Priority Management of Emergency Vehicles at Intersections Using Self-organized Traffic Control

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***Abstract*—Biologically inspired approaches have the potential to solve many of the difficult networking problems awaiting practical solutions. The recently proposed Virtual Traffic Lights (VTL) is one example (or instance) of this powerful approach for solving some fundamental transportation problems[1], [2]. The successful operation of VTL scheme ultimately depends on the *local rules* used by vehicles approaching an intersection for electing a leader that manages the traffic at that intersection by serving as a virtual traffic light. In this paper, it is shown that by using a different set of local rules at intersections, one can support priority management of emergency vehicles in a self-organized manner. The proposed VTL-Priority Intersection Control (VTL-PIC) protocol can detect the presence of an emergency vehicle and assign priority to the emergency vehicle at an intersection. Large-scale simulation results show that while the travel time of emergency vehicles can be reduced significantly, the impact of the proposed algorithm on the travel time of other vehicles is negligible.**

I. Introduction

Enabled by new and emerging wireless technologies, namely Dedicated Short Range Communications (DSRC) and Vehicular Ad Hoc Networks (VANETs) technologies, a number of automotive-based communication applications have been proposed to improve the level of road safety (i.e., *safety* applications such as Emergency Electronic Brake Light, Post Crash Notification). Main objective of these applications is to direct normal traffic *around* an accident area; *but not* to assist an emergency response team rushing to the scene of accident.

Using the self-organized traffic control paradigm first reported in [1], we propose the use of DSRC and VANET technologies to enable an *active and post-incident* safety application that aims at facilitating and prioritizing the motion of emergency vehicles (EVs) through traffic in urban areas. It has been shown by several previous studies that in the case of fire incidents, a reduction in response time by minutes or even seconds (i.e., the time it takes for the firefighters to reach the scene of accident after a fire incident is detected and reported) is very critical. Similarly, in the case of health-related incidents, chance of survival drops by roughly 10% for every additional minute a patient stays in cardiac arrest.

Our proposed system is designed based on a concept similar to what is being used today; i.e., assigning the highest priority to the EVs. However, instead of allowing the EVs to pass through intersections without obeying the traffic lights, our system aims to provide "green-wave" signal displays for the EVs. By having always-green signals displayed to the EVs, the proposed system allows the EVs to move at a faster speed and also prevents EV-involved accidents (e.g., each year in the US, 80 EV crashes occur that involve fatalities [3]). In addition, since the proposed scheme enables traffic control (if necessary) at every intersection, the EV-involved accidents at non-signalized intersections could also be prevented.

The remainder of this paper is organized as follows. The proposed solution is described in detail in Section III. Simulation setting and the preliminary performance evaluation of the proposed protocol are presented in Section IV. Related work is discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Background

Priority management scheme proposed in this paper is based on the self-organized traffic control paradigm first proposed in [1]. It was shown later that this self-organized traffic control paradigm is an instance or example of biologically-inspired solutions to several fundamental transportation problems [2]. In the proposed self-organized traffic control paradigm, using vehicle-to-vehicle (V2V) communications, vehicles communicate among themselves (i.e., in *ad hoc* manner without the help from infrastructure) to resolve conflicts at intersections and determine who should cross the intersections first (i.e., they establish the "right of way"). Without any centralized infrastructure, the proposed scheme operates in a distributed manner under the assumption that each vehicle periodically broadcasts *hello* messages to announce its presence, current position, and velocity to other nearby vehicles. A vehicle can therefore construct the local map and determine if there is an ensuing conflict at the intersection it is about to approach. In situations where a conflict is detected, vehicles involved in the conflict perform the following three steps:

A. Leader Election process

As vehicles approach the same intersection (when, a conflict is detected), they must agree on electing one of them to act as the *leader* for the intersection. The elected leader will serve as *temporary traffic light infrastructure* and is responsible for creating and broadcasting traffic light information. Other vehicles act as passive nodes, listen to and obey the traffic light information broadcasted from the leader. To avoid unnecessary leader election process, the leader is presented with red light and stops at the intersection while leading it.

B. Generation of Traffic Light information

Once a leader is elected, it determines how long each approaching direction should receive the right of way (i.e., phase layout of the traffic light). This phase layout could be

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pre-programmed or dynamically configured based on several parameters such as the volume of traffic in each direction, level of congestion at the intersection, priority of roads, etc. To enable a fair use of the intersection, the number of cars waiting in each road should also be taken into account. Phase preemption could also be enabled - once the VTL leader detects that the road with the green light has no additional vehicles attempting to cross the intersection, the current phase is interrupted and the green light is given to the next connecting road [1].

C. Leader Handover

When the green light is in the leader's lane, a new leader must be elected to maintain the virtual traffic light infrastructure. The new leader can be elected by two possible mechanisms: - i) the current leader hands over the leading task to one of the vehicles stopped before a red light at the intersection or ii) the new leader election is performed if there are no stopped vehicles under red lights.

It has been shown by extensive simulations that the aforementioned traffic control scheme (i.e., Virtual Traffic Light (VTL) system) could provide up to 60% improvement in traffic flow [1], [4]. Such a significant improvement is due to two reasons: i) VTL can render traffic control truly ubiquitous as compared to only 20% of intersections that are currently equipped with traffic lights; and ii) VTL reduces the dead period of intersections (i.e., unnecessary red lights when green light is given to the road with no additional traffic). Interestingly, despite a substantial improvement in traffic flow, it is also reported in [1] that the VTL system slightly increases the time a driver is exposed to red light.

It should be noted that the above *virtual traffic light* system operates based on the following assumptions [1]:

- All vehicles are equipped with the DSRC radios.
- All vehicles share the same digital map and positioning system device that has lane-level accuracy.
- The RF propagation problems such as obstructions due to buildings at the corners of intersections do not disrupt the necessary vehicle-to-vehicle communication for electing a leader that will serve as a virtual traffic light [5].
- Other communications problems due to collision of transmitted packets or beacon messages by vehicles is not severe.

A detailed discussion on potential technical and non-technical issues and challenges for implementing the VTL system can be found in [4].

In this paper, we propose a self-organized traffic control paradigm that aims to facilitate and expedite the motion of EVs through traffic in urban areas in the case of an accident or emergency situation. The proposed traffic control scheme could easily be extended to address the priority management of other transportation systems (e.g., transit buses, light rails, etc). Such extensions, however, are beyond the scope of this paper. Similar to the VTL scheme, the proposed priority intersection control scheme has a negligible impact on the flow of normal traffic.

III. Proposed Algorithm For Enabling Priority Intersection Control

The proposed scheme is an important new application that builds upon of the VTL system described in [1], [2] by incorporating new local rules (i.e., mechanisms): by detecting the presence of an EV, the proposed scheme, namely Virtual Traffic Lights with Priority Intersection Control (VTL-PIC), assigns priority (i.e., gives the right of way) to the road (or approach) on which the EV travels. To enable the priority scheme, two additional mechanisms (i.e., local rules) are designed and added to the original VTL scheme. In the following, we briefly describe these two additional mechanisms.

A. Detection of an EV when it approaches and leaves an intersection

Upon approaching an intersection, the EV periodically broadcasts a PIC request message to announce its presence and to demand priority until it receives a PIC grant message from a vehicle that is leading the intersection (i.e., the intersection leader). Note that in addition to the PIC request message, the intersection leader can detect the presence of the EV when it receives a hello message generated by the EV.

Besides PIC request messages, when the EV crosses the conflict point (intersection), it periodically broadcasts a PIC clear message for a certain period of time so that the intersection can now resume its normal operation for normal traffic management. In the case when PIC clear messages are lost, the intersection leader can also detect the departure of the EV when it does not receive hello messages from the EV (or does not receive PIC clear message after PIC request) for a certain period of time.

B. Priority assignment scheme

Once the presence of an EV is detected, phase layout configuration of the traffic signals of the intersection needs to be re-computed and broadcasted to vehicles involved in the conflict at the intersection. While there are a number of algorithms that could be used for priority assignment, a simple scheme (i.e., the road on which the EV is traveling always gets the green signal) is used in our protocol to illustrate how priority intersection control could be used in conjunction with the VTL system.

Since the VTL scheme is used as the underlying mechanism of the proposed VTL-PIC protocol, the VTL-PIC will also share the same benefits as the VTL scheme. To put things into perspective, benefits of the VTL-PIC protocol on the travel time of EVs can be described as follows:

- **Given the same amount of traffic, an EV in VTL-PIC scheme encounters less severe traffic congestion as compared to the congestion found in typical scenarios with physical traffic lights.**

It has been shown in [4] that because of a more efficient use of intersections as a *resource* and the fact that the VTL renders traffic control ubiquitous (i.e., traffic control at every intersection), during rush hours traffic congestion takes place at a much later stage (i.e., more vehicles need to be in the network before traffic congestion kicks in) as compared to the typical scenarios with physical traffic lights and identical traffic generation rate. As a result, vehicles and especially the EV reach their destination locations within a much shorter time duration when VTL scheme is employed. Furthermore, when traffic congestion is inevitable (i.e., generated traffic exceeds the capacity of the road network), the VTL scheme could resolve the congestion situation more quickly; hence, travel time of the EV is substantially reduced.

- **"Green-wave" allows EVs to travel at higher speeds such that they do not need to slow down when approaching intersections.**

Since VTL-PIC always assigns green signals to the road on which the EVs are traveling, the EVs will encounter green-wave phenomena as they pass through intersections (i.e., series of traffic lights are coordinated and present progressive green displays to the EVs). This results in a higher traveling speed of the EVs as compared to the conventional operation where the EVs have to slow down significantly as they see red signals when approaching intersections (i.e., as reported in [3], at least 26% in average EV travel time could have been saved). In addition, by assigning higher priority to the roads EVs travel on, VTL-PIC protocol could clear up the EV's route by also giving higher priority to vehicles that travel in front of the EVs to cross the intersections.

- **The proposed scheme can prevent potential EV-crash accidents that take place at intersections.**

By presenting green signal to the EV's direction, other vehicles that approach from different directions are presented with red signals, and hence, are prepared to stop and give the right of way to the EV. Note that because of ubiquitous traffic control enabled by the VTL-PIC scheme, it is expected that the proposed protocol could prevent a significant number of EV-crashes (i.e., more than 25% of EV-crashes [6]), thus making *both signalized* and *non-signalized* intersections safer for both emergency and normal vehicles.

IV. Simulation Setting and Results

SUMO traffic mobility [7] is used as the simulation platform to evaluate the proposed VTL-PIC protocol. A 10×10 Manhattan grid network topology is assumed in the simulations with 125-meter block length.

Traffic generation pattern used in the simulations is depicted in Figure 1 where the traffic generation rate (e.g., R_1 and R_2 [veh/hr]) varies based on one of the varying parameters, number of total vehicles injected into the simulations, N. This is used to capture the traffic behavior during the rush-hour period: there is a first wave of commuters that try to enter/leave the city sooner to avoid traffic jams and is then followed by the period during which most commuters enter/leave; and finally another wave with the remaining vehicles [4]. Hence, as an example, the relationship between these three parameters can be formulated follows:

$$R_1 = \frac{N}{3}, \qquad R_2 = 2R_1 = \frac{2N}{3}$$

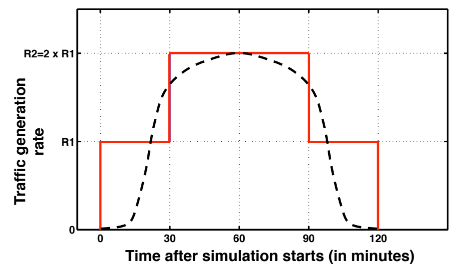

Fig. 1. Traffic generation pattern used in the simulations. While the dotted line shows the realistic traffic generation rate, the staircase in blue color shows the approximation used in the simulations.

One EV is artificially added into the simulation at $t = 5400$ seconds (i.e., after 90 minutes after the simulation starts). The EV starts from the center of the source area toward its destination in the top-right of the network while other vehicles have random start and end locations. All vehicles including the EV are assumed to be equipped with GPS positioning systems and DSRC radio devices with a transmission range of 200 meters. To isolate the effect of network omissions, we assume that there is no packet loss in the network; i.e., all packets sent are correctly received at the receiver(s).

Three different traffic control schemes are implemented and evaluated: i) baseline scheme where only physical traffic lights are used at intersections and an EV does not receive any priority at intersections[1], ii) VTL scheme where the virtual traffic light is used as the traffic control mechanism at intersections; however, it does not give priority to the EV, and iii) VTL-PIC scheme where both VTL and priority scheme are implemented.

Figures 2 and 3 depict the average travel time of the EV and non-EVs, respectively. While the travel time of non-EVs are similar for both VTL and VTL-PIC schemes, up to 45 seconds of travel time for the EV can be saved with the proposed VTL-PIC scheme and up to 120 seconds is saved over the baseline scheme with physical traffic lights. It is worth mentioning here that in most cities about $15 - 25\%$ of intersections are equipped with infrastructure-based traffic lights [1], [2]. Hence, in reality, the expected benefit in prioritizing emergency vehicles could be much more than 120s with respect to the baseline scheme.

V. Related Work

Several approaches have been proposed for priority management at intersections for emergency, municipal, and mass transit buses. These approaches are usually known as Emergency Vehicle Preemption (EVP) systems. While theses systems have been shown through empirical studies to reduce response time for emergency vehicles, all of the proposed schemes rely on some kind of infrastructure and require additional costly equipment and/or centralized traffic control centers; hence, coverage and benefits of such systems are fundamentally limited by the investment available.

[1] An EV is treated as a normal vehicle. This assumption is valid in a heavily congested urban scenario; vehicles could not move to the side to give way to the EV.

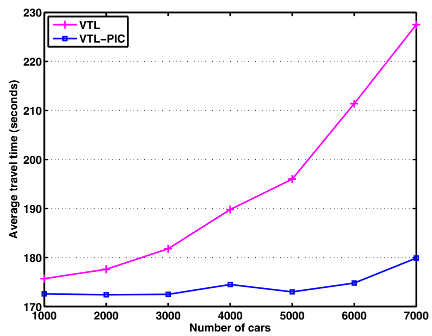

Fig. 2. Average travel time of the EV which is added to the network at $t = 90$ minutes for lunchtime scenario.

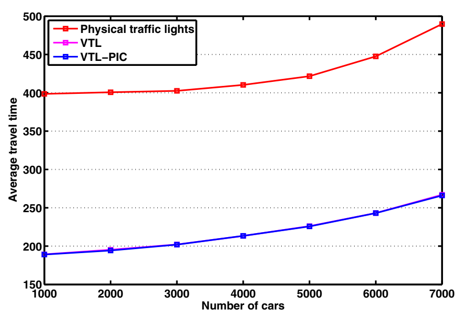

Fig. 3. Average travel time of non-EV vehicles. Observe that there is negligible difference between the non-EV travel time when VTL and VTL-PIC schemes are used for lunchtime scenario.

A centralized control system is the most basic system where EVP mechanism could be implemented in the most straightforward manner - arrival of the emergency vehicles to an intersection is recognized by the traffic signal controller through light, sound, or radio waves depending on the technology used at a particular intersection. Once detected, the centralized urban traffic control software decides if signal preemption is warranted and if necessary, interrupts the normal green-yellow-and-red cycle to change the light to green for the emergency vehicle. Examples of such systems include Global Traffic Technologies (GTT)'s Opticom^{TM} Central Management Software [8] and GERTRUDE [9].

Another alternative for implementing an EVP is to allow local intersections to make a preemption decision. This system therefore could operate without a backbone network connecting all intersections to a centralized control center; hence, it is a more scalable solution than the centralized system. Nevertheless, there are obvious disadvantages to this approach which are twofold: i) higher installation, operation and maintenance cost per intersection; and ii) lower efficiency in EVP due to lack of coordination between consecutive intersections. Examples of such systems include EMTRAC systems [10], E-ViEWs Safety Systems [11].

VI. Conclusion

We have proposed a self-organized traffic control scheme that helps facilitate emergency response operations (i.e., facilitate and expedite the movement of emergency vehicles through traffic in urban areas). In the proposed VTL-PIC scheme, vehicles can resolve the ensuing conflicts at intersections by themselves and implement a priority scheme that can prioritize emergency vehicles at intersections. The premise of this priority management scheme is vehicle-to-vehicle communications using DSRC technology. Local rules at intersections corresponding to the detection of the presence (and absence) of an emergency vehicle as well as the priority scheme that assigns priority to the emergency vehicles are the key mechanisms for the successful operation of the VTL-PIC scheme. Simulation results show that, with VTL-PIC, an emergency vehicle is able to arrive at the scene of accident up to 2 minutes earlier as compared to a conventional system which is equipped with physical traffic lights at every intersection. Such an improvement is very significant as it can save many lives. Results also show that the proposed VTL-PIC protocol has a negligible negative impact on the travel time of non-emergency vehicles.

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