Observing space-time queueing dynamics at a signalized intersection using connected vehicles as mobile sensors

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Abstract

The existing efforts on study queueing dynamics at signalized intersections mainly focus on the estimation of queue length, queue location or queue time using fixed sensor data or mobile sensor data. Methods using fixed sensor data are limited due to the low coverage of fixed detectors. Mobile sensor data such as mobile phone data only contains vehicle locations. None of the data contains high-resolution (i.e. 0.1 second) driving details nor signal timing information at signalized intersections. Considering the availability of high-frequency connected vehicle data, this paper develops an integrated macroscopic and microscopic traffic flow theory based approach to observing queueing dynamics at signalized intersections using connected vehicles as mobile sensors, e.g. V2I driving records and I2V signal phase and timing (SPaT) information from the high-resolution connected vehicle dataset. Different to the tradition works on queueing dynamics that mainly focus on queue length estimation based on macroscopic traffic flow model, the proposed integrated approach observes space-time queueing dynamics within three regions – queue formation region, queue region, and queue dissipation region with corresponding vehicle microscopic behavior of deceleration, stop, and acceleration. We examine the proposed approach using real world connected vehicle data that contains signal phase and timing and real driving records at a signalized intersection in Ann Arbor, Michigan under both normal and oversaturated conditions.

Keywords: space-time queueing dynamics, connected vehicles, mobile sensors, integrated macroscopic and microscopic traffic flow theory based approach
INTRODUCTION

Queue formation and dissipation process are fundamental for intersection performance measures [1][2] and control optimization at signalized intersections [3][4][5] through efficiently allocating the available capacity (e.g., minimize intersection delay, minimize the maximum queue length). In the past decades, a rich body of literature has been devoted to the methods of estimating queue length at signalized intersections using loop detector data and signal timing information. These methods can be broadly categorized as statistical models [6][7] to estimate queue lengths using arrival and departure profiles at intersections, and macroscopic traffic flow (i.e. shockwave theory) models [8][9][10][11] to estimate queue lengths by applying the shockwave theory.

Based on shockwave theory proposed in [12][13] and expanded to signalized intersection in [8][9], macroscopic traffic flow based models estimate queue lengths from the trajectory of traffic shockwaves. However, these models require adequate and accurate vehicle arrival input to describe the complex queueing process. The macroscopic traffic flow based models are improved to real time estimate queue length for oversaturated and queue spillover situations [10][11][14]. Liu et al. (2009) [10] propose a method applying shockwave theory to identify traffic state changes and estimate time-dependent queue length from second-by-second event-based signal data for cases that queues exceed the detector location. Ban et al. (2011) calculate sample queuing delays from measured sample intersection travel time by exploiting linear relations between two neighboring sample vehicles. Their model constructs real time queue length using the detected non-delay arrival time observed from the estimated queuing delay patterns. In addition, Ban et al. (2013) [15] study the discharging process of individual vehicle and estimate the location of an individual vehicle in the queue at signalized intersection by investigating the relation between vehicle discharge time and the location in queue applying kinematic equation of the vehicle acceleration behavior (i.e. the microscopic traffic flow dynamics).

While most of the current works study queueing process using fixed sensor data and GPS-based data, connected vehicle technologies bring more promising foundations for studies on queue formation and dissipation since it provides 0.1-second high-resolution data of both vehicle location and Signal Phasing and Timing (SPaT) information. Lin et al. (2015) [16] present three intersection control algorithms for three types of area in the road network with connected vehicle technologies and run a simulation case in VISSIM-COM to improve the traffic performance. Feng et al. (2015) [17] introduce a traffic signal control strategy at an intersection to reduce intersection delay. Tiaprasert et al. (2015) [18] present a model to estimate queue length for adaptive signal control under connected environment and validate the model in VISSIM simulator.

Although significant progress has been made in recent years, there are still a number of challenging questions to be addressed to systematically estimate vehicle queue length in both space and time dimensions. First, the existing queue length estimation methods need fully observed flow and occupancy information using fixed sensors, which has restrained applications due to current limited arterial detector deployment for wide areas. Second, current studies prefer to identify traffic states change to estimate real time queue length but fail to capture the dynamics in space dimension at intersections. Third, some methods based on shockwave theory estimate real time queue length under the assumptions that penetration rate is relatively high and uniform arrival rate using sampling data. Nevertheless, high penetration cannot be guaranteed when intersection density is low.

As discussed above, most of the existing studies on connected vehicle technologies focus on signal control strategies to improve operation performance at signalized intersections. To investigate queueing process at signalized intersections, it is necessary to present an approach to systematically observing queue formation and dissipation dynamics in both space and time dimensions using high-resolution connected vehicle data (i.e. 0.1-second driving records and Signal...
Phase and Timing (SPaT) information). Considering the availability of high-frequency connected vehicle data, this paper develops an integrated macroscopic and microscopic traffic flow theory based approach to observing queueing dynamics at signalized intersections using connected vehicles as mobile sensors, e.g. V2I driving records and I2V signal phase and timing (SPaT) information from the high-resolution connected vehicle dataset. Different to the tradition works on queueing dynamics that mainly focus on queue length estimation based on macroscopic traffic flow model, the proposed integrated approach observes space-time queueing dynamics within three regions – queue formation region, queue region, and queue dissipation region with corresponding vehicle microscopic behavior of deceleration, stop, and acceleration at a Road-side Unit (RSU)-equipped signalized intersection.

The paper is structured as follows. The next section presents the statement of the problem. Then, we propose an integrated macroscopic and microscopic traffic flow theory based approach to observing the space-time dynamics of queueing process at signalized intersections using connected vehicles as mobile sensors. Using a real world high-resolution connected vehicle dataset, we select a signalized intersection in Ann Arbor, Michigan to implement the proposed integrated approach using V2I driving records and I2V SPaT messages from the Safety Pilot Model Development (SPMD) program and conduct the numerical analysis. Concluding remarks are given in the last section.

**PROBLEM STATEMENT**

A traffic queue dynamics include two processes - queue formation and queue dissipation. Both processes are dynamic in time and space with a queue front and queue end. The queue front and queue end will meet when the traffic queue is clear. Different to most of the existing queue estimation methods, we use high-resolution V2I vehicle records and massive I2V SPaT messages from a connected vehicle dataset. The V2I records include location, speed, acceleration, and timestamp. The SPaT messages provide current signal state, timestamps, corresponding movement, and lane identification. Although connected vehicle data is promising for queueing process observations, there are still questions to be addressed using these high-resolution data. The existing methods based on macroscopic traffic flow (shockwave theory) dynamics focus on fully observed traffic flow information using fixed sensor data at intersections, which may not be directly applied to connected vehicle data since the relatively low penetration rate.

While some methods estimate queue lengths by detecting traffic state changes using GPS-based data, there is still a need to develop an approach to identifying space-time dynamics of queueing process using a combined vehicle locations and SPaT messages dataset. The main objective of this paper is to observe the space-time queueing dynamics given trajectory data of a connected vehicle and SPaT information at a signalized intersection based on an integrated macroscopic and microscopic traffic flow theory based approach. To apply the integrated approach, we have the following definitions, assumptions and notation.

**Definition 1. Queue.** A sequence of vehicles waiting to be served by the system where the rate of flow from the front of the queue impacts the speed of other vehicles in the queue.

**Definition 2. Queue Front Position.** Queue front position is defined as the start position of a queue in space and time dimensions, i.e. the space-time position of the first vehicle in a queue.

**Definition 3. Queue Rear Position.** Queue rear position is defined as the end position of a queue in space and time dimensions, i.e. the space-time position of the last vehicle in a queue.

**Definition 4. Queue Length.** One definition of queue length is the total number of vehicles accumulated in the queue. The other definition is the distance from the queue front position to the queue rear position of a queue. We focus on the second definition of queue length in this paper to
consider the queue dynamics. Note that queue is changing over space and time, we focus on real
time queue length in both space and time dimensions.

**Definition 5. Queue Formation Region.** Queue formation region is an area between the
rear of the queue (i.e. the trajectory of queue formation wave) and the free-flow driving (i.e. the
trajectory of the free-flow wave).

**Definition 6. Queue Region.** Queue region is an area between the rear of
the queue (i.e. the trajectory of queue formation wave) and the front of the queue (i.e. the trajectory
of discharge wave).

**Definition 7. Queue Dissipation Region.** Queue dissipation region is an area between the
front of the queue (i.e. the trajectory of queue discharge wave) and the free-flow driving (i.e. the
trajectory of the free-flow wave).

We also have four assumptions on using connected vehicles as mobile sensors to observe
space-time queue dynamics at signalized intersections.

(i) Only the locations of connected vehicles within the Dedicated Short Range
Communication (DSRC) range at an RSU-equipped intersection are known.

(ii) The high-resolution (0.1-second frequency) signal timing information of a
concerned approach (in a lane) at an RSU-equipped intersection is known.

(iii) The time-dependent acceleration rate and deceleration rate of connected vehicles
are known.

(iv) The queue will discharge completely in at most two continuous cycles, i.e.
gridlocks will not exist more than two continuous cycles.

Notation:

- $v_f$, free flow wave speed.
- $v_q^n$, queue formation wave speed during cycle $n$.
- $v_d^n$, queue dissipation wave speed during cycle $n$.
- $v_p^n$, queue departure wave speed during cycle $n$.
- $q_{a}^{n}$, average arrival flow rate during cycle $n$.
- $q_m$, saturation flow rate, the equivalent hourly rate at which vehicles can traverse an
intersection approach.
- $k_{a}^{n}$, average arrival density during cycle $n$.
- $k_m$, critical density, the density at which capacity occurs under free flow.
- $k_j$, jam density.
- $acc^t$, the acceleration rate of sample vehicle at time $t$.
- $dec^t$, the deceleration rate of sample vehicle at time $t$.
- $L_q$, the estimated queue location.
- $L_{\text{max}}$, the maximum queue location.
- $L_{sf}$, distance from the stop line to the free-flow driving.
- $L_{fq}$, distance from the free-flow driving to the queue.
\( T_g^n \), the end of green time during cycle \( n \).

\( T_r^n \), the end of red time during cycle \( n \).

\( T_{\text{max}}^n \), the time that has the maximum queue length during cycle \( n \).

\( T_{ds}^n \), the queue dissipation start time during cycle \( n \).

\( T_{fs}^n \), the queue formation start time during cycle \( n \).

\( T_{fe}^n \), the queue formation end time during cycle \( n \).

\( t_f \), the time that flow recovers to free-flow driving.

**METHODOLOGY**

On one hand, the existing macroscopic traffic flow model is used to identify shockwaves by solving the partial differential equations in the macroscopic traffic flow model. Based on the fundamental diagram that flow is a function of density, shockwave velocity can be calculated. On the other hand, the microscopic traffic flow model is used to investigate discharging behavior at an intersection using kinematic equations, in which acceleration rate is considered in the queueing process. However, none of the two methods can be directly applied to observe the space-time dynamics of queue formation and dissipation processes at a signalized intersection simultaneously using connected vehicles. Most of the works applying the microscopic traffic flow model fail to capture the queue formation dynamics from the deceleration behaviors of vehicles.

In this section, to observe the dynamics of queue formation and dissipation processes in space and time dimensions, we introduce an integrated macroscopic and microscopic traffic flow theory based approach to identifying three regions in space-time diagram at a signalized intersection – queue formation region, queue region, and queue dissipation region that can model vehicle deceleration, stop, and acceleration behavior using connected vehicles as mobile sensors. This methodology includes two major components: (1) the macroscopic traffic flow model to identify the queue region; and (2) the microscopic traffic flow model to identify queue formation (i.e. deceleration) and queue dissipation (i.e. acceleration) region.

**The Macroscopic Traffic Flow Based Method**

Traffic shockwaves can be illustrated using the flow-density fundamental diagram. Several shockwaves are generated at a signalized intersection due to the changes of signal control and queueing process. The queue formation wave, queue dissipation wave, and queue departure wave are determined by the tangent of the chord between any two vertices on the fundamental diagram in Figure 1.
Normal Conditions

We use Figure 2 to show the difference between the existing macroscopic traffic flow model based methods and the proposed integrated approach for the normal conditions. Instead of roughly estimating queue lengths from the shockwaves, we consider queue formation and dissipation regions as a set of queue formation waves and queue dissipation waves respectively. In Figure 2, the dashed lines represent queue formation wave \( v^n_q \), queue dissipation wave \( v^n_d \), and queue departure wave \( v^n_p \) respectively identified based on macroscopic traffic flow theory. The existing methods only focus on the unique shockwaves and the queues constructed by the shockwaves but ignore the acceleration and deceleration behaviors. To observe the space-time dynamics of queueing processes, our integrated approach introduces space-time dynamic queueing regions – queue formation region (Region I), queue region (Region II), and queue dissipation regions (Region III) (i.e. the regions represented by the four solid lines in Figure 2). Noted that the waves in this paper are determined by the deceleration and acceleration behaviors from real driving data and signal information using our integrated approach. The method to identify Region II and III will be discussed as the microscopic part of the integrated approach in the next subsection.
As is shown in Figure 2, the integrated based trajectory decelerates until stopped as the signal turns red. Then the flow and density condition between the arrived and the stopped traffic in Figure 1 will change (i.e. the shockwave $v_q^n$). The signal change from green to red interval causes an interruption of intersection traffic flow, which forms a shockwave - the queue formation wave $v_q^n$ moving toward upstream of the intersection in Figure 2.

\[
v_q^n = \frac{0 - q_a^n}{k_f - k_q^n}
\]  
(1)

\[
v_d^n = \frac{q_m - 0}{k_m - k_f}
\]  
(2)

\[
v_p^n = \frac{q_m - q_a^n}{k_m - k_a^n}
\]  
(3)

The above shockwave speeds can be determined using Eq. (1)-(3), which are also applied in [10][11]. The queue formation wave $v_q^n$ can be determined by $0, k_f$, jammed flow and density, and $q_a^n, k_q^n$, average flow and density during cycle $n$. Queue formation wave keeps moving upstream of the intersection. At the start of the green time $T_f^n$ (i.e. the end of red time during cycle $n$), the
queue begins to discharge with shockwave speed $v_d^n$, which is determined by $0, k_j$, jammed flow and density, $q_m, k_m$, saturation flow and density in Eq. (2). By calculating queue formation wave $v_q^n$ and queue dissipation wave $v_d^n$, we can identify the queue region in the space-time diagram (i.e. Region II in Figure 2 and Error! Reference source not found.). Vehicles in the queue region will be forced to stop and the flow-density condition will be different.

As the queue dissipation wave $v_d^n$ generally has higher speed than queue formation wave $v_q^n$, they will meet at time $T_{l_{max}}^n$ where the queue length will reach maximum. In [10][11], queue departure wave $v_p^n$ is considered to be generated when queue dissipation wave $v_d^n$ and queue formation wave $v_q^n$ meet. However, vehicles outside the queue may also be affected by the queue ahead them and decelerate when passing by an intersection. For example, the last vehicle within in queue region (Region II) will not fully stop but just decelerate when passing through the intersection. In this paper, queue departure wave $v_p^n$ may or may not intersect with the other two waves.

**Oversaturated Conditions**

Under the oversaturated conditions in Error! Reference source not found., the start of the red time of the upcoming cycle $n + 1$, a residue queue will be generated if the current queue cannot be fully dissipated. The residue queue formation wave can be calculated in Eq. (4.1).

$$v_q^{n+1} = \begin{cases} 0 - q_m \\ k_j - k_m \\ 0 - q_a^{n+1} \\ k_j - k_a^{n+1} \end{cases}$$

![Figure 3 Shockwave Propagation with a Vehicle Trajectory under Oversaturation](image_url)
The queue formation wave of the upcoming cycle \( n + 1 \) can be calculated in Eq. (4.2) which is similar to \( v_q^n \). The queue end position will follow the trajectory of queue formation wave \( v_q^n \) and queue departure wave \( v_p^n \) within the queue region (i.e. Region II in Figure 2 and Error! Reference source not found.). The shockwave motion described above demonstrates the queueing process at a signalized intersection. The queue will accumulate at the beginning of red time and dissipate at the beginning of green time. Once high-resolution vehicle trajectory data and signal timing data are available, the space-time dynamics in the queue region can be observed from the vehicle arrivals and start and end time of signal change. To recover queue formation and dissipation process, we need to observe the deceleration and acceleration behaviors of vehicles, which needs the microscopic traffic flow theory.

**The Microscopic Traffic Flow Based Method**

The microscopic traffic flow theory based method in this paper focus on the deceleration behaviors of vehicles during the queue formation process and the acceleration behaviors of vehicles during the queue dissipation process. Kinematic equations are used to estimate vehicle’s queue location given the real-time speed and acceleration rate from the high-resolution connected vehicle data. Then by observing vehicle’s deceleration behaviors approaching the stop line at an intersection, the time that a vehicle joins the queue can be determined using the estimated queue location during the queue formation process.

**Normal Conditions**

The key point to estimate queue location of an individual vehicle is the deceleration process during the queue formation process, which will illustrate the dynamics in the queue formation region (region I). Similarly, vehicles will accelerate to free-flow driving during the queue dissipation process, which reveals the dynamics in the queue dissipation region (i.e. region III) in Figure 2 and Error! Reference source not found.. It should be noted that the regions of queue formation and dissipation could be small since most of the deceleration and acceleration processes are finished in a short time interval. Also, the two regions may have irregular shapes due to the variety among different driving styles.

\[
T_{ds}^n - T_f^n = \frac{L_q}{v_d^n} \quad (5)
\]

Speed and acceleration rate are important to observe queueing dynamics and estimate vehicle’s queue location and queue time. The flow will recover to free flow affected by the queue dissipation wave \( v_d^n \). The relation of the discharge start time \( T_{ds}^n \) and estimated queue location of the individual vehicle \( L_q \) is shown in Eq. (5). Based on the kinematic equations of an individual vehicle, acceleration rate \( acc^t \) will be used to demonstrate the relationship between queue location \( L_q \), the distance from stop line to free-flow driving \( L_{sf} \), the dissipation start time \( T_{ds}^n \), and free-flow recovery time \( t_f \), as is shown in Eq. (7).

\[
\bar{a} = \frac{\sum_{t=0}^{T_{ds}^n} acc^t}{|t|} \quad (6)
\]

\[
L_q + L_{sf} = \frac{FFS^2}{2\bar{a}} + FFS \left( t_f - T_{ds}^n - \frac{FFS}{\bar{a}} \right) \quad (7)
\]
The distance from stop line to free-flow driving $L_{sf}$ can be estimated from the speed profile of
the connected vehicle. We can also derive the average acceleration rate $\ddot{a}$ between the dissipation
start time and the free-flow recovery time from the driving records of the high-resolution connected
vehicle dataset (Eq. (6)). Then the dissipation start time $T_{ds}^n$ and queue location $L_q$ can be solved by Eq.
(5)-(7). Based on kinematic equations, we can observe the queue dissipation dynamics within the queue
dissipation region (region III in Figure 2) from the estimated dissipation start time $T_{ds}^n$, queue location
$L_q$.

$$T_{fe}^n - T_{fs}^n = \frac{L_{fq}}{v_q^n}$$

(8)

$$\ddot{d} = \frac{\sum_{t=T_{fs}^n}^{T_{fe}^n} dec^t}{|t|}$$

(9)

$$L_q + L_{fq} = \frac{FFS^2}{2\ddot{d}} + FFS \left( T_{fe}^n - T_{fs}^n - \frac{FFS}{\ddot{d}} \right)$$

(10)

Similarly, the queue formation start time $T_{fe}^n$ and the distance from the free-flow driving to
the queue $L_{fq}$ can be solved as in Eq. (8)-(10). After identifying the queue formation region (region
I in Figure 2) between the free-flow driving wave $v_f$ and the queue formation wave $v_q^n$, we can
observe the dynamics of queue formation process from free-flow driving to the queueing status.

**Oversaturated Conditions**

Vehicles under saturated conditions (i.e. $q_m, k_m$) generally join two queues passing by an
intersection. The vehicle’s queue location $L_q'$ and $L_q$, the queue join time (i.e. the queue formation
end time $T_{fe}^n$ and $T_{fe+1}^n$) for each queueing can be estimated respectively. $L_q$ and $T_{fe+1}^n$ can be
calculated using the equations discussed above. $L_q'$ during the first queueing is estimated in Eq.
(11).

$$L_q' = L_q + \frac{(T_{\bar{g}}^{n+1} - T_{\bar{r}}^n)q_m}{k_j}$$

(11)

In Error! Reference source not found., the green time interval $T_{\bar{g}}^{n+1} - T_{\bar{r}}^n$ multiplies
saturation flow rate $q_m$ equals the number of vehicles pass through the intersection during cycle $n$.
The distance that saturated vehicles can move forward from the first queue to the second queue is
$$\frac{(T_{\bar{g}}^{n+1} - T_{\bar{r}}^n)q_m}{k_j},$$
where $k_j$ is the jam density. Correspondingly, the queue join time of the first and
second queue $T_{fe}^n$ and $T_{fe+1}^n$ can be determined as following equations. $T_{fe}^n$ is determined in Eq.
(12), where $L$ is the DSRC communication distance centered by RSU and $t_o$ is the time that a
vehicle first time enters the DSRC range. The queue join time of the second queue $T_{fe+1}^n$ is
calculated in Eq. (13), where free flow travel time $\frac{L_{aq} - L_q}{FFS}$, acceleration time $\frac{FFS}{2\ddot{d}}$ and deceleration
time $\frac{FFS}{2\ddot{d}}$.
\begin{align}
T_{fe}^n &= t_0 + \frac{L - L_q'}{FFS} + \frac{FFS}{2d} \\
T_{fe}^{n+1} &= T_{fe}^n + \frac{L_q'}{v_d^n} + \frac{L_q' - L_q}{FFS} + \frac{FFS}{2a} + \frac{FFS}{2d}
\end{align}

Given the records of one connected vehicle at any time and corresponding SPaT messages, the dynamics within the queue formation and dissipation regions (region I and III in Figure 1) under saturated conditions can be observed based on the estimation results using Eq. (11)-(13).

**NUMERICAL ANALYSIS**

In this section, we first introduce the dataset used in this paper. We will demonstrate the proposed integrated macroscopic and microscopic traffic flow theory based approach in the previous section to identify the queue formation, dissipation and queue regions using high-resolution connected vehicle data and analyze queueing process dynamics in space and time.

**Dataset Description**

In this paper, we use a high-resolution connected vehicle dataset over two separate months from Safety Pilot Model Deployment Data (SPMD) program to demonstrate the proposed method. Our dataset in this paper contains two part – V2I vehicle driving records and I2V SPaT messages. Each record in the dataset contains anonymous id, longitude, latitude, velocity, acceleration rate, and timestamp. We focus on signalized intersections in Ann Arbor, Michigan, in which we extract over 2150 connected vehicles’ daily trajectories. We use the map of intersections extracted from OpenStreetMap as the underlying transportation network for our method.

To capture the signal timing information at the signalized intersections, we utilize SPaT messages that contain signal states, timestamps, corresponding movement, and lane identifications. Based on the extraction of travels passing through the RSU-equipped intersections, we find that almost all the least frequently traveled days are at weekends (i.e. Day 6, 7, 13, 14, 20, 21, 27, and 28 in Figure 4). This indicates that drivers of connected vehicles travel more on workdays than at weekends.
To demonstrate the proposed integrated approach, we select one signalized intersection and connected vehicles passing through it to observe the queueing dynamics. As is shown in Figure 5, an RSU is equipped at a 4-way signalized intersection. Each link in the network of this intersection is a two-way link. The turn movements at the intersection are also demonstrated in the figure. By observing the SPaT messages sent from the RSU in this intersection, the selected intersection is under actuated control.

For simplicity and practicality, we select the turn movement 7 during peak hours in April, 2013 to implement using the proposed approach. For a random day, the within-day pattern of turn movement 7 at the intersection is shown in Figure 6.
Queueing Dynamics at a Signalized Intersection under Normal Conditions

We first extract trajectories of connected vehicles passing through the selected intersection on the selected day from the V2I records of the high-resolution connected vehicle dataset contains. Then we select a 2.5 minutes’ trajectory of one vehicle (ID: 7***9) at 11 am on April 1, 2013 to test queueing regions identification by the integrated approach for the through turn movement of the selected intersection. To test the identification of queue formation region, queue region, and queue dissipation region (region I, II, and III in Figure 7), we extract another connected vehicle (ID: 7***1) that passing through the intersection with same turn movement to test the identification. The result in Figure 7 shows that the time-distance trajectory of the second connected vehicle fits well with the queueing regions identified using the first connected vehicle. And based on the result, the intersection during the time period we select is under normal traffic condition.

To observe space-time dynamics of queueing process based on the results in Figure 7, we add some blue lines as auxiliary lines. After we identifying the queue formation, queue, and queue dissipation regions, we find that the queue lengths in Region II are changing over space (i.e. the queue rear and front positions of different trajectories/vehicles is changing) and time (i.e. different queue join time). Moreover, the space-time dynamics of queue formation and dissipation processes (i.e. deceleration and acceleration distance and time is changing) can also be observed in Region I and III.
Queueing Dynamics at a Signalized Intersection under Oversaturated Conditions

We select connected vehicles passing through for turn movement 7 the intersection with two queues as a case under oversaturated condition. Using a 3 minutes’ trajectory of one connected vehicle at 13 pm on April 3, 2016 and corresponding SPaT messages, we identify the queueing regions for the first and second queues respectively. Note that in Figure 8, the departure wave $v_p^n$ is translated to better illustrate the queue dissipation region (Region III) identified by the integrated model for the first queue. Similarly, the departure wave $v_{p+1}^{n+1}$ is translated so the queue dissipation region can be clearly shown for the second queue. To test the identification by the integrated model using the trajectory of one connected vehicle, we extract trajectory from another connected vehicle that enters DSRC range 45 seconds later.

In Figure 8, the red and green intervals are shorter than that under the normal condition, which indicates that signal changes are more frequent under oversaturated condition. The first deceleration curve of the second vehicle strictly locates in queue formation region (Region I) for the first queue. The second deceleration and the second non-moving curves also strictly locate within the queue formation and queue regions (Region I and II) respectively for the second queue. It is noted that the first non-moving curve of the second vehicle is not fully located in the queue region (Region II) for the first queue, which may be caused by the traffic interruption at intersection 2 (in Figure 5) (i.e. the traffic from link 2 increase the queueing time of the first queue for the second vehicle). Generally, the results in Figure 8 show that the integrated approach generates an acceptable result for the identification of queue formation, queue, and queue dissipation regions using connected vehicle data under oversaturated condition.

![Figure 8 Queueing Regions Construction with Two Connected Vehicle Trajectories(Oversaturated)](image-url)
The results in Figure 8 show space-time dynamics of the queueing processes for the case under oversaturated condition. The second queue, as the main queue process, last much longer than the first queue (i.e. the residue queue). The queue rear and front positions of within Region II of the second queue change more than the first queue over space and time.

CONCLUSION

In this paper, we propose an integrated approach based on macroscopic and microscopic traffic flow theory to observing space-time dynamics of queue formation and dissipation processes using high-resolution connected vehicles as mobile sensors. Based on shockwave theory and kinematic equations, the integrated approach is used to estimate queue front position, queue rear position, and free-flow driving position, through which the queue formation wave, the queue dissipation wave, and the departure wave can be determined respectively. Given any mobile sensing data such as connected vehicle data, the queue formation, queue, and queue dissipation regions can be identified based on the three shockwaves. The queueing regions consist of a set of corresponding shockwaves so the acceleration and deceleration behaviors could be used to improve the observability of intersection queueing. Different from the existing works, the integrated approach considers microscopic driving behavior of individual vehicles by constructing the queue formation and dissipation curves to observe queueing dynamics in space and time dimensions.

To test the proposed integrated approach, we extract V2I records and signal timing I2V messages from the SPMD high-resolution connected vehicle data in Ann Arbor, Michigan. We extract driving trajectories of four connected vehicles on two separate days to show the cases under normal conditions and oversaturated conditions respectively. We also visualize the region identifications with trajectories of two neighboring vehicles and signal changes in a space-time diagram.

Using the proposed integrated approach, a precise queue estimation can be achieved given high-resolution mobile sensing data. By constructing queueing regions for the complete queueing process, the queue formation and queue dissipation dynamics can be captured. This approach enables to observe queueing process with more reliable estimations in space (queue length) and time (queue time) at signalized intersections. Furthermore, the proposed work provides a method to improve traffic state observability at signalized intersections using high-resolution connected vehicles as mobile sensors.

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