Co-operative, Integrated Vehicle-Intersection Control for Sustainability (CIVIC-S)

Position Paper by

Adel W. Sadek[1], Chunming Qiao[2], Sean Wu[3] and Kevin Hulme[4]
[1] *Depart of Civil, Structural & Environmental Engineering & Institute for Sustainable Transportation & Logistics*
[2] *Department of Computer Science and Engineering & Institute for Sustainable Transportation & Logistics*
[3] *Department of Industrial & Systems Engineering*
[4] *New York State Center for Engineering Design and Industrial Innovation (NYSCEDII)*
University at Buffalo, the State University of New York, Buffalo, NY 14260

1. Problem Statement and Motivation

If one were to review the state-of-the-art in highway traffic and intersection control, from a Cyber Physical System (CPS) standpoint, one would immediately notice two inherent assumptions that limit and constrain the level of control or optimization possible. The first assumption is that control is to be exerted on only the infrastructure side (i.e., by controlling the traffic signal cycle length, splits and offsets for example). The second assumption is that, once the traffic conflicts have been eliminated, the only objective the designer had to be concerned with was *traffic operations efficiency*; as a result, the objective used in the majority of signal control algorithms involved minimizing a measure of delay or a combination of delay and number of stops. The reasons for the aforementioned two assumptions are quite obvious. Before the advent of Connected Vehicle (CV) technologies and Cyber Transportation Systems (CTS) ideas, it was not possible to control individual vehicles (e.g., control the vehicles' speeds). Moreover, in the absence of information about individual vehicle trajectories, and the ability to control such trajectories, the best one could hope for was to minimize the average vehicle delay, with little attention, if any, paid to environmental and sustainability-related metrics.

Fortunately, we are beginning to witness the relaxation of the two constraining assumptions mentioned above, thanks to recent work aimed at realizing the CV and CTS environment, which will create a widely connected network that can be accessed by vehicles, transportation system infrastructure components, handheld smart devices, among others. This in turn will facilitate wireless vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) communications and will allow for control actions to be exerted on both the infrastructure and the vehicle sides. It will also allow for new ideas and paradigms for signal control. Regarding the second assumption, current global concerns about energy availability and Global Climate Change (GCC) have underscored the importance of managing traffic so as to reduce fuel consumption and minimize harmful emissions. As a result, there has been some research recently which focused on utilizing ITS applications to reduce emissions and fuel consumption.

2. Proposed Solution and Research Challenges

To address the aforementioned limitations, this paper is proposing the notion of *co-operative, integrated vehicle-intersection control for sustainability (CIVIC-S).* Specifically, we focus on intersection control ideas that involve dynamically and jointly controlling the speed of approaching vehicles and the signal timing parameters, by taking advantage of the connected vehicle-infrastructure environment, while explicitly considering *multiple control objectives including sustainability, efficiency and safety.* While there has been some work already done in that area, what has been truly lacking is due consideration to three key issues or research challenges which needs to be addressed in future research. These include researching:

(1) How the development and deployment of Co-operative Vehicle Intersection Control (CVIC) systems is going to evolve over time, and how their operations may be optimized over the different phases of their incremental deployment. This is important because the deployment of such systems would naturally have to be incremental in nature (and perhaps slow in the beginning), with market penetration rates and sophistication levels increasing over time;

(2) Human factors issues related to: (1) the impact of advisory messages on driver performance for drivers in both instrumented vehicles (IVs) and non-instrumented vehicles (NIVs) in the context

of controlling the approach speed to an intersection; and (2) driver response and acceptance of various levels of automation and human-machine interaction (HMI). With respect to driver's acceptance of various levels of automation, one example would be to allow the vehicle speed to be automatically controlled, while drivers maintain steering and override capabilities.

(3) How a truly global optimization framework that considers multiple objectives and the whole range of control or decision variables (i.e. control on both the vehicle as well as the infrastructure or traffic signal sides) may be developed.

While we cannot claim that we have the full answer to the three questions poised above, we will attempt in this paper to offer some initial insight. First, we note that the notion of a global optimal solution is a challenging task since optimizing any one of our objectives independently can potentially impact the others negatively e.g., advising some vehicles to travel at high speeds might reduce travel delay but it will also lead to increased emissions, poor fuel efficiency and increased accident risk. Moreover, even for a single objective (e.g., minimizing fuel consumption), one has to deal with several practical implementation issues due to the gradual deployment process, such as 1) low market penetration of instrumented vehicles (IVs), 2) low penetration of intelligent intersections; 3) imperfect communication (and sensing) networks (which leads to incomplete or inaccurate traffic information). In addition, one has to deal with human-factors issues related to the driver-in-the-loop, and especially in the case of mixed traffic streams which consist of both instrumented and non-instrumented vehicles. The multi-objective optimization problem is thus even more challenging since there are many factors and parameters that could affect each individual objective (sustainability, delay and safety). This makes it difficult to identify the complex and intertwined relationships between those factors, let alone to perform joint optimization of multiple objectives.

A key question therefore is whether one should optimize for each individual vehicle or optimize system-wide. Ideally, if one could minimize the fuel consumption of each and every vehicle, then the system-wide fuel efficiency is also maximized. However, due to the presence of non-instrumented vehicles (NIVs), whose fuel efficiency can't be optimized by any CIVIC scheme, one can only hope to optimize for the IVs. Worse, the interdependence among the NIVs and IVs can severely limit the effectiveness of a CIVIC scheme. For example, even though an IV was supposed to travel at a speed of *X* mph so as to be able to go through several traffic lights without having to stop , an NIV in front of the IV, unaware of the traffic light schedule, may travel at Y < X mph, forcing the IV to also travel slower.

On the other hand, even if all vehicles were IVs, approaches that try to come up with an aggregate system-wide optimization function would most likely be infeasible due to the difficulties to mathematically formulate and solve the optimization objective function. To address the above dilemma, we advocate for novel approaches based on the notion of ***platoon control***, where an IV will be treated as the leading vehicle of a loosely-formed platoon consisting of NIVs (which will likely follow the leading IV without any external intervention) as well as other IVs (see Figure 1). Such a *platoon-based* approach not only addresses the low penetration issue, but also reduces the complexity of the optimization problem since the number of such platoons will be no greater than the number of IVs.

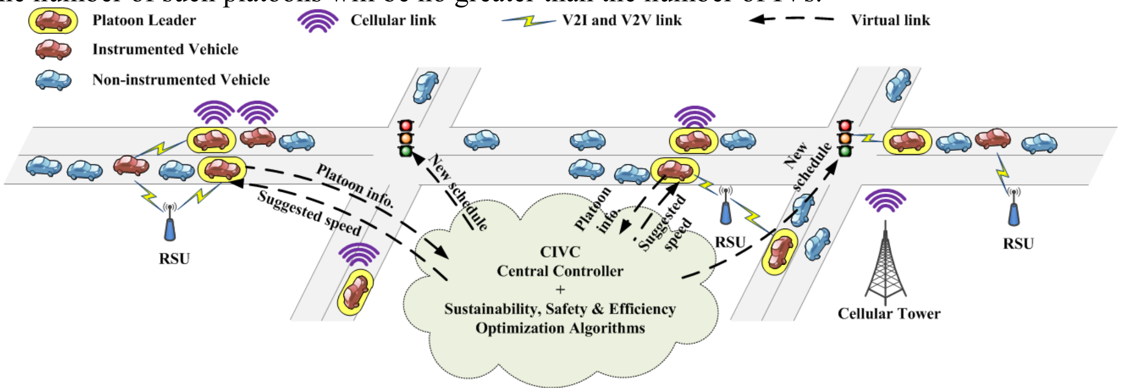

Figure 1. Platoon-based, Multi-objective Cooperative Vehicle-Intersection Control

Note that, due to the human-factors issues mentioned above, the issue related to how to provide incentives to each platoon-leader leading IV (and its driver) could also pose new challenges. For example, even when the leading IV can go through several traffic lights at a constant speed (which will result in the highest fuel efficiency for the IV), a platoon-wide optimized CVIC solution may require the leading IV to accelerate so as to enable the following vehicles (possible NIVs) to also go through as many traffic light as possible to reduce their fuel consumption.

3. Use of an Integrated Traffic-Driving-Networking Simulator (ITDNS) to Research the aforementioned Challenges

In a recent NSF-funded CPS Medium project, we designed and developed the ITDNS which consists of a driving simulator or DS (e.g., UB's surround-screen, 6 D.O.F. motion simulator), a network simulator or NS (e.g., NS-2), and a microscopic traffic simulator or TS (e.g., PARAMICS). The ITDNS uses a federated mode as shown in Fig. 2 below to enable realistic simulation by overcoming the limitations of each individual simulator; these limitations include the lack of realistic background traffic in a typical DS and NS, lack of capability to simulate the possible delay and loss of the CTS messages in DS and TS, etc.

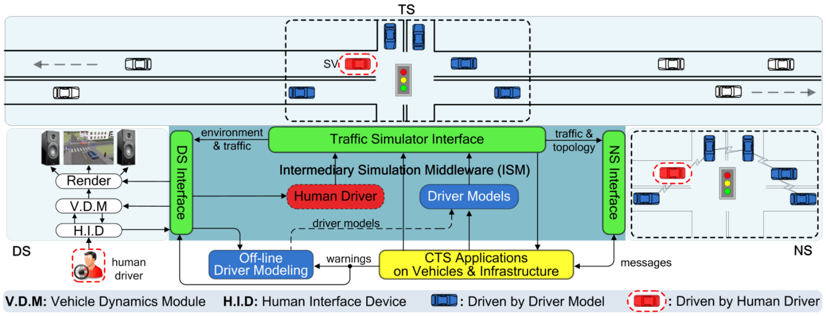

Fig. 2. Framework of the 3-in-1 Integrated Simulator for Cyber-Transportation System.

Given the complexity of the open research questions related to CIVIC-S previously mentioned, and the critical need for properly accounting for the issues related to human response and behavior, we plan to take advantage of ITDNS to: (1) evaluate system performance under the different design options and deployment scenarios of CIVIC-S systems; (2) understand and model human response and acceptance; and (3) to evaluate and refine our platoon-based control and optimization algorithms. We will design a road network with traffic signals in the ITDNS; wireless Access Points (APs) will be set up along the road at specific locations. The human test driver in the DS component will be first given the control of one of the instrumented platoon leaders in our scenario and will exchange information about their platoon and receive speed suggestions from the central coordinator using a realistic wireless vehicular networking protocol. For modeling the environmental impact of the various designs and control algorithms (i.e. modeling fuel consumption and emissions rates for the different pollutants), the vehicle trajectories from the TS will be used to run the MOVES2010 model [1]. This will build on previous work by the PI and his graduate students which integrated MOVES with the micro-simulation models [2,3].

References

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