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Advanced Intersection Management for Connected Vehicles Using a Multi-Agent Systems Approach

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***Abstract*—Transportation is responsible for approximately a third of greenhouse gases (GHG) and a major source of other pollutants including hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). Intelligent Transportation System (ITS) technology can be used to lower vehicle emissions and fuel consumption, in addition to reducing traffic congestion, smoothing traffic flow, and improving roadway safety. As wireless communication advances, connected-vehicles-based Advanced Traffic Management Systems (ATMS) have gained significant research interest due to their high potential. In this study, we examine the concept of ATMS for connected vehicles using a multi-agent systems approach, where both vehicle agents and an intersection management agent can take advantage of real-time traffic information exchange. This dynamic strategy allows an intersection management agent to receive state information from vehicle agents, reserve the associated intersection time-space occupancies, and then provide feedback to the vehicles. The vehicle agents then adjust their trajectories to meet their assigned time slot. Based on preliminary simulation experiments, the proposed strategy can significantly reduce fuel consumption and vehicle emissions compared to traditional signal control systems.**

I. Introduction

A variety of Intelligent Transportation System (ITS) techniques have been proposed and applied to not only improve roadway safety and relieve traffic congestion, but also reduce fuel consumption and emissions. Many of these techniques fall into the ITS area of Advanced Traffic Management System (ATMS) [1].

As wireless communication techniques rapidly advance, new connected-vehicles-based ATMS concepts are emerging in the research literature. With the capability to exchange real-time traffic information by using vehicle-to-vehicle (V2V) and/or vehicle-infrastructure (V2I/I2V) communications, more efficient management strategies can be developed. Example applications include: 1) intersection approaching warning systems; 2) lane change warnings [2]; 3) variable speed limits; 4) adaptive traffic signals [4 - 5]; 5) automated traffic intersection control [3]; and 6) cooperative adaptive cruise control.

There has been recent interest in applying Multi-Agent Systems (MAS) in different traffic scenarios because they have the potential to solve complex real-world problems [10]. In this research, we have taken a multi-agent approach to improve intersection efficiency using the capabilities of connected vehicles. With V2I and I2V communications, a vehicle agent (VA) can request a reservation for its space-time occupancy when passing through the intersection and preplan its trajectory before it enters the intersection in order to avoid collisions and minimize its waiting time. Simultaneously, an intersection management agent (IMA) can make reservations for each VA to optimize its driving strategies, ranging from adjusting speed changes to selecting a desired lane. Using connected vehicle technologies, this multi-agent system can potentially improve intersection traffic congestion and minimize energy and emissions along urban arterials by avoiding unnecessary acceleration/deceleration and idling at intersections as compared to those with standard traffic signals that are in use today.

In general, such an intersection management system using a multi-agent approach consists of at least three major components: 1) a vehicle behavior planning module; 2) a dynamic intersection time-space reservation module; and 3) individual vehicle trajectory planning that could possibly include vehicle platoon formation. Fig. 1 illustrates an intersection with these major components. This paper focuses

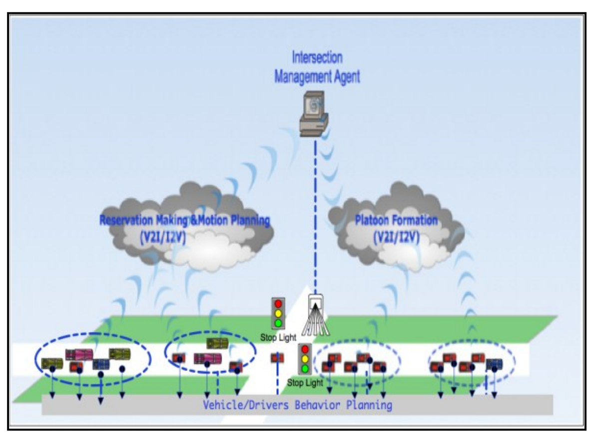


Figure 1. An intersection with the multi-agent based management system

on the development and evaluation of the dynamic time-space reservation connected vehicles techniques. The rest of this paper is organized as follows. Section II provides some background information about the proposed methodology, which is described in Section III. Simulation setup and results are presented in Section IV, and Section V concludes this paper with further discussion on future work.

II. BACKGROUND

A. Advanced Traffic Management Systems

Advanced Traffic Management Systems (ATMS) have been studied extensively in the last decade and a large variety of algorithms have been developed to improve safety, relieve traffic congestion and reduce fuel consumption and pollutant emissions on urban highways and local streets through the deployment of state-of-the-art sensing, communications, and data processing techniques. To address these problems, ATMS take advantage of available traffic information provided by infrastructure-based sensors (e.g., embedded loop detectors, radar, video cameras) and vehicle sensors that are coupled with on-board V2V and/or V2I communications. Real-time management solutions are then being developed and delivered using wireless communications to improve traffic system operation.

B. Connected Vehicles

Coupled with other technologies such as smart sensors and on-board computer processing, the connected vehicles technique can fulfill tasks such as identifying hazards on the roadway, providing warnings to drivers, and sharing information with others over communication networks.

To support numerous applications in safety, mobility, and sustainability, a vehicle communication network should have: 1) high-speed transactions among vehicles (vehicle-to-vehicle or V2V), and 2) communications between vehicles and the infrastructure (V2I and or I2V). V2V applications rely on sharing information between vehicles such as safety warnings and traffic information. V2I/I2V applications typically have roadside units (RSU) and vehicles as the communicating nodes. The major benefit of these vehicle communication networks is to improve safety, mobility and sustainability by tightly integrating infrastructure and vehicles as a *system*, rather than relying on isolated individual vehicles traveling on a roadway.

A number of applications have already been initiated by using probe data from connected vehicles to modify traffic control strategies and improve overall system performance. Such probe data may include vehicle activity (e.g., position and velocity) and other traffic or roadway information (e.g., slick roads). For example, with the knowledge of signal plan and a collection of priority request arrival times from probe data, the heuristic algorithm developed in [6] can reduce average bus delay by 50% without negative impacts on other vehicles. Rim and Kim [7] proposed a model to estimate lane-level travel times under a V2I environment. Individual vehicles' speeds and positions at every second were used as the inputs to the proposed model, and the survey showed that the mean absolute percentage error (MAPE) was reduced by less than 10% with a 20% penetration rate. Oertel and Wagner [8] developed a new approach to control traffic signals at isolated intersections in which individual vehicles' delays were estimated and used to adjust the green splits. This delay-based control strategy outperformed the other conventional schemes if the penetration rate is above 10%.

C. Traffic Simulation Tools

A variety of traffic simulation software has been developed to model traffic networks. For example, SimTraffic is a Synchro-companion program that allows visual simulation of a surface street traffic network. Other traffic simulation systems include CORSIM, Paramics, and VISSIM which are designed to simulate high fidelity traffic on surface streets and freeways. Many researchers have integrated wireless communication simulation components to these traffic simulation models to investigate a variety of ITS applications, with limited success.

Recently a new tightly integrated traffic simulation/wireless communication system has been developed, which is called SUMO (Simulation of Urban Mobility) [11]. It is a highly portable microscopic road traffic simulation package developed by the Institute of Transportation Systems at the German Aerospace Center. With SUMO, the advance traffic control can be implemented in Veins (Vehicles in Network Simulation), which is an Inter-Vehicular Communication (IVC) simulation framework composed of an event-based network simulator (e.g., OMNeT++, NS2) and a microscopic traffic simulation model (e.g., SUMO) through a Traffic Control Interface (called TraCI). Because SUMO was developed from the ground up to handle traffic and communications together, it has the potential to simulate much more complex scenarios. In this study, we use SUMO to evaluate the performance of the proposed intersection management system.

III. METHODOLOGY

In this section, an advanced traffic management system for connected vehicles using a multi-agent systems approach is proposed. The block diagram illustrated in Figure 2 outlines different approaches in context, with the yellow blocks showing the components used in this study.

In our design, the ATM system consists of two components: Vehicle Agents (VA) and an Intersection Management Agent (IMA). In order to maximize traffic throughput and to better utilize the capacity of the intersection, the IMA needs to manage the space-time occupancies based on vehicle dynamics. Figure 3 gives the time-space occupancies for example vehicles coming from one direction in one lane. The total time-space is divided into n x n grids. To avoid collisions, only one vehicle can occupy one grid. Once Vehicle A, B, and C decide their trajectories, some grid cells (e.g., the yellow, green and purple in Fig. 3) have already been reserved based on their future dynamics.

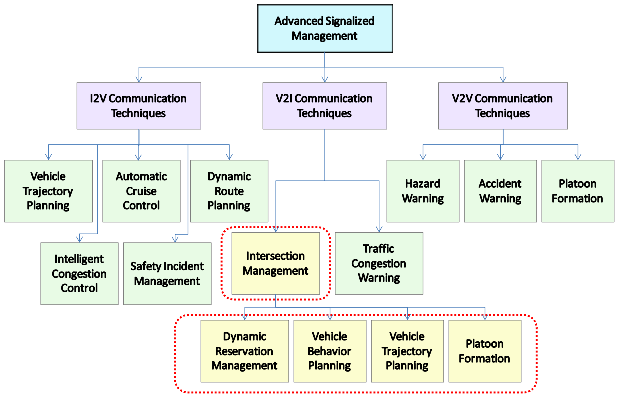


Figure 2. Advanced traffic management research structure

Also, the time slots (s1 (t1, t2), s2 (t3, t4), s3 (t5, t6)) represent the occupancies when vehicles travel through the intersection. For the multi-direction case, the time-space occupancies of the intersection will be shared by all the vehicles from all approaches. This would be represented by a rectangle solid located at the intersection of multiple planes. As we can see from this diagram, the capacity of the intersection is limited. The key to improving the traffic throughput is equivalent to maximizing the total time-space occupancies. In this study, we focus on maximizing the time-space occupancies in the intersection cross-area. To achieve this goal, the two types of agents need to have real-time communications and work collaboratively. On one hand, the IMA needs to arrange the vehicle's arrival times in order to maximize the reservation number; on the other hand, each VA has to preplan its own trajectory to avoid collisions and to arrive at the intersection with its predetermined arrival dynamics.

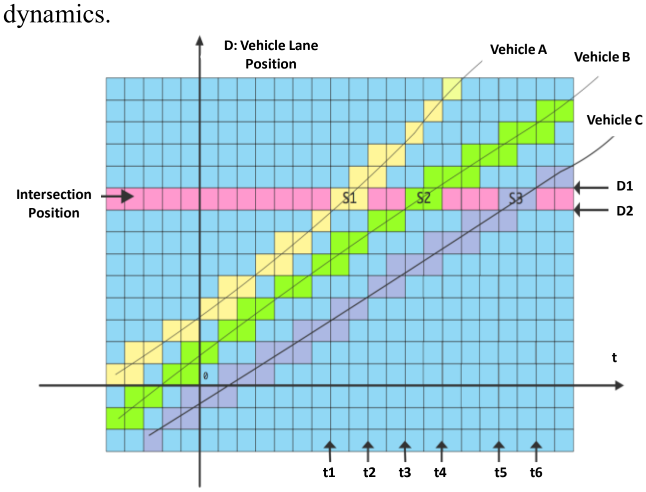


Figure 3. Road Time-Space Occupancies for Vehicles in one direction

As mentioned in the first section, due to different control objectives (safety, mobility, and environment), the management mechanisms for vehicle agents are developed separately according to their locations in the intersection. In this study, the proposed strategy is designed primarily to address problems when vehicles are approaching the intersection.

A. Assumptions

For simplicity, several assumptions were made in the management mechanism.

- Each VA should be a fully controllable agent.
- All the agents are equipped with (V2I/I2V) wireless communication devices.
- Each VA can get its preceding vehicle's dynamic information (speed, position).
- Each VA can get its own dynamic information (speed, acceleration, turning angle, position, road map, and etc.) from its on-boarding devices.
- No message drops in communications and unlimited communications capacity.
- A VA cannot enter the intersection without a reservation.

B. Dynamic Reservation System

In order to enter the intersection, each VA will keep sending reservation requests to IMA until it obtains one.

To determine whether a request from the VA can be met or not, the IMA needs to use some control policies.

According to a vehicle's arrival lane, turning intention and priority, three levels of policies are required to be followed when making reservations:

1) *Level 1. Priority-based Policy: Request with higher priority (here is 1) will be processed first. The request message received by IMA can be classified as: Request message and Cancel-and-Reapply (CnR) message. Request message is used for the VA who doesn't have a reservation in current status, and whose priority is set to 0. CnR is designed for the VA who needs to reapply a reservation immediately after its current reservation is canceled, and its priority is set to 1.*
2) *Level 2. With-Lane-based Policy: If messages have the same priority, vehicle arrival lane and position will be examined. If any of the VAs that are traveling ahead of the request VA along the same lane has not obtained a reservation, then the request will be rejected. IMA then sends a reservation-rejected message to the VA.*
3) *Level 3. First come, first serve (FCFS) Policy: If messages have the same priority but different arrival lane and turning intention, the IMA will serve the earlier message.*

After deciding which messages will be processed, the IMA will check its current Reservation Table, and find any available slots for these VAs to reserve a space-time occupancy cell.

C. Multi-Agent Behavior Design

In this Advanced Traffic Management system, in order to guarantee that agents can operate without any collision, vehicle agents and intersection management agents need to follow a set of separate behaviors. Figure 4 and Figure 5 show the flowchart of those two types of actions. The MAS mode and Default mode in the flowcharts are vehicle motion planning modes that are describe later in the paper.

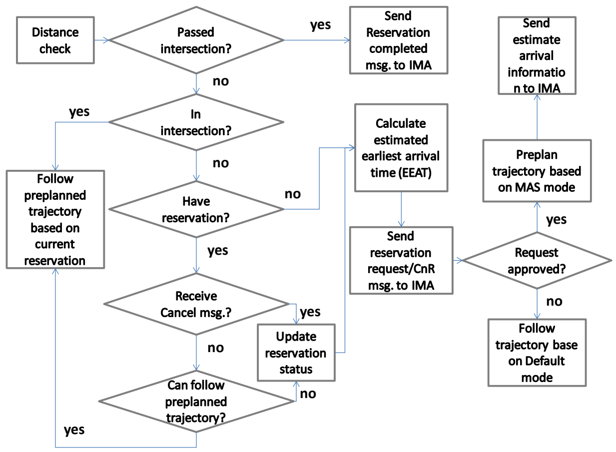


Figure 4. Vehicle agent actions

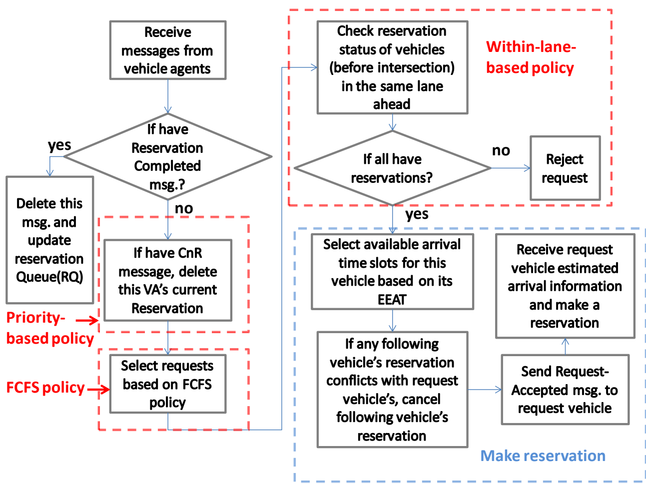


Figure 5. Intersection management agent actions

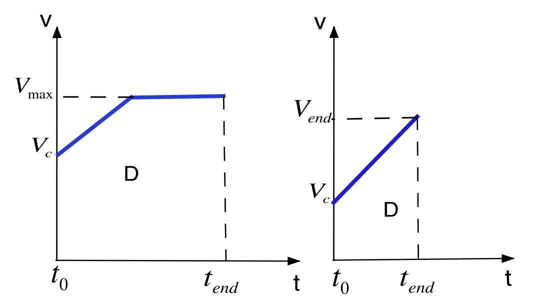
D. *Vehicle Motion Planning*

One of the keys to reduce traffic congestion and pollutant emission is to prevent vehicles from unnecessary stops before entering the intersection. The three-level reservation policy, by itself, reduces vehicles stop-and-go actions and therefore allows vehicles entering the intersection at a relatively high speed most of the time. Although this policy will be effective in this regard, there is still room for further improvement on the vehicle itself. Therefore, it is crucial to carry out appropriate vehicle motion planning before it enters the intersection. A cooperative approach between VAs and the IMA may provide appropriate motion estimations.

In this section, two motion-planning modes are designed according to different status of vehicles: 1) Default Mode (arriving at maximum speed and in shortest time) and 2) MAS (maximum arrival speed) Mode. Note that in the simulation the Krauss Car-Following Model (KCFM) [9] will govern all the vehicles whenever and wherever they are. In the following diagrams, it should be noted that for simplicity, piecewise linear function is designed to satisfy those constraints to construct the speed profiles.

(1) Default Mode:

Most of the time, a vehicle agent will not hold any reservation; even when they are in the communication network. However, to improve traffic flow and reduce total travel time, vehicles still need to be piloted in a certain mode. Under these considerations, the default motion mode is designed for vehicles to arrive at the intersection in the shortest amount of time. We can illustrate how the estimation procedure works using a time-velocity diagram as shown in Figure 6. In this figure, V_c is the current speed of VA, t_0 is current time, D is the distance between VA and IMA, V_{max} is the roadway speed limit, t_{end} and V_{end} are the arrival time and speed at intersection, a_{max} is the maximum acceleration, and a_{min} is the maximum deceleration. Two scenarios need to be considered according to the current position of the vehicles. In case 1, the distance between a vehicle and intersection is long enough for the vehicle to accelerate to the roadway speed limit. In case 2, a vehicle cannot accelerate to the road speed limit even using the maximum acceleration because the distance is too small. Thus, the vehicle still has to accelerate to a higher speed using a_{max} to shorten the arrival time.



(a)case 1: $V_{end} = V_{max}$ (b) case 2: $V_{end} < V_{max}$

Figure 6. Time-Velocity diagrams for estimation of arrival time and arrival speed using Default Mode

(2) Maximum Arrival Speed (MAS) Mode:

Once a vehicle agent receives the Available Time Slot information from IMA, it is guaranteed to have a place in the intersection reservation queue. In MAS mode, we need to construct the trajectory with a given ending time and maximize the arrival speed at the same time. Figure 7 shows the time-velocity diagram that is used by vehicle to plan its trajectory with a given arrival time.

After choosing a target time slot, a vehicle using the start time point of this slot as its arrival time at the intersection, t_{end}. Then VA makes an acceleration/or deceleration decision based on V_{avg}, which is defined as a constant velocity that vehicle applies to travel distance D in t_{end}, and V_{avg}=D/ t_{end}. After V_{end} is determined by the velocity profiles in Figure 8, the VA uses an intersection map to simulate its trajectory in the intersection in order to get its departure time t_{dep}. If the slot

(t_{end}, t_{dep}) can be fitted in the selected time slot, the VA sends it to the IMA and adjusts its motion based on this preplanned trajectory. Otherwise, it will redo the trajectory planning using the next earliest time slot.

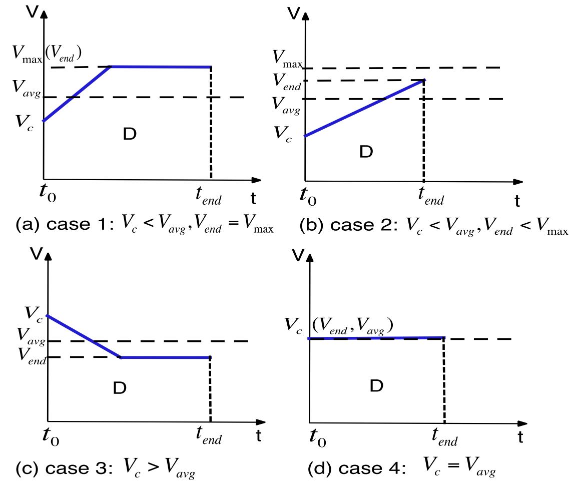


Figure 7. Time-Velocity diagrams for estimation of arrival time and arrival speed using MAS mode.

IV. SIMULATION SETUP AND RESULTS

A. Simulation Setup

A virtual advanced traffic management system for connected vehicles using the multi-agent approach was created in SUMO, and the performance of this system was evaluated under different traffic conditions. Additionally, we compared the results with those from conventional traffic signal control in terms of average travel time, fuel consumption and pollutant emissions.

For each experiment, the general simulation setup is:

- An isolated intersection with one lane in each direction
- Lane length: each lane is 500 meters (from vehicle initial point to the center of the intersection)
- Speed limit for all lanes is 17.8 m/s (40 miles per hour)
- Maximum acceleration: 2.5 m/s^2
- Minimum acceleration: -2.5 m/s^2
- Vehicle type: light duty vehicle
- Vehicle length: 2.5 meters
- Vehicle safety gap: 2.5 meters
- Only one vehicle is allowed in intersection cross area at a time
- Simulation time step: 0.1 seconds
- Total simulating steps: 10000 steps
- Communication range is 300 meters

We considered vehicles spawned from two directions (West-to-East and North-to-South) with various traffic volumes. For both directions, each individual vehicle's initial speed is set to be 0 m/s and traffic volume varies from 54 to 1227 vehicles spawned in 1000 seconds.

Two intersection control strategies have been tested for each experiment: 1) Advanced traffic management using multi-agent approaches and connected vehicles strategies; and 2) Fixed timing signal: total cycle is 70 seconds, with green phase 30 seconds, yellow phase 4 seconds, and all-red clearance 1 second.

B. Travel Time Analysis

The Advanced Traffic Management (ATM) Approach significantly outperformed conventional traffic signal control in terms of average travel time under different traffic demands. As we can see from Table I, the reduction percentage of vehicle (from both directions) average travel time ranges from 45.82% to 87% when traffic volume varies from 54 vehicles to 1227 vehicles spawned in 1000 seconds. As illustrated from the table, when traffic gets more congested, ATM approaches can more efficiently use the roadway occupancies compared to traditional signal control method.

TABLE I. VEHICLE AVERAGE TRAVEL TIME FOR TWO-DIRECTION TRAFFIC FLOW EXPERIMENTS

Vehicles Spawned Probability (Uniform Distribution U (0,1))	Vehicles Spawned Volume Within 1000 Seconds	Average Travel Time Using Traditional Signal Control (s)	Average Travel Time using ATM approach (s)	Reduction Percentage
0.1	56	114.59	62.09	45.82%
0.3	598	168.39	61.05	63.74%
0.5	814	430.93	61.10	85.82%
0.7	1227	480.59	61.07	87.29%

C. Emissions and Fuel Consumption Analysis

In order to evaluate emissions and fuel consumption, we used the emission model based on HBEFA (the Handbook of Emission Factors for Road Transport) which has been integrated into SUMO. The objective of the emission analysis is to observe the variations of the evaluation metrics under different traffic conditions.

The evaluation metrics include emissions of CO_2, CO, HC, NOx and fuel consumption. Cumulative emissions of the four pollutants and energy consumption for all vehicles were obtained from the emission evaluation of the simulation runs. As shown in the results, both emissions and fuel consumption are significantly reduced by using the proposed system. The percentage of reduction for ATM control system ranges from 41% to 71% for CO, 65% to 75% for CO_2, 55% to 78% for HC, 63% to 74% for NOx, and 65% to 75% for fuel consumption when traffic volume varies from 54 to 1227 vehicles spawned in 1000 seconds. Figure 8 shows fuel consumption reduction and CO_2 (major part of greenhouse gas emissions) reduction under different traffic demands.

It is shown that the proposed system is able to significantly reduce vehicle emissions, as well as fuel consumption. Such reduction may result from the better utilization on the intersection's time-space occupancy of the proposed system by avoiding unnecessary stop-and-go maneuvers.

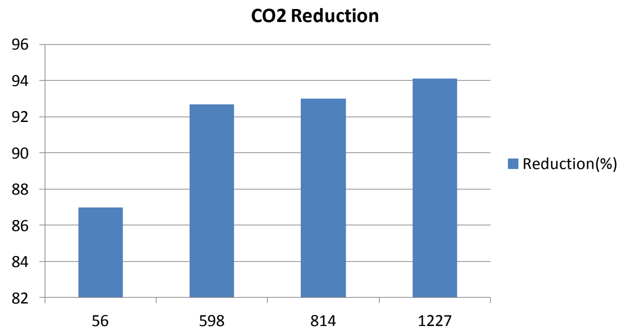


Figure 8. CO_2 reduction for a range of traffic volume in the two-direction traffic scenario

V. Conclusions and Future Work

An advanced traffic management system for connected vehicles using a multi-agent system approach is developed and evaluated in this study. The overall goal for this advanced traffic management system is to make the traffic flow smoothly, increase intersection throughput, and reduce energy consumption and pollutant emissions. Multi-layer reservation policies were proposed and interactions between vehicle agents and the intersection management agent were presented in detail. In addition, a vehicle motion planning algorithm was developed based on these policies. The simulation results showed that the proposed advanced traffic management system can considerably alleviate traffic congestion as well as reduce pollutant emissions and fuel consumption.

In future work, the proposed system will be tested in a more complicated traffic network (e.g., with turning movements and multi-lane roadways). A more realistic communication protocol between vehicle agents and intersection management agents based on DSRC and SAE J2735 protocols will also be developed and implemented. We also plan on doing a detailed analysis on the system capacity (i.e., the traffic demand level at which the system will break down).

References

[1] Barth, M. (2009) "Environmentally Beneficial Intelligent Transportation Systems", *12th IFAC Symposium on Control in Transportation Systems*, Redondo Beach, CA, September 2009.

[2] Park, H., B. L. Smith (2011) "Integrated Traffic/Communication Simulation Evaluation Environment for IntelliDrive Applications Using SAE J2735", *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, January 2011.

[3] Fajardo, D., P. Stone (2011) "Automated Intersection Control: Performance of a Future Innovation Versus Current Traffic Signal Control", Austin, *Proceedings of the 90th Annual Meeting of the Transportation Research Board,* January 2011.

[4] Crenshaw, P. (2000) "FHWA Adaptive Control Survey," presented at the TRB Committee on Traffic Signal Systems Meeting, 2000 Midyear Meeting, Seattle, Wash., July 9–10, 2000.

[5] Head, L. and P. Mirchandani (1998) "The RHODES Prototype: A Technical Review," *Adaptive Traffic Signal Control Systems Workshop*, TRB Midyear Meeting, Asilomar, Calif., July 1998.

[6] Head, L. (2011) "Heuristic Algorithm for priority traffic signal control", *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, January 2011.

[7] Rim, H., S. Kim (2011) Estimation of Lane-Level Travel Times (L2TT) in V2X-based Traffic Information System", *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, January 2011.

[8] Oertel, R. and P. Wagner (2011) "Delay-Time Actuated Traffic Signal Control for an Isolated Intersection", *Proceedings of the 90th Annual Meeting of the Transportation Research Board*, January 2011.

[9] Krauss, S., P. Wagner, and C. Gawron (1997) "Metastable states in a microscopic model of traffic flow", *Phys. Rev. E55*, 1997.

[10] Desai, P., Loke, S.W., Desai, P., and Singh, J., (2011) "Multi-agent based vehicle congestion management", Proceedings of the IEEE Intelligent Vehicles Symposium, Baden Baden Germany, 2011.

[11] SUMO: Simulation of Urban Mobility, see: http://sumo.sourceforge.net/.