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Invited paper

A survey of vehicular communications for traffic signal optimization

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ABSTRACT

Traffic congestion is an ever increasing problem on our roadways and city streets. The main contribution of this survey is a taxonomy of adaptive traffic signal control strategies achieved through various levels of vehicular communications.

Strategies to optimize traffic signals fall into three categories based on the level of vehicle involvement. The first category involves those strategies that utilize legacy devices with no vehicular involvement. The second category comprises those strategies that utilize vehicles on the road to wirelessly transmit data about themselves (e.g. location, velocity). The third category involves strategies that utilize the vehicles' on-board computation power to help optimize traffic signals. The bulk of this survey deals with the second category as it appears to be the most prevalent in the research literature. We are however, quick to point out that the third category seems to be gaining momentum, as the prevalence of smartphones has suggested supplementing legacy traffic monitoring with traffic-related reports submitted by the driving public.

1. Introduction

In 2011, in the United States there were over 250 million vehicles criss-crossing four million miles of roadways [1]. Since most US roadways function close to capacity, congestion is a common occurrence triggered by chance fluctuations in traffic flow. Recent statistics from the US Department of Transportation (US-DOT) and National Highway Traffic Safety Administration (NHTSA) have revealed that over half of all roadway congestion is caused by traffic-related incidents and poor traffic light scheduling, rather than by recurring rush-hour traffic in big cities [2–4]. In fact, 27% of the total delay due to congestion is experienced in non-peak times [5].

Worse yet, according to the NHTSA, congested roadways and city streets are the leading cause of tens of thousands of traffic-related fatalities [6]. In addition to the loss of life and property caused by traffic accidents, the US-DOT has shown that congestion costs the nation, year after year, over 2.9 billion gallons of wasted fuel, 5.5 billions hours of lost productivity, and releases 56 billion pounds of carbon dioxide [5]. For example, in 2011 individual drivers experienced an average of 38 hours of sitting in congested traffic.

There are four basic approaches to the problem of preventing congestion or mitigating its effect:

1. Promote the use of public transportation and carpooling,
2. Increase the bandwidth of the current roadways,
3. Increase average speed, and
4. Decrease the travel delay on the existing roadways.

The focus of the first category of approaches is to reduce the number of vehicles on our roadways by increasing the number of passengers in each vehicle through the use of buses and carpools, or by removing them altogether through the use of light rail. This category is further partitioned into two sub-categories, those that remove vehicles by placing drivers and passengers into other vehicles, and those that place drivers and passengers into non-roadway transportation, such as light rail. Carpooling and bus systems both use existing roadways, but increase the passenger count per vehicle. Alternatively, rail systems remove vehicles from the roadway completely. In both cases, the number of vehicles is reduced, thus effectively reducing traffic flow intensity. Both are worthwhile considerations for any municipality, but are not within the scope of this survey.

The second category of approaches is concerned with adding more roadway infrastructure to give vehicles alternate paths and lanes to get to their destination. In effect, this approach proposes to increase the bandwidth of the roadway system. In the past, adding more lanes or new roads has been a strategy for dealing with traffic, but at a great cost. According to the Florida Department of Transportation, adding a single lane to an existing road costs between $1.5 million and $4.75 million per mile [7]. Adding

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a new four-lane roadway costs as much as $13.5 million per mile. In certain circumstances, providing additional roads is necessary; however, there are other alternatives that must be considered first.

The third category involves approaches focused on increasing the average vehicular speed. This can be done by increasing the posted speed limits, by creating a set of dedicated lanes with an increased speed limit (e.g., High Occupancy Vehicle (HOV) lanes), or by platooning. Due to safety reasons, increasing speed limits can only be considered under certain circumstances. HOV lanes are an additional set of lanes with added cost, and are usually restricted to highways and, under current practice, only to peak hours. Platooning was defined in [8] as "a collection of vehicles that travel together, actively coordinated in formation". In theory, platooning offers better roadway utilization, higher throughput, improved gas mileage, and increased safety [9,10]. While interesting in their own right, the approaches in this category are not within the scope of our survey.

Finally, the last category of approaches strives to minimize travel delay on existing roads, either by routing the vehicle to the shortest path or by retiming the traffic signals to optimize flow and, thus, decrease delay. One approach to implementing this latter strategy is to employ guidance systems that provide the driving public with information on current traffic conditions, expected travel times, delays, road construction and the like. The idea is using this information, the drivers can decide for themselves what alternative best suits their needs. Systems that display travel times on overhead highway signs have been utilized in Europe and Japan for more than three decades. Recently, the high penetration of smartphones has made it possible to provide the drivers with the latest traffic conditions. Google Maps, 511 Traffic [11], and WAZE [12] are examples of applications that can display the current traffic conditions on a smart phone. The next step in these guidance systems is to predict future traffic conditions, and to offer individualized guidance information to best reduce travel time of individual drivers. Although guidance is an interesting and worthwhile topic, the rest of this paper will focus on optimizing traffic signals.

The remainder of this survey is organized as follows. Section 2 offers basic concepts of traffic signals and vehicular communications. Of particular interest is the role played by vehicle-to-infrastructure communication in providing the traffic controller with real-time information so that it can provide the best timing for the traffic signals. Specifically, in Section 3 we describe strategies that require no contribution from the vehicles. In Section 4 we describe strategies that involve vehicular communications where each vehicle provides information about itself. Further, in Section 5 we describe strategies where the vehicles play an active part in determining the timing of traffic signals. Section 6 offers an in-depth discussion of the most representative papers surveyed. Section 7 presents our vision of the future of traffic signal optimization. Finally, the paper concludes with Section 8 that offers concluding remarks.

2. Background on traffic monitoring, traffic signals and vehicular communications

The main goal of this section is to present background material that may be useful in understanding the technical presentation in the remainder of the paper. With this in mind, Subsection 2.1 introduces basic concepts of traffic monitoring, Subsection 2.2 presents basics of traffic signal optimization, and Subsection 2.3 presents the rudiments of vehicular communications.

2.1. Traffic monitoring

Legacy traffic monitoring and incident detection techniques, that are still in widespread use today, employ Inductive Loop Detectors (ILD), video detection systems, acoustic tracking systems and microwave radar sensors [13,14]. By far the most prevalent are the ILDs, which are placed on the roadway every mile or so. The ILDs measure traffic flow by registering a signal each time a vehicle passes over them. Each ILD, including hardware and controllers, costs around $8200; in addition, adjacent ILDs are connected by optical fiber that costs $300,000 per mile [15]. It is well documented [16] that the legacy equipment installed in support of collecting traffic-related data is expensive and costly to maintain and repair. Not surprisingly, transportation departments worldwide are looking for less expensive and more reliable solutions for traffic monitoring and incident detection [10].

To be effective, innovative traffic-event detection systems must enlist the help of the most recent technological advances.

For example, recent advances in sensor technology have produced cement-based piezoelectric sensors that do not corrode, cannot be damaged by thermal expansion of the road, and can be made of inexpensive materials [17]. These sensors can be embedded in the roadway and detect vehicles like ILDs. They have been the basis of the NOTICE system [18] that involves embedding intelligent sensor belts in roadways and using these belts to detect traffic-related events ranging from congestion to lane obstructions and potholes. NOTICE has a great deal in common with ILDs since both systems are intrusive and contribute to weakening the structural integrity of roadways. Extrapolating from past experience with ILDs, sensor belts embedded in the roadway are very likely to suffer from reliability problems and to contribute to the creation of potholes.

An idea that exploits the prevalence of smartphones is to supplement legacy traffic monitoring with traffic incident reports submitted by the driving public. A recent implementation of this idea has lead to 511 Traffic that offers an at-a-glance view of road conditions in a given geographic area [11]. Unfortunately, 511 Traffic is a centralized system that accumulates and aggregates traffic-related feeds at Traffic Monitoring Centers and, due to inherent delays often displays stale traffic information [19].

Finally, the Mobile Millennium project at UC Berkeley exploits information collected by probe vehicles to infer information about the traffic [20]. Relying solely on traffic data collected by probe vehicles seems to work best in urban environments that experience high concentration of vehicles and less well on highways where there may be no "critical mass" of probe vehicles [21].

2.2. Basics of traffic signal optimization

The reason traffic signals exist is to assign the right-of-way at intersections. Control of a particular direction is partitioned into three traffic light phases: green, yellow, and red. The interval from when the green phase begins and the red phase ends is the cycle time. The phase and cycle timings for each direction are controlled by a traffic signal controller.

Most traffic signals in the US run a set of predefined timing plans that set the signal's cycle length and green phase length based on the time of the day. In most cases, the optimization of the signal systems currently occurs off-line at either the isolated intersection or corridor level. One of the major disadvantages of this approach is that it requires data on traffic-turning movements be regularly collected to develop optimized traffic signal plans off-line. A second major disadvantage is that the time-of-day based signal timings do not adapt well to unexpected changes in traffic demand. For example, if an incident on the roadway network