ADVANCED TRAFFIC SIGNAL CONTROL ALGORITHMS

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Abstract

The goal of this project is to develop advanced signal control strategies for mobility, safety, and environment based on connected vehicle data, i.e., real-time information on vehicles' location, speed and characteristics as well as communication to the signal control infrastructure. This document is the final report for the project. It describes the findings from the literature review on existing adaptive signal control systems, their features and operational experiences from their implementation. Several performance measures are proposed for evaluating signal control algorithms, and procedures for estimating the performance measures from connected vehicle data were developed using statistical techniques and kinematic wave theory. We developed and tested through simulation a number of control strategies to improve mobility: queue spillback avoidance, control for congested networks, and dynamic lane allocation. The results indicate that the proposed strategies improve the traffic performance. We also developed strategies for improving intersection safety with emphasis on avoidance of red light running (RLR) related collisions. A prototype in-vehicle driver speed advisory system for minimum fuel consumption and emissions was also developed. Field tests show that the prototype system achieved significant fuel savings. In addition, when an ambulance approaching the junction, it will communicate the traffic controller in the junction to turn on the green light. This module uses Zigbee modules on CC2500.

Keywords: *Traffic signals, adaptive control, connected vehicles, mathematical models.*

1. INTRODUCTION:

1.1 Problem Statement:

Highway congestion is in large part caused by the inefficiency with which the roadway network capacity is managed. Traffic signals are the mechanism for managing arterial network capacity, yet the control of traffic signals has not significantly changed over the past several decades, despite rapid and profound changes in electronics, sensors and communication technologies, and software. The main impediment to improvements in traffic signal control systems has been the limited ability of available surveillance systems (fixed-point detectors) to measure the true state of the traffic network and its response to signal control changes. Vehicle to infrastructure (V2I) and vehicle-to-vehicle (V2V) cooperation could provide this comprehensive real-time information on the movements and interactions of vehicles in the entire road network and allow a transformational change on traffic control methods.

Although a majority of the large cities in the United States employ pre-timed traffic control, it is estimated that almost 80 percent of all traffic signals in the nation use traffic detectors, mainly for local intersection control (traffic actuation) and a small number of traffic responsive systems. Regardless of the principle of operation, these systems essentially rely on "point" detection and therefore provide only binary information on the presence or absence of vehicles. The traffic signal control algorithms based on this type of vehicle information were developed in the late 1970s and are, with minor modifications, still in operation today.

There is a significant gap between the theoretical advances in traffic control methodologies plus the developments in hardware and software, and the real-world practice in traffic control:

- Existing models inadequately describe traffic operations at intersections, arterials and networks, especially at near-capacity or oversaturated conditions;
- Computational complexity for signal optimization is too high for practical application on typical size signal controlled street networks
- Control actions in real-time have until now are based on flow and occupancy observations at fixed and limited locations which may not be appropriate for the entire range of traffic conditions.

1.2 Project Goal and Objectives:

The goal of this project is to develop advanced signal control strategies based on the impending widespread availability of probe data from connected vehicles, leading to a transformational change in how we control traffic along urban arterials and networks.

Vision of real-time information to transform traffic signal operations: The advent and progressive deployment of vehicle-infrastructure cooperation through connected vehicles offers the potential for significant improvements is in the efficiency of traffic signal control. Ideally, knowledge of the location, speed, routing and destination of every vehicle in the network in real-time allows for optimal signal settings and significant improvements in traffic performance compared to existing control strategies. However, traditional infrastructure-based traffic detectors only provide point specific information on the presence of vehicles. Ultimately, with full market penetration of traffic data probes, it will be possible to know the complete current state of the traffic network and to predict how it will evolve. With this knowledge, meaningful measures of performance can be estimated accurately for the network, and signal control strategies can be defined and adjusted to optimize those measures. Examples include:

- Knowledge of the vehicle trajectories provides improved prediction of traffic arrivals which permits development of control strategies for i) delay minimization at individual intersections, and ii) coordinated signal operation along arterials or networks to minimize travel time and/or number of stops for the entire traffic stream or for specific origin-destination pairs;
- Knowledge of the vehicle trajectories permits the development and implementation of optimized signal settings that explicitly minimize fuel consumption and air pollutant emissions;
- Knowledge of trajectories of vehicles approaching the signalized intersection approach permits implementation of safety related control measures to reduce red light running, such as adaptive all-red-extension, and offset adjustments to reduce vehicle arrivals during the yellow clearance interval without compromising the intersection traffic performance.

Vision of real-time information to transform the driving experience: In conjunction with the new traffic control strategies, Connected Vehicle (CV) systems can also bring traffic signal status and alert/advisory information into the vehicles, allowing drivers and the in-vehicle systems themselves to better cooperate with the traffic signal control systems. The benefits of this improved cooperation could include more efficient and safe operation at the intersections and traffic signal based alerts to encourage driving habits for less fuel consumption. At this level, efficient traffic management is not only the responsibility of the roadside infrastructure, but it can be shared with the vehicles, so that they can work together as a well integrated system.

The project has the following objectives:

- Develop comprehensive set of performance measures for evaluating probe based signal control systems
- Develop procedures for estimating the selected performance measures based on CV data
- Develop and evaluate new control strategies enabled by the CV data.

2. LITERATURE REVIEW

This Chapter describes the findings from the review of the state-of-the-art and state-of practice of traffic signal control systems and strategies. The review of the literature placed emphasis on algorithms, systems and strategies developed over the last ten years, with particular attention to the application of probe vehicle data for traffic control on urban street networks.

2.1 Sources of Information

The literature search was primarily based on the following ongoing and recently completed major research studies:

- PATH TO 6322 “Measure and Field Test the Effectiveness of Adaptive Signal Control” [1]
- NCHRP Synthesis Project 20-05 “Adaptive Control Systems” [2]
- NCHRP 3-90 “Control Strategies for Oversaturated Conditions,” [3]
- NCHRP 3-97 “Traffic Signal Control Strategies for Varying Demands and Capacities” [4]
- NCHRP Project 3-66: “Traffic Signal State Transition Logic Using Enhanced Sensor Information” [5]

Connected Vehicle Traffic Signal Information Exchange Meeting

We attended a two-day Connected Vehicle traffic signal information exchange meeting at Arizona State University in Tempe Arizona on December 14 and 15, 2010 organized by Edward Fok of the FHWA Resource Center, San Francisco, and Greg Krueger of USDOT. “The objective of the meeting was to use the input from the meeting to build a three to five year vehicle-to-infrastructure (V2I) technologies traffic4 signal research program plan”. Meeting participants received copies of the progress notes for this project provided by Edward Fok of FHWA Resource Center with permission from the project AOTR. The meeting was very well attended and all participants were actively involved in discussions on how connected vehicles can make a significant difference in traffic signal operations and control. Detailed meeting minutes [6] were provided by the meeting organizers.

2.2 Findings

Traffic signals along arterials and networks operate as coordinated to provide progression to the major through movements. Different timing plans (cycle length, green times and offsets) are implemented to account for the variability of traffic throughout the day. Most of the existing signal systems use fixed time timing plans prepared off-line based on historical data (often called "first generation strategies”). These plans are typically implemented by time of day (TOD), e.g., am, midday and pm peak periods. This is illustrated in Figure 2.1A. Fixed-time plans, however, cannot deal with the variability of traffic patterns throughout the day, and they become outdated because of the traffic growth and changes in traffic patterns. An increasing number of first generation control systems use traffic actuated controllers operating in coordination with a common background cycle length. These systems provide improved through progression by utilizing the spare green time in the signal cycle from the "early" termination of actuated phases [7]. At the same time, they may reduce the total intersection delay by responding to the cycle-bycycle fluctuations in traffic volumes. Simulation results and field studies have shown that coordinated actuated signals significantly improved the performance on the arterial through traffic at the expense of the cross-streets.

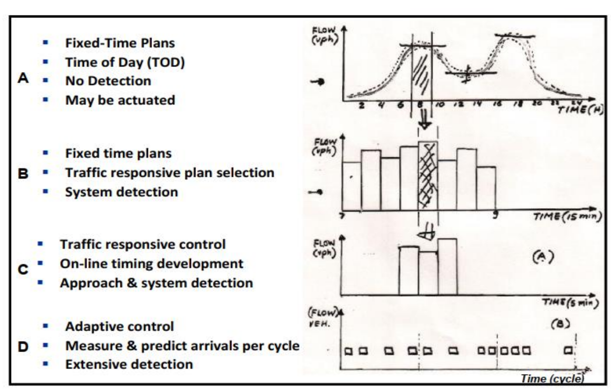

Figure 2.1 Traffic Signal Control vs. Variability of Traffic Flow

A number of signal systems employ several fixed-time timing plans to account for the variability of traffic flow. These timing plans are typically selected based on volume and occupancy data collected from system detectors located in key locations of the network (Figure 2.1B). The system operator may also override the timings based on real-time surveillance data. "On-line" control systems update the timing plans in real-time based on data from detectors located on each intersection approach. Such strategies fall into two major categories: i) traffic responsive or timing plan update (e.g., "UTCS Second Generation", SCATS and SCOOT) that adjust the signal settings while maintaining a common cycle length (Figure 2.1C), and ii) adaptive control policies (OPAC, RHODES, PRODYN) that continually optimize the timings at each intersection over a short time interval (rolling horizon) as shown in Figure 2.1D. Note that often all on-line systems are called adaptive.

3. TRAFFIC SIGNAL CONTROL FOR SAFETY: MINIMIZATION OF VEHICLE ARRIVALS IN THE YELLOW INTERVAL

Empirical studies at a signalized intersection on El Camino Real in San Mateo, CA indicate that the arrival flow during the yellow change interval approximately 200 ft. (60 meters) from the stopline is the most significant factor for red light running (RLR) frequency [48]. Intuitively, higher yellow arrival flow indicates more drivers need to make stop-and-go decision and consequently correlated with higher RLR frequency.

We investigated the relationship of the arrival flow in the yellow interval on RLR frequency using the NGSIM data set from Peachtree Blvd, described. Figure 3.1 shows vehicle trajectories traveling on the southbound direction of Peachtree Blvd during the 4:00 – 4:15 pm peak period. Three types of vehicle trajectories are plotted: red for RLR vehicles, yellow for vehicles entered the intersection during the yellow interval, and cyan for the first stopped vehicles. As it is shown in Figure 3.1, the last (4th) intersection has a high RLR frequency, where the head of the approaching platoon was truncated with the onset of red. In this scenario, drivers are likely to follow the head of the platoon but ended up with running a red signal. Drivers are also likely to run into the red light when the tail of the platoon is truncated by the onset of red.

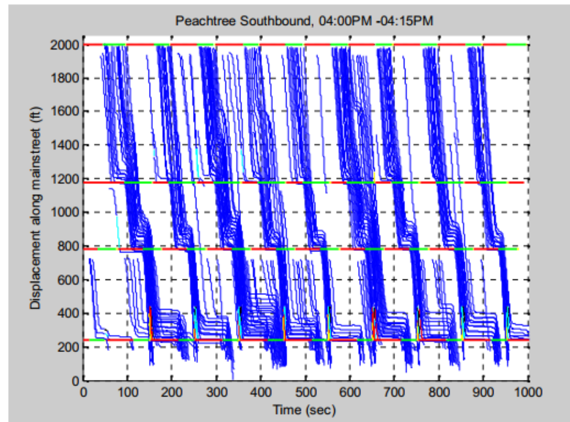

Figure 3.1 Vehicle Trajectories: Peachtree Blvd SB (4:00 – 4:15PM)

In order to quantify the effect of yellow arrival flow on RLR frequency, we calculated the yellow arrival flow on each approach at the four Peachtree Blvd intersections, for both 12:45 – 1:00 pm and 4:00 - 4:15 pm time periods. The yellow arrival flow was defined as the number of vehicles arriving at 150 ft. (45 meters) upstream from the intersection stopline during the yellow interval (3 seconds). The relationship between RLR frequency and yellow arrival flow is illustrated in Figure 3.2. It is clearly shown that higher yellow arrival flow indicates higher frequency of RLR, which is consistent with the finding from the El Camino intersection

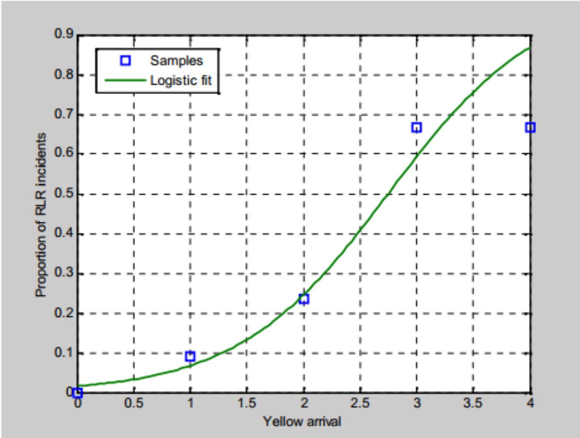

Figure 3.2 RLR Frequency vs. Arrival Flow in the Yellow Interval -- Peachtree Blvd

We also utilized the data collected at the San Pablo and Brighton Avenue intersection to test the effect of yellow arrival flow on RLR frequency. The yellow arrival flow was calculated at 200 ft (60 m) upstream from the intersection stopline (approximately 4 seconds travel time traveling at the speed limit of 35 mph). Figure 3.3 shows the comparison between the distribution of yellow arrival flow for cycles with RLR occurrences and that for all signal cycles. As it is shown in Figure 8.3, the yellow arrival flow for cycles with RLR occurrences is much higher than that on non-RLR cycles

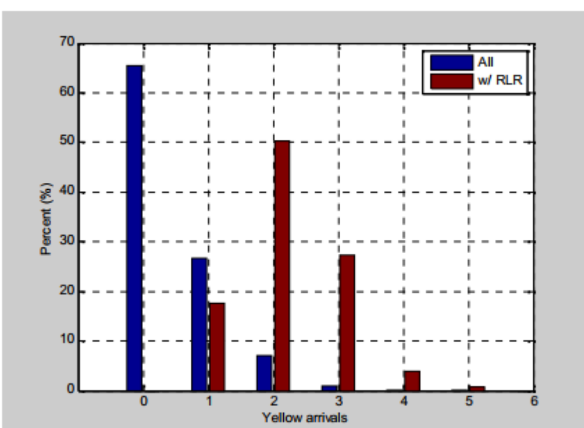

Figure 3.3 Distribution of Yellow Arrival Flow: San Pablo Ave/Brighton Ave

4. DRIVER ADVISORIES FOR MINIMUM FUEL AND EMISSIONS

A significant body of research exists on developing control strategies to reduce fuel consumption and air pollutant emissions in signal controlled networks. However, with the recent advances in ITS technology, it is now possible to develop driving strategies where vehicle velocity trajectories can be dynamically adjusted. Connected vehicle data provide detailed knowledge of vehicle trajectories as they travel in signal controlled networks. In addition, the traffic controller's signal phase and timing (SPaT) information is known and can be communicated directly to individual vehicles. This information can be used to develop algorithms for providing real-time speed advisories to drivers to minimize fuel consumption and emissions.

We developed an in-vehicle prototype system to provide speed advisories to drivers for minimum fuel consumption. In addition to the speed recommendation a control strategy for signal priority to individual vehicles (APIV) was investigated alone as well as in combination with the speed advisory system. The prototype system consists of a research vehicle, a cloud server and several traffic signals equipped with wireless communication devices. The vehicle was equipped with PCs for the computation of the speed recommendation as well as the capability to display the speed recommendation directly in a programmable instrument cluster. The connection to the cloud server is maintained via a cellular 4G connection. The traffic signals send information about their future timings via a 3G connection to a cloud server, which forwards the appropriate information to the research vehicle. The system was first tested in a controlled environment: a fixed time traffic signal with no cross traffic or other traffic present at the Richmond Field Station campus of UC Berkeley. Compared to the uninformed driving scenario the speed advisory system achieved significant fuel savings: using the speed advisory system, fuel savings of 13.6% were observed. For the APIV approach without the speed advisory fuel savings of 19.1% were achieved. The combination of both approaches showed fuel savings of 28.4%. Further analysis indicates that fuel savings for the informed driving scenario are mainly from the drivers' early slowing down and cruising through the intersection without having to come to a complete stop. The fuel savings due to APIV are mainly contributed by an increased proportion of driving through green. The system was also tested on a real-world arterial El Camino Real with three coordinated actuated traffic signals. A new speed advisory algorithm was developed for actuated coordinated traffic signals and the presence of other vehicles. Due to limited time and resources, it was not possible to do any meaningful measurements on the El Camino Real field tests. Nevertheless important observations were made during the test runs performed. It was observed that is extremely difficult to follow recommended speeds that are continuously changing over time, while driving with other vehicles. This indicates that besides the speed advisory algorithm itself, the method of displaying the speed recommendation is crucial for the success of similar systems in the future

5. CONCLUSION

5.1 Summary of the Study Findings

The goal of this project is to develop advanced signal control strategies based on connected vehicle (CV) data, i.e., real-time information on vehicles' location, speed and characteristics as well as communication to the signal control infrastructure. A comprehensive literature review was performed with emphasis on existing adaptive traffic signal control systems and connected vehicle data and traffic control. We developed algorithms for the estimation of performance measures based on CV data. Several control concepts were developed and tested to improve mobility and safety. A prototype system was also developed and field tested to provide real-time speed advisories to drivers to minimize fuel consumption and emissions.

5.2 Future Research

The deployment of vehicle-infrastructure cooperation through connected vehicles offers the potential for significant improvements is in the efficiency of traffic signal control. This research project produced analysis procedures for estimating performance measures and several promising control concepts based on connected vehicle data for improving mobility, safety and reducing adverse environmental impacts. Ongoing and future research will cover but not limited to the following topics: Further research is needed on the queue spillback avoidance control strategy to consider multiple intersections upstream of the critical one so that spillbacks are avoided in the whole network and queues are distributed homogeneously among all affected links for more efficient traffic operations. Also, the proposed control strategies for congested grid networks need to be further evaluated on networks a range of geometric, traffic and control conditions. Further research is needed on the dynamic lane group (DLG) concept includes further testing of DLG on different intersection configurations and on arterial streets. Also research is needed on mitigations for adverse DLG impacts such the intensive lane changing upstream of the intersection including deployment of mid-block pre-signals, dynamic lane signs and in-vehicle advance information to drivers regarding the lane configuration at the intersection approach.

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