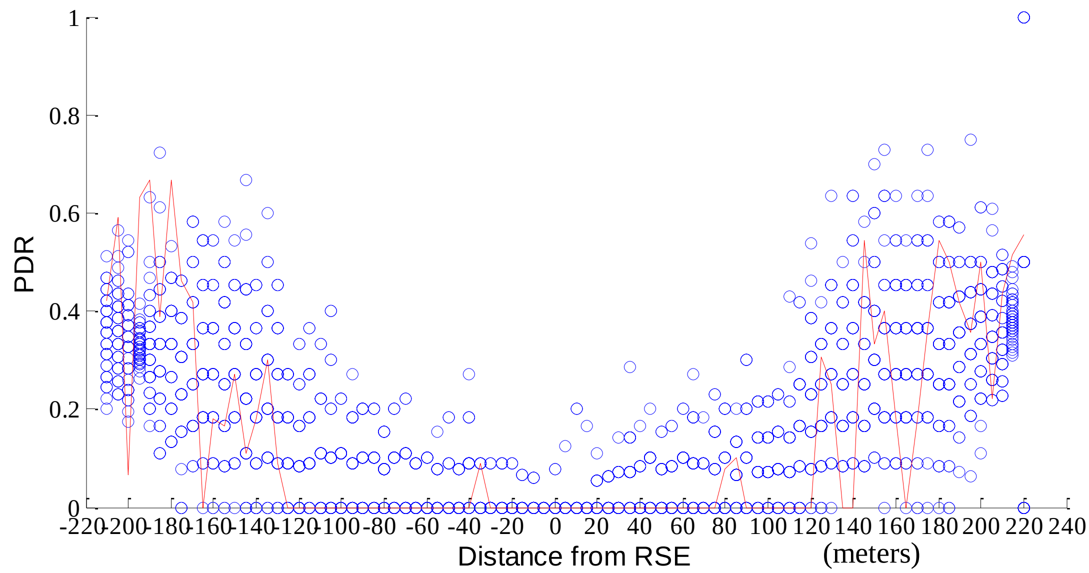
Line: Field Test PDR Dots: Simulated PDR

Figure 4 Packet Drop Rate by Distance (Calibrated Parameter, Calibration Data)

VALIDATION OF THE CALIBRATED SIMULATOR

The calibrated simulator needs to be validated to further prove its effectiveness. NCTUns was run for 50 times with both default parameter set and calibrated parameter set, using the 2.5 minutes data not used in the calibration. The PDR result of the calibrated parameter set is displayed in **Figure 5**. The PDR of default parameter set is not shown because it is very similar to **Figure 3**. Again, NCTUns simulator with default parameter set underestimates PDR, while the PDR points of the simulator with calibrated parameter set cover the field observed PDR line. The average RMSE of the default parameter set is 0.247, while the average RMSE of the calibrated parameter set is 0.16: a 35.2% reduction.

As the calibrated parameter set matches well with the validation trajectory data, the simulator is considered to be valid.



Line: Field Test PDR Dots: Simulated PDR

Figure 5 Packet Drop Rate by Distance (Calibrated Parameter, Validation Data)

CASE STUDY

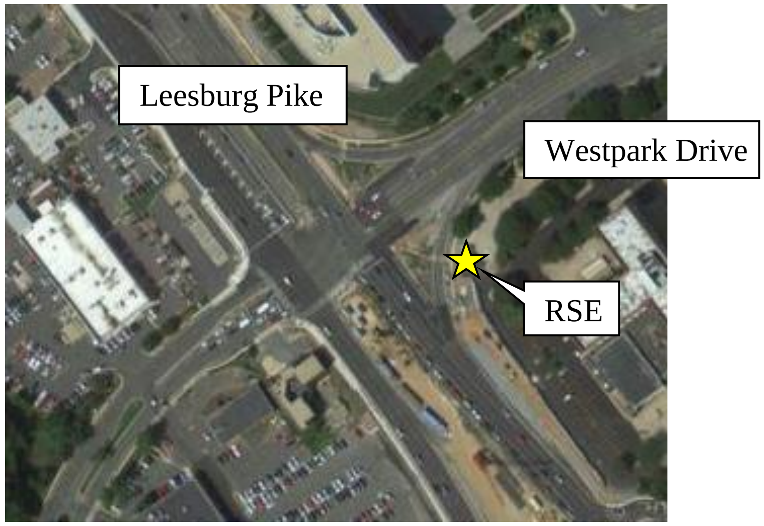


Figure 6 Multiple-Vehicles Case Study Intersection

The purpose of this case study was to investigate the performance of the calibrated NCTUns in emulating CV applications based on DSRC in a multiple vehicles scenario. The intersection of Leesburg Pike and Westpark Drive near Tysons Corner, VA was taken as the simulation testbed (**Figure 6**), as this intersection has at least four lanes in each approach, and hundreds of vehicles jam near it during peak hour. It is assumed that a RSE is installed near the intersection and receives HIA messages from the vehicles on all four approaches. Then, the RSE transmits BSM messages back to these vehicles. The traffic volume as well as some other characteristics of the intersection is listed in **Table 3**.

Table 3 Configurations of the Case Study Intersection

	South Bound	North Bound	East Bound	West Bound
Through	3284*	3428	268	530
Turn left	370	112	496	694

Turn right	493	186	49	836
Maximum Number of Vehicles on the Whole Network: 266 Minimum Number of Vehicles on the Whole Network: 5 Maximum Vehicle Speed: 35 mph Minimum Vehicle Speed: 0 mph				

*: All the volumes are in vehicles/hour

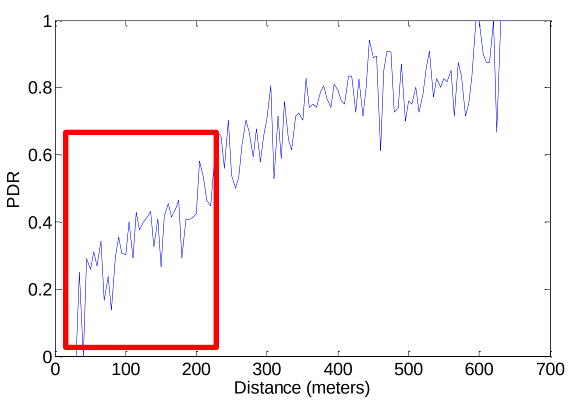
This case study was run in off-line mode, i.e., traffic simulator ran first for three minutes and generated a trajectory file with GPS coordinates and speed information of each vehicle at each time stamp. Then, the trajectory file was fed into the calibrated NCTUns simulator. At each time stamp, NCTUns simulated the V2V, V2I and I2V communications, determining whether each communication was successful or not.

Analysis of the Results

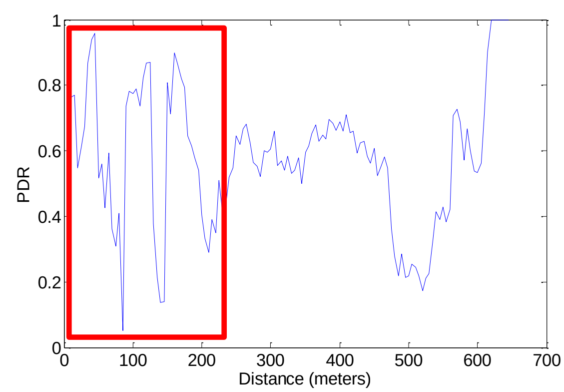
Without losing generality, V2I communications data were used to analyze how PDR and latency were affected by various factors. **Figure 7(a)** shows how PDR changes by the V2I distance when the total number of vehicles on the network is between 60 and 70. PDR increases approximately linearly with distance, and reaches 1.0 when distance is 600 meters. Such PDR-distance relationship only exists when the vehicles sending and receiving signals at the same time are not too many. **Figure 7 (b)** shows PDR in a jammed condition when the total number of vehicles on the network is between 230 and 240. The relationship between PDR and distance becomes vague. Traffic engineers are interested in the PDR within a short V2I distance, such as 200 meters, because that's critical for safety-related applications.

The red box in **Figure 7 (a)** shows that PDR is between 0 and 0.4 within 200 meters when vehicle count is between 60 and 70. **Figure 7 (a)** trend is very similar to the findings of Bai et al. [52]. The red box in **Figure 7 (b)** shows that PDR becomes very volatile and highly unpredictable, ranging from 0.1 to 0.9, when vehicle count is between 230 and 240. Considering the fact that 240 vehicles are not rare at busy and big intersections, the highly volatile PDR will bring great trouble to safety-related applications. This finding is consistent with [39], which states that the obstructing vehicles significantly decrease the received signal power and packet drop rate. When DSRC devices are implemented, these potential problems must be considered.

According to the simulation results, the average latency of the communication appears to be very small (up to the 10^{-4} magnitude of seconds). Thus, latency may not raise any concerns toward safety critical applications. However, the packet drops generate some "time gap" between two successful communications. The authors believe that such time gaps are worth being explored as they reflect the duration of no packet transmissions.



(a) Between 60 and 70 vehicles



(b) Between 230 and 240 vehicles

Figure 7 Vehicle-2-Infrastructure Packet Drop Rate by Distance in the Case Study

To show the finding in more detail, a vehicle's trajectory and time gaps are shown in **Figure 8**. It is observed that the time gap can be as long as 0.5 seconds for some vehicles within 100 meters from the intersection, as shown by the dotted box. Such time gaps would produce serious delay in the safety-critical applications and degradation of the applications' performance. **Figure 8** does not show any obvious relationship between distance and time gap when distance is within 100 meters. When over 100 meters, time gap tends to increase with distance, but this trend is vague. This is consistent with another study [53], which states that packet inter-reception time is almost independent of speed and distance between vehicles.

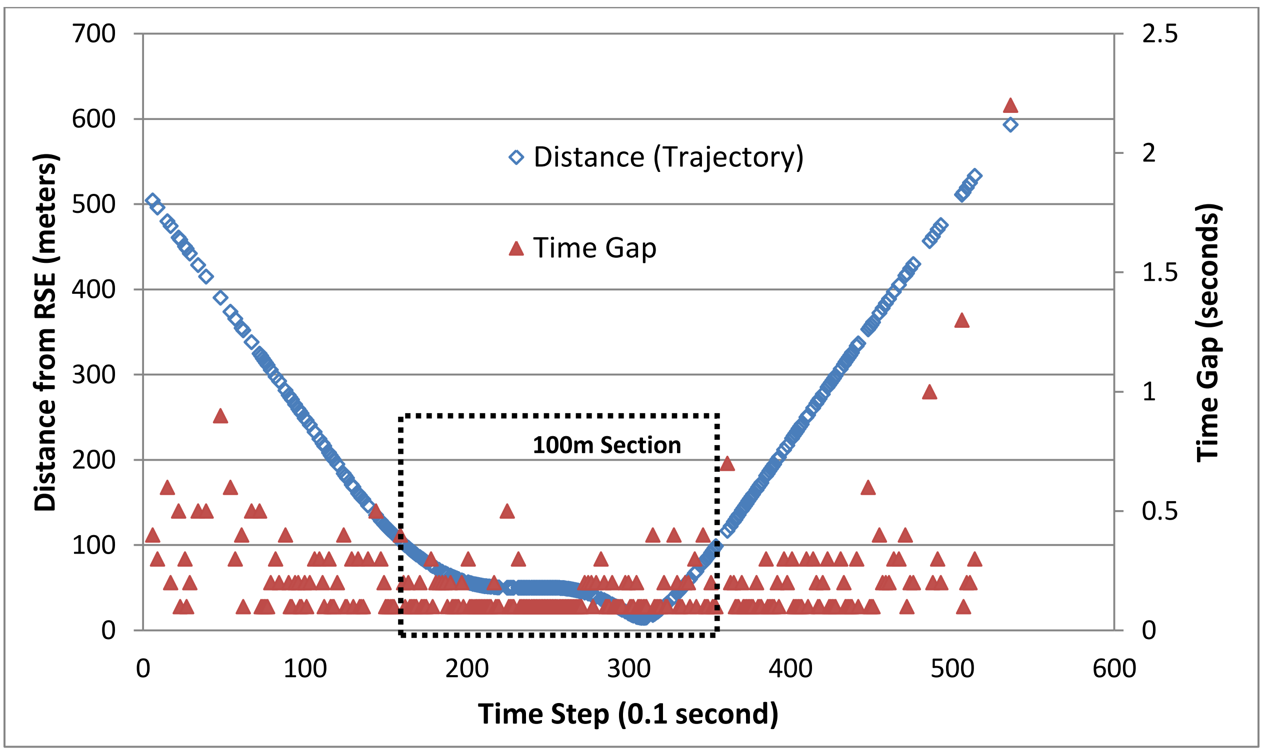


Figure 8 A Vehicle's Trajectory and Time Gap

By applying the calibrated NCTUns simulator in a busy intersection, this case study reveals potential challenges that need to be considered when safety critical CV applications are designed and implemented, such as PDRs and resulting time gaps between two successful communications.

CONCLUDING REMARKS

Field tests of the DSRC devices showed that there were packet drops in the Vehicle-to-Infrastructure communications, but the packet drops cannot be replicated by NCTUns, a wireless communications simulator supporting DSRC standards, with default settings. This study successfully calibrated the physical layer parameters of NCTUns to replicate the field observed packet drops. A Latin Hypercube Sampling technique was used to do simulation experimental design. The calibrated simulator was validated by field tested data which were not used in calibration. In addition, a case study showed how this calibrated NCTUns simulator could be used in a multiple vehicles scenario at a signalized intersection. Based on the findings from the experiments, the following conclusions are made: (1) the default setting used in NCTUns does not help replicate field conditions, (2) the proposed LHS based approach properly calibrated the NCTUns simulator, and (3) an evaluation on packet drops using the calibrated NCTUns at an intersection indicates that potential latency (i.e., time gap between successful communications) due to repeated packet drops can be detrimental to safety critical applications.

The calibrated parameter settings could potentially be used in slower speed conditions (less than 40mph) on rural roads or intersections without major LOS obstructions. NCTUns simulator needs to be re-calibrated if applied in an environment significantly different from the one used in this study. The future work includes conducting V2I and V2V communication experiments under various environments. Then, NCTUns DSRC parameters can be calibrated for each distinctive environment to provide advisory simulator settings for other researchers. An on-line simulation framework developed by the authors incorporates the traffic simulator (VISSIM) and NCTUns in real time, and can be used for future research. The findings of some theoretical studies on DSRC channel could be incorporated into NCTUns for more accurate simulation of the vehicular environments, such as modeling the effects of buildings and vehicles as obstruction and reflection objects.

ACKNOWLEDGEMENTS

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The List of Acronyms

ACM	A la Carte Message
ANOVA	Analysis of Variance
BSM	Basic Safety Message
CICAS	Cooperative Intersection Collision Avoidance Systems
CV	Connected Vehicle
DSRC	Dedicated Short Range Communications

FSM	Free space model
FSSM	Free space shadowing model
HIA	Here-I-AM
ITS	Intelligent Transportation Systems
I2V	Infrastructure-to-Vehicle
LHS	Latin Hypercube Sampling
LOS	Line-of-sight
MOE	Measure of Effectiveness
NLOS	Non-line-of-sight
OBE	Onboard Equipment
PDR	Packet Drop Rate
RMSE	Root Mean Square Error
RSE	Roadside Equipment
TFHRC	Turner Fairbank Highway Research Center
TGM	Two-ray-ground model
VII	Vehicle Infrastructure Integration
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WAVE	Wireless Access in Vehicular Environment

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CHAPTER 6

IMPLEMENTATION CHALLENGES

Predefined Control Speed

A predefined control speed needs to be determined before the users submit reservation requests. This is the speed that all the users on the reserved lane will be operated to follow. The predefined control speed should be lower than the highway design speed. Weather and work zones will be major factors that influence the speed. For example, if tomorrow is forecasted to snow, the predefined control speed should be set to be lower than normal. In addition to weather and work zones, the overall demand on the highway (including both reserved and general-purpose lanes) will change the predefined control speed. Since the general-purpose lane is more likely to be congested with higher demand, reducing the operational speed on the reserved lane will make it easier for the cars to change into the reserved lane. Also changing the operational speed will affect the capacity. With human drivers, the flow rate is highest (i.e. capacity) when the highway speed is 50 mph, when the free flow speed ranges from 55 to 75 mph according to 2010 HCM [1]. However, how the maximum throughput changes by the operational speed in the Cooperative Adaptive Cruise Control (CACC) environment remains a problem and needs more studies.

Maintaining a predefined control speed on the reserved lane is critical for keeping proper operation of the reservation system, since any delay will accumulate and jeopardize all the following reserved trips. The Connected Vehicles technology based CACC will provide a solution to stabilizing the traffic flow [2, 3]. More advanced CACC will make the driving on the reserved lane completely automatic, and minimize the speed variations on the reserved lanes. Future research topics include CACC algorithm design and evaluation, in terms of mobility benefits and emission reductions.

Since the left most lane is likely to serve as the reserved lane, changing into the reserved lane means crossing one or more general-purpose lanes. This is no easy task especially when the general-purpose lanes are congested. As a result, the exact time and location of the vehicles merging into the reserved lane cannot be accurately controlled. In that case, the vehicle density of the reserved lane will change dramatically. To maintain a smooth and uniform traffic flow along the reserved lane as much as possible, the vehicles' speed need to be adjusted in real time, no matter higher or lower than the predefined control speed. Such traffic flow smoothing is a new research topic for the CACC.

Predefined Maximum Flow Rate

The predefined maximum flow rate ties to the predefined control speed, emergency vehicle responses, and the "overselling" strategy. Large scale application of CACC will provide the needed data to determine the relationship between the control speed and maximum throughput. The predefined maximum flow rate should be smaller than the maximum throughput at given speed level. Being more robust to emergency conditions will require a lower proportion of the maximum throughput being reserved. A higher "no-show" rate might encourage a higher proportion.

A cost that the highway reservation system needs to pay is the lower utilization rate on the reserved lanes. Firstly the maximum flow rate should be lower than the theoretical maximum throughput of the reserved lane, to make it easier to maintain the predefined control speed and accommodate emergency vehicles that cannot make reservations ahead of time. The lower utilization of the reserved lanes could also be caused by some vehicles cannot change lanes into the reserved lanes, if multiple general-purpose lanes are severely congested. In addition, a certain amount of "no-shows" are expected for all similar reservation systems. In the airline industry, the companies oversell their tickets based on the estimated “no-show” rate, and provide some incentives so that some customers can change the flight, if all the customers show. The reserved highway could use a similar strategy. Such a strategy needs to be fine-tuned based on real “no-show” rate, for example using higher “over-selling” rate when the “no-show” rate increases.

DSRC Communication Challenges

Successful operation of the reservation system is based on reliable real-time V2V, V2I, and I2V communications. CACC relies on real time V2V communications to transmit the messages among the platooning vehicles every 0.1 seconds, and also the assisted lane changing between the reserved and general-purpose lanes. Other functionalities, such as token validation and on-the-fly request sending, need reliable V2I and I2V communications. Thus, Connected Vehicles technology is a cornerstone of the whole highway reservation system. Since the Connected Vehicles communications are prone to packet drops and latencies [4], all the modules that rely on real time vehicular communications have to be carefully designed to accommodate the potential packet drops and signal latencies.

Exception Handling

Exceptions include any unexpected changes that reduce the travel supply or increase the travel demand or change the operational speed. For example, emergency vehicles will lead to travel demand increase. Capacity reductions could happen due to traffic accidents, bad weather, etc. The emergency vehicles are handled by reducing the maximum allowable flow rate, so that the emergency vehicles can access the reserved lane without making reservations.

When the capacity reduction happens, the affected users will be notified and their trips can either be cancelled or changed. This will be another interesting future research topic. This is actually similar to the "overselling" strategy. If the capacity of the reserved lane is cut into a half due to some emergency, a half of the reserved trips need to cancelled or changed. Certain incentives can be provided so that some people will accept cancellations or changes, in a similar way of how the airline companies deal with the overbooked flights.

Before being implemented, the CACC technology on the reserved lane needs to be fully tested in different scenarios and carefully designed to minimize the crashes. In addition emergency response vehicles should be equipped along the reserved lane to clear the crashes as fast as possible.

Enforcement

Illegal vehicles should be kept out of the reserved lane by the enforcement center. Since the reserved lane has 100% market penetration rate of DSRC and CACC, it makes it easier to detect any illegal vehicles. Enforcement starts from receiving entering request from a vehicle. If the vehicle cannot provide a valid reservation, this vehicle will be rejected from merging into the reserved lane. A reservation is considered to be valid only if a vehicle shows in the right time at the right place. Since the users may not be able to arrive at the on-ramp just on time due to uncontrollable delays on local roads, certain amount of tolerance should be provided, say 2 minutes. If a user arrives more than 2 minutes earlier or later than the reserved time, s/he would be transferred to the on-the-fly center.

To detect non-DSRC and non-CACC vehicles on the reserved lane, other enforcement technology like camera and image recognition will be useful [5, 6]. The amount of fine for the illegal usage of the reserved lane also needs to be studied.

Privacy and Social Equity

Since users need to share their trip information with the reservation center to make reservations, only people who are willing to share such information can use the reservation system. Opted-out users can always use the general-purpose lanes. And the submitted information should be kept secret. So privacy might not an enormous concern of the reservation system.

Although wealthy people are more likely to use the reserved lanes, this whole highway reservation concept should not create too much social equity issues, for two reasons. The first reason is that only one lane of the highway is reserved only for peak periods. Comparing with the current all-lane-HOV policy on Interstate Highway 66 inside the Beltway [7] and the Interstate Highway 495 HOT lanes, the reservation system is unlikely to generate more social equity issues. The second reason is that the proposed roadway reservation system provides a travel time and no-congestion guarantee to users. All people have important things they do not want to be late, such as business meetings or interviews or picking up kids, thus the reservation system is an attractive option for all, not just for the wealthy people. Although it is unlikely that this system will create too much social equity issues, they should be further studied in the future.

Comparing with the social equity issues, the reservation system should worry more of how to satisfy people's expectations. Since the users are paying to use the reserved lanes, they expect not to be late in any case, or they have a high expectation. If these expectations are not satisfied or violated, it would generate numerous complains, which might halt the whole reservation system. Thus, the emergency response system needs to be well established with all possible scenarios considered and prepared for.

Highway Reservation Subsystems

The proposed highway reservation system should include five subsystems when implemented: reservation center, traffic monitor center, on-the-fly center, traffic operation center, and enforcement center. Reservation center deals with the reservation requests from the users based on certain rules, no matter First-Come-First-Serve or Higher-Pay-Earlier-Serve, and stores the scheduled trips in a database. The reservation center is also in charge of determining the predefined control speed based on weather forecast and other information. Traffic monitor center monitors the real time traffic, such as the vehicles entering and leaving the reserved lane, and general purpose lane conditions. On-the-fly center handles on-the-fly requests from general-purpose lanes, decides if they should be accepted based on the scheduled trip database and current traffic condition on the reserved lanes. Traffic operation center's role includes maintaining the predefined control speed on the reserved lanes, and assisting the lane changing behaviors between reserved lanes and general-purpose lanes. Enforcement center serves to ensure that only vehicles with valid reservations can travel on reserved lanes.

Reservation Center

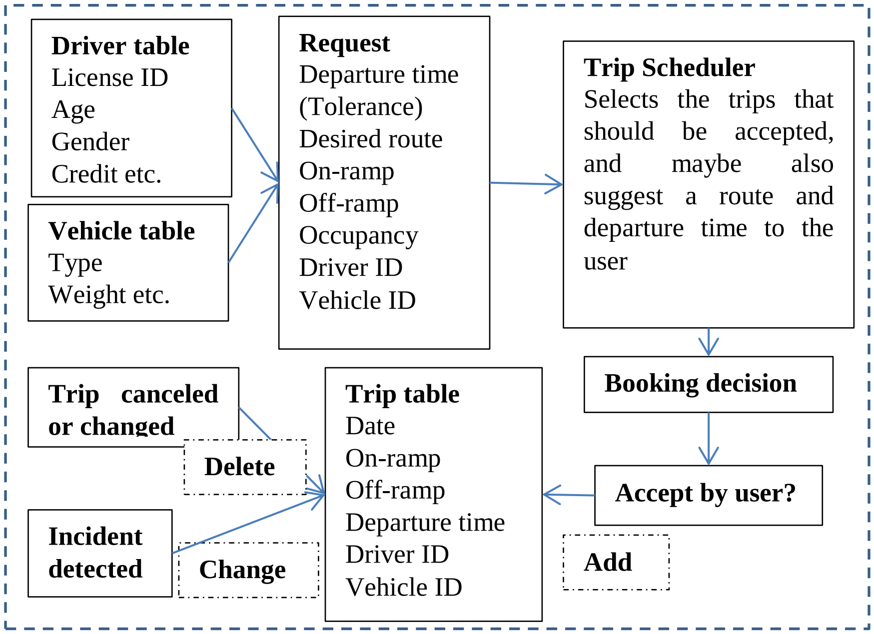

Figure 1 Framework of Booking Center

Booking center is the core of the highway reservation system. It decides if a trip request should be accepted, rescheduled, rerouted, or rejected. These decisions are based on different rules, such as First-Come-First-Serve, Higher-Pay-Earlier-Serve, or Random Draw: the pros and cons of these different rules need more study. The users should provide trip information including desired departure time, desired route, vehicle occupancy, driver ID, and vehicle ID. The trip requests must be made a certain amount of time (say half an hour) before the desired departure time. Any requests made after that or asking for immediate access are treated as on-the-fly requests, and they will be handled by the "on-the-fly center".

Traffic Monitor Center

Traffic monitor center has two functionalities: detecting entering and exiting vehicles, and collecting speed, density and traffic flow rate information from the reserved lanes. The detected entering and exiting vehicles' information are needed by the enforcement center to identify illegal cars, and also needed by the operation center to provide lane changing assistance. The basic functionalities of the traffic monitor center are shown in **Figure 2**.

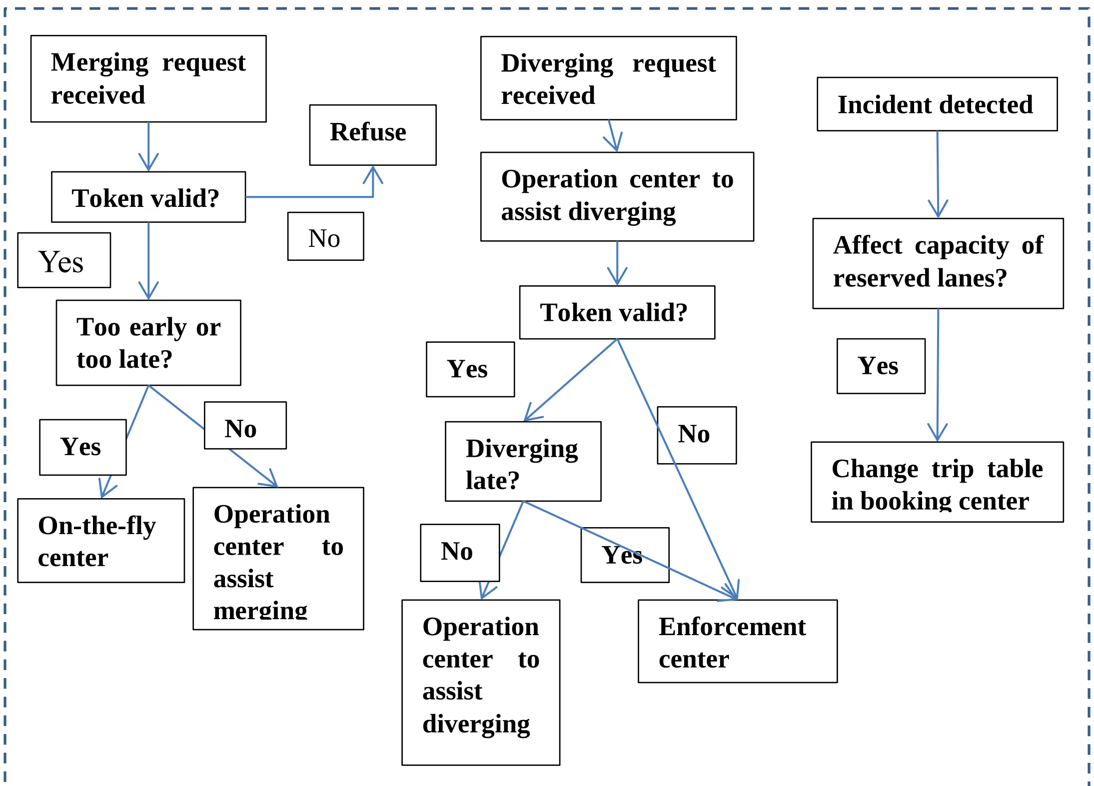

Figure 2 Framework of Traffic Monitor Center

Operation Center

Operation center has two functions: merging & diverging assistance, and maintaining the predefined speed. All the cars on the reserved lane need to have CACC. One possible way of maintain the predefined speed is selecting a leading vehicle from every five cars and this leading car receives speed advisories constantly from the operation center. The four cars between will simply follow the leading one. In this case, the platoon size is five.

Since the speed of reserved lanes is expected to be higher than the general purpose lanes, the lane changing between them will need special assistance, especially in congestion. For example a vehicle can either merge into the front of a platoon or to the end of a platoon, or have the upstream vehicles decelerate to create the needed gap. Iftode [8] proposed a merging policy in a position paper. The entering request-to-yield message is sent to oncoming vehicles, and the first car beyond a predetermined number of hops would be required to yield. A lot of studies have been conducted about the vehicle interactions in merging and diverging areas, such as Hidas [9] and Daamen et al. [10]. Merging and diverging assistance system has been studied recently by a lot of researchers, such as Ran et al. [11], Ferlis [12], Purboobpaphan et al. [13], and Park and Smith [14].

On-the-fly Center

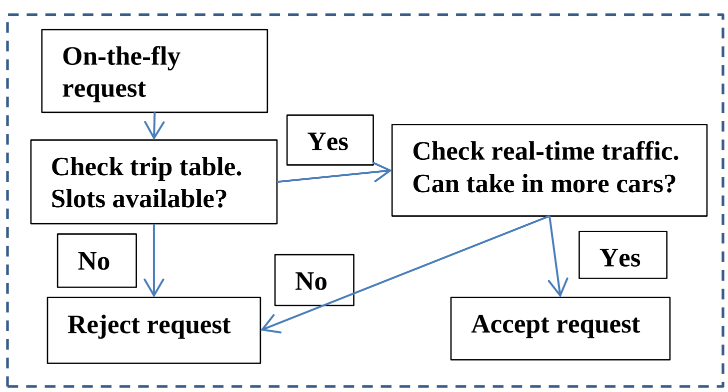

Figure 3 Framework of On-the-fly Center

The on-the-fly center deals with the reservation requests from the vehicles that are on the general purpose lanes and ask for immediate access into the reserved lane. Also if some vehicles arrive at the on-ramp too early or too late, they are likely to be transferred to the on-the-fly center. When an on-the-fly request is received, the on-the-fly center firstly checks the scheduled trip database to see if more slots are available along the requested route, and then the real-time traffic condition. If more vehicles can get into the reserved lane without creating congestion or safety concern, the on-the-fly request will be accepted and a token is issued to the vehicle. Then this vehicle will be transferred to the operation center to assist the lane changing.

Enforcement Center

The enforcement center serves to ensure that only vehicles with valid tokens can travel on reserved lanes. Since all the vehicles need to have Connected Vehicles devices installed to use the reservation system, the enforcement can simply checks these vehicles' tokens to detect any violations. Since vehicles without Connected Vehicles devices may enter the reserved lanes illegally, some other technology is also needed, to detect these vehicles, such as cameras.

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CHAPTER 7

CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

CONCLUSIONS

This dissertation brought a reservation concept into the management of highway system based on state-of-the-art Connected Vehicle technology. The reservation system provides a guarantee of congestion-free traffic for the commuters, and other time-sensitive travelers. These users can take advantage of this system to plan the trips ahead of time and worry no more of being delayed on the highway. Opted-out people can always use the general-purpose lanes. Since the reserved lanes do not have to be physically separated from the general-purpose lanes by barriers, drivers can also request immediate access to the reserved lanes by making on-the-fly reservation requests.

Chapter 2 of the dissertation is a mathematical optimization model, capable of finding the optimal scheduling plan for minimum system cost. The system cost is quantified as a sum of early arrival scheduling cost or late arrival scheduling cost and travel time cost. For the morning commuters, the early arrival cost per hour is the lowest in the three, while the late arrival cost per hour is the highest of the three. The optimization model minimizes the total system cost by redistributing the peak hour travel demand to earlier or later non-peak hours. This model used Vickrey's bottleneck model to propagate the trips through the traffic network. In the optimal result, traffic volume of all the links is at or under the capacity, lending support to bringing capacity constraint into the reservation system. In the two case studies, by applying reservation system on a highway network, the total system cost reduced by 20% to 25%, comparing with a user-equilibrium traffic assignment. These two numerical examples showed the proposed approach is well capable of solving the reservation optimization problem.

Chapter 3 is a proof-of-concept study of the reservation system using a microscopic traffic simulator (VISSIM) instead of the Vickrey's model. The reservation center handled the reservation requests based on a first-come-first-serve rule. A highway segment was controlled by the reservation system during a morning peak hour from 7:00 am to 8:00 am. This study considered on-the-fly reservations. The reservation system controls the total number of tickets issued to the vehicles so that the traffic volume does not exceed the capacity. The results show that as traffic demand increases, the reservation scenario further outperforms the baseline in terms of Vehicles-Hours-Traveled and CO_2 emissions. When the travel demand on freeway is 30% higher than the capacity, the total VHT reduced 24.6% from the baseline, and the CO_2 emissions reduced by 18.3%.

The optimization model in Chapter 2 works under two assumptions: all the travelers are homogeneous in terms of travel time values, and they are fully compliant with the reservation system's scheduling plan. Neither assumptions hold in real life. The proof-of-concept study in Chapter 3 is based on a first-come-first-serve rule to handle the reservation requests. Since the commuters are the dominant users of the reservation system and they are well aware of the trip schedule, they will take advantage of the first-come-first-serve rule and make the reservation request as early as possible, which means right after the system opens. Being late by a few milliseconds in that rush could mean the request being rejected, which is clearly not the way the reservation system is expected to work in. That's why an auction-based implementation of the reservation system is proposed and tested using an agent-based simulation technique. All the users need to submit a bid to reserve a highway spot and their requests are handled based on a higher-bid-earlier-serve rule. Since the users have different value of time, the highest bid they can afford is different. The auction-based system addressed the limitations in Chapter 2 and Chapter 3. Chapter 4 illustrates the agent-based simulation tool that helps test the auction-based concept. At converging, the number of users and the total collected revenue become stable. The auction system is more like a personal tolling system that finds the maximum amount a user is willing to pay. Or it transfers more consumer surplus to the operators, since high-time-valued and risk-averse travelers pay higher. The users are provided a chance of buying insurance for a protection of their travel, against highway congestions.

Chapter 5 focuses on the communication quality of the Connected Vehicles technology, since all the functions of the reservation system rely on real-time Vehicle-2-Infrastructure, Infrastructure-2-Vehicle, and Vehicle-2-Vehicle communications. The wireless communications experience latencies and packet drops, which might lead to a serious downgrade of the Cooperative Adaptive Cruise Control (CACC) on the reserved lane, and a lane-changing assistance system. Chapter 5 describes the calibration of an NCTUns simulator for the DSRC to replicate the real world vehicular communication environments, using field test data executed on an instrumented intersection at the Turner Fairbank Highway Research Center. Physical layer parameters (e.g., data rate and transmission power) as well as channel models are calibrated. The calibrated simulator provides a tool to evaluate the Connected Vehicle applications under unreliable communications.

Chapter 6 discusses the implementation challenges and future research topics related to the highway reservation system. The predefined operational speed and predefined maximum flow rate are the two factors that need to be determined before the users submit their reservation requests. The exception handling system is of vital role to the reservation system, to provide satisfactory service when emergency conditions happen. Since users will pay for the reserved slot and the selling point of the highway reservation system is congestion-free traffic, any delays or unexpected situations would jeopardize the users' confidence. That's why the exception handling system has to be fully tested under as many different scenarios as possible.

This dissertation provides an innovative traffic management approach to the US DOT and transportation industries. The auction-based implementation is like a personal tolling system that transfers more consumer surplus to the managed lane operators. If operated by a private sector, the reservation system generates more revenue. If operated by US DOT, the reservation system serves as a potential source for the US highway maintenance. Compared with HOV lane, the reservation system is a more efficient way of using the lanes, as HOV lane might not be fully utilized without enough carpooling. Compared with HOT lane, reservation system is cheaper to implement since it does not need to build additional infrastructure. Also HOT might face a sudden bump-up of the traffic and be congested, before the price can be increased to stop that from happening. In one word, the reservation system introduces a smarter and efficient way of utilizing current highway system. For the transportation academic research, this dissertation provides an optimization model that solves a dynamic traffic assignment problem with departure time choices, an agent-based model that simulates heterogeneous traveler behaviors, and a wireless communication simulation tool that can emulate unreliable wireless communications with packet drops and latencies.

RECOMMENDATIONS

The key recommendations for research community are exploring more of different aspects of the reservation system, including economic studies of different reservation rules, and the operational level studies of the reserved lanes. The more we know of this system, we will be more confident to answer questions from general public and legislation. For the state/local agencies, the recommendation is taking this reservation system into consideration when they think of possible transportation solutions. For the general public, the recommendation is being open and at least giving this system a chance before saying “no” to it.

FUTURE RESEARCH

Future research should focus on one of the three areas. The first one is about the reservation rule. Three kinds of rules are considered in this dissertation: first-come-first-serve rule, highway-bid-earlier-serve rule, and auction-based rule. Future work can test other rules and compare their pros and cons from an economic and user acceptance perspective. The second research direction is an exception-response system. The reserved lane speed has to be relatively stable for proper functioning of the reservation system. However, the traffic flow is highly dynamic even with the help of CACC. Also emergency situations such as incidents or bad weather might lead to a reduction of the design speed or capacity. How to respond to these exceptions remains to be studied. The third research direction is developing a lane changing assistance system to help vehicles move into and out of the reserved lanes, especially under high speed differential. All the subsystems that need real-time vehicular and V2I/I2V communications need to consider latencies and packet drops.