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A distributed framework for network-wide traffic monitoring and platoon information aggregation using V2V communications

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ABSTRACT

This study explores an innovative framework for distributed traffic monitoring and information aggregation using vehicle-to-vehicle (V2V) communications alone. We envision the proposed framework as the foundation to an alternative or supplemental traffic operation and management system, which could be particularly helpful under abnormal traffic conditions caused by unforeseen disasters and special events. Each equipped vehicle, through the distributed protocols developed, keeps track of the average traffic density and speed within a certain range, flags itself as micro-discontinuity in traffic if appropriate, and cross-checks its flag status with its immediate up- and down-stream vehicles. The micro-discontinuity flags define vehicle groups with similar traffic states, for initiating and terminating traffic information aggregation. The framework is validated using a microscopic traffic simulation platform VISSIM and its built-in component object model. Vehicle groups are successfully identified and their average speed and density effectively estimated. The impact of market penetration rate (MPR) is also investigated with a new methodology for performance evaluation under multiple traffic scenarios. Our simulation results show that the proposed framework lends itself better to more congested traffic conditions for any given MPR. With 50% MPR, the framework is able to provide information coverage for at least 37.76% of the simulated roadway facility under various traffic scenarios. This indicates that proposed framework could be useful with an MPR as low as 50%. Even with an MRP of 20%, the coverage ratio, under relatively congested traffic, can still reach around 58.82%. The framework is able to provide accurate speed estimation at high spatial resolution for the simulated roadway facility. The maximum relative error is under 10% for relatively congested traffic even with MPR as low as 20%. When there is a wider range of speed distribution (less congested traffic), the worst-case maximum relative error is still under 15% when MPR = 20%. The density estimation is more sensitive to MPR, and is more accurate under low demand and high MPR scenarios. As expected, the accuracy of both speed and density estimation increases with MPR for any given traffic scenario.

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1. Introduction

With connected vehicle (CV) technologies on the horizon, we envision an alternative/supplemental traffic operation and management system for transportation networks, supported solely by vehicle-to-vehicle (V2V) designated short-range communications (DSRC). This paper investigates two of the most fundamental components of such a system—distributed traffic monitoring and platoon information aggregation. The impact of the total market penetration rate (MPR) of equipped vehicles on such a system is also examined.

The envisioned system is not meant to replace existing traffic operation practices based upon current roadway and intelligent transportation system (ITS) infrastructures, or the slew of emerging ITS's exploiting vehicle-to-infrastructure (V2I) communications, but rather as an alternative or supplemental system that is particularly suitable under abnormal traffic scenarios caused by extreme and special events. These events, such as unforeseen disasters and emergency evacuation or major sport and culture occasions, can cause unusual traffic volume and irregular spatial distribution of vehicles in transportation networks. A major disaster often paralyzes cities for an extended period, not only because of physical damages to roadway infrastructures, but also the lack of coordinated traffic control as existing traffic operation infrastructures may suffer damages as well. V2I systems or even V2V systems that rely on infrastructure (such as cellular communication technologies) may not function well either due to the same reason. V2V DSRC systems, however, would withstand this situation as long as vehicles are running in the network. On the other hand, the unusual traffic volume and patterns caused by special events may not be readily handled by existing traffic operation systems, and can add extreme stress to communication infrastructures (such as cellular base stations) due to demand surge. V2V DSRC systems, again, could prevail in this situation without causing excessive communication overhead. Therefore, we believe traffic operation and management systems based solely on V2V DSRC are a relevant concept worth investigating.

As a mobility application of connected vehicles, traffic monitoring and platoon information provision are two essential functional requirements of such a system. Constantly monitoring the traffic condition in a transportation network will enable traffic-responsive transportation operation methods that are generally more effective. 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 (mobile and some undamaged fixed) relay and control infrastructure, not all vehicles will be able to, nor shall they do, communicate with the infrastructure individually. (This precludes machine learning or statistical classification as potential platoon identification methods as they are centralized in nature and require large amount of training data.) Therefore, the essential traffic monitoring and platoon information provision to the envisioned system must be carried out in a localized, distributed, and cooperative manner.

In this study, we have developed an innovative framework for distributed traffic monitoring and information aggregation based on V2V DSRC communications alone. Each vehicle, through the distributed protocols in the proposed framework, will keep track of the average traffic density and speed within an appropriate range (which is smaller than its communication range), and flag itself as either the lead or the anchor of a vehicle platoon (micro-discontinuity) as appropriate, utilizing fundamental concepts from traffic flow theories. To validate their own flag status, each vehicle will also engage its immediate up- and down-stream vehicles and perform a self-correction mechanism. Finally, 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. Furthermore, the impact of the market penetration rate of equipped vehicles on the proposed framework is also investigated.

The contribution of this study is threefold: (1) Unlike most of the relevant studies in transportation engineering, the proposed framework is a distributed traffic monitoring and aggregation approach using V2V DSRC alone. As such, the framework is not limited by the availability of roadside equipment (RSE) and can be applied to the entire transportation network. (2) Although a few distributed algorithms have been proposed in the field of vehicular ad hoc communication networks, most of them are limited to congestion detection only, and others suffer from the issue of communication overload. The proposed framework is able to monitor and report vehicular traffic information for both congested and uncongested conditions. (3) The impact of MPR is systematically examined and the proposed framework is found to deliver well even under relatively low MPR.

The paper is organized as follows. Section 2 reviews current ITS approaches to traffic monitoring. Section 3 describes the proposed framework in details. Section 4 presents simulation results and analysis, followed by conclusion and discussion in Section 5.

2. Relevant Literature

The focus of our literature review is on emerging traffic monitoring and information processing methods exploiting connected vehicle technologies. Existing research can be categorized into two groups based on whether infrastructure (both transportation and communications) is involved or not.