ABSTRACT
The recent interest in IntelliDrive(SM) and vehicle connectivity has gone past previous notions of automatic collision notification, internet browsing and off board navigation. Now, in addition to applying the 5.9 GHz ITS band for cooperative collision avoidance, other applications using connectivity between the vehicle and signalized intersections have emerged. Contemporary applications enhancing fuel economy and reducing green house gases (GHG) are the subject of current research and development. Cooperation between vehicle electronics and intelligent traffic management systems could change the landscape for addressing future ECO (economical and ecological) requirements. This manuscript will outline development within one automotive supplier targeted at using connectivity as an enabling technology for sustaining the vision of smart and green transportation systems.

CURRENT SITUATION/PROBLEM DESCRIPTION
Based on a 2008 Texas Transportation Institute report for the United States, greater than $87B and more than 4B hours are wasted per year due to inefficient transportation networks. Given that for the foreseeable future Americans will continue to use autos, buses and trucks for transporting goods and people, constructive solutions for improving the mobility efficiency of the nation's roadways, highways, arterials, and surface streets will be necessary. There is simply not enough land or money to continue to add lanes; the transportation system must become much more efficient.

Several techniques are currently in place to assist in mobility efficiency: ramp metering, travel time websites and actuated intersections. The USDOT has initiated a substantial ITS research program entitled IntelliDrive™ based on the belief that connectivity between vehicles and between vehicles and infrastructure can improve the present situation even further. The connectivity solution can provide localized and network wide information allowing transportation engineers to optimize traffic flow and efficiency to improve mobility, optimize fuel use and minimize harmful vehicle emissions.

But let's bring this to a more personal level. Have you ever experienced the case when arriving at a stop light, you see no other vehicle in the vicinity, but you wait for the “normal” signal cycle? It seems like a waste of time, fuel and an unnecessary burden on the environment. Have you ever been on a major surface street with a green light ahead, only to see the light cycle change to red upon your approach, with no one present on the cross streets? Or the vehicle that is at the cross street is only waiting for right turn on red, but activates the actuated intersection, requiring you and other cars travelling in your direction to stop? What a waste! And furthermore, how about the occasions when you drive down a major urban arterial and catch stop light after stop light at each intersection. Isn't there a better way?

ROOT CAUSES
The problems described above appear to be due to mistiming between the signal phase and the arriving traffic. At un-actuated intersections, this may be due to instantaneous traffic flow patterns that are different from those used to set the signal cycles. In adaptive systems, the controller is made aware of approaching vehicles through loop detection, radar detection or CCTV image processing. Such systems may be effective at detecting vehicle presence, but aren't able to make estimates of vehicle type, vehicle dynamics (e.g., acceleration, brake pressure, yaw rate or path prediction) and
turn signal indicators. Moreover, timing coordination between signals on arterials or system wide for urban grids may be computationally difficult to optimize and adapt for large cities.

**COUNTERMEASURES**

In this paper, we describe two methods (Red Light Pre-emption and Green Light Extension) under development to improve flow within individual signal controlled intersections and along urban arterials. We believe that the best way to optimize traffic efficiency is to provide the control mechanisms with the most accurate and timely information possible. It's not essential to have a central traffic control system in place. In some large networks, that would not be optimum, in fact.

In the solutions we propose, we use IntelliDrive connectivity to communicate full BSM (Basic Safety Message) information to the signal controller, updated not just once, but at a 5 or 10 Hz rate. As a result, we know not only how many cars are approaching in which lane, but also whether they are accelerating, braking, and/or planning to turn (using vehicle dynamics and state). We can also gain indications about the vehicle classification. For example, two fully loaded semi-tractor trailer trucks in a left hand queue lane require longer intersection clearance times than a Chevy Camaro and Ford Mustang. This way, the traffic controller can obtain much more timely data about the area traffic status, and effectively adapt signal timing according to instantaneous traffic flow, including red light pre-emption and green light extension.

**Red Light Pre-emption and Green Light Extension**

IntelliDrive system technology has been introduced by the US Department of Transportation as a transformative connectivity system of solutions set out to improve the safety, mobility and environmental stewardship for tomorrow's livable and sustainable communities. One way to improve urban system efficiency is to minimize sustained vehicle stops at red light signals where one might more efficiently proceed if no safety issues were created.

The application described utilizes much of the system functionality that would already be in place for V2X safety applications including accurate vehicular positioning, two way wireless message exchange and coordination between roadside traffic control and the vehicle. This is meant to accomplish safety optimization while at the same time increased throughput to minimize wasted time, fuel and GHG emissions while vehicles are stopped at red light approaches. Such a solution will require coordination of the behavior of vehicles and signal controllers based on information exchange including present and predicted future intersection state maps for optimum safety and efficiency.

Today's actuated intersections can already provide many elements of the fundamental functions of the pre-emption application concept. At traffic actuated intersections, the signal timing changes from cycle to cycle depending on the detected approach of vehicular or pedestrian traffic. Cycle times and green extension times are most often predetermined by models for intersection throughput (e.g., Minimum Delay Model and Hybrid Model). What we propose to do with IntelliDrive connectivity is to adapt the appropriate cycle times and extensions to achieve the “state optimum”. This concept provides the opportunity to modify traffic control parameters based not on average but instantaneous flow data obtained from oncoming vehicle (later pedestrian, bicycle, motorcycle, and so on) broadcast messages. IntelliDrive data could be used either alone or in combination with other more traditional sensors in actuated intersection equipment and accommodate short term fluctuations in traffic flow.

There are standard methods for dealing with dynamic traffic flow. Minimizing delays by using statistical models for closed form or iterative optimizations to achieve the desired operational characteristics of individual intersections and networked control have been used. We will utilize IntelliDrive 5.9 GHz based WAVE/DSRC communications systems to transfer data about the vehicles to the intersection controller through the Road Side Equipment (RSE). In the system described, only a single simple intersection model with a fully actuated controller is contemplated. We use only one approach from each of four directions at a perpendicular intersection with a red, yellow, green signal matched to each approach. For a visual example see Figure 1. Of course, much more elaborate intersections and controller programming is possible, but our idea is to begin to understand how such simple systems interact and affect driver behavior before moving on to more complex situations. A strong requirement of the architectural approach is enabling extensibility of the algorithm to support intersections with multiple approaches and movements.

We will use fully actuated operation characterized by all phase timing controlled by detector activations and/or IntelliDrive Basic Safety Messages (BSMs) from approaching vehicles. In our specific demonstration case, we have what amounts to a continuous detector as IntelliDrive equipped vehicles broadcast their instantaneous location coordinates and velocity vectors multiple times per second. Such information may or may not trigger a red light pre-emption and / or a green light extension, depending on the signal phase timing and approach positions and velocities of other oncoming vehicles.
The cooperative system description begins with a simple block diagram example illustrated in Figure 2. Functionality in the vehicle includes an indication that the pre-emption or green light extension was activated at the signal ahead. Roadside applications processing features include activation of the signal controller pre-emption and green light extension sequences for a specific approach, when it's safe to do so.

The decision to actuate an interruption to the normal phase cycle depends not only on the state of a specific Remote Vehicle (RV) approach, but also on the state of the other vehicles converging on the intersection and the current state of the signal phase. Calculation of the complete intersection dynamic state is most efficiently accomplished by the roadside controller entity. That way, the phase timing is
based on the decision obtained from the roadside applications processor, and the indication of the exception is broadcast to the oncoming vehicles.

An architecture for the On Board Equipment (OBE) software is provided in Figure 3. This implementation includes functionality that might be associated with V2V safety, but adds the components that interpret wireless message data sent from the RSE indicating that a Green Light Extension (GLE) or Red Light Pre-Emption (RLPE) has been broadcast from the closest intersection of interest to the approaching vehicle. The OBE GLE and RLPE applications, perhaps better termed “message parsers”, will interpret whether the host vehicle is on the approach that has executed the signal exception or not, and decide whether to display the ECO event indicator in the Driver Vehicle Interface (DVI).

The OBE continues to broadcast its BSM Part I (cf SAE J2735 November 2009) as it would normally do in V2V safety mode, with those applications (e.g. Emergency Electronic Brake Light, Forward Collision Warning, Intersection Movement Assistance, etc.) continuing to run. Those broadcast messages are received by the RSE and used to formulate an intersection state map. During normal operation, all V2V safety functionality continues in the OBE including DVI for inform and warn states for any relevant V2V collision avoidance application.

A possible architecture for the software in the roadside applications processor is provided in Figure 4 and shown below.

In our proposed design, the RSE uses an intersection remote vehicle (RV) classification algorithm to categorize up to 60 vehicles converging upon the intersection, based on the information contained in the Basic Safety Message “heartbeats”. It assigns a specific directional approach (e.g., North, South, East, West, or 1, 2, 3, 4) to each vehicle, and calculates the distance to the approach stop bar. It simultaneously assigns a weighted score for each approach direction based on the number of vehicles, their speed and their distance to the stop bar. For example:

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\text{Approach Score}[x] = \sum_{n=1}^{\text{vehicles}} \left( \frac{C_1}{DTS_n} + C_2 v_n \right);
\]
The approach direction with the highest score is eligible for either a GLE or RLPE depending upon the existing phase at the time of the calculation, and the relative scores of the crossing approach directions. For example, where $C_3$, $C_4$ are configurable parameters.

If no GLE or RLPE is awarded, the signal controller continues its normal (or default) signal phase timing until such time as the appropriate conditions exist for an intervention. The duration of the GLE and RLPE are determined by the signal controller, compliant with the local jurisdictional requirements and / or demonstration parameters. The RSE interfaces to the signal controller and requests GLE and / or RLPE events be processed for the
approach(es) that has (have) a significant enough Approach_Score dominance to warrant execution of the exception to default controller phase timing.

DESIRED STATE
The desired end objective is to have 100% knowledge of each user location, velocity, and heading so that network efficiency can be optimized by various algorithms. One prototype algorithm was proposed in the section above, however we believe once the capability for the RSE to obtain and utilize the dynamic BSM information from all approaching vehicles is implemented, alternative methods may be created to further optimize system traffic flow and network throughput efficiency for various roadway topologies. We merely propose implementation of this early prototype as a tool to illustrate capability and initiate further test, evaluation and optimization.

RESULTS ANALYSIS
The IntelliDrive\textsuperscript{SM} based RLPE and GLE applications for both OBE and RSE have been successfully implemented and tested in a controlled environment at DENSO's Vista, California facility.

Experiments conducted showed oncoming traffic broadcasting BSMs while approaching a long cycle red successfully and repeatedly initiates a red light pre-emption at approximately 100 m (@ 25 mph) with no cross path traffic. The OBE within the vehicle informs the driver that the red light directly ahead has been successfully pre-empted and that improved fuel efficiency and reduced GHG resulted. The pre-emption expires when the conditions for the exception request are removed. In this example, the event ends when the vehicle moves past the stop bar and through the intersection.

In a second set of experiments, repeatable successful green light extension activations were also demonstrated to prolong a “go” cycle and avoid unnecessary stops at lights with a lower number of approaching vehicles in the cross path. However, our experiments also showed that algorithm refinements are necessary because a slow moving or stopped vehicle keeps activating green light extensions until it traverses the stop bar location. An indication is again provided to the driver during the green extension that the ECO application saved fuel, time and lowered unnecessary Green House Gas emissions.

POSSIBLE FUTURE WORK
Likely extensions to this preliminary implementation and evaluation include increasing the complexity of the intersection model, for example including (controlled) left and/or right hand turn lanes, multiple lanes in each approach and alternative decision algorithms. The architecture and implementation approach are well suited for all these expansion possibilities.

SUMMARY
IntelliDrive\textsuperscript{SM} connectivity can enable signalized intersections to dynamically respond to traffic flows and variances in vehicle arrival to increase throughput based on continuous exchange of information between vehicles and signal controllers. In this manuscript, we described a simple model for implementation of such functionality in both RSE and OBE domains, and presented test results summarizing performance enhancements at a single controlled intersection test track. We also discussed possible additional future work once the simple concept was proven by verification in a live system.

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