Enabling Distributed Vehicular Traffic Control and Safety Applications with VGrid

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Introduction

According to a recent American Automobile Association (AAA) report, the US loses hundreds of billions of dollars annually due to traffic accidents and congestion. Therefore, any traffic management measure that reduces traffic accidents and congestion by even a small proportion could translate into huge savings. Although the specific triggers of traffic congestion are numerous, one can broadly attribute them to *bottlenecks*, or hot spots on the road. Two types of bottlenecks can be found: fixed bottlenecks and dynamic bottlenecks. The former can be places where two or more roads merge together, number of lanes drop to fewer numbers, grades become steeper, or curves become tighter. On the other hand dynamic bottlenecks can be locations of accidents that temporally blocks one or more lanes, slowly moving vehicles in a traffic stream (such as trucks on a steep climb), or icy road sections during winter. It has been reported that accidents caused more than half of congestion hours in this country. As such, measures to reduce the occurrences of traffic accidents are highly desirable from both safety and congestion management perspectives. One such measure, variable speed limit control, has been demonstrated to hold great potential in stabilizing traffic flow and reducing the number of accidents.

There is a huge untapped opportunity to leverage new communication and wireless technologies for distributed control and smoothing of traffic flow. For example, the current-generation of Intelligent Transportation Systems (ITS) collects traffic statistics from fixed roadside sensors and processes the data at a central location to decide the optimal traffic-light schedules (timing) or to plan construction detour routes. The feedback loop in these systems occurs over a period on the order of weeks or months. A well-designed, distributed traffic control and management system can drastically reduce this time to an order of seconds or minutes. An important goal is the design and development of a unified framework and the underlying algorithms *to monitor and control vehicular traffic flow by extending existing road-side sensor infrastructure with an ad hoc network of in-flow vehicles equipped with storage, processing, and sensing capabilities.* Specifically, we seek to address the following two open problems:

- Question 1: **How do we exploit the emerging wireless communication technologies to enhance traffic safety and mobility?** We will evaluate the existing wireless technologies (e.g., ad hoc routing protocols, DSRC channels, etc.) and propose necessary modifications to enable effective vehicular traffic management through a distributed architecture.
- Question 2: **How do we develop an integrated simulation platform that captures realistic vehicular movement (driver behavior), detailed wireless communication models, as well as networking protocol interactions?** Our simulation platform will contribute to improving existing evaluation methodologies for the general transportation research community, particularly for research related to vehicle-infrastructure integration.

Within a geographic area, an ad hoc network of vehicles equipped with sensors and in-vehicle processing capability can form an *ad hoc cluster of sensors and grid computers*, which we refer to as **VGrid**. Figure 1 shows traffic control and management infrastructure that we envision, where VGrid collect and process real-time traffic data using *in-vehicles sensors and computers* to make distributed control decisions. Our proposed VGrid can complement and extend the existing fixed infrastructure by distributing previously centralized control functions, such as traffic statistics collection and dissemination of traffic advisory messages, to local intelligent agents, including in-vehicle sensors and computers. For example, to ease the merging of traffic from two lanes to one, the affected vehicles can exchange velocity and/or position information and schedule the best arrival time at complex highway interchanges.

Unlike traditional grid computers, in VGrid, both the topology and the node membership change with time. We propose to exploit these dynamic characteristics to detect congestion on-the-fly and control vehicular traffic flow. When the vehicles forming the ad hoc grid computer are themselves part of the vehicular traffic flow that is being controlled, the system has a characteristic of being a self-referential system. Such a system has the following unique feature: the capacity of the grid computer increases as congestion increases, which is precisely when more capacity is needed (up to a certain point) to accurately determine the vehicular flow characteristics that can smooth and homogenize the traffic flow and thereby optimize the associated delay and throughput.

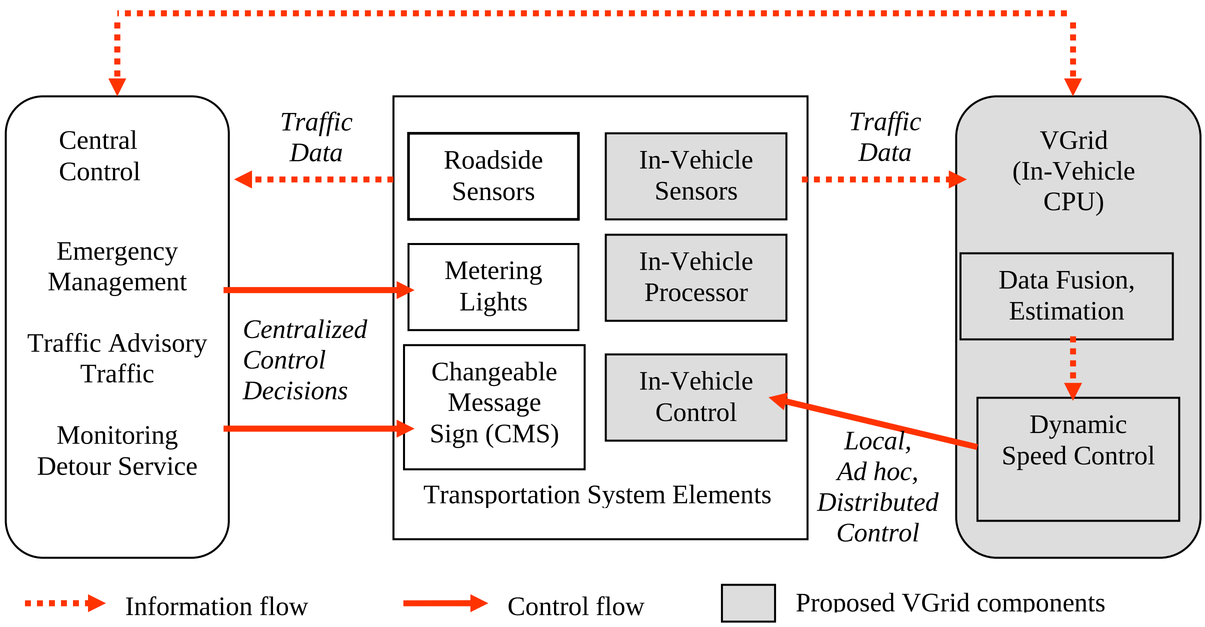

Figure 1. Introducing local, distributed traffic control loops with the aid of VGrid.

Distributed Traffic Control via Ad Hoc Sensing and Computing

We propose to apply cooperative ad hoc computing in VGrid to dynamically "control" vehicular speed to achieve a smooth flow. Our current efforts are focused on the following research tasks:

- **Data Fusion Using Ad Hoc Sensors and Computers:** As shown in Figure 1, VGrid leverages in-vehicle sensors and wireless communications to exchange position and velocity information. Real time vehicular flow statistics from multiple sources need to be "fused" together (sometimes with historical profile) to infer traffic conditions for traffic management decisions. We will explore two new approaches to this data fusion problem: (1) A hybrid solution where intelligence is added to existing road-side sensors to communicate with vehicles to perform local computation and provide immediate feedback to drivers, e.g., in the form of speed warning or variable speed limits; (2) A distributed solution where in-vehicle control units exchange information collected through in-vehicle sensors with other vehicles to "estimate" the current traffic state.
- **Dynamic Traffic Control:** The collected data from distributed sensors will be combined to detect "congestion" or "problems" and compute desired driving speed. In our research, we will explore the application of VGrid to dynamic speed control with increasing complexity: a) speed warning, b) variable speed limits (VSLs), and c) cooperative driving. The first type of speed

control provides early warnings of drastic changes in travel speed ahead, so that drivers can respond to these changes in time to avoid collisions. VSLs assign dynamic speed limits to road sections to smooth traffic flow. The third type of dynamic speed control, cooperative driving, can be thought as a crystallization process. The vehicular ad hoc nodes in the traffic stream act like nuclei (one can also think them as highway patrol cars) that coordinate their driving so as to bring a smooth, orderly flow pattern in the traffic stream. This is made possible through the sensing, communication and computation capabilities of VGrid.

- **VGrid Architecture Design:** We will also address the VGrid architectural design issues, e.g., how the different functional elements interact with existing fixed infrastructure to implement data collection, state estimation, and traffic control algorithms. We have identified five major components: fixed roadside sensors, central coordination center, changeable message signs (for VSLs), in-vehicle sensors, and in-vehicle computers (control units). New addressing, routing, and transport protocol will be needed to support robust, fault-tolerant, and secured communications among these components. We leverage and build upon existing work including our own on communication network protocol performance and cross-layer optimization in vehicular ad hoc networks.
- **Simulation Platform:** The proposed VGrid architecture and its intended applications are complex and, barring a few simple cases, often defy analytical treatment. We are developing a simulation platform that integrates the communication, data processing, computing and traffic control functions with a realistic traffic mobility model. The traffic mobility model is based on the well known cellular automata model, with modifications to its time-space resolution and driving behavior rules to suit the communication, computing and traffic control requirements of VGrid. Using this simulation platform, we will study performance characteristics of VGrid under different communication and grid computing designs and how they affect the design and effectiveness of the intended traffic management applications.

Bios

The ideas presented in this position paper are part of a multi-disciplinary **NSF funded project** titled "**Distributed Vehicular Traffic Management via DSRC-Enabled Vehicles**" led by co-PIs Michael Zhang (Civil Engineering), Chen-Nee Chuah (Electrical and Computer Engineering), and Dipak Ghosal (Computer Science).

Michael Zhang's research is in vehicular traffic modeling and control. He received the NSF CAREER grant NSF-9984239 in 2000 to develop improved continuum models of traffic flow. He serves as Associate Editor for Transportation Research, Part B: Methodological and Area Editor of Networks and Spatial Economics. Besides academic journals, Zhang's research was also reported by the San Francisco Chronicle and The Sacramento Bee as well as at 2003's AAAS meeting in Denver, Colorado.

Chen-Nee Chuah's research is in computer networking, with emphasis on network measurements, control plane design, and wireless communications. Chuah's isa recipient of the NSF CAREER grant (0238348, Aug 2003-July 2008) on *Robust, Stable, and Secure Routing*. This project leverages her experience in collecting and processing real-time measurements from distributed vintage points. Together with three other colleagues from Toyota, Daimler Chrysler, and U.C. Berkeley, Chuah co-organized the first ACM Workshop on Vehicular Ad Hoc Networks (VANet), which is collocated with ACM MobiCom 2004.

Dipak Ghosal's research is in computer networks with emphasis in transport and application layer protocols and parallel and distributed computing. He received the NSF CAREER grant (9703275) in 1997 to investigate management and control issues in high speed networks. Many of the research results are applicable to the proposed research. The NSF award on pseudo-serving deals with a peer-to-peer paradigm for dissipating flash-crowds on the Internet. The algorithms for controlling the scalability of p2p system are relevant to the proposed research.