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Cyber-Physical Integration to Connect Vehicles for Transformed Transportation Safety and Efficiency

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Abstract. In this paper, we explore a distributed cyber-physical solution using connected vehicle technology (CVtech) to substantially mitigate transportation systems' safety and efficiency problems. Future vehicles, by communicating with other vehicles (V-V), roadside infrastructures (V-R), and personal communication devices (V-P), will adapt to the external regional environment and consequently avoid collisions and congestion. We proposes to seamlessly integrate networked and embedded sensing, computational intelligence, and real-time communication (cyber) into transportation infrastructure including vehicles and roadsides (physical) to facilitate self-organization and system coordination. Specifically, this research addresses two specific themes: Foundations by advancing basic theories in component fields and abstracting the particular knowledge into core principles that integrate cyber and physical processes; and Methods and Tools by designing alternative architectures, modeling a unified online system of cyber and physical elements. The integration of research and education will prepare the future workforce to operate and advance CPS.

Keywords: Cyber-physical system, vehicle communications. data mining

1 Introduction

On Tuesday, January 17, 2012 at about 4:00 PM, a 23-year-old man from Springfield, MA was speeding in the breakdown lane on Interstate 91 southbound near Exit 17 when his car slammed into the rear of a disabled tractor trailer, according to state police. The man was in a 1995 Nissan Altima with no passenger and he was pronounced dead at the scene. As a result of the accident, the breakdown lane and the far right lane were closed for cleaning up and accident investigation, which caused a major traffic tie-up for about five hours. This tragedy was just one out of 6 million car accidents reported annu-

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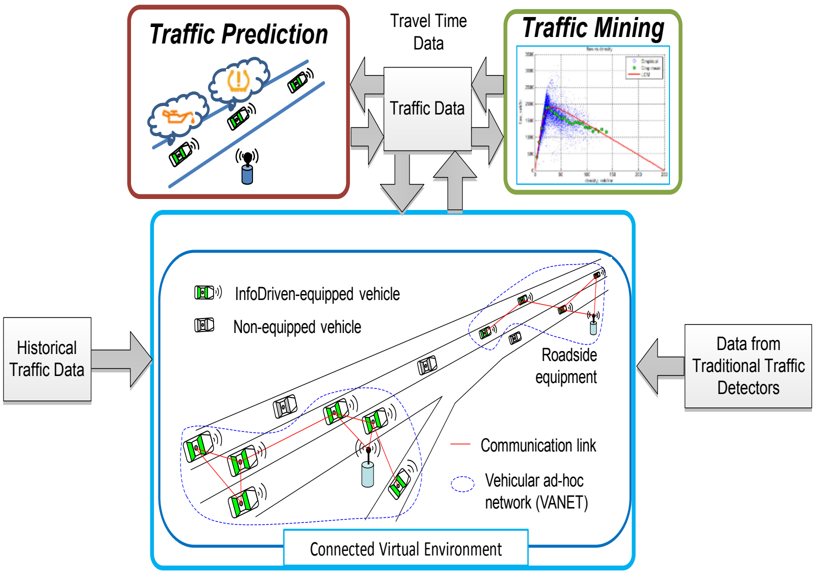

Fig. 1. Traffic Data Mining and Prediction

ally in the United States [1], which adds to a total cost of $232 billion with accidents and congestion combined [2].

More than 57% of these car accidents can be directly or indirectly attributed to drivers' inattention, lack of cooperation, and poor decisions [3] . This is so because our current transportation systems rely almost exclusively on drivers to monitor their surroundings, decide actions next, execute control maneuvers, and make route choice. Many accidents are resulted from a momentary lapse of attention or a slight misjudgment. To address these human limitations, connected vehicle technology [4] has been proposed and its promising future has been demonstrated by proof-of-concept and pilot studies [5] [6] [7] [8]. However, we have yet to fully exploit its capability by integrating cyber (sensing, computing, and communications) and physical (vehicles and roadside) components. Without this, we cannot proactively warn drivers of an imminent collision and facilitate self-organization among drivers to avoid joining and worsening congestion.

In this paper, we describe a coordinated and distributed transportation cyber-physical system of tomorrow with transformed safety and efficiency. The overall objective of this proposed research is to advance the Science of Cyber-Physical Systems (CPS), the first of NSF CPS Research Target Areas, by providing a unified perspective to capture interacting dynamics of a connected vehicle paradigm, see Figure 1. Our proposed system will enable an ever-vigilant CPS Co-Driver which is able to assist its human driver by proactive safety hazard warning and self-organization for optimal routes. Compared with existing knowledge base, the work in the paper is unique and transformative because we not only integrate knowledge of component fields into each other to advance the state of the art of individual field but also merge these fields into a Science of Cyber-Physical Systems in transportation.

2 Enable real-time and reliable vehicle communication

Highway safety applications impose strict requirements of timeliness and reliability on vehicle communication. Although dedicated short-range communication (DSRC) protocol has been developed in IEEE 802.11p, it does not consider the influence of traffic dynamics on data rate and channel access. In addition, the protocol is designed for one-hop applications, while a reliable multi-hop scheme is required to minimize communication delay within traffic. The objective of this aim is two-fold: (a) to quantify the optimal data rate and channel access probability by integrating traffic dynamics into DSRC protocol, and (b) to determine the optimal selection of relay vehicles for reliable multi-hop communications. At the end of this aim, we expect to have an optimized DSRC scheme to ensure real-time and reliable vehicle communication. Our approach (a) is to incorporate vehicle dynamic positions and status into VANET design. Consider a traffic stream in local equilibrium where all vehicles move with the same speed v and inter-vehicle spacing x. Assume that a vehicle (with ID 0) suddenly brakes with deceleration rate b at time $t = 0$. The driver of the following vehicle (with ID 1) sees the braking light and applies brake after some perception-reaction time of τ_{pr} seconds. Without inter-vehicle communications, the collision between the first two vehicles will inevitably cause a chain of collisions among subsequent vehicles. However if vehicles are able to communicate, a trailing vehicle $i, i > 1$ is able to start slowing down only after $\tau_{pr} + \tau_c(i)$ seconds after the braking of vehicle 0 where $\tau_c(i)$ is the incurred delay of communications to inform vehicle i. Hence as it can react well before observing the brake lights of its immediate leader, the probability of a collision is reduced.

Further, system integration with traditional layered approaches often loses the timing efficiency provided by DSRC at lower layer. The team proposes a joint design of MAC, mobility prediction, resource reservation, and congestion control protocols for strict real-time applications. The real-time performance can be guaranteed if control signaling messages are exchanged in a cross-layer manner. A real-time control engine will be developed to achieve real-time communications with four components: mobility prediction, resource reservation, network traffic congestion control, and real-time MAC protocol. The proposed MAC protocol is a time-bounded protocol. The prerequisite of V-V communication for traffic safety applications is timely medium-access. We propose to design a time-bounded medium-access control protocol with traffic control and resource reservation in a cross-layer manner as shown in Fig. 2. Mobility predictions can be done based on the history of vehicle locations and vehicle speeds. The limited bandwidth resources will be preserved through time slot assignments to achieve guaranteed time-bounded message delivery among vehicles. The prerequisite of DSRC for traffic safety applications is timely medium-access. An effective design is time-bounded medium-access control protocol with traffic control and resource reservation in a cross-layer manner. To do so, traffic dynamics is predicted using historical vehicle positions and speeds; the limited bandwidth resources is pre-reserved through time slot assignments to achieve guaranteed time-bounded message delivery among vehicles; high-level congestion traffic control can be implemented through traffic classification and priority-based delivery.

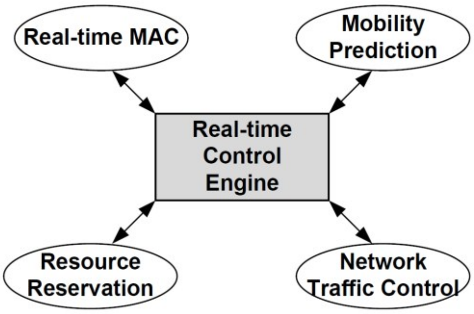

Fig. 2. High-Level Model of Real-Time Communication Control Engine

3 Mine traffic data for dynamic vehicle routing

Connected vehicles are able to generate detailed and very accurate traffic data in real time. These data, if properly utilized, can greatly improve transportation efficiency. Unfortunately, the efficiency impact of the connected vehicle technology hasn't been given the deserved attention. Existing travel time prediction and dynamic vehicle routing models are not ready to fully embrace the opportunities made possible through connected vehicles.

As shown in Figure 1, roadside equipment (RSE) units deployed at strategic locations exchange information with OBEs installed on passing by vehicles. Both RSEs and neighboring OBEs are interconnected and share traffic information. Vehicles outside the range of any RSE may still be connected to the rest of the vehicle and infrastructure network via neighboring vehicles. This vehicle and infrastructure network can generate very accurate traffic information (i.e., vehicle trajectories) in great detail, based on which some fundamental traffic problems related to efficiency can be well addressed from a brand new perspective, including: (a) How to accurately infer current and predict future traffic conditions at locations with and without RSE coverage; and (b) How to best utilize the inferred and predicted traffic information for improving traffic operations. Proposed solutions to these questions based on the CVTech are detailed below. Traffic condition at a location can be represented as a variable vector $x = \{xt, x_{t-1}, x_{t-2}, \ldots, x_{0,}\}$ where time t represents now and t-1 a moment ago. In addition x_t itself is a vector, e.g. $x_t = \{l_t, q_t, k_t, v_t\}$ where l, q, k, v denote traffic location, flow, density, and speed, respectively. The objective here is to predict into the future, e.g. finding $x_{t+1}, x_{t+2}, \ldots$ based on what is known.

Traffic data are collected across time and space. The data analysis must take account of spatial and temporal autocorrelation, which are the characteristics at neighborhood locations that are often positively or negatively correlated. Thus reliable traffic prediction should depend on previous traffic information and vehicles in close vicinity. A traditional model of traffic prediction only on temporal information could yield unstable parameter estimates. Such a method is defined as a function f to calculate an estimate of x at time t+1, using the (d-1)k time steps back from time t. Thus we have $x_{t+1}=f(x_t,x_{t-k}, \ldots,x_t$-(d-1)k) where d is the number of inputs and k is the time delay. In this paper, we proposes a new method to use temporal, spatial, traffic flow, density, and speed information simultaneously using tensor feature regression. Tensors of higher orders have been proved to be effective data structures to model complex science and engineering problem. We extract five-order (traffic location, flow, density, speed, time) tensor features to represent traffic information. The five-order tensor is a multi-dimension matrix to store traffic information uploaded from OBEs to RSEs. It includes time series data in the same location as temporal information, and it includes the surrounding traffic information at the same time as spatial information. In the new tensor regression approach, the predicted traffic information at time t+1 is calculated as $x_{t+1}=f(N(x_t),N(x_{t-k}), \ldots,N(x_{t-(d-1)k}))$ where $N(x)$ is the surrounding vicinity locations of location x, and t varies between d time-steps. A tensor regression method can then be built. In a matrix formulation for such a regression model, we have $Y=xW+e$, where Y is the predicated traffic data, W is the parameter vector to be estimated during the learning stage, e consists of residuals. In the learning stage, all the historical data are available and can be built in d time-steps back. W is estimated to fit the model by the Ordinary Least Squares method, $W=(x^Tx)^{-1}x^TY$. A predicated value is given by $Y'=xW$, and the residual is $e=Y-Y'$. Every time a vehicle with OBE passes by a RSE, it receives updated traffic information from and sends its origin, destination, and vehicle trajectory data to the RSE. From the trajectory data, a lot of useful information can be obtained, including speed, acceleration/deceleration rate, and travel times of upstream segments in the past few minutes. Such information can be correlated with the traffic data obtained from upstream/downstream RSEs and traditional loop detectors. A mathematical relationship can then be established using the tensor regression method. The RSE mines the trajectory and loop detector data and continuously provides estimates and predictions of the traffic states of areas not covered by RSEs.

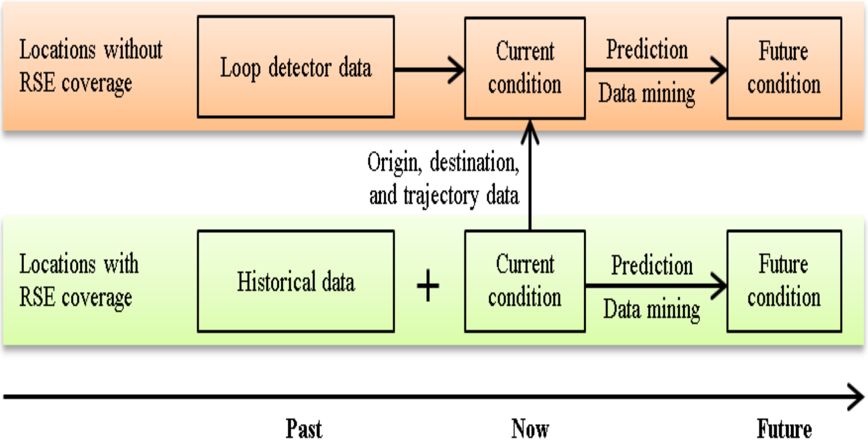

Fig. 2. Traffic Estimation and Prediction for Areas not Covered by RSEs

4 Coordination by traffic flow optimization

Building on the above studies, scenario-based analysis can be conducted to search for an optimized future state if drivers are willing to perform system-wide coordination. More specifically, a few schemes can be identified to allocate traffic to less congested routes and revoke the simulation to update system state. Once an optimal scheme is found, re-routing information and associated benefits are disseminated to drivers for them to make educated choice. Many congestion problems can be effectively addressed by allowing self-organizing and system-wide coordination. System-wide coordination requires optimized traffic assignment among alternative routes and such a problem can be formulated as follows. In order achieve personal goal (e.g., shortest travel time), one needs to minimize objective function $miny(x) = \sum_n \int_0^{x_n} t_n\,(q)dq$, where n denotes a specific route, q denotes flow, $t_n(q)$ denotes travel time given n and q, and x_n assignment of flow on route n. Once optimized traffic assignment is found, incoming drivers are prompted with recommended route choices and associated benefits. To simplify the problem, the optimization is performed at RSEs and concerns only their local networks.

5 Conclusions

In this paper, compared with existing knowledge base, the proposed research is *unique* and *transformative* because we not only integrate knowledge of component fields into each other to advance the state of the art of individual field but also merge these fields into a *Science of Cyber-Physical Systems* in transportation. We studied traffic-responsive real-time and reliable vehicle communication scheme, field theory model built on connected vehicles, networked vehicle routing algorithms. The outcomes of this research are to revolutionize vehicle automation and highway safety. The proposed methods and tools for interdisciplinary problem solving are extensible and transformative. Less highway accidents and reduced congestion resulted from this research amount to billions of dollars savings, let alone improved quality of life and boosted national economy.

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