Traffic Density Estimation of Signalised Arterials with Stop Line Detector and Probe Data

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Abstract: This research aims to develop a reliable density estimation method for signalised arterials based on cumulative counts from upstream and downstream detectors. In order to overcome counting errors associated with urban arterials with mid-link sinks and sources, CUmulative plots and Probe Integration for Travel timE estimation (CUPRITE) is employed for density estimation. The method, by utilizing probe vehicles' samples, reduces or cancels the counting inconsistencies when vehicles' conservation is not satisfied within a section. The method is tested in a controlled environment, and the authors demonstrate the effectiveness of CUPRITE for density estimation in a signalised section, and discuss issues associated with the method.

Keywords: Density estimation, Signalised arterial, Probe data, CUPRITE, Data fusion

1. INTRODUCTION

This research aims to develop a reliable density estimation method for signalised urban networks. Recently, the existence of the Macroscopic Fundamental Diagram (MFD) with dynamic features was verified in congested urban network in Yokohama city by Geroliminis and Daganzo (2008). Similarly to the conventional link-based fundamental diagram, the MFD represents area traffic states by defining the traffic throughput of an area at given density levels, and describes the dynamics of area-wide traffic conditions. Thus, the MFD can help in comprehensive understanding of network traffic conditions, and many studies have been reported on traffic control strategies and network state estimations based on the MFD's concept (Daganzo, 2007, Geroliminis et al., 2012, Haddad and Geroliminis, 2012, Horiguchi et al., 2010, Keyvan-Ekbatani et al., 2012, Knoop et al., 2012, Yoshii et al., 2010).

In order to apply the MFD to real world, reliable variables' estimations are essential. The variables include section traffic flow and density. Urban signalised network is usually equipped with stop line detectors and/or mid-link detectors. These detectors count vehicles passing and measure the occupancy that can be converted into traffic density. Although density is a key variable in the MFD analysis, the signalised networks' density estimation from point measurements cannot be straightforward. Unlike the case of freeway networks, where uninterrupted flow is expected, signalised arterials are characterized with stop-and-go behavior, and the density from a point measurement cannot be a representative of the whole section. In particular, the occupancy (or the density) obtained from the stop line detectors are highly affected by the stopping vehicles during red time phases (WU et al., 2011). Therefore, the development of sound estimation methods is necessary.

A number of literatures on density estimation models exist for signalised arterial sections. The models include classical input-and-output procedures (Sharma et al., 2007, Webster, 1958), the use Kalman filetering with occupancy as a measurement (Papageorgiou and Vigos, 2008, Qian et al., 2012, Vigos et al., 2008), the model based on kinematic wave theory (Liu et al., 2009), and the use of mobile sensor to estimate intersection delay and queue length (Ban et al., 2011). This previous research has shown promising results with possible direction for further improvements. However, the study sites have been limited to the sections without mid-link sink and/or source points, where conservation of vehicles is expected within the section.

When the vehicles' conservation is assumed, density is available simply from vehicles' cumulative counts at upstream and downstream of the section, i.e., the subtraction of cumulative counts at downstream from the one at upstream gives the number of vehicles existing in the link. However, this method is subject to detectors' counting errors and mid-link sources and sinks, which violate the vehicles' conservation assumption and cause significant errors in estimation. In order to overcome this issue, CUmulative plots and Probe Integration for Travel timE estimation (CUPRITE) (BHASKAR et al., 2009, BHASKAR et al., 2010, BHASKAR et al., 2011) model has been proposed, which integrates probe vehicle data with cumulative counts. Although it is originally designed to estimate link travel time, CUPRITE calculates the link density at the same time. This research, by employing the CUPRITE model, develops a suitable method of density estimation for signalised networks with mid-link sinks and sources.

The method is tested in a controlled environment, using a microscopic simulator AIMSUN. The test bed consists of upstream and downstream intersections and a mid-link sink and source, where the vehicles' conservation is not satisfied. The stop line detectors are installed to obtain cumulative counts of upstream and downstream. Also, probe vehicles' samples are introduced in order to correct the error in the cumulative counts. The authors demonstrate the effectiveness of CUPRITE for density estimation in the signalised section, and discuss issues associated with the method.

2. DENSITY ESTIMATION FOR SIGNALISED ARTERIALS

2.1 The Classical Procedure and its Issue

Cumulative plots are the cumulative number of vehicle over time at a specific location of the network. The classical density estimation deploys the cumulative plots at upstream and downstream ends of the section. The vertical distance of the upstream and downstream plots at given time, *t*, represents the number of vehicles between these two locations.

This method works when the detectors' counts are perfect and conservation of vehicles within the section is assumed, where the plots are based on only those vehicles that traverse the section from upstream to downstream ends. However, practically, detectors are not perfect and one can easily observe 5% random error in detector counting. Moreover, urban network has mid-link sources and sinks, such as parking or side-streets, which results in non-conservation of vehicles between upstream and downstream locations. Due to the detector counting error; non-conservation of vehicles between plots location; and any such combination over time, there is relative deviation (RD) among the plots.

In order to explain RD, let us consider a scenario of the network with only mid-link sources, where an upstream detector is overcounting. In Figure 1: U(t) is the cumulative plot observed from the overcounting upstream detector; U'(t) is from a perfect detector, which only counts the vehicles traversing the whole section. U(t) deviates from U'(t), or there is RD between U(t) and D(t). If RD is left unchecked, then the error can exponentially grow with time. Hence, the RD issue is critical in the application of the classical procedure. Note that

U(t) and D(t) will eventually "diverge" from each other if: upstream detector is overcounting; or downstream detector is undercounting; or there is mid-link sink. U(t) and D(t) will eventually "cut" each other if: upstream detector is undercounting; or downstream detector is overcounting; or there is mid-link source. If the plots diverge then the density is highly overestimated and if the plots cut then density estimates are negative. In practice, there is complex combination of detector errors, mid-link sources, and mid-link sinks over time, which defines the relative deviation for each estimation interval.

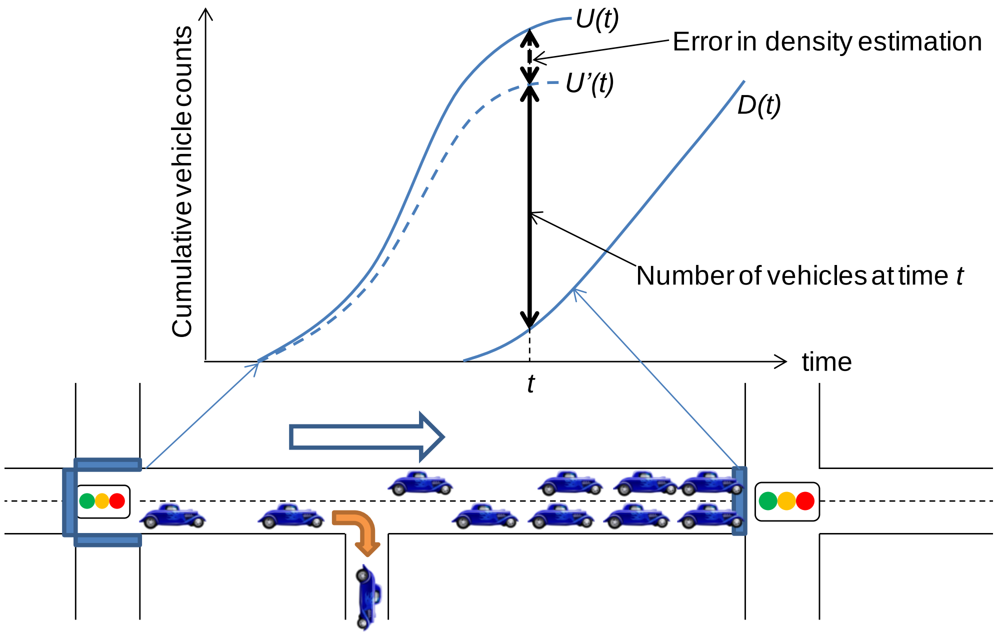

Figure 1 Relative Deviation (RD) in mid-link sink section

2.2 CUPRITE for Density Estimation

In order to address the RD issue associated with the classical procedure, CUPRITE integrates probe vehicle samples with cumulative plots. By introducing probe samples that traverse the whole section, the cumulative plots are modified and the counting inconsistencies can be reduced or cancelled. This method was originally developed for average travel time estimation as represented with the horizontal distance of the redefined plots. This research employs the vertical distance of the plots, the number of vehicles in the section, for the section density estimation.

Here probe vehicles are the vehicles equipped with vehicle tracking equipments. We assume that the times when the probe vehicle is at upstream (t_u) and downstream (t_d) locations are accurately obtained. The travel time of this vehicle is $t_d - t_u$. We define the rank of the probe vehicle in the cumulative plots as $D(t_d)$ (given that downstream counts are correct and we fix probe's rank with downstream cumulative plots D(t)) and define the point through which upstream plots U(t) should pass.

Figure 2 and Figure 3 summarise the CUPRITE architecture for density estimation assuming a mid-link sink case, where upstream detector is overcounting (for detail, refer to Bhaskar, et al. (2011)).

Step 1: Cumulative plots are defined with upstream and downstream detector counts (Refer to Bhaskar, et al. (2010) for details on how to integrate loop and signal data for estimation of cumulative plots)

Step 2: Probe data (the list of $[t_u]$ and $[t_d]$) is fixed with downstream cumulative plots and the rank for each probe vehicle is defined $[D(t_d)]$.

Step 3: Points through which U(t) should pass are defined from the list of $[t_u]$ and $[D(t_d)]$.

Step 4: U(t) is redefined by vertical scaling and shifting the plots so that it passes through the points defined in Step 3 (Refer to Bhaskar, et al. (2011) for details about Step 2 to Step 4).

Step 5: Finally, average density is defined as the vertical distance between the plots.

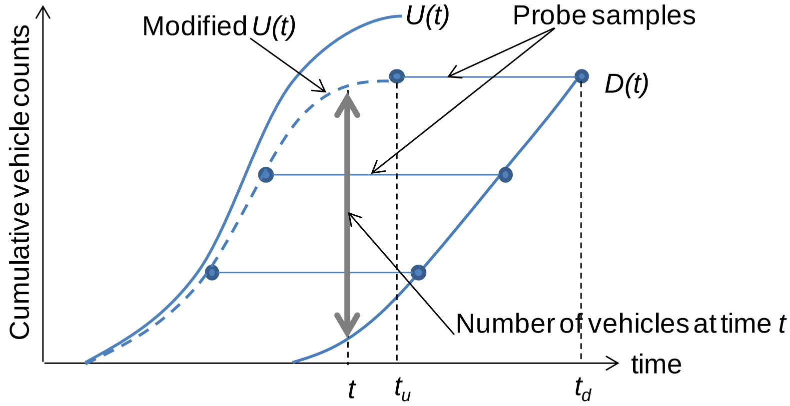

Figure 2 Illustration of CUPRITE for density estimation

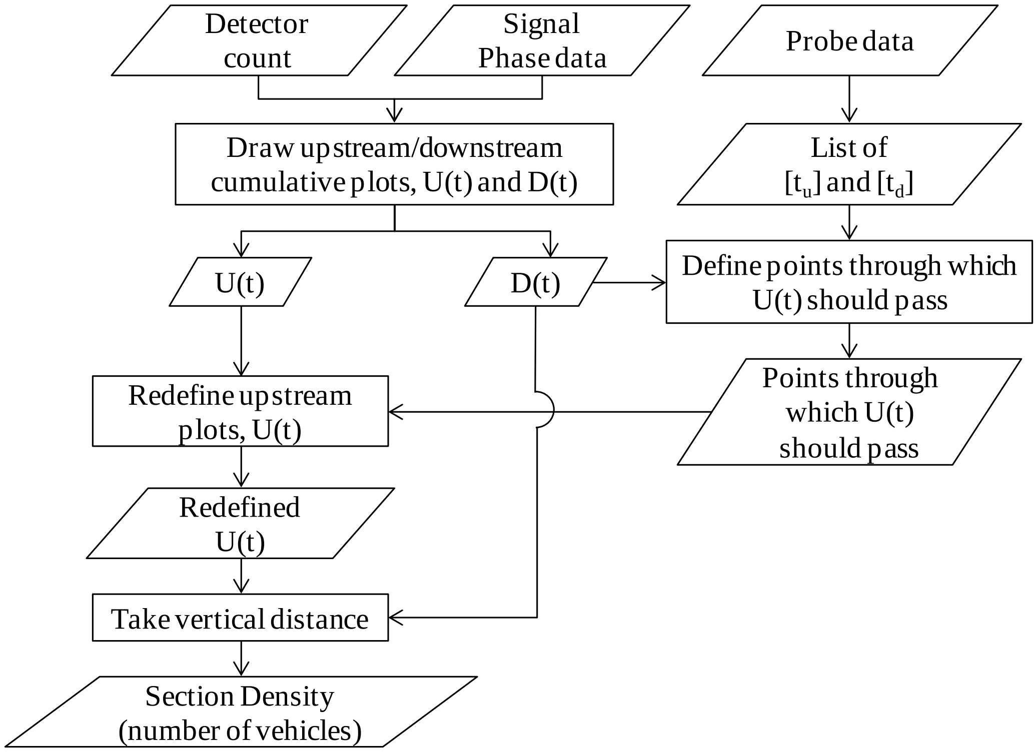

Figure 3 Architecture of CUPRITE for density estimation

In this paper, we evaluate the performance of the methodology under the scenarios where cumulative plots have significant RD. We consider mid-link sources and sinks. As discussed earlier, mid-link sources and sinks violate the assumption of conservation of vehicles on the link, which is vital for the application of cumulative plots.

We apply CUPRITE to estimate the density under different scenarios. The estimated density is evaluated against the benchmark density as defined below.

2.3 Benchmark Estimation

In order to keep the consistency, benchmark density is also measured with cumulative plots. For this, we install additional detectors in the mid link (M1 and M2 in Figure 4), i.e., immediate upstream and downstream of the mid-link source and/or sink, which provides cumulative curves, M1(t) and M2(t), respectively. The benchmark value is calculated as:

$$Benchmark(t) = \big(U(t) - M1(t)\big) + \big(M2(t) - D(t)\big) \quad (1)$$

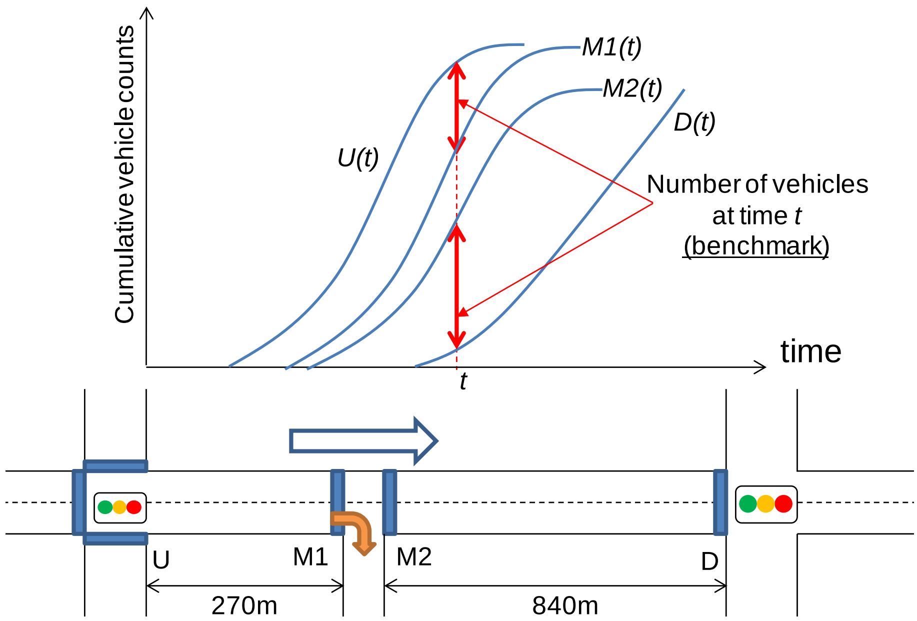

Figure 4 Benchmark density

3. DENSITY ESTIMATION TESTING

3.1 The Simulation Settings

The testing network consists of two lanes section between two consecutive signalised intersections with 120 seconds cycle time and 0.25 green split. The section has one mid-link sink (or source) point at 840 metre from the downstream intersection (Figure 4). The vehicles for the mid-link sink (or source) are randomly selected from the vehicles traversing the section.

Demand is generated for 1 hour, which increases during the first quarter, keeps the maximum for the next half an hour and then decreases in the last quarter. The degree of saturation at the downstream signal is set to 1.2. With regard to the significance of RD, 10% mid-link sink/source cases are tested. Percentage of sink vehicle is defined as the ratio of vehicles lost into the sink to the vehicles observed at upstream. Percentage of source vehicle is defined as the ratio of vehicles gained from the source to the vehicles departing from downstream.

3.2 Test Scenarios

CUPRITE assumes either upstream or downstream counts are correct. The reliable plots are fixed and the others are modified by integrating with probe data. Practically, downstream counts are more reliable than the upstream ones when the section is equipped with stop line detectors. This is because left and right turn generally shares lanes. Hence defining cumulative plots for the study link with the data from shared lane needs turning proportion, which is hard to obtain in real world (refer to Bhaskar et al.,(2012)). Due to the lack of turning proportion, downstream curve is more reliable, and modifying upstream curve is usually a better strategy in real world application.

However, in density estimation, another issue is raised. Let us assume mid-link sink case, where upstream detector is overcounting. The downstream counts include only the vehicles traversing the whole section, whereas the upstream counts consist of both traversing vehicles and sinking vehicles at the mid-link section. If the downstream curve is considered to be correct and the upstream curve is modified accordingly, the obtained curve is based only on the traversing vehicles and does not include the sinking vehicles (Figure 5). Hence, the density should be underestimated. On the other hand, fixing upstream curve and modifying downstream one assumes that every vehicle that entered from upstream goes through the section (Figure 6), which should result in overestimation.

In order to assess the impact of this over/underestimation issues, this section demonstrates the results from both strategies; 1) fixing downstream and modifying upstream and 2) fixing upstream and modifying downstream. Then, discussion follows to figure out the better approach for density estimation.

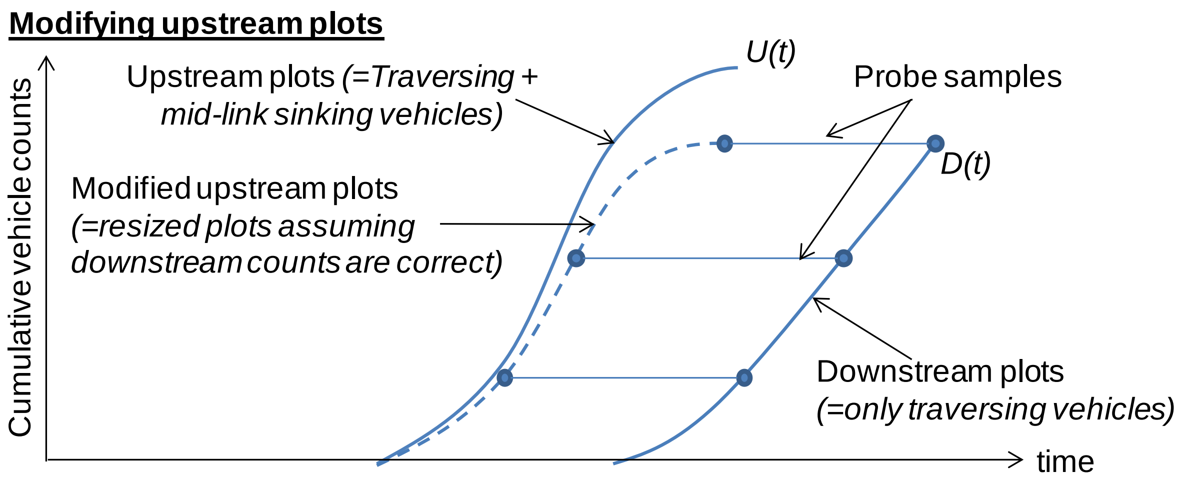

Figure 5 Fixing downstream and modifying upstream counts

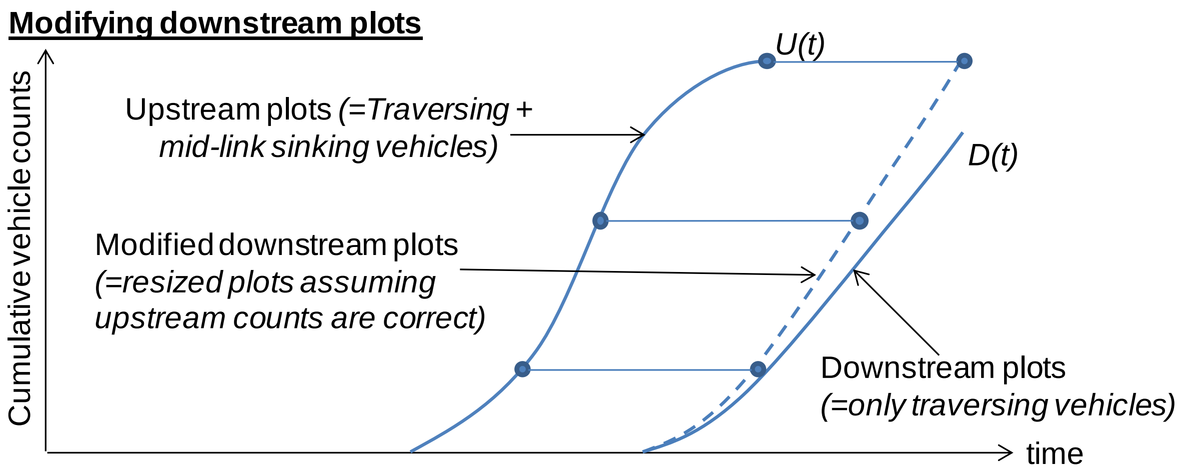

Figure 6 Fixing upstream and modifying downstream counts

3.3 The Results

3.3.1 Mid-link sink case

Figure 7 and Figure 8 show the estimation results of mid-link sink case. The probe sample is available every 5 minutes for modifying the cumulative counts. When downstream plots are assumed to be correct and upstream plots are modified (Figure 7), the CUPRITE estimates the density quite accurately. On the other hand, when upstream plots are fixed and downstream plots are corrected, the CUPRITE overestimates (Figure 8). The results partly confirm the issues mentioned in section 3.2. In order to assess the estimation accuracy, let us introduce the index, accuracy (%), as defined below.

$$MAPE = \frac{\sum_i \frac{|benchmark_i - CUPRITE_i|}{banchmark_i}}{N} \tag{2}$$

$$Accuracy(\%) = (1 - MAPE) * 100 \tag{3}$$

Fixing downstream curve gives the better accuracy (96.59%) than fixing upstream (84.14%). When upstream curve is fixed and downstream curve is modified (Figure 8), every vehicle that entered from upstream, including the one sinking in mid-link section, is counted in the density estimation. In this case, the vehicles which actually sink in the mid-link section are added into the queue at the downstream intersection, which has significant impact on the density estimation. On the other hand, when downstream curve is fixed (Figure 7), the obtained curve is based only on vehicles traversing the whole section and does not include the vehicles actually sinking in the mid-link section. This should have caused underestimation of density. However, since the upstream of the mid-link section is free flow, the sinking vehicles stay in the section just for a short period, and they do not have significant impact on the section density. Therefore, ignorance of them does not affect the density estimation accuracy in this example. Note that if the mid-link section is located further downstream or the whole section is fully congested, this ignorance should cause estimation error, which is demonstrated in the following section.

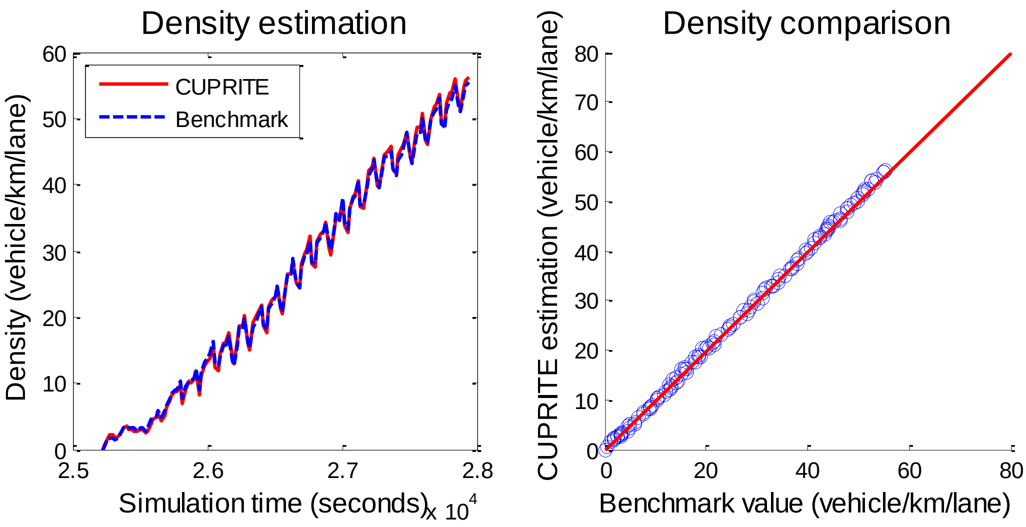

Figure 7 CUPRITE estimation vs Benchmark (10% mid-link sink, fixing downstream)

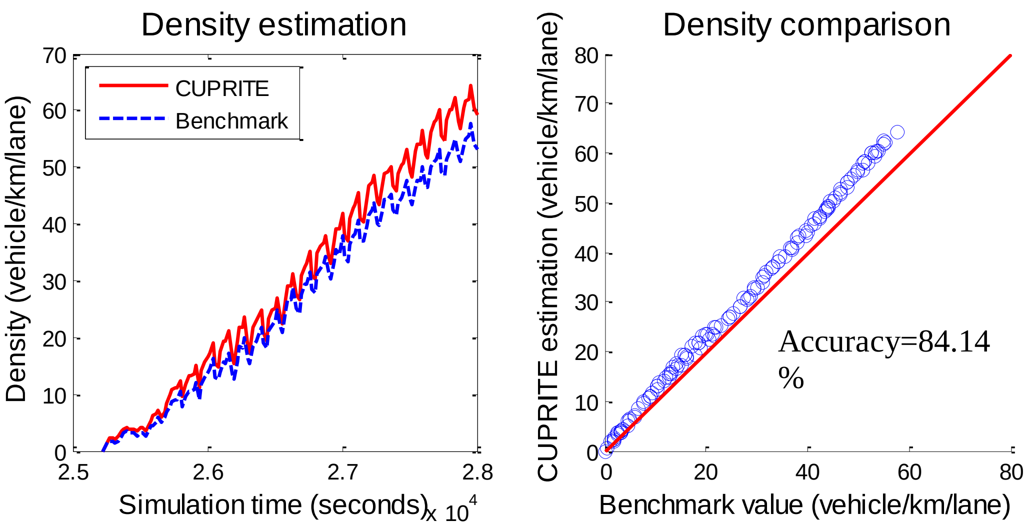

Figure 8 CUPRITE estimation vs Benchmark (10% mid-link sink, fixing upstream)

3.3.2 Mid-link source case

Figure 9 and Figure 10 show the results of mid-link source case. In this case, fixing downstream and correcting upstream gives quite accurate estimation (Figure 9), whereas fixing upstream results in slight underestimation (Figure 10). The accuracies are comparable in both bases, although fixing downstream results in slightly better estimation. In mid-link source case, vehicles coming from the mid-link section should contribute to the queue at the downstream intersection, and has non-negligible impact on section density. Therefore, fixing downstream is a reasonable strategy so that all the vehicles entering the section are taken into density estimation. On the other hand, if upstream curve is fixed and downstream is modified, only vehicles which traverse the whole section are considered, and the ones coming from the mid-link section cannot be considered. This causes underestimation of density, and the accuracy become worse as the percentage of source vehicle increases.

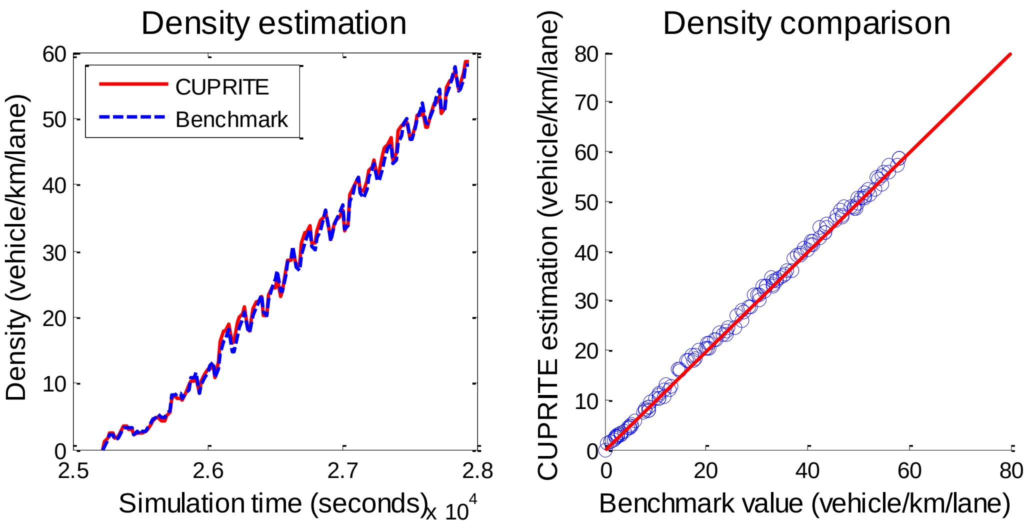

Figure 9 CUPRITE estimation vs Benchmark (10% mid-link source, fixing downstream)

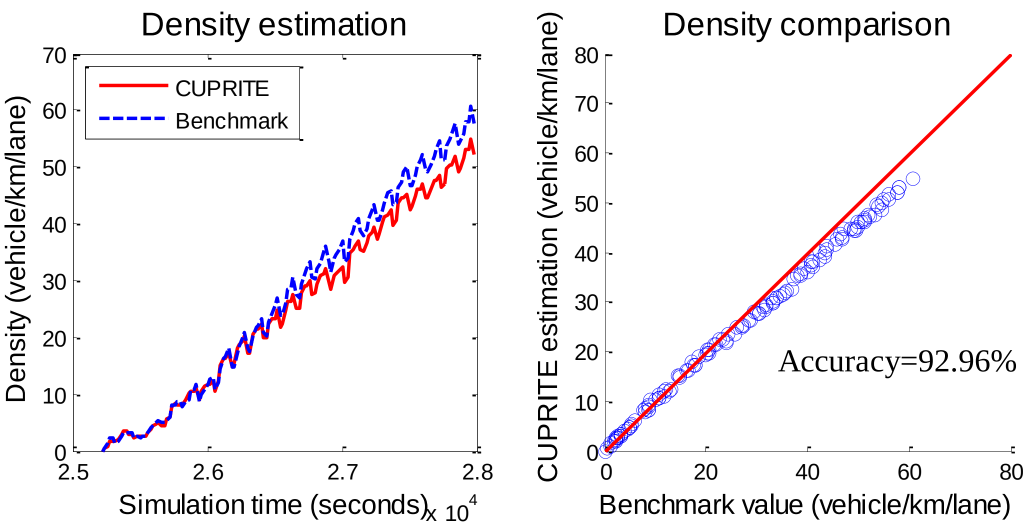

Figure 10 CUPRITE estimation vs Benchmark (10% mid-link source, fixing upstream)

4. IMPACT OF NETWORK GEOMETRY

As discussed in section 3.3.1, if the mid-link section is located close to the downstream intersection, ignoring the sinking vehicle should impact the density estimation. Figure 11 illustrates the impact of mid-link sink section on the density estimation. When mid-link sinking point is located at the middle of the section and the queue does not build up to the mid-link point, the sinking vehicles can reach to the point at the free flow speed. Since they stay in the section only for a short period, their impact on section density is quite limited. However, if the mid-link point is closer to the downstream intersection, the queue most likely blocks the sinking point. Here the sinking vehicles have to stay in the queue before reaching to the point, and they do contribute to the section density.

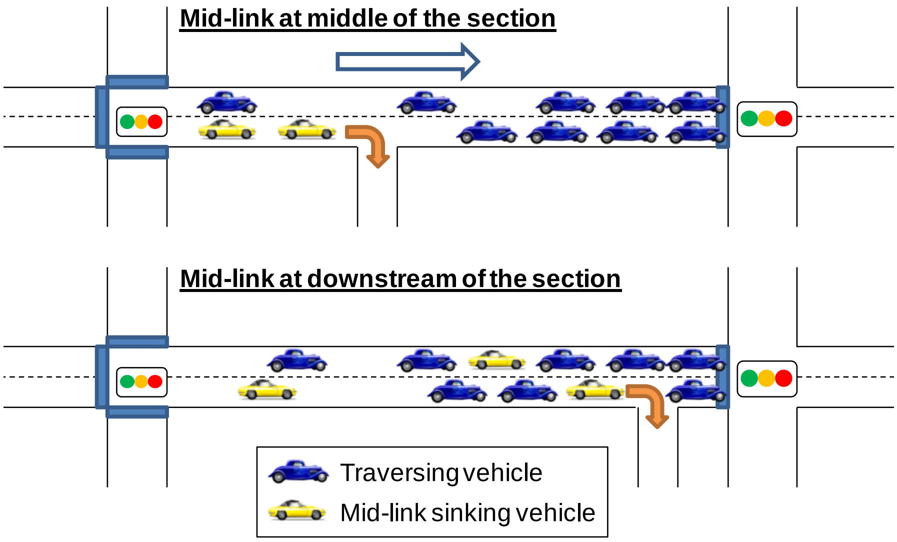

Figure 11 Impact of network geometry in density estimation

This section demonstrates the issue associated with the mid-link sink case and proposes a preferable approach for applying CUPRITE in density estimation. Figure 12 shows the test network with the mid-link section at 20 metre from the downstream intersection.

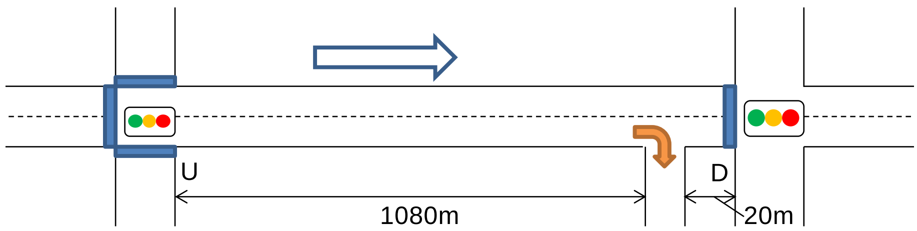

Figure 12 Test network with mid-link section close to the downstream intersection

Figure 13 and Figure 14 show the estimation results of 10% mid-link sink. Fixing downstream curve underestimates the density (90.22%), whereas fixing upstream results in overestimation (91.47%). When downstream curve is fixed and upstream curve is modified (Figure 13), the obtained curve is based only on vehicles traversing the whole section and ignores the vehicles sinking in the mid-link section. As discussed above, the sinking vehicles are not negligible for section density in this network configuration, and therefore the estimation accuracy decreases compared with the case where the mid-link point is located in the middle of the section (Figure 7).

On the other hand, when upstream curve is fixed (Figure 14), every vehicle, including the one sinking in mid-link section, is counted in the density estimation. The estimation accuracy improves from the one where the mid-link point is located in the middle of the section (Figure 8). Since sinking vehicles go through the section almost entirely in this network configuration, adding them into the density estimation has positive impact on section density estimation.

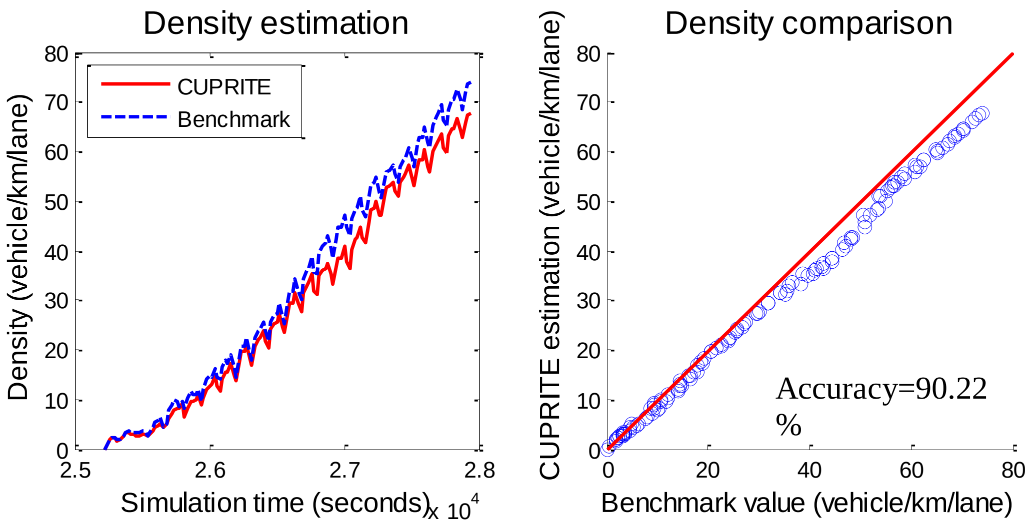

Figure 13 CUPRITE estimation vs Benchmark (10% mid-link sink, fixing downstream)

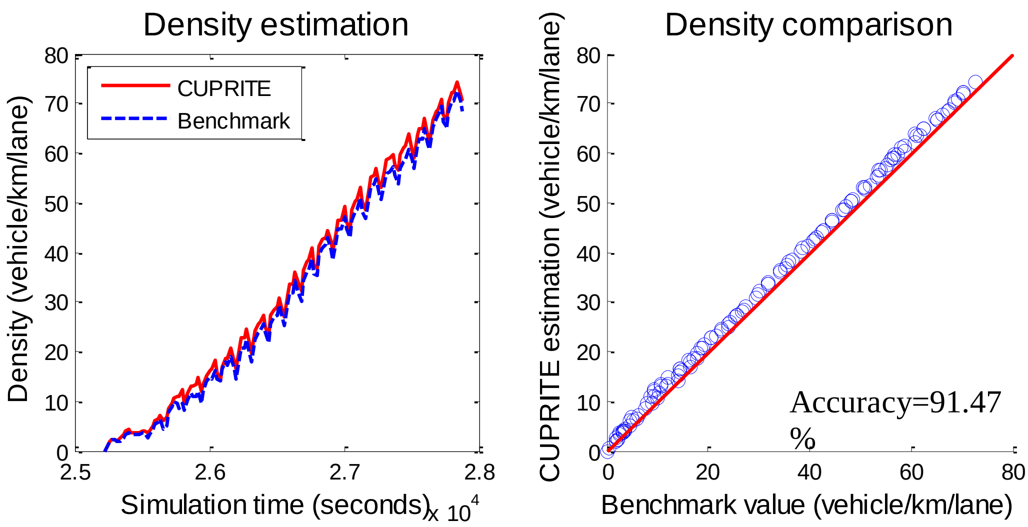

Figure 14 CUPRITE estimation vs Benchmark (10% mid-link sink, fixing upstream)

Finally, Figure 15 and Figure 16 show the estimation results of 20% mid-link sink. When the percentage of mid-link sink increases, the degree of underestimation also increases when downstream plots are fixed (Figure 15). By increasing the sinking vehicles, ignoring them in the density estimation impacts more significantly. On the other hand, relatively good estimation is obtained by fixing upstream plots (Figure 16) with comparable accuracy with the one from 10% mid-link sink case (Figure 14). Above results suggests that fixing upstream can be a better strategy when the percentage of mid-link sink is large; in other words, when larger RD is observed.

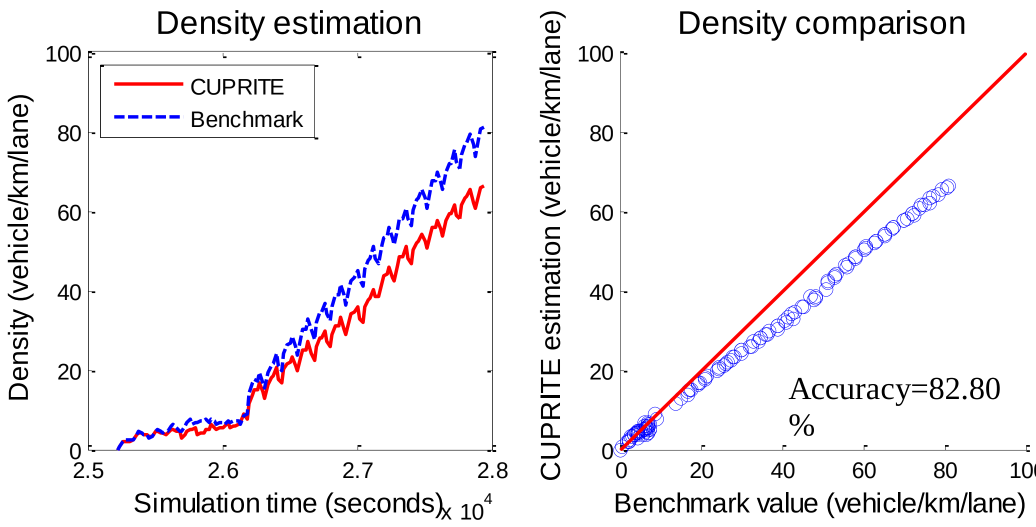

Figure 15 CUPRITE estimation vs Benchmark (20% mid-link sink, fixing downstream)

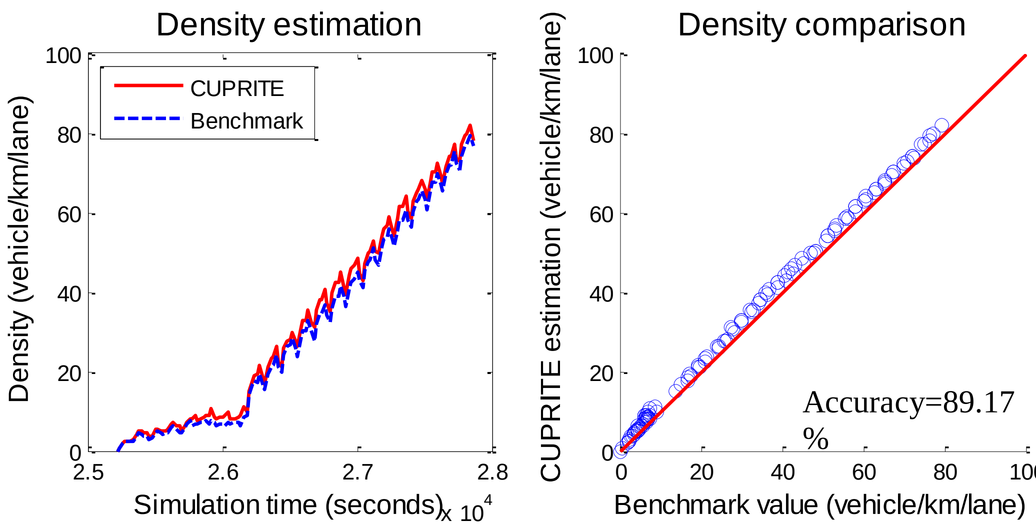

Figure 16 CUPRITE estimation vs Benchmark (20% mid-link sink, fixing upstream)

5. CONCLUSIONS

This research aimed to develop a reliable density estimation method for signalised arterials with available data sources such as stop line detector and probe samples. In order to overcome the RD issue associated with urban arterials with mid-link sinks and sources, CUPRITE was employed for density estimation. The method was tested in a controlled environment. Through a couple of test cases with a mid-link sink and source, the authors demonstrated reasonable estimation accuracies, which confirmed the effectiveness of CUPRITE for density estimation in the signalised section. The proposed method can be utilised for network surveillance and the MFD analysis once plenty of probe samples are available, such as Bluetooth samples in Brisbane, Australia (Tsubota et al., 2011, Kieu et al., 2012).

The authors also demonstrated some limitations of the method. The test results confirmed that, for CUPRITE application, fixing downstream curve gives better density estimation in most cases. However, in particular network configurations, this strategy does not always work; when the queue reaches to the mid-link sink point, fixing upstream can result in better estimation, especially when larger RD is observed. In order to generalise the strategy, i.e. whether upstream or downstream plots should be fixed, further investigation is needed for practical application. Future research needs include the sensitivity analysis of the percentage of mid-link sink/source vehicles. Also, the method needs to be tested in various network geometries and traffic conditions by changing the location of the mid-link section and the degree of saturation of downstream intersection.

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