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IMPACTS OF TRAFFIC SIGNAL CONTROLS ON A DISTRIBUTED TRAFFIC MONITORING SYSTEM USING V2V COMMUNICATIONS

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DISCLAIMER

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ABSTRACT

Our previous work has developed a distributed framework for network-wide traffic monitoring and platoon information aggregation using vehicle-to-vehicle communications alone (*1*), which is the foundation of an envisioned virtual traffic operations system that could supplement existing operation systems or serve as an alternative in extreme situations. The performance of the distributed monitoring system depends on both the market penetration rate and the spatial distribution of equipped vehicles in the road network. The latter is affected by traffic dynamics. Traffic signal controls at intersections play a significant role in governing traffic dynamics and will in turn impact the distributed monitoring system. The objective of this study is to investigate such impacts. With the presence of traffic signal controls, signal timing plans as event data should be considered for evaluating the performance of the distributed traffic monitoring and platoon information aggregation system. Among various traffic control factors, such as the operation mode of a traffic controller and signal timing parameters, we choose g/C ratio as one of the possible key factors. The performance of the monitoring framework is investigated with different g/C ratios under multiple traffic scenarios. The simulation results show that a positive correlation exists between the accuracy of speed estimation and the g/C ratio. If a traffic signal is present (g/C<1), downstream coverage ratio usually increases with the g/C ratio as well. While the upstream coverage ratio and the relative error in density do vary with g/C ratio, the variation is not significant and no distinct trends are observed. This indicates that the density estimation is more robust, and it may be desirable and possible to enhance the speed estimation method utilizing density information to achieve higher accuracy. Moreover, since accurate traffic monitoring sets the foundation for advanced traffic control strategies, we argue it is important to consider the resulting performance of traffic monitoring, together with other mobility measures when designing intersection control mechanisms.

Keywords: Connected Vehicles, Vehicle-to-Vehicle Communications; Traffic Monitoring; Signal Controls

1. **INTRODUCTION**

The rapid advancements of connected vehicle (CV) technologies have enabled both safety and mobility applications that utilize vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. Cooperative traffic operations/management strategies, as one category of CV mobility applications, have been gaining increasing attention in the past decade. Examples include cooperative intersection controls, dynamic speed harmonization (variable speed limit), etc. Most of these applications rely on V2I designated short-range communications (DSRC) and other communication networks (e.g., GPS-enabled mobile phones) and require RSUs or a server to communicate with each equipped vehicle to gather and process traffic information (see (*2, 3*) for comprehensive literature reviews). With the exception of individual intersection control at a very fine detailed level, aggregate vehicular traffic pattern is often a more common and ready-to-use input to transportation operations. For example, prevailing vehicular flow rate and speed at certain locations and the evolution of vehicle queue formation in a road network is often more important than individual vehicle trajectories for arterial management and operations. On the other hand, due to communication limitations such as communication bandwidth and reliability, as well as the storage and processing capacity of control infrastructure, not all equipped vehicles will be able to, nor shall they do, communicate with the infrastructure individually.

We have proposed a distributed framework for network-wide traffic monitoring and platoon information aggregation using V2V communications alone (*1*) to support cooperative traffic operations/management strategies. A set of distributed protocols, which are performed by each equipped vehicle, are developed to identify platoons and compute aggregated traffic information (density and speed) of identified platoons. This framework allows traffic monitoring and platoon information provision to be carried out in a localized, distributed, and cooperative manner. The framework is capable of monitoring and reporting vehicular traffic condition for the entire road network, instead of only at specific locations where RSUs are installed. This framework could serve as an alternative or supplemental system that is particularly suitable under abnormal traffic scenarios caused by extreme and special events. The system is validated using VISSIM and its built-in component object model under multiple traffic scenarios and market penetration rate (MPR). The simulation demonstrated the distributed traffic monitoring system can produce reasonable results with MPR as low as 20%. In addition to MPR, the performance of the distributed monitoring framework also depends on the spatial distribution of equipped vehicles in the road network, which is affected by traffic dynamics. Intersection control plays a significant role in governing traffic dynamics and will in turn have impacts on the distributed traffic monitoring and information aggregation framework. The objective of this study is to investigate such impacts.

Although the relationship between vehicular traffic dynamics and V2V communication has been extensively studied in both transportation and wireless communication communities, no prior work has explicitly looked into the relationship between intersection control and the performance of V2V communications or any traffic monitoring or information dissemination system based on V2V communications. Relevant works can be divided into two categories. The first category examines information propagation through V2V communications. The performances of interest include connectivity, propagation delay, propagation distance, message delivery ratio and packet reception rate, etc. MPR, traffic conditions, and transmission range are factors that would affect theses performance measures. Many studies have developed either analytical or simulation methodologies to quantify such relationship (*4*–*15*). The other stream of studies focuses on the performance of traffic monitoring (e.g. congestion detection and traffic pattern classification) through V2V. Accuracy is the main concern of such monitoring systems and is often assessed using simulations with similar influencing factors as adopted by studies in the first category (*16*–*25*). This study takes one step further to explore how intersection control affects the distributed traffic monitoring system based on V2V communications in (*1*).

Since accurate traffic monitoring sets the foundation for advanced traffic control strategies, we argue it is important to consider the resulting performance of traffic monitoring, together with other mobility measures (such as throughput, delay, vehicle progression, etc.), when designing intersection control mechanisms. By examining how intersection control affects the distributed traffic monitoring framework in (*1*), this work will bridge this gap and provide insights on this issue.

2. A DISTRIBUTED TRAFFIC MONITORING SYSTEM USING V2V COMMUNICATIONS

This section briefly describes the main outcomes from our previous work (*1*) to provide some background knowledge for this study. The distributed framework is designed for network-wide traffic monitoring and platoon information aggregation using V2V communications alone. It consists of two major components: 1) distributed traffic monitoring for platoon identification and 2) cooperative platoon information aggregation.

2.1 Distributed Platoon Identification

A platoon is a group of vehicles with similar states. This simple statement is in fact ambiguous: the terms “similar” and “state” are both subject to interpretation. To identify a platoon, the metric(s) to determine “state” and the threshold(s) to define “similar” must be specified.

On the other hand, if we consider a platoon as a group of vehicles with similar states, then two adjacent platoons should display different traffic states, in terms of both platoon density and speed. The boundary vehicles of the two platoons should be able to detect such difference, which we term micro-discontinuity to differentiate it from the concept of shockwave in macroscopic traffic flow theory. Thus, platoon identification becomes micro-discontinuity identification, and the problem now lends itself very well to distributed computing based on V2V DSRC.

During each time interval, an equipped vehicle with communicate with vehicles in its communication range, and will keep track of its down- and up-stream traffic states (both density and speed) within a limited range. This range, called computation radius, is much smaller than the communication range, and will be discussed later. The vehicle is said to have detected a micro-discontinuity if the sum of the absolute differences between the up- and down-stream density and speed is greater than a predefined threshold value. This threshold value will be discussed later as well. Common cases of micro-discontinuity can be observed when a queue is being formed or discharged, in a moving bottleneck, and a group of loosely spaced vehicles traveling at similar speeds etc. When a micro-discontinuity is detected, a vehicle will then set a flag in its own memory for future communication and computation to finalize the platoon boundaries. This is because that it is possible multiple consecutive vehicles within close vicinity will flag the same type of micro-discontinuity (e.g. the first few vehicles approach a stop sign may all consider themselves the head of the platoon); it is also possible that vehicles at the boundaries of potential platoons may not flag themselves as micro-discontinuities. To reduce the number of consecutive flags generated, the value of the micro-discontinuity threshold should be chosen carefully. Furthermore, to clean up consecutive and correct missing flags when they do occur, a self-correcting mechanism is needed.

The computation range needs to be small enough to detect sizable headways within the range. For example, suppose all vehicles are traveling at constant speed v, and there is a sizeable headway between vehicles j and k. From a traffic operations perspective (for example, traffic signal timing), it is possible that these vehicles should be treated as two platoons. But if the computation range is too large, vehicles k and j may not detect any difference between their downstream and upstream traffic conditions, and would consider themselves as part of a single platoon. To avoid this problem, the computation range is set to 50 meters. This is not to say that the minimum space headway the algorithm is able to detect is 50 meters.

A good micro-discontinuity threshold should allow us to correctly identify potential micro-discontinuities while minimizing the number of consecutive discontinuities. The threshold value is related to the computation radius. We performed a series of tests using microscopic traffic simulation to find a good threshold value with the computation radius set to 50m. We found that 75 is a reasonable threshold. Note that we do not intend to find an "optimal" threshold value in this study, as there is arguably a well-defined optimality condition.

Even with a carefully-chosen threshold value, consecutive and missing micro-discontinuity flags may still occur due to intrinsic randomness in traffic. To resolve these problems, a self-correcting mechanism is proposed. The micro-discontinuity identification process is performed every time interval. In this study, the interval Δt is set to one second. A small time lag ε, $\varepsilon \ll \Delta t$, after the process is finished, each vehicle will launch the self-correcting mechanism to check the status of its immediate downstream (if itself is a lead) or upstream (if itself is an anchor) vehicle, if there is any vehicle within its computation range. If the other vehicle has 1) no flag, the vehicle will send a message to the other vehicle to correct the missing flag; 2) same type of flag, the vehicle simply removes its own flag; 3) a different type of flag, the vehicle does nothing. This is equivalent to setting the first (last) vehicle with a lead (an anchor) flag the actual lead (anchor) of the platoon.

2.2 Traffic Information Aggregation

Once platoons are identified, a contention-based cooperative multi-hop protocol is developed to make sure that platoon information is aggregated in the most effective and accurate manner with minimum communication overhead. The identified lead vehicles will start a cooperative traffic information aggregation protocol, a process of forwarding and aggregating local traffic information through multi-hop V2V DSRC. This process could be initiated at time $n\Delta t + 2\varepsilon$. Figure 1 provides an illustration of the concept.

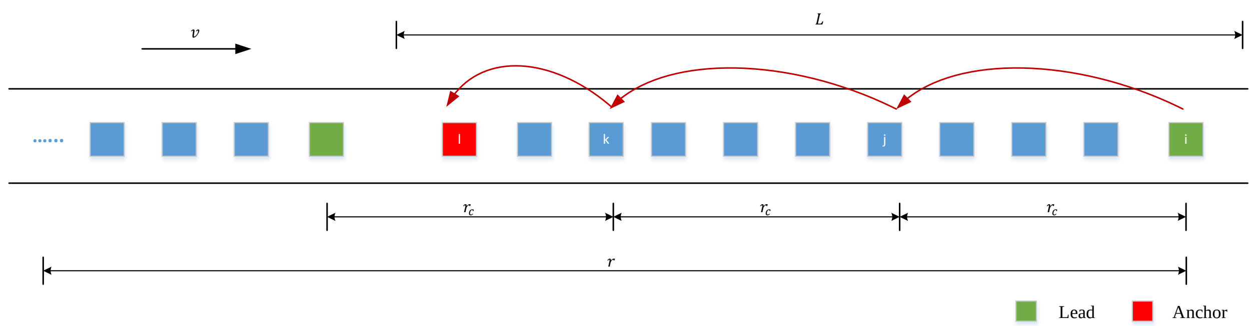


Figure 1 Information Aggregation

Upon termination of the information aggregation protocol, the group density, average speed, number of vehicles, and length will be available immediately. The aggregated information can be disseminated to all vehicles on the network and signal controllers through multi-hop V2V communications. Such information dissemination is beyond the scope of this study and will be explored in our future research.

3. METHODOLOGY

This research will investigate how intersection control affects the distributed traffic monitoring framework in (*1*). We will focus on signalized intersections, one of the most common intersection control mechanisms. With the presence of traffic signal controls, signal timing plans as event data should be considered for evaluating the performance of the distributed traffic monitoring and platoon information aggregation system. Among various signal control factors, such as the operation mode of a traffic controller and signal timing parameters, this paper will investigate the impacts of g/C ratio as one of the possible key factors. To quantify the relationship, the performance evaluation methodology developed in (*1*) is adopted and new evaluation scenarios that incorporate traffic signal controls are designed.

3.1 Measuring Performance of the Distributed Traffic Monitoring Framework

To quantitatively analyze the impact of MPR, Lou et al. (*1*) proposed a methodology on the basis of dynamic fragmentation as illustrated in Figure 2. Consider the aggregated traffic condition under 100% MPR (denoted as case g) as the ground truth, and denote results from a p% MPR (denoted as case p) scenario (where $0 < p < 100$) as case g. Each fragment in the top two rows in Figure 2 is a platoon identified by the distributed traffic monitoring framework at any given time point t, for case p and case g respectively. In the bottom row of Figure 2, the road segment is further divided into smaller fragments by combining the fragmentation of both cases. We can now compare the differences in traffic states between cases p and g for each fragment as shown in the bottom row of Figure 2. Three performance measures are considered: coverage ratio, relative errors of aggregated density, and relative errors of aggregated speed. The sum of the relative differences of each fragment, weighted by fragment length, over the entire road segment is considered an overall performance measure at time t. This measure for a single simulation time step can be further averaged over the total simulation duration T. We will use the average performance over time as the metric for the analysis in this paper. For more details regarding their definitions and calculations, please refer to (*1*).

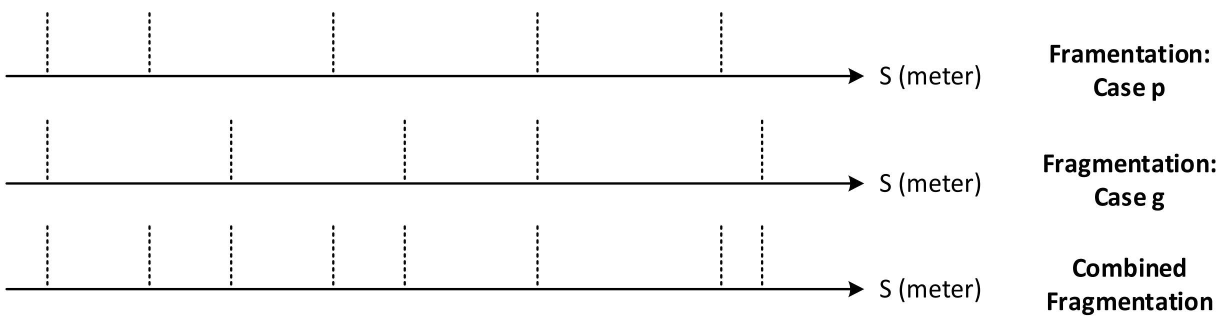


Figure 2 Illustration of Dynamic Road Fragmentation

The analysis of how traffic signal controls affect the performance of the distributed monitoring system utilizes the same comparison methodology. In this paper, the analysis will concentrate on how the performances vary with respect to different traffic signal timing plans while fixing the traffic scenario and the MPR.

Traffic signals could operate in different modes, such as pre-timed, actuated and adaptive. Regardless of the operation mode, some basic timing parameters are universal. They include cycle length, phase sequence, phase times and so on, which will affect the performance of the distributed traffic monitoring system. For each approach, phase time directly governs the throughput and the spatial-temporal distribution of vehicles. This study will focus on the impacts of phase times. For a pre-timed signal timing plan with fixed cycle length, different phase times can be achieved by varying g/C ratios. Therefore, pre-timed signal timing plans with the same cycle length but different g/C ratios will be investigated with the evaluation framework, and the performances of the monitoring system with respect to different g/C ratios will be further analyzed and compared.

With the presence of a traffic signal controller, spatial and temporal separations are introduced to the traffic flow. Consider a simple traffic network with a single lane, a signal controller placed in the middle of network will divide the network into downstream and upstream segments. Meanwhile, the time domain will be separated into effective green and effective red for each movement. The performance of the monitoring system could be calculated for only the upstream segment, only the downstream segment, or both up- and down-stream segments. Similarly, we could calculate the performance of the monitoring system during the whole cycle, only during effective green, or only during effective red. This leads to $3 \times 3 = 9$ combinations of time-space windows for our analysis. To gain detailed insights, this study will focus on the four elementary space-time windows, namely the downstream/effective green (DG), downstream/effective red (DR), upstream/effective green (UG), and upstream/effective red (UR).

Simulation results show very larger relative errors in speed exist for g/C<1 compared to g/C=1. Besides the speed fluctuations caused by traffic signals, this is also attributed to the fact that our algorithms in the distributed monitoring system would not split a platoon if it happens to cross the stop bar. It will reduce the accuracy of density estimation as well. The issue is easy to fix with an extended process of micro-discontinuity identification where event-data will be utilized.

3.2 Evaluation Scenarios with the Presence of Intersection Control

In this study, the same network as in (*1*) is adopted. A pre-timed traffic signal is placed at 1,000 m downstream from the vehicle input. Four different signal timing plans are created with the same cycle length of 120s, and g/C ratios of 1 (which is equivalent to a freeway segment without traffic signals), 2/3, 1/2, and 1/3. Four traffic scenarios are examined. They are low-speed low-demand (LSLD), low-speed high-demand (LSHD), high-speed low-demand (HSLD), and high-speed high-demand (HSHD). The settings of speed and demand for the four traffic scenarios will remain the same as in (*1*). Five different MPR values, namely 20%, 50%, 70%, 90% and 100%, are adopted. Multiple simulation replicates are performed with a range of random seeds using VISSIM traffic simulation for a given traffic scenario and a given MPR. The simulation has a 180-second traffic warm-up period followed by 180 seconds for the actual simulation. For a given space-time window, the performances of the monitoring system under the same traffic scenario and MPR, but with different g/C ratios, are compared.

4. RESULTS

Radar charts are presented to show the performances of the distributed monitoring system (Figure 3 to Figure 8). Each axis in any of the charts corresponds to a combination of a space-time window and a particular value of MPR. Take the first quadrant in Figure 2(a) for example, the axes are DG_20%, DG_50%, DG_70%, and DG_90%. For a chart, there are several circles representing different values of the corresponding performance. The circles in Figure 2 correspond to 80%, 60%, 40% and 20% from outer to inner ones. The center represents 0% relative error. The performances with respect to g/C ratios of 1, 2/3, 1/2, and 1/3 are represented using blue, red, grey, and green lines respectively. That g/C ratio equals 1 represents the scenario without traffic signals at the intersection, so there are no blue lines for the DR and UR quadrants.

4.1 Relative Error in Density

Two main reasons would lead to high relative error in density estimation. The first reason is traffic being sparse traffic (i.e. traffic is low in density). One possible explanation is that a higher proportion of equipped vehicles are likely to identify themselves as isolated vehicles (see (*1*) for more details) with sparser traffic, which may not be the case and will result in higher estimation error. The other reason is the uneven spatial distribution of traffic. This means traffic density varies substantially over the roadway segment. With a non-100% MPR, the high variation in density itself may not be well captured by the distributed monitoring system, and is likely to lead to high relative error in estimation.

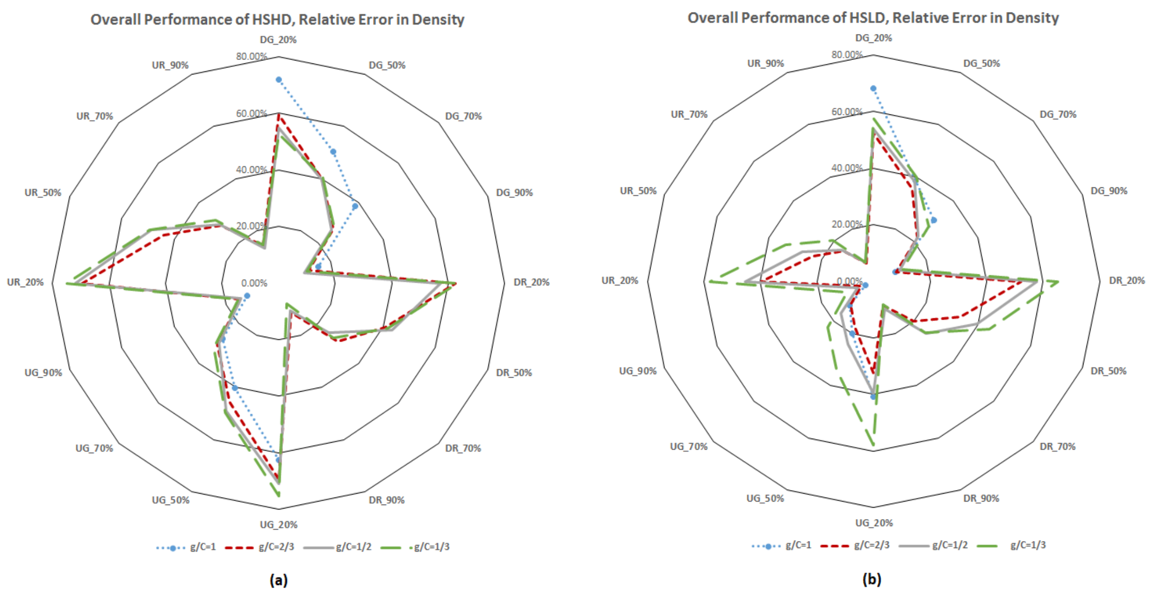
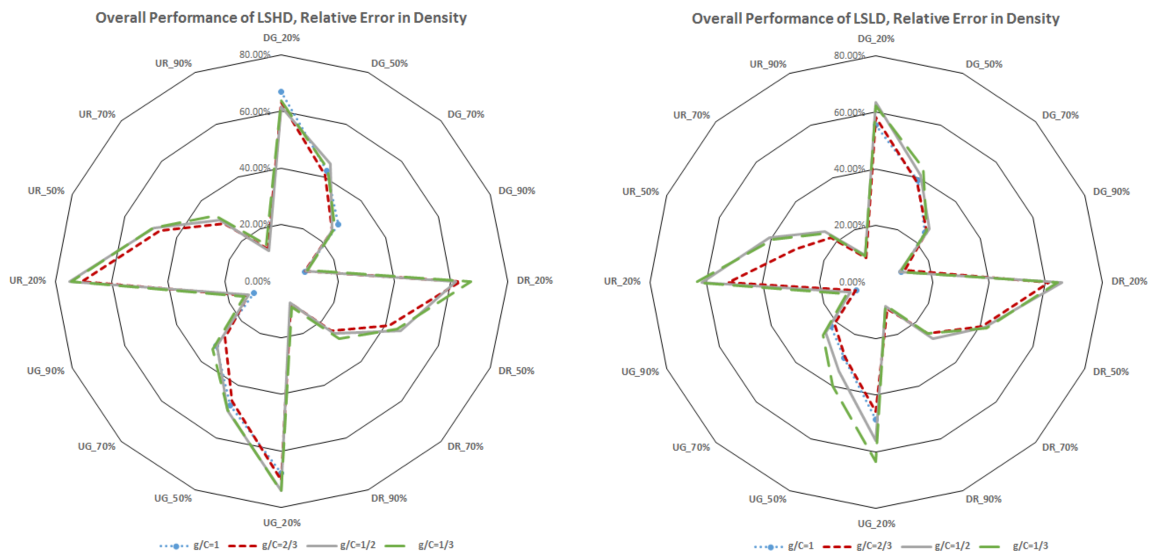


Figure 3 Relative Error in Density under HSHD and HSLD

Figure 2 shows that there is no significant difference in system performance for g/C ratios of 2/3, 1/2, and 1/3 under HSHD and HSLD. For DG under HSHD (first quadrant in Figure 3(a)), removing the signal (g/C = 1) always leads to a higher relative error in density for any MPR. With the presence of a signal controller, the downstream traffic will be dominated by the discharged vehicles. With HSHD, vehicles will be discharged at a higher rate during green interval compared to the flow rate when g/C=1.On the contrast, a g/C ratio of 1 always leads to the lowest relative errors in density for UG. The reason is related to the spatial distribution of equipped vehicles. Newly generated vehicles from the upstream source will first speed up in the network and then decelerate when they approach the intersection. This is because that vehicles are generated with initial speeds below their desired speeds (speed limit) in VISSIM and that congestion exists near the intersection under HSHD scenario even during green intervals. As a result, traffic is not uniformly distributed over the upstream segment, which is denser near the intersection and less dense near the upstream source compared to g/C=1. A significant difference between free flow (g/C = 1) and interrupted flow (g/C < 1) is only observed for DG. This indicates that the introduction of traffic signals, under traffic scenario HSHD, has a positive effect on the performance in terms of accuracy in density for DG.

For HSLD, when a signal is present (g/C < 1), a lower g/C ratio usually leads to a higher relative error in density (shown in Figure 3(b)). For downstream, sparser traffic is expected during either green or red phases with a lower g/C ratio. For upstream, more stopped traffic is held near the intersection with a lower g/C ratio, and the overall spatial distribution of traffic in the upstream segment would have higher spatial variance during both phases. For DG, removing the signal altogether does not lead to much difference in relative error in density. The performance under g/C=1 for UG does not differentiate itself with those under g/C ratios of 2/3 and 1/2. Significant difference is only observed when comparing to g/C=1/3.



(a) (b)

Figure 4 Relative Error in Density under LSHD and LSLD

The impact of traffic signals on relative error in density is minimal for LSHD. The system performances under the four g/C ratios are basically the same as illustrated in Figure 4(a). The low speed and high demand setting may make traffic more uniformly distributed over both downstream and upstream segments during both green and red phases.

The g/C ratio does not seem to affect density estimation for DG and DR under LSLD either. For UG and UR, the relative errors corresponding to g/C ratios of 1/3 and 1/2 are greater than those with g/C ratios of 1 and 2/3 (see the second and third quadrants the Figure 4(b)), but the differences can be ignored when MPR=70% and 90%. This is because that the traffic is less uniformly distributed with lower g/C ratios.

These analyses have revealed that there is no clear pattern of the impact of g/C ratio on the accuracy of density estimation, which seems to depend on the traffic scenario. Generally speaking, denser traffic and more uniformly distributed traffic usually lead to higher accuracy of density estimation.

4.2 Relative Error in Speed

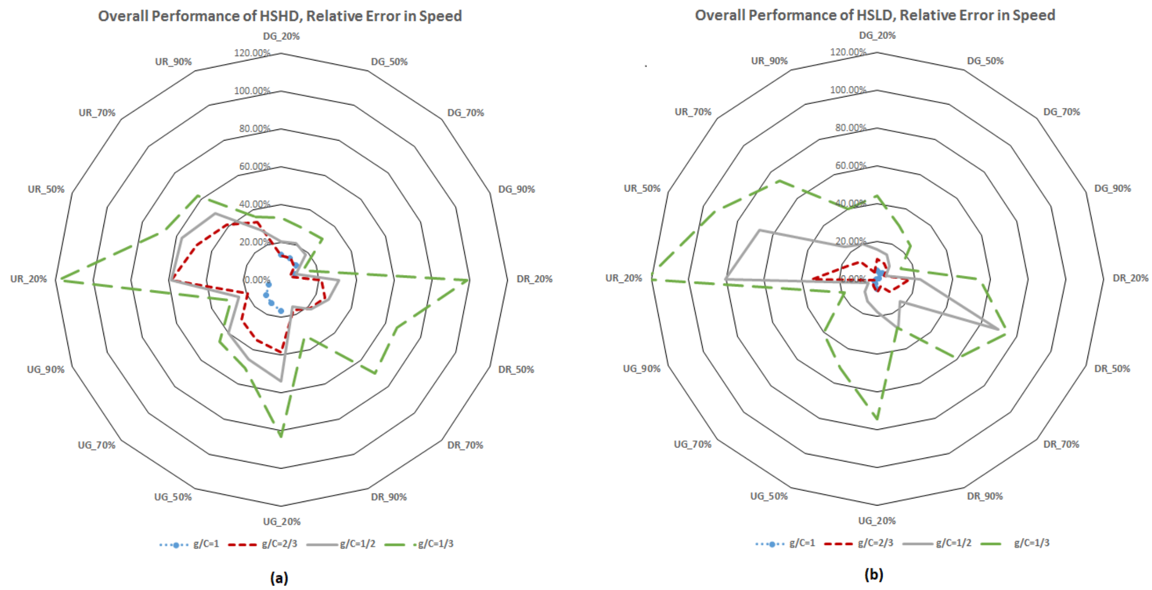


Figure 5 Relative Error in Speed under HSHD and HSLD

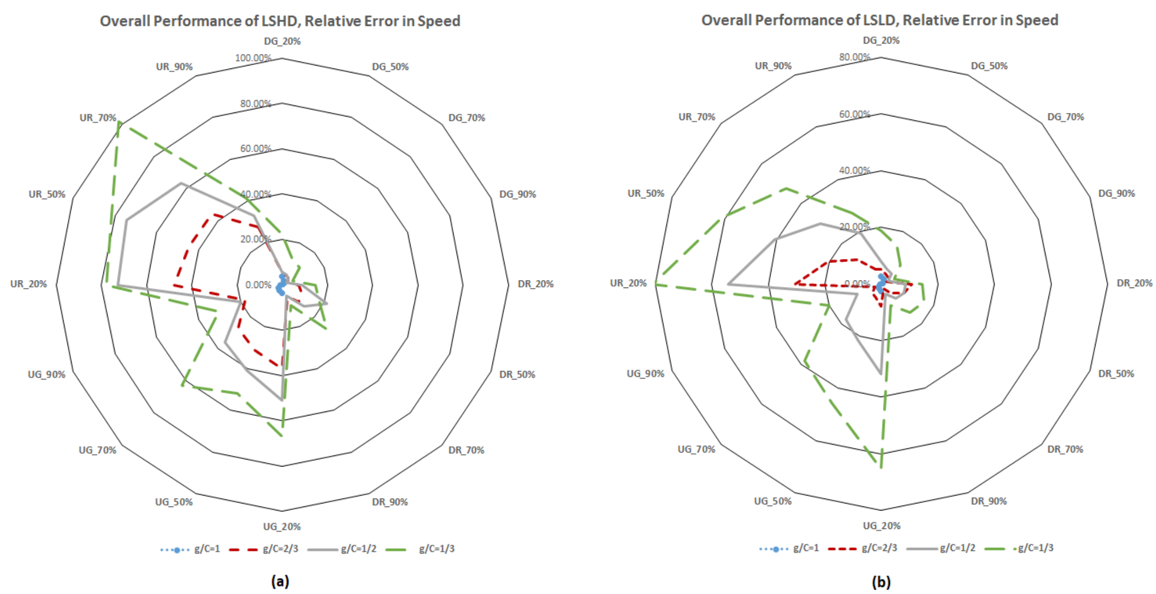


Figure 6 Relative Error in Speed under LSHD and LSLD

Compared to relative error in density, relative error in speed shows a clear pattern with respect to g/C ratios (see and Figure 4 and Figure 6). As we can see from Figure 5, the presence of traffic signal significantly reduces the accuracy of the speed estimation for HSHD traffic scenario. Moreover, the smaller the g/C ratio, the higher the relative error in speed for any given space-time window and MPR. The reason is that with a smaller g/C ratio, a longer red interval within the cycle will lead to a greater amount of stop-and-go traffic. Speed fluctuation in stop-and-go traffic is general higher, and would result in a bigger relative error in speed. These observations hold for all four traffic scenarios.

Compared to HSHD and HSLD, Figure 6 shows that the two low speed scenarios (i.e. LSHD and LSLD) have much lower relative error in speed for downstream segment during both phases. This is because that the low speed limit and less speed fluctuation (compared to upstream) reduce the variation in speed for downstream traffic.

4.3 Coverage Ratio

Higher traffic demand or denser traffic leads to fewer isolated vehicles and thus tends to have higher coverage ratio on a roadway segment for a given MPR. This is the main reason behind the difference in coverage ratios with different g/C ratios.

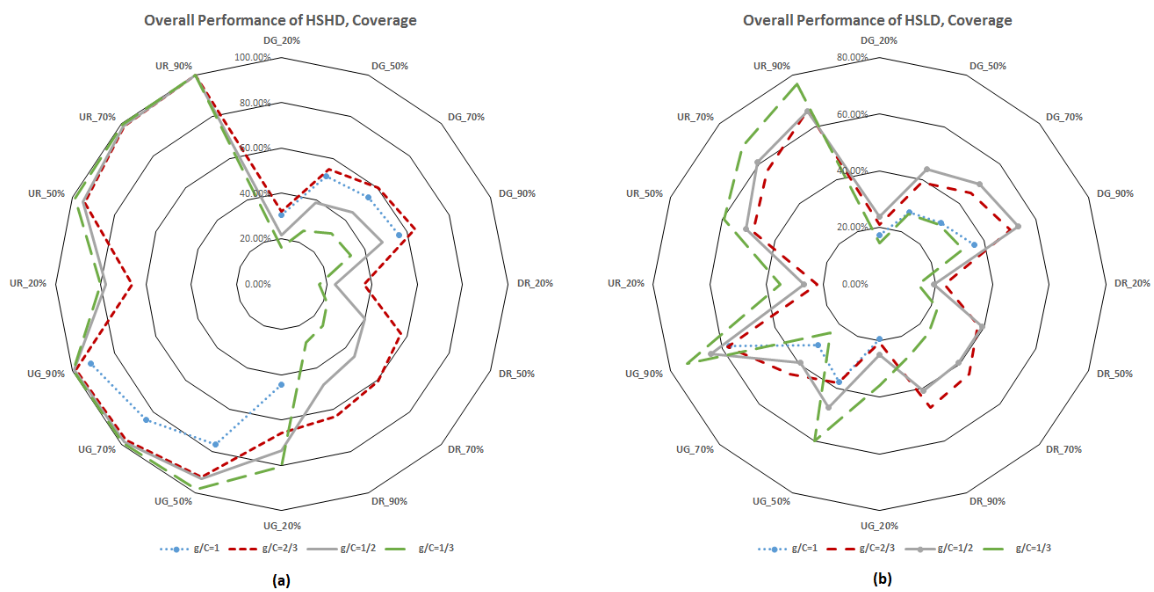


Figure 7 Coverage Ratio under HSHD and HSLD

Figure 7 shows the coverage ratios of the traffic monitoring system under HSHD and HSLD. From Figure 7(a), it can be seen that the system performs similarly in space-time windows UG and UR (second and third quadrants) when a signal controller is present (g/C < 1), where no significant difference among different g/C ratios is observed. Comparing to free flow (g/C = 1), the presence of traffic signal will lead to higher coverage ratio for UG. This due to the fact that more traffic is held upstream as the result of traffic signals. But with the network being relatively congested, the amount of upstream traffic does not vary much with the g/C ratio, as long as it is less than 1. For DG, lower coverage ratios are reported for g/C ratios of 1/2 and 1/3 compared to g/C=1. However, the highest coverage is observed when g/C = 2/3. The discharge rate with g/C = 2/3 may be higher than the flow rate with g/C = 1. The observation also indicates an optimal g/C ratio with respect to coverage ratio for downstream traffic during green intervals may exist, and is left to be identified with more experiments. For both DG and DR, the coverage ratio increases with the g/C ratio (g/C<1).

For HSLD, a higher coverage ratio is associated with a lower g/C ratio for UR since longer red intervals lead to more traffic being held upstream when the network is not very congested. It applies to UG as well (except when MPR=70% where the lower g/C ratio, the smaller coverage ratio). The opposite is observed for DR (except MPR=50% where the coverage with g/C = 2/3 is slightly lower than that with g/C = 1/2). The is straightforward since a lower g/C ratio will lead to less traffic discharged to downstream. Similar to DG under HSHD, the presence of traffic signals results in a higher coverage ratio for DG except for g/C = 1/3, comparing to g/C = 1. This is because for this traffic scenario, g/C = 2/3 and g/C = 1/2 both lead to higher total throughput during the same amount of time (green interval) comparing to g/C = 1 due to a higher discharge rate, but not g/C = 1/3.

Figure 8(a) shows the performances under LSHD. The coverage ratios are comparable with each other under g/C ratios of 2/3 and 1 for DG. Similar to HSHD, lower coverage ratios are observed for the other two g/C ratios, and g/C = 1/3 results in the lowest coverage ratio for both DG and DR. The presence of traffic signal leads to a lower coverage ratio for UG, and the lower the g/C the lower the coverage ratio. For UR, the system performances are almost the same with traffic signal.

The patterns under LSLD are much clearer due to the fact that traffic is light. For DG and DR, a monotonically increasing relationship exists between coverage ratio and g/C ratio when a signal is present. For UG and UR, a decreasing relationship is observed. However, the differences in coverage ratio among the signals are smaller in comparison to those under DG and DR.

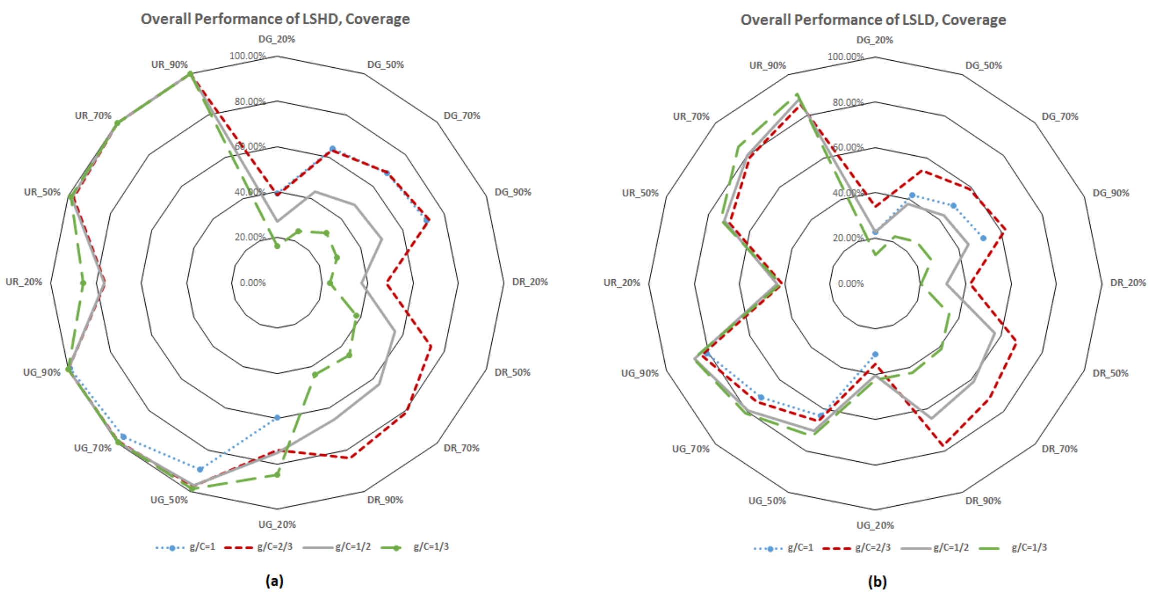


Figure 8 Coverage Ratio under LSHD and LSLD

5. CONCLUSIONS

This study investigates the relationship between the performance of a distributed traffic monitoring system proposed in Lou et al. (*1*) and the traffic signal controls. Only g/C ratios of pre-timed signal timing plans are examined as one of the possible key factors in this study. More specifically, the performances of the monitoring framework are investigated using VISSIM and its built-in COM on a simply network under three pre-timed signal timing plans with same cycle length but different g/C ratios. It is found that g/C ratio does have effects on the system performance. The simulation results show that a negative correlation exists between the relative error in speed and g/C ratio. Except for the high speed low demand traffic scenario, a positive correlation is found between the coverage ratio and the g/C ratio for the downstream segment only; the g/C ratio does not seem to affect the upstream coverage ratio significantly. The system performances vary in terms of the downstream coverage ratio and the accuracy of density estimation under different traffic scenarios and space-time windows.

This study concentrates on pre-timed signal timing plans and only investigates the g/C ratio as the key factor. However, the analysis can be easily extended to advanced signal timing plans with more designated phases. The platoon identification process itself will not be affected by different signal timing plans. The same evaluation methodology can be adopted without any change as well. It will be interesting to explore the impacts of cycle length, phase sequences, and even different control modes on the system performance. Furthermore, statistical and machine learning methods (e.g. artificial neural network, Kriging, and random decision forest, etc.) can be adopted to establish a more solid model regarding the relationship between the performance of the distributed traffic monitoring system and various signal timing parameters.

Advanced traffic control strategies require accurate traffic monitoring as their foundation. Therefore, we argue that the performance of traffic monitoring needs to be considered as well as traffic mobility when designing traffic signals. This study provides some insights on how traffic signal timing affects the performance of the distributed monitoring system. The tradeoff between the performance of the distributed traffic monitoring and mobility measures needs further investigation in the future research.

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