TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
2019, Vol. 2673(4) 753–761

DOI: 10.1177/0361198119837178
journals.sagepub.com/home/trr
SAGE

Left-Turn Spillback Probability Estimation in a Connected Vehicle Environment

Xiaowei Cao[1], Jian Jiao[1], Yunlong Zhang[1], and Xiubin Wang[1]

Abstract

At intersections in which the left-turn bay does not have sufficient length or the left-turn volume is relatively high, left-turn vehicles may spill back and block the adjacent through traffic. This paper aims to develop quantitative measures of the left-turn spillback, and by using the results on spillback probability, develop a suitable signal control strategy. We first develop an improved queue length estimation method for vehicles in the left-turn bay based on Comert and Cetin's general queue length estimation method with connected vehicles, after which we propose a probabilistic model to measure the left-turn spillback probability at an intersection in a connected environment. The model accuracy is validated with results from microscopic traffic simulation. The effect of bay length is also studied. In the end, a signal control demonstration is presented to show the efficiency of the proposed method in signal control.

Intersection queue length estimation is important to signal timing. Our intuitive observation tells us that signal timing is about reducing vehicle queueing at the intersection. A better knowledge of the intersection queueing enables development of better signal timing. In a special circumstance in which left-turn vehicles often block through traffic when they exceed the left-turn bay capacity, the left-turn vehicular queue estimation is of particular significance. This is because blockage of through traffic undermines the intersection efficiency and gives suboptimal signal timing. This paper specifically deals with the left-turn vehicular queue as well as the probability that this left-turn queue spillback obstructs through traffic movement.

We have positioned our study in the context of connected vehicles. Connected vehicles are a promising new technology built on short range wireless communication (*1*). The application of connected vehicles allows communication between vehicles, and between vehicles and the infrastructure, and therefore shows promise to overcome the limitations of fixed location detectors by providing more longitudinal vehicle and traffic information. This additional longitudinal traffic information offers a new opportunity to left-turn traffic treatment and therefore, the entire intersection signal timing. This is because the left-turn vehicles have to stop on the through lane waiting to enter the left-turn bay, this is called left-turn vehicle spillback, and occurs if the left-turn volume exceeds the capacity of the left-turn bay. Left-turn spillback blocks through movement and reduces the through capacity at intersections. Therefore, the study of left-turn spillback is necessary for better intersection operation or signal timing. This paper proposes a probabilistic model for the left-turn spillback estimation by first starting with queue length estimation from connected vehicle applications, and presents a demonstration on how left-turn spillback estimation can help improve the signal timing.

Our study problem specifically assumes a known vehicle arrival process that follows a Poisson distribution along an approach in which left-turn and through movements are both present. The left-turn traffic first enters a left-turn bay with a fixed capacity. The capacity is measured by the maximum number of cars that can wait within it while waiting for the left-turn signal. In this paper, we only study one approach, irrelevant of other approaches to this type of intersection. These details allow us to develop models for this left-turn spillback study. If we apply the spillback model to improve signal timing, the signal timing for the intersection is assumed to follow the pre-timed control.

[1]Zachry Department of Civil Engineering, Texas A&M University, College Station, TX

Corresponding Author:
Address correspondence to Xiaowei Cao: caoxiaowei@tamu.edu

The remainder of this paper is organized as follows. Section 2 provides a brief literature review on queue estimation and signal control using connected vehicles. Section 3 describes the algorithm for estimating queue length of intersections with a left-turn bay. Section 4 and 5 introduces how the left-turn spillback is estimated and results from different situations are also provided. Section 6 describes application of the proposed estimation model to improve the signal control of various intersections. Section 7 closes the paper with conclusions and future research.

Literature Review

The main focus of this paper is about improved left-turn queue estimation using the connected vehicle technology with an application to signal timing. Several studies have been conducted on queue length estimation with connected vehicle (or probe vehicles) technologies since its inception. Before the advent of connected vehicles, researchers had studied queue estimation using traditional technologies such as loop detectors (*2*, *3*), which are mainly based on cross section data. New technologies such as connected vehicles can generate trajectory data, which brings new opportunities and presents new challenges to modeling (*4*). Comert and Cetin reported analytical formulas that were able to estimate the expected queue length and its variance based on two variables, the location of the last connected vehicle and the market penetration ratio, along with the probability distribution of the arrival process (*5*, *6*). Tiaprasert et al. proposed another mathematical model for queue length estimation that does not require queue characteristics to be known and applied a discrete wavelet transformation to enhance the accuracy and consistency of the estimation under different equipped vehicle penetration ratios (*7*). An event-based model published by Li et al. was developed together with a data fusion method that combined both trajectory data and loop detector data (*8*). Queue length can also be estimated by shockwave methods with trajectory data, as proposed by Cheng et al. (*9*). Badillo et al. presented an algorithm that combined loop detector data with real-time vehicle probe data from connected vehicles for the queue length estimation (*10*).

A few studies have examined the left-turn capacity, spillback and the resulting through traffic blockage (also referred to as left-turn blockage). One of the early works was performed by Messer and Fambro (*11*). The relationship between the left-turn capacity and the geometric layout was studied and guidelines to avoid spillbacks were developed. The problems with short left-turn bays were further investigated by Yin et al. (*12*) and Zhang and Tong (*13*). To model a left-turn blockage, a cell transmission model was developed by Wang et al. (*14*).

For more information about vehicle connectivity and potential challenges, readers are referred to Lu et al., who gave a review of the state-of-the-art literature (*15*). In a more general signal control area, new signal control strategies have been developed to take information from connected vehicles into account, such as the study conducted by Guler et al. (*1*). Goodall et al. developed a predictive microscopic simulation algorithm with a rolling-horizon strategy and used real data to optimize an objective function over a short period of time (*16*). Feng et al. proposed a framework that combined adaptive signal control with dilemma zone protection, multimodal signal priority and coordination (*17*). They also used detector data to improve the framework's performance under low market penetration rates. Zohdy et al. developed a signal control algorithm based on the latest cooperative adaptive cruise control (CACC) system to reduce intersection delay and fuel consumption (*18*). Furthermore, Lee et al. presented a cooperative vehicle intersection control (CVIC) algorithm that does not even require a traffic signal (*19*). In comparison, our paper is focused on left-turn traffic spillback estimation in a new data environment of connected vehicles.

Queue Length Estimation

This aim of this section is to estimate the total queue length at the intersection (Figure 1) if locations of connected vehicles in the queue are all known. The total queue length here refers to the total number of queued vehicles in both the left-turn bay and the adjacent

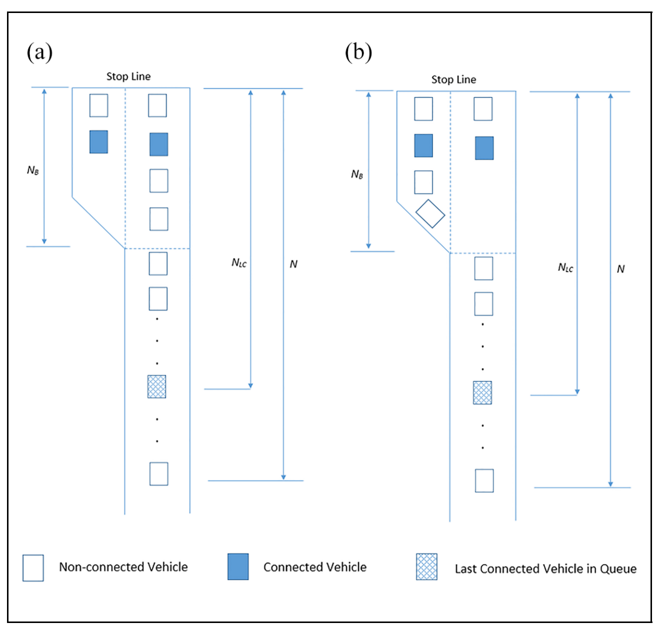

Figure 1. Layout of lane approach with left turn bay (**N_B = 4**): (a) no left-turn spillback; (b) left-turn spillback occurs.

through lane. Technically, the goal is to determine the expected value of the total queue length given the locations of connected vehicles. The geometry of this approach is a through lane along with a left-turn bay, which has a length of 4 vehicles.

It is assumed that the distance of connected vehicle from the stop line can be measured using location tracking technologies. The location of vehicles in a queue will be measured by the number of vehicles to the stop line. The arrivals are assumed to follow a Poisson distribution. The notations used in this paper are introduced as follows:

p: penetration rate;

λ: average arrival rate;

N_{LC}: location of the last connected vehicle in the queue in the through lane, in number of vehicles; (as shown in Figure 1b, in the presence of spillback, N_{LC} is the sum of N_B and the queued vehicles after the left-turn bay in the through lane until the last connected vehicle; in the absence of spillback, N_{LC} is the total number of the queued vehicles in the through lane until the last connected vehicle;

N: location of the last queued vehicle in the through lane from the stop line, in the number of vehicles; (as shown in Figure 1b), in the case of spillback, N is the sum of N_B and the queued vehicles after the left-turn bay in the through lane; in the absence of spillback, N is the total number of the queued vehicles in the through lane;

N': total number of queued vehicles in both left-turn bay and adjacent through lane;

N_B: bay storage length in number of vehicles;

ρ_{LT}: left-turn vehicle percentage among vehicles coming in the approach of interest;

N_{LT}: number of left-turn vehicles ($N_{LT} = N' \times \rho_{LT}$);

N_{TH}: number of through vehicles ($N_{TH} = N' - N_{LT}$).

N can be calculated based on Comert and Cetin's method (4) using equation 1 below:

$$E(N) = \sum_{n = N_{LC}}^{\infty} \frac{n[(1-p)\lambda]^n}{n! \sum_{k = N_{LC}}^{\infty} \frac{[(1-p)\lambda]^k}{k!}} \tag{1}$$

As shown in Figure 1, the final status before the through green phase starts should either be 1a or b. All of the parameters (N, N_{LC}, N_B) in this figure are for the number of vehicles. Here, N_B is equal to 4, meaning that the bay can store 4 vehicles.

In Figure 1a, N is the expected number of queued vehicles in the adjacent through lane. Similarly, in Figure 1b, if we switch the left-turn queued vehicles with those in the adjacent through lane before the dashed line, the graph will be the same as 1a. Clearly, the expected total queue length is the sum of N and the number of vehicles in the left-turn bay, which can be any number within $[0, N_B]$.To simplify the calculation, we assume the probability of any number of vehicles within $[0, N_B]$ in the left-turn bay to be equal. This assumption may seem abrupt and is likely too strong. However, we conjecture that this is a provable fact under the Poisson assumption as similar results appear to have been proved in other areas, such as inventory control. The equation used to find N' is shown below:

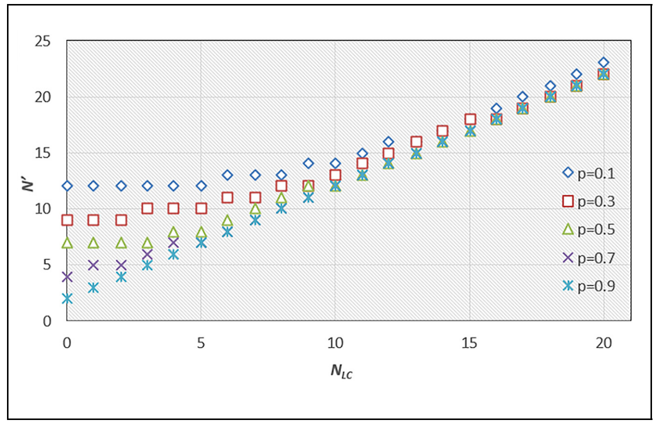

Figure 2. Expected value of total queue lengths versus the location of the last connected vehicle.

$$E(N') = \frac{\sum_{i=0}^{N_B} \sum_{n = N_{LC}+i}^{\infty} \frac{n[(1-p)\lambda]^n}{n! \sum_{k = N_{LC}+i}^{\infty} \frac{[(1-p)\lambda]^k}{k!}}}{N_B} \tag{2}$$

In addition to the situation shown in Figure 1, it is possible that the last connected vehicle is queued in the left-turn bay. There are two situations in which this can happen. First, the arriving volume is low from the approach of interest, implying a low probability of a left-turn spillback. The other situation is that the connected vehicle penetration rate is very low, and that we only know the locations of a few vehicles. It is difficult to estimate the total number of queued vehicles given such limited information, unless the total number of queued vehicles is large enough (see the results in Figure 2). As this study does not focus on examining the impact of the penetration rate, we assume that the last connected vehicle is always in the adjacent through lane in the following sections, which is a reasonable assumption especially in the simulation because we set up the arriving traffic volume to be large enough to generate sufficient cases of left-turn spillback. In these simulations, the probability of the last connected vehicle being in the through lane is relatively high.

To understand Equation 2: i is the number of queued vehicles in the left-turn bay. As indicated earlier, i is a number between 0 and the capacity of the left-turn bay. Zero indicates that no queued vehicles are in the left turn bay. The total number of queued vehicles in this approach may be estimated by using the total number of

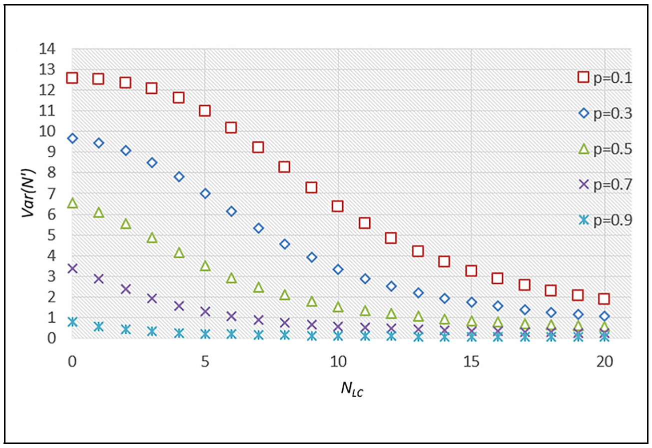

Figure 3. Variance of total queue length versus $\boldsymbol{N_{LC}}$.

queued vehicles before the last connected vehicle (all of the vehicles from the stop line to N_{LC}), including the ones in the through and left-turn bay. Then, Comert and Cetin's method is used to obtain the expected total queue length.

Figure 2 shows the relationship between the expected total queue length versus the location of the last connected vehicle for five different penetration rates, p. The bay length is set to be 4. Based on the figure, the expected queue length converges to the location of the last connected vehicle as N_{LC} increases. Also, the difference between the expectations for low and high penetration rates are much bigger when N_{LC} is small, and becomes negligible when N_{LC} is large enough.

To study the accuracy of the estimated queue length given different penetration rates p, the variance of the queue length (given as N_{LC}) can be written as follows:

$$\mathrm{Var}(N') = \frac{\left(\sum_{i=0}^{N_B} \sum_{n=N_{LC}+i}^{\infty} \frac{n^2[(1-p)\lambda]^n}{n! \sum_{k=N_{LC}+i}^{\infty} \frac{[(1-p)\lambda]^k}{k!}}\right) - [E(N')]^2}{N_B} \tag{3}$$

The results, as shown in Figure 3, show the variance of the expected total queue length versus the location of last connected vehicle for different p values. The results are consistent with the intuition that the variance decreases with higher p values. The variance is larger if N_{LC} is small; and as N_{LC} becomes larger, the variance tends to zero even for small p values. This implies that the number of total queued vehicles can be estimated with a better accuracy if N_{LC} is large. Obviously, higher p values also lead to a better estimation.

Spillback Estimation

After the expected total number of arrivals is obtained, we are able to find the possibility that left-turn spillback occurs during the green phase. As mentioned earlier, spillback occurs when at least one through vehicle is blocked and cannot move through. A blockage of the through movement also means that there are at least $N_B + 1$ left-turn vehicles before the first blocked through vehicle.

The probability of having a left-turn spillback is defined as P_{sb}. As the left-turn bay capacity is N_{LT}, the following equation can be used:

$$P_{sb} = \frac{\sum_{i=N_B+1}^{N_{LT}} \binom{N_{TH}-1+i}{i}}{\binom{N'}{N_{LT}}} \tag{4}$$

The numerator is the number of combinations, each of which has a spillback, and the denominator is the total number of combinations for all of the queued vehicles, with, and without spillback.

Analysis of Spillback Probability, Left-Turn Percentage, and Bay Length

To evaluate the accuracy and reliability of the spillback estimation, the computed result was compared with simulation results from VISSIM. VISSIM simulation results are regarded as the real-world scenarios for evaluation purposes. First, VISSIM runs the simulations and produces files of vehicle trajectory data. Second, Matlab is used to process the output files by investigating queue conditions at the end of every red phase of the interest approach and determine whether there is spillback or not. Next, the probability of left-turn spillback is calculated by dividing the number of cycles with spillback by the total number of cycles in the simulation. The results from the proposed estimation are compared with those from the simulations.

Simulation Setup

An illustrative, isolated intersection was set up for the left-turn spillback test in VISSIM. The layout of the intersection is shown in Figure 4. The intersection has four legs with a left-turn bay for each approach. As the intersection was used to test left-turn spillback, only one approach is investigated. In this case, we selected the eastbound approach for study. It should be noted that the proposed estimation method can be applied to intersections with multiple through lanes. As only the queues in the left-turn bay and the adjacent through lane will be used in our model, the number of through lanes does not impact the results. For simplicity, during the simulation only one through lane was set up for each approach. We decided that a volume of 900 vph should be used for this

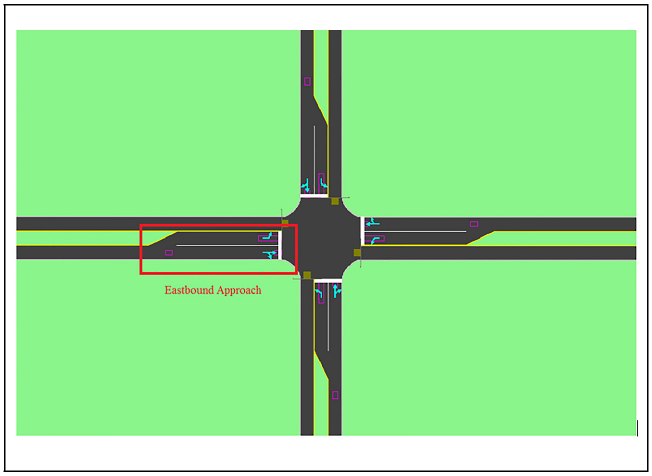

Figure 4. Layout of intersection for left-turn spillback simulation.

study to ensure a reasonable level of spillback probability. Low volumes of spillback rarely occur. The signal timing of the intersection was obtained from SYNCHRO 9 optimization with the same intersection settings. There were four phases for this intersection, which are east-west through, east-west left-turn, north-south through, and north-south left-turn. We use actuated control in the simulation. The detailed setting includes: a 2 s critical gap, a 15 s minimum green time for through phases, a 35 s maximum green time for through phases, a 10 s minimum green time for left-turn phases, and a 25 s maximum green time for left-turn phases.

VISSIM includes randomness in every cycle of simulation. Although the volume is set to be 900 vph for an approach, the actual number of vehicles arriving at the intersection in each cycle varies randomly. This is also true for the left-turn percentage: as in one cycle it can either be greater or smaller than the pre-defined value for the turning percentage. For example, a setting of 50% left-turn percentage may actually have 20% or 70% left-turn vehicles in a specific cycle. This characteristic of VISSIM reflects real world scenarios, but can be an issue for a fair comparison with the calculated result. The proposed left-turn estimation method is based on knowledge of the left-turn percentage of the queue at the end of each cycle. Therefore, to obtain an accurate left-turn percentage at the end of each cycle, the simulation results were collected by classifying the queueing condition of each cycle by specific characteristics and then aggregating cycles with the same characteristics together. The results of the VISSIM simulation are classified into two categories: the total number of queued vehicles during the red phase and the total number of left-turn vehicles queued during the red phase. For the total number of vehicles queued during the red phase, the numbers 18, 19, 20 and 21 occur most often in the aggregated results, and are considered to best represent the current volume setting. The total number of left-turn vehicles in the queue must be greater than the bay length (represented by the number of vehicles that the bay can accommodate) for spillbacks to occur. For a bay length of 4 vehicles for example, the total number of left-turn vehicles has to be at least 5. On the other hand, when the number of left-turn vehicles is larger than 11 the spillback probability is almost 1. This gives a range of 5 to 11 left-turn vehicles in the queue. The number of total queued left-turn vehicles corresponds to different left-turn percentages during a cycle. Therefore, the results are classified into categories according to the specific number of total queued vehicles and the specific number of total queued left-turn vehicles. The probability of spillback is calculated in each category.

To account for different left-turning percentages and to include enough samples, three levels, 35%, 50% and 70%, representing medium, high and very high values of left-turn percentages, were selected as inputs in VISSIM. Each level of left-turn percentage was run in VISSIM 50 times with 50 random seeds for a total of 500,000 seconds. All of the simulation results were then aggregated and further classified according to the categories defined previously. To investigate the effect of the left-turn bay length, the storage length in VISSIM was modified to accommodate 3, 4, 5, 6 and 7 vehicles. The same simulation process was then applied to scenarios with different bay lengths.

Simulation Results

Figure 5 shows the relationship between the estimated left-turn spillback probability and the actual results obtained from simulation. Four different values of queue lengths, N', were selected to test the proposed method under different volumes. The reason for this was because as mentioned previously, even if the volume is set to 900 vph in VISSIM, the actual number of arrivals during each cycle can still be quite different owing to the software characteristics of VISSIM. To study the accuracy of the proposed method under different volumes, N' can be used as a substitution for the actual volume. To study the effect of the left-turn ratio, a different number of left-turn vehicles should also be examined. As the number of left-turn vehicles needs to be an integer, it is straightforward to use the number instead of a fixed ratio.

Based on the graphs, it is obvious that the actual left-turn spillback probability (e.g., in the simulation) is consistent with that of the estimated probability obtained from the proposed model. In most cases, the model estimated probability is slightly greater than the actual value. The reason for this is that our model considers all of the spillback combinations. However, it appears that the simulation results do not cover all of those cases in the

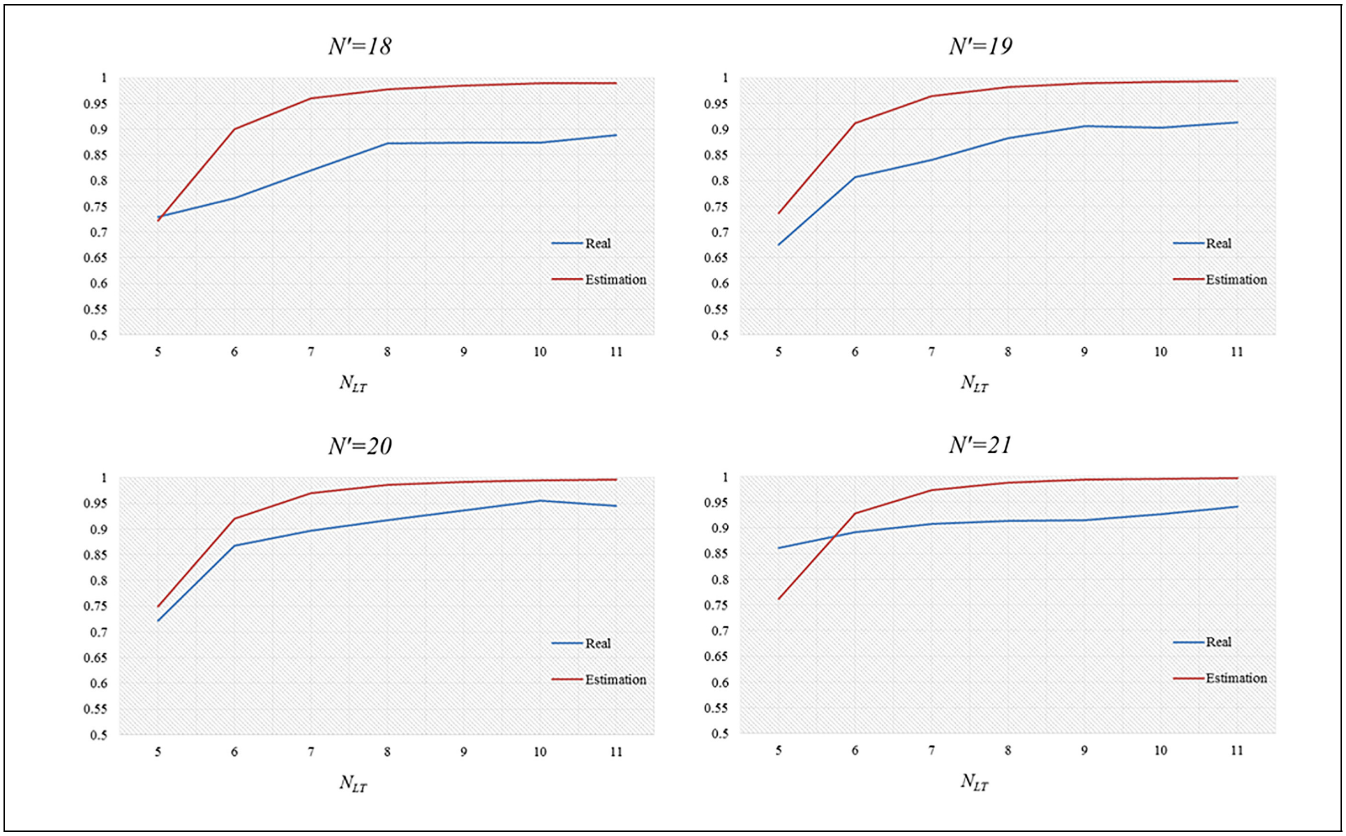

Figure 5. Estimated left-turn spillback probability versus real probability for different $\boldsymbol{N'}$ and $\boldsymbol{N_{LT}}$.

finite simulation time. The actual situation, as in the simulation, is more complicated. For example, some left-turn drivers in the through lane may change their mind to go through at last, which can impact the real spillback probability calculation.

In actual situations, different intersections have different bay lengths. Figure 6 shows the spillback probability estimation compared with simulation results. For the purpose of illustration, the total number of arrivals is set to be 18 and 8 of them are left-turn vehicles. From Figure 6, it is easy to recognize that the proposed method works better when the bay length is small, which also means that a left-turn spillback is more likely to occur. A longer bay length results in less accurate estimations. The reason could be that when left-turn spillback occurs only a few times during a certain time interval, it is more difficult to accurately predict the occurrence and probability of the spillback. This finding can also help assess whether a left-turn bay is long enough to keep the spillback probability below a threshold during peak hours. Bay extension would be necessary if the spillback probability is too high, especially during the peak hour.

The spillback probability estimation can be implemented in two major categories: adjacent through capacity analysis and real time signal control, the latter of which

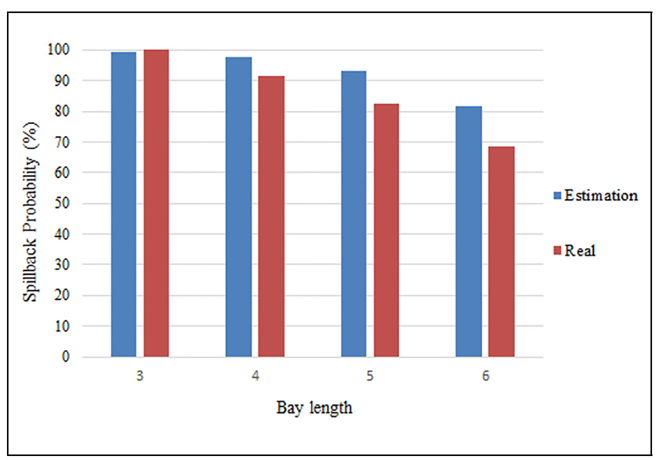

Figure 6. Estimated left-turn spillback probability versus real probability for different $\boldsymbol{N_B}$.

is demonstrated in the next section. For adjacent through capacity estimation the model described by Zhang and Tong can be applied using the following equation (*13*):

$$\text{Capacity} = P \times \left(\frac{N_{TH}n - s_{TH}g_{TH}}{C}\right) + \frac{N_{LN}s_{TH}g_{TH}}{C} \tag{5}$$

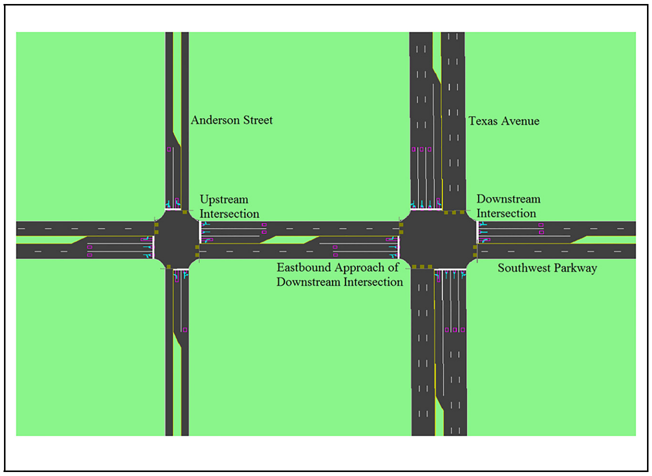

Figure 7. Layout of two consecutive intersections for signal control simulation.

In which P is the probability of left-turn spillback, N_{TH} is the number of vehicles arriving in the adjacent through lane before the spillback in each cycle, n is the number of cycles in the peak hour at a signal intersection, N_{LN} is the number of through lanes in the approach, g_{TH} is the green interval for adjacent through, s_{TH} is the saturation flow rate for the through movement, and C is the cycle length.

Improving Signal Control using Spillback Estimates

As mentioned previously, the proposed left-turn spillback estimation method can be used to improve signal control. A demonstration of the implementation is presented in this section. A real world case in College Station, Texas with two consecutive intersections is selected for the demonstration. Figure 7 shows that Southwest Parkway intersects with Anderson Street to form the upstream intersection and intersects with Texas Avenue to form the downstream intersection. A left-turn spillback occurs frequently at the eastbound approach of the downstream intersection, especially during peak hours, as vehicles turn into the major arterial, Texas Avenue. This results in long queues and large delays at the downstream intersection, and it is desirable to adjust signal timing strategy to improve the traffic conditions. Therefore, this downstream intersection was selected as the major intersection to examine.

The real volume data and signal timing are input into the VISSIM simulation for comparison. The simulation is run for 3600 seconds. The input volume is set to be 1000 vph for the eastbound traffic at the upstream intersection, resulting in an average volume of 900 at the downstream intersection on Texas Avenue. Owing to the randomness, the actual arrivals in each cycle vary. An observation shows that about 30% of the cycles have spillback.

There are two methods for signal timing adjustment using the left-turn traffic spillback information. The first is to adjust the timing of the downstream intersection directly whenever spillback is detected. The second is to reduce the incoming traffic of the upstream intersection after spillback is detected at the downstream intersection. Taking into account that the downstream intersection involves a major arterial (e.g., the Texas Avenue), this section only demonstrates the second method, which adjusts the upstream intersection signal timing to reduce the incoming traffic. The arrivals on the major arterial will not be affected by the signal timing adjustment. As the volume on Anderson Street is relatively low, most of the incoming traffic to the downstream intersection comes from the eastbound approach of the upstream intersection. Therefore, adjusting the through phase green of the eastbound approach alone is able to satisfy the need for downstream volume reduction.

The proposed method calculates the probability of a spillback every second. The upstream intersection signals are adjusted immediately once the calculated spillback probability exceeds a certain threshold. The detailed signal control strategy is summarized as follows:

Simulation clock starts at time $i = 0$.

- Step 1: Given $p, \lambda, N_{LC}, \rho_{LT}$. Calculate P_{sb} at time i. If $P_{sb} \geqslant \alpha$, go to step 2. Otherwise, go to step 3.
- Step 2: If through phase is green at upstream intersection, switch to next phase immediately, $i = i + t$. Go to step 1; otherwise, go to step 3.
- Step 3: If $i \leqslant T$, $i = i + 1$, go to step 1; otherwise, simulation ends.

p is set up as 0.1 and 0.9 in the test for the purpose of comparison.N_{LC} is assumed to be the last connected vehicle in the through lane adjacent to the left-turn bay on the eastbound approach of the downstream intersection. α is the threshold that is used to decide if the spillback probability is too high, as described earlier. $t$represents travel time from the upstream intersection to the downstream intersection based on the distance divided by the speed limit. Those two parameters could be chosen based on a real situation or practical judgment. In this paper, α is set to be 50% and t is equal to 20 seconds. T is the total simulation period, which is 3600 seconds, as mentioned previously, for each run. We conducted 20 runs in total.

ρ_{LT} is set up in a different way as it can vary from cycle to cycle. However, based on the given connected vehicle information, the total number of connected vehicles in the through traffic and the total number of left-turn vehicles before the last connected vehicle are both

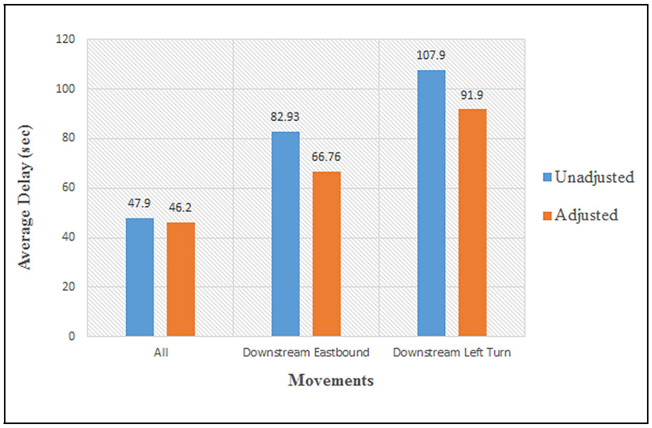

Figure 8. Average vehicle delay comparison.

available as well. As a result, the estimated left-turn ratio is obtained. It should be noted that in calculating the left-turn ratio, only the vehicles in the adjacent through lane and left-turn bay are used. For example, if there are a total of 10 through connected vehicles and 5 left-turn connected vehicles: $\rho_{LT} = \frac{5}{5+10} = 33.3\%$.

If the upstream through phase is switched to the next phase, P_{sb} will not be assessed for the succeeding 20 sec. The reason is that the adjusted incoming volume requires this travel time to arrive at the downstream intersection to actually have an impact on the spillback probability. Therefore, during this period, no judgment is needed.

The results of the simulations are presented in Figure 8. VISSIM provides results on the average vehicle delay (e.g., delay per vehicle) for each movement of the two intersections. The bars under "unadjusted category" are for results from the original signal timing and the bars under "adjusted category" represent results from the adjusted signal timing based on the proposed method. The first group in Figure 8 represents the average delay for all the vehicles entering the two intersections. The second group of bars represents the average delay of vehicles on the eastbound approach of the downstream intersection. The last group represents the average delay of only left-turn vehicles on the eastbound approach of the downstream intersection.

In Figure 8, the average vehicle delay decreases by about 20% on the eastbound approach at the downstream intersection. The average delay for left-turn vehicles decreases by about 15%, which shows that the proposed method can significantly help reduce the spillback probability and improve the intersection performance. The overall average delay also decreases, but to a lesser degree. The reason could be that reducing the green phase at upstream intersection for the eastbound traffic would increase the delay at that intersection. However, as the upstream intersection is not a major one, the overall results suggest that the proposed signal adjustment method is effective.

Two different p values (0.1 and 0.9) were tested respectively and the results were exactly the same using the proposed method. These results are reasonable for an intersection with a high left-turn volume such as in this case. The reason for this is that according to Figure 3, when N_{LC} is large enough (long left-turn queue), as is the case in this simulation, the impact of the penetration rate is not significant any more. Another explanation is that a higher p value causes more connected vehicles in the queue. However, only the position of the last one is used to calculate the spillback probability, therefore the impact is limited. However, further cases with different N_{LC} values should be investigated in the future.

Conclusion

This paper focuses on estimating left-turn vehicle spillback probability. It starts with the total queue length estimation for vehicles on a through lane with a left-turn bay using the location of the last connected vehicle. The results show that total queue length estimation is more accurate if the connected vehicle penetration rate, p, is larger. Furthermore, a larger N_{LC} can also improve the estimation if p is small.

We then proposed an equation to calculate the probability of left-turn spillback, which was tested using a VISSIM micro-simulation. Several cases were compared to assess the accuracy of the proposed equation with varying traffic volume, left-turn ratio, and bay length. The results showed that the proposed equation is able to provide a fairly accurate spillback probability, especially for large left-turn ratios. The equation works better for shorter bay lengths, but the overall result for different bay lengths is still considered to be convincing.

Finally, an improved signal control in a connected vehicle environment was demonstrated based on the spillback probability obtained from the proposed equation. The main idea is to adjust the upstream signal phase to decrease the incoming volume to the major intersection that has a high spillback probability. The results suggest that such a strategy is very effective in reducing protentional left-turn spillback without causing an extra delay to the whole system. The average delay decreases by 20% for all of the vehicles going from an upstream intersection to a downstream intersection. If left-turn vehicles are considered independently, the decrease is by about 15%. Overall, the proposed spillback treatment strategy is considered to be effective.

As indicated earlier, we only considered that left-turn spillback occurs to the left most through lane for a multiple lane approach. This assumption is based on an equal lane balance, which is somewhat reasonable in a real situation. The impact of an unequal lane balance under a multiple lane situation can be investigated in future work.

Future work includes relaxing the requirements for the last connected vehicle in estimating the left-turn spillback. A real time signal control method may potentially be developed for the general intersection when a high spillback probability is detected.

Author Contributions

XC and JJ conceived the idea for the paper, performed the literature review, proposed the analytical method and performed the numerical simulations. YZ advised the technical development and helped position the research, conduct the analysis and improve the presentation. XW proofread the manuscript and helped correct errors and inconsistencies, and finally improved the presentation. All authors discussed the results, future work and contributed to the final manuscript.

References

1. Ilgin Guler, S., M. Menendez, and L. Meier. Using Connected Vehicle Technology to Improve The Efficiency of Intersections. *Transportation Research Part C: Emerging Technologies*, Vol. 46, 2014, pp. 121–131.
2. Sharma, A., D. M. Bullock, and J. A. Bonneson. Input-Output and Hybrid Techniques for Real-Time Prediction of Delay and Maximum Queue Length at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2007. 2035: 69–80.
3. Liu, H. X., X. Wu, W. Ma, and H. Hu. Real-Time Queue Length Estimation for Congested Signalized Intersections. *Transportation Research Part C: Emerging Technologies*, Vol. 17, No. 4, 2009, pp. 412–427.
4. Argote, J., E. Christofa, Y. Xuan, and A. Skabardonis. Estimation of Measures of Effectiveness Based on Connected Vehicle Data. *Proc., 2011 14th International IEEE Conference on Intelligent Transportation Systems*, Washington, D.C., 2011, pp. 1767–1772.
5. Comert, G., and M. Cetin. Queue Length Estimation from Probe Vehicle Location and the Impacts of Sample Size. *European Journal of Operational Research*, Vol. 197, No. 1, 2009, pp. 196–202.
6. Comert, G., and M. Cetin. Analytical Evaluation of the Error in Queue Length Estimation at Traffic Signals from Probe Vehicle Data. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 12, No. 2, 2011, pp. 563–573.
7. Tiaprasert, K., Y. Zhang, X. B. Wang, and X. Zeng. Queue Length Estimation using Connected Vehicle Technology for Adaptive Signal Control. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 16, No. 4, 2015, pp. 2129-2140.
8. Li, J. Q., K. Zhou, S. Shladover, and A. Skabardonis. Estimating Queue Length under Connected Vehicle Technology: Using Probe Vehicle, Loop Detector, and Fused Data. *Transportation Research Record: Journal of the Transportation Research Board*, 2013. 2356: 17–22.
9. Cheng, Y., X. Qin, J. Jin, and B. Ran. An Exploratory Shockwave Approach for Signalized Intersection Performance Measurements using Probe Trajectories. Presented at 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.
10. Badillo, B. E., H. Rakha, T. W. Rioux, and M. Abrams. Queue Length Estimation using Conventional Vehicle Detector and Probe Vehicle Data. *Proc., 15th International IEEE Conference on Intelligent Transportation Systems*, IEEE, 2012, pp. 1674–1681.
11. Messer, C. J., and D. B. Fambro. Effects of Signal Phasing and Length of Left Turn Bay on Capacity. *Transportation Research Record: Journal of the Transportation Research Board*, 1977. 644: 95–101.
12. Yin, K., Y. Zhang, and B. X. Wang. Effects of Signal Phasing and Length of Left Turn Bay on Capacity. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. 2257: 103–110.
13. Zhang, Y., and J. Tong. Modeling Left Turn Blockage and Capacity at Signalized Intersection with Short Left Turn Bay. *Transportation Research Record: Journal of the Transportation Research Board*, 2008. 2071: 71–76.
14. Wang, P., S. L. Jones, S. Gurupackiam, and L. Wang. Novel Cell Transmission Model-Based Simulations of Left-Turn Blockages inside Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 2013. 2390: 60–67.
15. Lu, N., N. Cheng, N. Zhang, X. Shen, and J. W. Mark. Connected Vehicles: Solutions and Challenges. *IEEE Internet of Things Journal*, Vol. 1, No. 4, 2014, pp. 289–299.
16. Goodall, N., B. Smith, and B. Park. Traffic Signal Control with Connected Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, 2013. 2381: 65–72.
17. Feng, Y., M. Zamanipour, K. L. Head, and S. Khoshmagham. Connected Vehicle-Based Adaptive Signal Control and Applications. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2558: 11–19.
18. Zohdy, I. H., and H. A. Rakha. Intersection Management via Vehicle Connectivity: The Intersection Cooperative Adaptive Cruise Control System Concept. *Journal of Intelligent Transportation Systems*, Vol. 20, No. 1, 2016, pp. 17–32.
19. Lee, J., and B. Park. Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm under the Connected Vehicles Environment. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 13, No. 1, 2012, pp. 81–90.

The Standing Committee on Traffic Signal Systems (AHB25) peer-reviewed this paper (19-01000).