CRITICAL NATIONAL NEED IDEA

"Wireless Visual Sensor Networks for Urban Traffic Management"

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White Paper

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A collaborative effort between:

- The Center for Transportation Research
- The Wireless Networking and Communication Group
- The Center for Perceptual Systems

Main contact:
Professor Al Bovik
The Curry / Cullen Trust Endowed Chair Professor
Department of Electrical & Computer Engineering
The University of Texas at Austin
Austin Texas 78712
Phone: (512) 471-5370
Email: bovik@ece.utexas.edu
Webpage: http://live.ece.utexas.edu/people/bovik/

Participants:
Professor S. Travis Waller
Department of Civil, Architectural and Environmental Engineering
Transportation Engineering

Professor Robert Heath
Department of Electrical & Computer Engineering

Professor Sriram Vishwanath
Department of Electrical & Computer Engineering

The Problem

Urban areas face increasingly acute vehicular traffic congestion. Current methods for measuring traffic flow on a real-time basis are antiquated and limited in their capacity to assess traffic dynamics. Buried inductive loop detectors at intersections are extensively used in the USA and Europe to measure traffic speed, occupancy and volume on freeways and arterials. The data obtained is used by traffic management centers to make real-time operational decisions such as timing ramp meters, incident detection, congestion identification, actuated signal timing and control [1], [2]. However, street loop detectors suffer from serious limitations. Firstly, the installation and maintenance cost are very high, requiring saw cuts into the pavement, causing traffic disruption, lane closures, hazards and delays. The saw cuts reduce the structural strength and stability of pavements causing crack propagation [3], [4]. Secondly, the loops are not reliable and frequently malfunction due to loop wire failure, corrosion, pavement deterioration [5], crosstalk due to magnetic coupling between closely placed sensors, and breakups in transmission [6]. Thirdly, inductive loop placements are sparse and unable to measure spatial continuums of traffic flow, localized disruptions, vehicle trajectories, queue lengths, and can't supply images of traffic situations for human visualization and analysis.

Owing to these limitations, visual sensors in the form of visible light video and infrared (IR or night-vision) cameras are being explored as tools for traffic data acquisition. Video cameras suggest the ability to measure vehicle time stamps, monitor multiple lanes, pinpoint vehicle locations, measure spatial and temporal traffic characteristics such as trajectories, densities, and velocities, and can be used to classify vehicles types at higher accuracy and fidelity levels than loop detectors. Despite a higher equipment cost, installation and maintenance is much cheaper than loop detectors [7]. Successful and ubiquitous wirelessly networked flow-detecting traffic cameras should have a transformative impact on a city's urban congestion and management of hazardous situations. One such application that we propose to investigate will be advanced signal control and information provision strategies that are reactive to the evolving spatial and temporal dynamics in the urban traffic system.

A variety of efforts have commenced towards the control of urban traffic using video cameras, such as a widely deployed one in Valencia, Spain that uses humans to read the videos without automated analysis [8]. Such a system is infeasible in large city environments having thousands of intersections owing to the intense manpower needed to survey all of the available cameras. The problem is reminiscent of the nearly 4 million (non-traffic specific) surveillance cameras deployed around London, UK, without intelligent networking to unite them, without adequate manpower to reliably observe them, and without the software to automatically analyze them.

It is true that considerable effort has been applied to using images and videos to analyze various traffic situations, such as collision detection and monitoring [9], [10], tracking and behavior determination [11], [12], and vehicle identification and classification [13]. Of course, there is also a vast military-oriented literature on automatic vehicle detection, tracking, classification, and recognition. With very few exceptions, the general approach taken in these prior efforts has been to attempt to identify discrete vehicles, by segmenting the image/video stream using attributes of intensity, shape, boundary contours, texture, color, distinctiveness, image or 3-D motion flow, or some combination thereof of these hard-to-compute descriptors. In these approaches, the bottleneck to success is the segmentation problem, which is exceedingly ill-posed and difficult to make insensitive to noise, clutter, unexpected objects or occlusions, and variations in vehicle size, condition, and lighting conditions. Indeed, the segmentation problem is so difficult that that it is regarded as unsolved, even in this limited context.

The answer to the traffic management problem is within the reach of broad technology efforts for the first time. What is needed to solve this problem is a broad and comprehensive program of research and development towards managing urban traffic using widely deployed smart cameras that are located at urban street intersections that are wirelessly networked together and with intermediate and centralized computing resources and that are interfaced with the traffic control network and with the signaling apparatus (red/yellow/green lights). There are significant technological challenges that must be surmounted to solve this problem and to reach actual deployment of the technology. These problems include the broad scale and synchronous acquisition, analysis, and processing of time-varying video traffic information in real time; the development of algorithms – at each traffic site - for ascertaining traffic density, traffic movement, and disruption patterns and causes, while operating in variable outdoor conditions (day/night/weather). A key aspect will be developing wireless networking protocols for sharing specific visual information across an urban-wide wireless network spanning hundreds or thousands of geographically distributed cameras, and for making intermediate and centric decisions based on this visual input towards understanding, managing and directing traffic on a local and a geographic basis, and for widely deploying these decisions to traffic control and signaling across the network grid.

Optimizing traffic flow in crowded urban environments by dynamical control of signaling is an extremely important problem, since it can significantly improve the fuel efficiency of vehicles enhancing green initiatives; it can enable emergency vehicles to better navigate dense traffic; it can help adapt traffic to road construction; it can lead to better handling of 9/11-like disaster scenarios; it can enhance law enforcement, and so on. Developing complex visual sensor networks in urban environments – ranging from the small city through the largest super-cities – that are capable of delivering the information needed to control the traffic network will require solving a wide range of particularly challenging and significant problems at many layers of abstraction and implementation. Without getting into technical specifics, yet while acknowledging the broad scale of the dynamics of the overall engineering problem, the overall sensor and decision network that would be required to lead to successful traffic control from visual traffic surveillance, will be a very large-scale, multi-stage feedback system that self-modifies based on dynamic changes in the physical traffic network. The stages include video acquisition and processing by smart cameras to extract robust and reliable dynamic traffic flow information; wireless communication using existing wireless infrastructure networks (WiFi or 3G) to share and aggregate accumulated traffic flow information and make decisions to optimize flow using opportunistic feedback to reduce the data glut; and control of traffic flow via intelligent, adaptive, dynamic signaling.

There is little question that monitoring and control of urban traffic is both a critical national need that justifies government attention, as well as a societal challenge, that if not addressed, will lead to worsened congestion; poorer use of fossil fuels and other energy sources; increased vulnerability to large-scale terrorist acts and natural disasters, any of which would significantly and negatively affect the function and quality of life of the nation, or of a part of the nation.

Maps to Administration Guidance

It is widely understood at all levels of Federal and regional government that traffic congestion is a severe and growing problem in all of the nation's urban areas. As detailed in a recent Texas Traffic Institute study [14], in 2005, the travel delay experienced by drivers was 4.2 billion hours, which is 1.7 billion hours (a 68% increase) more than the delay experienced in 1995. During the same period, the amount of wasted fuel increased to 2.9 billion gallons in 2005 from to 1.7 billion gallons (an increase of 70 %) and the congestion cost increased to 78.2 billion US 2005 dollars from 45.4 billion US 2005 dollars (an increase of 72 %). Note that in 2005, operational treatments resulted in a savings of 292 million hours of travel delay and 5.4 billion US $ of operational costs. The four main operational strategies surveyed were ramp metering, incident management, access management and signal coordination all of which require dense traffic surveillance to achieve maximum efficiency.

The Texas Governors Business Council Study [15] estimated that between 1990 and 2000 the total cost of congestion was 45.6 billion dollars (caused due to travel delay and wasted fuel). During the same period only 37 billion dollars were invested in infrastructure maintenance and enhancement. The amount of money which needs to be invested to control congestion over the next 25 years is estimated to be 218 billion dollars. However, such a huge investment would result in a total savings of around 354 billion dollars in travel delay and fuel over the next 25 years. An additional 157 billion dollars of benefits would be obtained through creation of 120,000 permanent jobs, reduction of hydrocarbons emissions by 775,000 tons and improvements in safety. Thus the return on investment in congestion management is expected to be around eight times in Texas.

The development and application of Intelligent Transportation Systems to solve transportation problems was established as a national priority by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 [16]. ITS have an important role to play in control of long term initiatives to control recurring congestion and short term initiatives to control non recurring congestion.

It is recognized that new and emerging technologies will be required to close the traffic control loop – from sensors to signaling. As early as the 1996 Olympics in Atlanta, Georgia, before the wireless revolution took hold, the city braced for a massive influx of visitors and vehicles. To deal with the traffic increases, the City installed “smart” cameras on the ground to monitor traffic volume and flow.

According to the Federal Highway Administration (FWHA) [17], an important aspect of traffic management is the detection and handling of non-recurring congestion caused by unforeseen circumstances such as incidents, work zones and weather conditions. These are increasingly affecting the reliability of travel time throughout the nation. To counter non-recurrent congestion there is an identified need to develop more innovative operational strategies based on intelligent transportation systems, including novel sensors, cameras, and communication systems.

It is important to note, as the FHWA has, that travel time reliability is an important factor affecting the route choices of travelers [18]. If the travel time reliability is low, then users will plan ahead and should assume an inflated travel time to ensure on-time arrival. For example, back in 1982, if the free flow travel time was 20 minutes, then on an average, the same trip took 23 minutes during peak hour. If the arriving on time was important the planned travel time was 32 minutes. By 2003 the planned travel time had increased to 40 minutes. To counter travel time unreliability, a number of strategies have been proposed including incident management, work zone management, freeway, arterial and corridor management, traveler information and value pricing using Intelligent Transportation Systems (ITS), such as intelligent signaling, new sensors, and wireless communications systems.

Solving these problems will require significant innovations in wide-area surveillance of traffic patterns using geographically deployed visual sensors, and equally significant innovations in visual information sharing, processing and networking. These topics are of high interest in the Exploratory Advanced Research Program of the Federal Highway Administration (FHWA), while visual sensor networks, which remain a nascent concept awaiting a transformative application such as traffic monitoring, is a key technology focus of the National Science Foundation under the Sensor Innovation and Systems Program and a variety of other programs.

Solving these problems will require a large and significant cross-disciplinary effort across relevant institutions and industry, promising high-impact innovations in several directions. Such a development as very large-scale wireless visual sensor networks dedicated to urban traffic management would be a watershed demonstration of the power of visual sensor networking and a life-transforming technology for urban dwellers.

Justifies Government Attention

According to the Federal Highway Administration, the problem of urban traffic congestion in the US is growing more severe each year. The upshot of this is a significant loss of human resources, significantly increased inefficiencies, reduced quality of life, and a greater environmental impact at a critical time. The problems are currently being poorly addressed by current traffic management methods and a sea change is needed in the way that traffic is handled. A larger percentage of the US roadway network is clogged, with a greater severity, and over longer periods, than ever before. Over the past 20 years, the amount of time spent by the average urban driver contending with congestion-related traffic delays has *nearly* quadrupled [19]. The average trip between any two points during peak travel periods averages a time-of-travel that is 40% longer than during non-peak travel periods. Unfortunately, rush-hour travelers now endure peak travel periods that now last around six hours of every working day in most major urban areas.

According to the Texas Transportation Institute (TTI) at Texas A&M University, urban congestion costs the US more than $70 billion per year – more than 3.5 billion man-hours lost to waiting in traffic, and more than 5.5 billion gallons of excess gasoline and diesel fuel lost to congestion. Aside from the monetary impact on individuals, families (about 1/5 of family expenses are already travel-related), companies, government, and society as a whole, the carbon and particle emission impact on the environment is quite significant.

As these problems worsen, it is becoming clear that old solutions, such as increasing the number of lanes, building new roadways and enforcing HOV traffic laws cannot solve the problem. Urban space is limited, and the resources needed to simply maintain the traffic network as our roads and bridges age and crumble exceeds the fiscal resources that are available at the local, state, and federal levels. A massive rebuilding of the traffic network to alleviate current congestion is an untenable solution.

It is becoming increasing apparent that dealing with the worsening traffic congestion and environmental problems will require new efficiencies in vehicle design, energy sources and fuel use, and new technologies for sensing, understanding, and managing the flow of urban traffic. The pace of technology deployment in traffic management has significantly lagged most other aspects of our daily lives. Despite our computerized and wired automobiles, offices, homes, and even coffee shops, traffic control still proceeds by fixed, non-adaptive signaling at intersections, sensing of traffic flow that is limited to underground inductive loops, and limited deployments traffic cameras that are largely deployed to capture red light offenders.

A much more far-thinking approach are Advanced Signal Control systems that seek to develop live signal timing plans that are reactive to traffic congestion dynamics as they occur. By accurately monitoring the queues, density and other parameters that could be delivered by a sophisticated wirelessly connected, intelligent, massively deployed smart camera video system in real time, signal timing plans could be deployed to optimize both local level (intersection) objectives such as throughput and delay, as well as geographic system level network wide objectives such as total system travel time.

Several advanced traffic-adaptive signal control system prototypes have been developed – the RHODES at the University of Arizona, OPAC at the University of Massachusetts, and RTCAL, a collaboration between the University of Pittsburgh and the University of Maryland. These prototypes are limited to simulation and do not deploy large-scale networked cameras to sense traffic flow and dynamics. The results of these simulations indicate that *significant* reductions in traffic delays, stoppages and fuel consumption can be achieved [20]. Other US studies indicate that the successful design and deployment of such a system could result in travel time reductions ranging from 10-30% with significantly improved air quality [21], [22].

Of course, the creation and deployment of a successful advanced signal control system will require wide-area networks of efficient and accurate traffic monitoring and surveillance systems that provide accurate and timely intersection queue length data to intermediate and central traffic management centers. Widely-deployed smart video cameras, which are a technology that is coming into their own in terms of the tradeoffs between resolution, hardiness, size, energy efficiency, and cost, ate the natural and emergent technology that will enable this transformative development. Supplying visual traffic data through a wireless network is a reliable and cost effective solution towards for collecting system-wide traffic data. Such a system will make it possible to identify congested arterial corridors and will enable the definition of reactive signal optimization strategies to alleviate congestion on such corridors. More importantly, a city-wide deployment will make it possible to holistically and adaptively optimize signaling throughout the traffic network to greatly improve traffic flow, and to identify and deal with stoppages as they occur in an efficient manner. The convergence of the requisite technologies has finally arrived to enable the visual control of traffic; what remains is the effort and expense to make it happen, the result of which will be, in the longer-term, huge monetary, temporal, quality-of-life, and environmental improvements moving forward.

The technology to solve the traffic problem exists, but has not been developed in this direction. Some of the most exciting frontiers of human inquiry involve the deployment, understanding and control of intelligent systems that consist of numerous intelligent and networked interacting sensors that gather data from diverse sources. At the forefront of such efforts are investigations of *wireless visual sensor networks,* wherein spatially distributed intelligent digital cameras share information, computation, storage, and decision-making with each other and other networked computing resources over wide-area wireless networks [23], [24].

Yet there remains significant work to be done to exploit these technologies. Visual sensor networks present unusual difficulties in several regards: the high dimensionality (3 or 4 dimensional) of the data, the vast data volume to be analyzed, communicated, and reanalyzed, maintaining the integrity of the visual signals [25], and the inherent complexity and diversity of visual data, which derives from the infinite variability of the visual environment. While there has been a surge of interest in visual sensor nets, the field remains in a nascent stage and successful large-scale and commercially deployed applications have yet to emerge. It is likely that compelling applications, such as the US urban traffic problem, will emerge that will drive research innovations and result in tangible products that use wireless visual sensor technology.

Meeting this challenge will require developing prototype systems for managing urban traffic using widely deployed smart cameras, fixed and located at urban street intersections, wirelessly networked with each other and with central computing resources and a traffic control network. It will be necessary to reliably acquire, analyze, and process time-varying visual (video) information in real time, with the specific goals of ascertaining traffic density, movement, and disruption patterns and causes, while operating in highly variable outdoor conditions (day/night/weather).

Another key aspect will be the necessity of developing new protocols for sharing traffic specific visual information across an urban-wide wireless network spanning hundreds or thousands of geographically distributed cameras, in order to make decisions based on the visual input towards understanding, managing and directing traffic, and finally, widely deploying these decisions to traffic control across the network grid.

The next generation of intelligent transportation infrastructure that we have been describing will rely heavily on a wireless infrastructure for conveying the multitude of data to the traffic management center. In fact, the FCC has allocated spectrum in the 5.9GHz band for just this purpose [26]. The motivations for wireless sensors are cost and maintenance. Wireless sensors require just a power source, whereas wired sensors also require a wired communication link back to the traffic management centers. Setting up and maintaining another wired communication network would be challenging. A major component of future efforts will be to propose and simulate the connection of cameras to existing wireless infrastructure networks. Increasingly, cities have public Wi-Fi (802.11) and/or commercial data networks (3rd generation wireless) deployed citywide. For example, roughly a third of downtown Austin, TX is currently covered by a public Wi-Fi network (http://www.ci.austin.tx.us/help/mesh/). This network can be effectively utilized for transporting video and other traffic information across the network.

Yet the goal should be to *critically* instrument the traffic network to leverage the existing data (Wi-Fi) network. If course, it should be instrumented in a cost-effective manner so that there is sufficient data rate and connectivity in the network, while ensuring that resources are not over-provisioned and do not create bottlenecks in the wireless data path. Further, it should be noted that cities across the nation have access to an emergency spectrum band used for communication between police, fire and ambulance services. This spectrum could be cleverly utilized by a wireless traffic-monitoring network. The radios installed along with cameras that would form the broad geographic deployment of the traffic monitoring network would necessarily possess the ability to communicate in both the traditional Wi-Fi ISM bands as well as the emergency bands, enabling high-data-rate communication using both the Wi-Fi and emergency spectrum in non-emergency situations, while deferring to emergency services in emergency situations.

A failure to address the urban traffic congestion problem will amount to a creeping disaster, leading eventually to dysfunctional urban traffic networks incapable of handling the ever-increasing traffic loads. Public transportation systems are an important part of the solution, yet remain overburdened and are extremely costly to deploy. As the impact on the environment increases to dangerous and nearly irreversible levels, as the federal budget is challenged by a severe global recession, highly cost-effective solutions must be deployed to address this problem. Laying out an intelligent, cameras-based traffic network for optimizing traffic flow is an ideal solution, requiring minimal invasive construction, power-efficient electronics technology, and a significant monetary and environmental return on investment. Furthermore, laying out the network will provide significant employment opportunities that will provide an excellent match to President Obama's green initiatives in the recently-enacted economic stimulus bill. The confluence of recently available technologies; pressing environmental, financial, and population needs; and the recognition that new, wide-scale, transformative approaches will be required to solve these problems, provides powerful support for immediate and aggressive governmental action in this direction. The imperative is heightened by the fact that a failure to act will cause the US to fall behind in this important direction.

Interest is such an effort would be very high across US industry, academia, and government agencies. Networking and wireless communications giants such as Cisco and Qualcomm are already committed to the development of networked video technologies, while all-digital smart camera has advanced by leaps and is the focus of efforts of companies such as Texas Instruments, Freescale, and National Instruments, amongst many others. Academic transportation institutions have long been ahead of the curve in proposing new technologies for traffic control. Participation in such a directed, beneficial, and relatively low-risk venture will likely be quite high.

Essentials for TIP Funding

Developing a complex visual sensor network capable of automatically or semi-automatically delivering the information necessary to control the traffic network will involve the solution of many significant problems, at many layers of abstraction and implementation. Owing to the scale and breadth of the problem, as well as the lack, until recently, of the requisite technological developments, this problem has not been broadly addressed or discussed in the public domain. Yet, there is no other viable solution forthcoming. While there are certainly other relevant technological developments, such as vehicle GPS systems, and cameras mounted on the interiors and exteriors of "smart cars," these developments do not provide a solution to the traffic management problem, although they are naturally of interest to the US automobile industry as selling points. GPS requires monitoring of individual vehicle locations at a level that exceeds comfortable privacy issues; on-vehicle camera systems may assist with vehicle spacing for safety purposes, but is too localized to assist with the traffic congestion problem. Both of these allied technologies require that all vehicles be equipped, which is a difficult scenario to envision given the wide span of vehicle ages and the proclivity for individual vehicle modification.

The fact remains, that *the only possible solutions to the urban traffic congestion problem are intelligent, advanced traffic control systems*. Wide and dense deployments of inexpensive, wireless-enabled, processing-capable cameras that can cover large urban traffic environments *are now possible*. We envision a scenario wherein cameras will be installed with optical paths directed down every street at every intersection of interest, which may include a large percentage of streets that are controlled by signals.

Yet, remarkably, there exists no current plans or funding efforts in this direction at the scale needed to achieve success, or even to test the efficacy of such a technology. While there are funding mechanisms for wireless networking, such as the NSF Sensor Innovation and Systems Program; and for intelligent transportation, such as the Exploratory Advanced Research Program of FHWA, these target much smaller-scale efforts that could not capture a meaningful segment of the problem. Opportunities for birthing such a project at the state funding level are non-existent, given the massive scope of the effort required, and the fiscal condition of most state budgets. Designing, modeling, simulating, testing, and building such a large and integrated sensor and decision network, that would also be a complex feedback system that would be self-modifying based on dynamic changes in the physical traffic network, is a large-scale application beyond the capability of conventional funding paths such as the NSF, and which will require an exceptional degree of cooperation between relevant government agencies.

It also represents an incredible opportunity to fast-forward technological innovations in many areas. These include video acquisition and processing over wide geographic areas by smart cameras; integrating the information learned between cameras to reach aggregate understanding of the complex (traffic) scenes; the invention of new paradigms for understanding traffic from a visual perspective, which will require discarding old methods of traffic image analysis that are based on decades-old military goals of vehicle detection and identification, and replacing them with new innovations on measuring visual traffic statistics and traffic flow analysis [27]; new methods for extracting relevant and highly robust traffic flow features in an efficient manner, without relying on dated and fragile "image segmentation," "vehicle detection" and "vehicle identification" techniques; methods for providing the wireless network with robust and reliable traffic flow dynamic information; wireless communication using the existing wireless infrastructure networks (WiFi or 3G) from the cameras to other cameras and intermediate processing stations to aggregate accumulated video traffic flow information and make decisions to optimize the flow; using opportunistic feedback to reduce the data glut; analyzing the capacity of hybrid wireless-wireline networks of cameras and other sensors (such as inductive loops) for traffic monitoring; and control of traffic flow through intelligent, adaptive, dynamic signaling. These diverse technological areas represent difficult, yet certainly surmountable tasks taken individually; taken as whole, which will require extreme sophistication when creating collective traffic sensing and control mechanisms, it is a problem of vast scale and difficulties that can be solved only with significant government attention and support.

Simply stated, we have been describing the most complex, sophisticated, largest-scale feedback control system ever envisioned, but one that is necessary and achievable, and that will have incalculable impact on our society, the economy, and on our fragile environment.

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