A Fuzzy based approach to Dampen Emergent Traffic Waves

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Abstract—**Adaptive Cruise Control (ACC) and Traffic Aware Cruise Control (TACC) are recent advancements in cruise control design that allow a semi-autonomous vehicle to slow itself when approaching vehicles. The issue with these technologies is that they focus on keeping the distance from a leading vehicle constant. This may lead to unwanted dynamics in the following traffic flow, could result in the creation of traveling waves. This paper focuses on maintaining a reference velocity based on the relative position of the preceding vehicle instead of slowing down to maintain a certain following distance. Doing so could reduce the amount of braking the vehicles behind the autonomous vehicle will do. With this kind of technology implemented, the number and duration of traffic jams could be greatly reduced. Simulation results and tests run on the University of Arizona's Cognitive Autonomous Test (CAT) Vehicle illustrate the feasibility and success of this new controller.**

Index Terms—**Control design, Autonomous Systems, Fuzzy control, Intelligent vehicles, Motion estimation.**

I. INTRODUCTION

The state of the art for automated driving in stop-and-go traffic is Tesla Motor's Traffic Aware Cruise Control (TACC). The system works by letting the user set a desired minimum following distance and a desired speed. When the vehicle moves into the set minimum following distance, the system adjusts the vehicle's velocity to match the velocity of the vehicle it is following [1]. TACC is a viable solution: however, by maintaining a set following distance, any velocity changes in the lead vehicle may be amplified, potentially resulting in traffic waves explained by the experiment in [2]. These traffic waves are waves of congestion that form and propagate upstream in regions where the velocity varies in time and space [3]. In essence, TACC is merely a newer version of the Adaptive Cruise Control (ACC) System found in most vehicles on the road today. This "new version" is only set apart by the ability to function at lower speeds and stop when necessary.

In this paper, we propose an innovative approach designed to reduce the traffic waves created by stop-and-go traffic, while mimicking a human-driver decision making process. Our strategy is implemented by controlling the following vehicle's velocity based on the preceding vehicle's velocity, in addition to the separation distance. By monitoring the preceding velocity, the following vehicle will start to slow down sooner: making it possible for a vehicle to reduce the amount of time spent in, or completely avoid, the stop phase of stop-and-go traffic. By doing so, the vehicles behind the following vehicle are able to further reduce their time in the stop phase. As a result, the traffic wave can be damped or dissipated, thus reducing the affects of the stop-and-go traffic situation.

There also exist a few experimental solutions that attempt to do the same thing as our controller. The most successful of these was the solution designed by the AUTOPIA group [4], [5], [6]. Their solution uses fuzzy logic to control the autonomous vehicle's throttle and brake to maintain a steady velocity at a safe distance. The issue with this solution is it requires expensive GPS equipment to determine location and the following distance information is calculated by receiving the GPS location and velocity of the the preceding vehicle via inter-vehicle communication. As a result, the solution is very expensive, only works for the two vehicles equipped with the special equipment, and has the potential to respond incorrectly if sent falsified information.

The controller described in this paper presents an alternative solution to the AUTOPIA controller, since it does not require special equipment and cannot be sent falsified information as a result of not using inter-vehicle communication. Instead, the way in which the distance information is gathered does not matter. For the purpose of this project, a SICK LMS 291 is used, but the distance estimation could come from lidar, sonar, or computer vision techniques. In addition, the output is a desired velocity in meters per second, which can be used by any vehicle-specific throttle/brake controller to be converted into throttle and brake angles. As a result, the design is very versatile and less likely to be compromised by outside entities.

The development of efficient control strategies to mitigate traffic congestion is relevant to companies and universities

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interested in autonomous vehicles because it represents a new way of controlling the velocity in car-following situations. Traffic congestion is also a major cause of greenhouse emission [7]. Therefore, fuel consumption may be reduced through the reduction of time spent sitting in traffic or accelerating to keep up in traffic. In addition, companies like Tesla Motors might be interested in type of controllers because it can also be used in semi-autonomous systems, as long as it has control of the brake and throttle.

If this new control system is properly implemented it could offer some significant improvements to stop-and-go traffic situations. According to the hypothesis found in [8], a single autonomous car reacting preemptively to a traffic jam could completely diffuse the situation. The result could be greener emissions, less stop-and-go traffic related accidents, and improved transit times on highways.

This paper is structured as follows: in section II, Strategy selection and assumptions considered in design are discussed. The actual implementation of the controller is explained in section III. In sections IV and V, results from simulation and real world testing on the University of Arizona's Autonomous car (CAT Vehicle) are presented. Conclusions are discussed in section VI and Future Research ideas are in section VII.

II. METHODS

Designing a control strategy that follows human-like behavior while aiming at smartly reducing traffic waves is not an easy task. Several approaches exist in this area: [9] used empirical data to create a car-following model, [10] reduced emissions by longitudinally controlling intelligent vehicles using a nonlinear model predictive control (MPC) approach, [11] used precise velocity controllers to reduce fuel consumption, [12] used inter-vehicle communication and fuzzy logic to change the speed of the vehicles, and [13] proposed an improved control strategy that takes into account the presence of numerous time-varying communication delays between vehicles. In this paper, we focus on a design that resembles human behavior, while aiming at attenuating traffic jams and maintaining a relatively simple implementation. With this goal, we propose a Fuzzy Logic based strategy which keeps a safe following distance while allowing for some leeway in the case of stop and go situations [14], [15]. In particular, we consider a setting where an autonomous vehicle follows a human driven car, under a stop-and-go situation. In order to mimic the decision process of a human driver, decisions for this controller are based on two inputs: (1) the following distance and (2) an estimate of the difference in velocity between the autonomous vehicle and the preceding vehicle.

Because recommended following distance rules are given in terms of time units, the following distance is converted into seconds by dividing the distance by the current velocity. This strategy also accounts for differences in velocity. The faster a vehicle travels, the more headway should exist. Driver's Education classes recommend three seconds of following distance, so this controller tries to maintain a safe following distance between three and five seconds, ideally at four seconds. This strategy is applicable for higher speeds, but if the velocity drops below a limit, some complications might arise. For instance, three seconds of following distance is zero meters when the vehicles are not moving. To account for this, the controller treats the following distance for all speeds below the lower limit L_L, the same as if the vehicle was traveling at L_L. The estimated distance value, expressed now in seconds, will then be fuzzified (to account for uncertainty) and associated with a membership function that characterizes the safety of the cars separation.

The relative velocity between the vehicles can be estimated using the measured distance and the current autonomous vehicle speed. The resulting measure is then fuzzified to characterize the absolute speed difference.

Using the fuzzy inputs, decisions will be made about how to effect the command velocity sent to the autonomous vehicle in order to prevent jams and provide a smoother velocity profile. The overall control strategy design is represented in Figure 3.

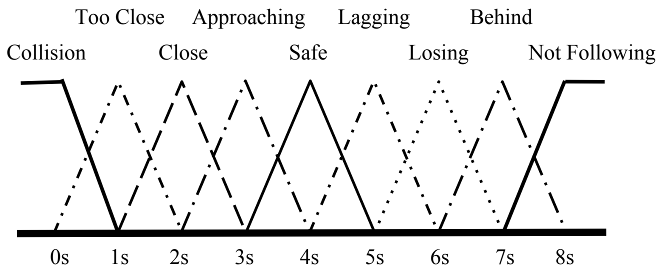

Fig. 1. Distances represented by fuzzy sets.

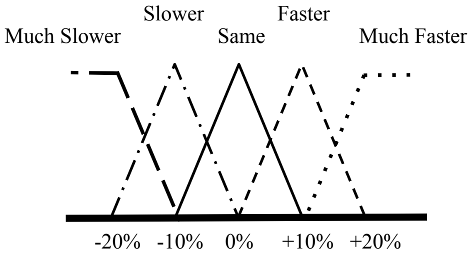

Fig. 2. Speed differences represented by fuzzy sets.

	Much Faster	Faster	Same	Slower	Much Slower
Collision	BH	BH	BH	BH	BH
Too Close	BH	BH	LD	MD	SD
Close	BH	LD	MD	SD	NC
Approaching	LD	MD	MP	NC	SI
Safe	MD	NC	NC	SI	MI
Lagging	SD	NC	MP	SI	MI
Losing	SD	NC	SI	MI	LI
Behind	NC	SI	MI	LI	USS
Not Following	USS	USS	USS	USS	USS

TABLE I
THE FUZZY LOGIC RULES.

III. DESIGN

The system model used for controller design considered as inputs:

- Relative distance between the vehicles $d = |x_1 - x_2|$. Where x_1 represents the position of the car to follow, x_2: autonomous car position; $x_1, x_2 \in \mathbb{R}_{\geq 0}$ in meters. Since, as described before, in our approach the distance is represented in terms of time to get to the car ahead, we consider the alternative time-equivalent distance input d_e, measured in seconds and with values within the continuous universe of discourse $[0, 8]$ for the controller.
- Speed difference between the vehicles Δv, which corresponds to the relative velocity between the cars, is estimated using distance and velocity measures from the autonomous vehicle. For design purposes, we consider Δv taking values within the range $[-20, +20]\%$.

The controller itself generates as output a commanded variation of speed for the autonomous vehicle Δu, with $\Delta u \in [0, 0.5] m/s$. To implement the fuzzy logic controller, membership functions were defined with triangular shapes in order to speed up processing and help make the decision process faster which is desired when controlling moving objects. Membership functions for the inputs are portrayed in Figures 1 and 2.

Distance estimation d for the system is based on filtered data from a 75Hz SICK LMS 291 laser scanner and the current velocity $\dot{x}_2$ in m/s is provided by the autonomous vehicle.

The controller output is obtained based on the entries in Table I. In the table, the outcomes are as follows: LD, MD, and SD for large, medium, and small decrease; LI, MI, and SI for large, medium, and small increase; NC for “No Change”; MP for “Match Proceeding”; USS for “Use Set Speed”; and BH for “Brake Hard”. The velocity is then changed according to the outcome of the fuzzy inference system as follows: a small increase or decrease is associated with a 20% change in velocity. A medium increase or decrease is associated with a 40% change in velocity. A large increase or decrease is associated with a 60% change in velocity. The outcome “Abrupt Brake” sets the output velocity to 0 m/s while “Use Set Speed” increases the velocity until it matches the set speed limit. The outcome “Match Preceding” sets the vehicle’s velocity to the estimated velocity of the preceding vehicle and “No Change” maintains the current velocity setting. The increase, however, has a limitation on it. Speeding up is not related to any safety concerns so it is necessary to ensure accelerations are comfortable. Thus, the largest increase in velocity is an additional 0.5 m/s. When the vehicle’s velocity drops below $L_L = 1 m/s$ using a percentage for change becomes undesirable. To solve this issue, all changes at these velocities are replaced by constants calculated from the percent change at 1 m/s. The fuzzy logic based control strategy described above was implemented using MATLAB and Simulink’s Robotics Toolbox to interface between ROS [16] and the Autonomous Vehicle.

IV. SIMULATION

Simulations were run in Gazebo [17], to test software-in-the-loop execution with realistic kinematic and dynamical models, as well as realistic sensor processing requirements. The simulations consisted of multiple vehicles following each other in a straight line and in a circle. The simplest simulation consisted of one preceding vehicle and one autonomous vehicle that followed the preceding vehicle in a straight line. The preceding vehicle was given a velocity profile, similar to a sine wave, and the velocity of the autonomous vehicle was determined by the controller.

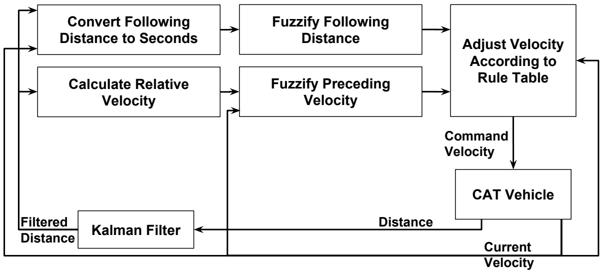

Fig. 3. A model showing the controller design.

In Figure 4, a plot of the recorded data from one of the simulations can be seen. The results show that the velocity of the autonomous vehicle was fairly constant throughout the entire simulation and was less oscillatory than the sine wave representing the velocity of the preceding vehicle. A sine wave was chosen because the speeding up and slowing down of the preceding vehicle resembles that of a vehicle in stop-and-go traffic. The nearly constant velocity of the autonomous vehicle means that the controller was successful in reducing the amount of stopping the autonomous vehicle had to do. This means that the controller has the potential to reduce traffic waves in stop-and-go traffic.

A similar simulation was run using a joystick to control the velocity of the preceding vehicle instead of a sine wave input. The results of the simulation can be seen in Figure 5. The results show that the velocity of the autonomous vehicle had very few oscillations despite the preceding vehicle speeding up, slowing down and stopping multiple times during the simulation.

Simulations were also run for two and three vehicles in a circle. The results from the simulations with three vehicles can be seen in Figures 6 and 7. The results show that the waves were even further damped when a third vehicle was introduced. This suggests that the waves would continue to be damped as more vehicles were introduced. The simulations were used to verify the function of the controller before it was tested in the real world. After data from the simulations confirmed that the controller was functioning correctly, it was then tested on the ByWire XGV autonomous vehicle.

V. REAL WORLD RESULTS

The designed control strategy was tested on a real world setting, consisting of a preceding vehicle placed to the left of the autonomous car. The SICK LMS 291 calculated the distance to and angle between the preceding vehicle and the autonomous vehicle, then measured distance and angle were used to calculate the vertical distance between the preceding

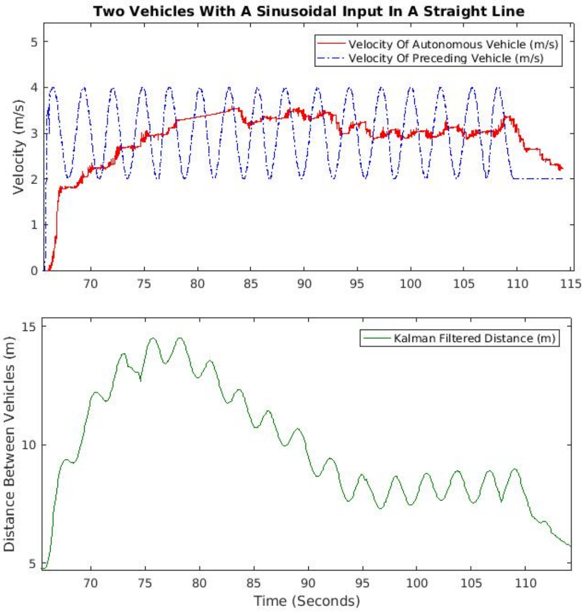

Fig. 4. Distance between and velocity of two vehicles with a sinusoidal input in a straight line.

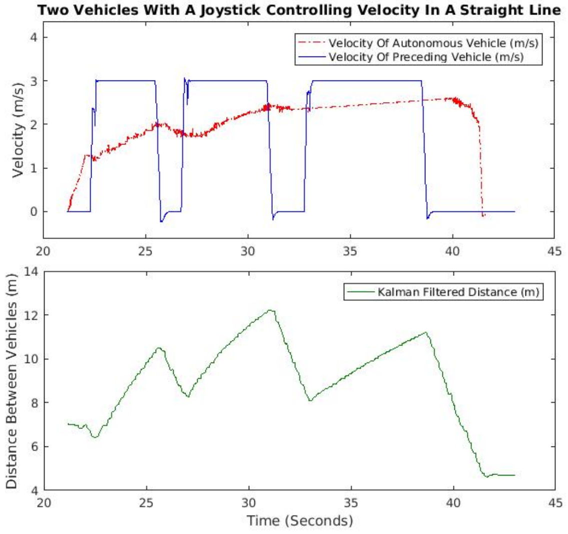

Fig. 5. Distance between and velocity of two vehicles with a joystick controlling the input in a straight line.

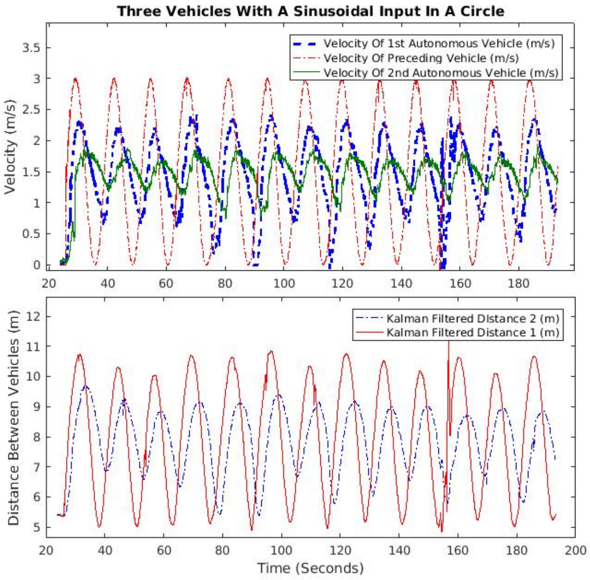

Fig. 6. Distance between and velocity of three vehicles with a sinusoidal input in a circle.

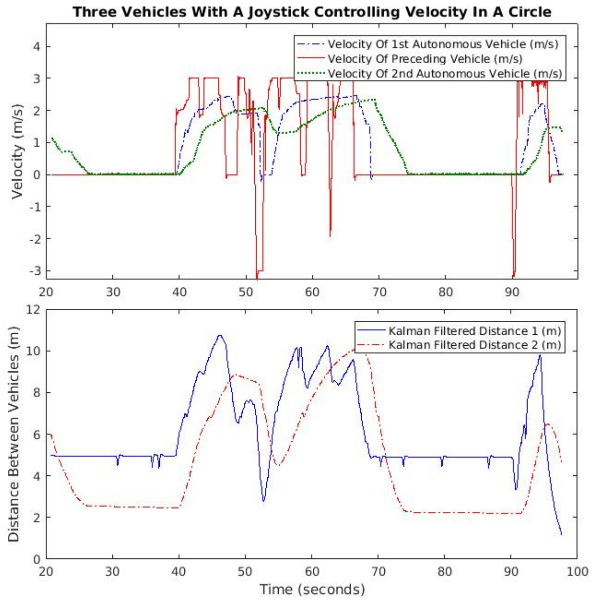

Fig. 7. Distance between and velocity of three vehicles with a joystick controlling the input in a circle.

vehicle and the autonomous car. This modification allowed for the controller to be tested as if the preceding vehicle was directly in front of the autonomous vehicle without the risk of the autonomous vehicle rear-ending the car in front of it. If the autonomous vehicle did not stop, it would simply pass the preceding vehicle to the left of it.

Experiments were performed in an open parking lot in a straight line and on a circle with a circumference of $260m$ and a radius of $41.38m$. In both cases, the controller commanded a velocity to the autonomous vehicle and the steering was controlled manually. The results from the straight line experiment can be seen in Figure 8. Initially, there was a large delay before the autonomous vehicle stopped, this was associated to a low level control PID implemented as part of the actuator system which translates velocity commands into throttle and brake commands. To make the control system more reactive, the low level controller was tunned to achieve a more aggressive response.

After those adjustments were made, experiment was repeated and the obtained velocity profile matched the expected in simulation results as can be appreciated in Figure 9. The driving velocity of the autonomous vehicle matched the commanded velocity reasonably without lurching, thus confirming the controller functioned as designed.

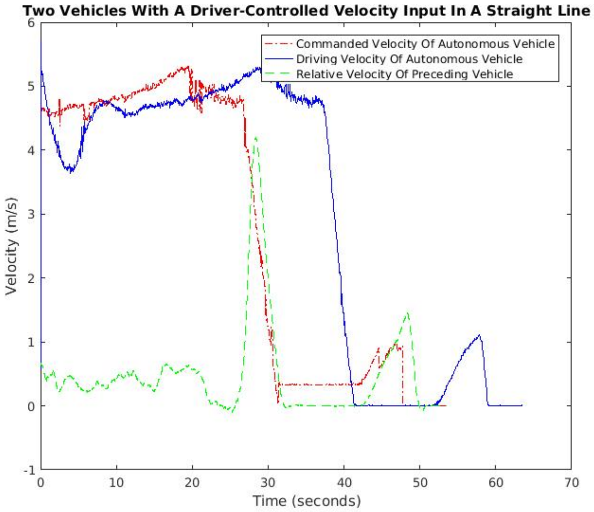

Fig. 8. Difference between commanded and actual driving velocity that demonstrates the delay.

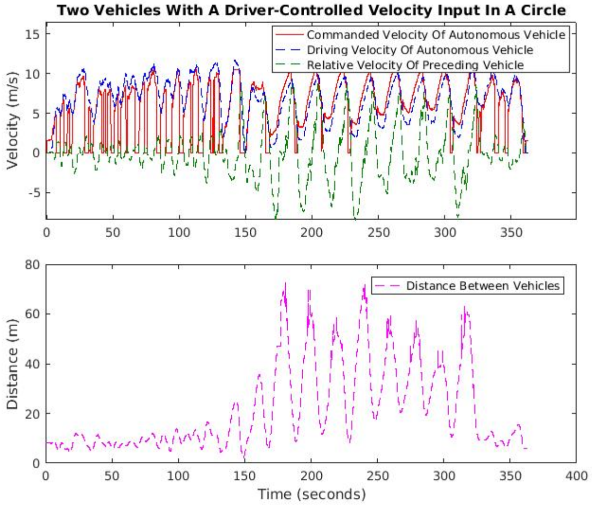

Fig. 9. Distance between and velocity of two vehicles with a driver controlling the velocity in a circle.

As a final test of the design and functionality, the controller was used in a simulated infinite traffic emulated with 22 vehicles driving on a circular track. The results from this experiment can be seen in Figure 10. In this test, the controller performed as designed by mimicking the actions of the preceding vehicle in a reduced manner. Approaching the preceding vehicle went smoothly and allowed for slower braking in the vehicles behind the autonomous vehicle. However, even though control logic designed performed well in simulation, the results differed from simulation as issues arose when the car started to speed up again.

The acceleration was not nearly fast enough to close the gap created by the abrupt halts. Over time, these gaps continued to grow and resulted in increased traffic waves. Results from this experiment show that emulating the human driver behavior with a smoothing profile is not enough to reduce traffic waves, instead, acceleration after stopping is critical parameter to achieve effective damping on traffic waves. If the vehicle does not accelerate fast enough, the benefits of intelligent braking will be diminished.

Practical results from 22 car experiment showed then that fuzzy logic based on regular driving rules will not perform good enough on crowded scenarios, without taking particular care of a more aggressive acceleration profile to compensate the gaps.

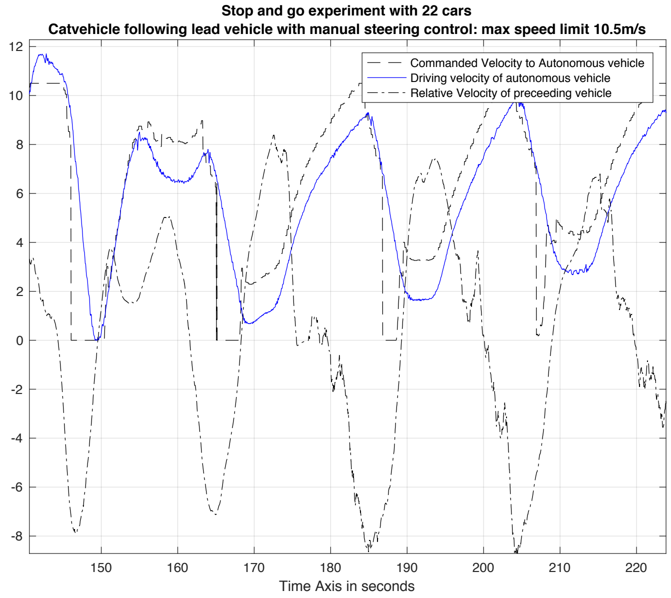

Fig. 10. Driving on a circular track with 22 cars.

VI. Conclusion

In this paper a velocity-based, car-following fuzzy logic based controller was presented. The goal was to create a controller that smoothened the velocity profile of the autonomous vehicle and mimicked human-like behavior. Preliminary results show that fuzzy control provides a promising alternative for traffic wave attenuation. The simulations run in Gazebo showed that the controller performed as intended and the simulation results were validated by the real world results for a classic 2 vehicle stop and go scenario. However, controller performance was not as expected (traffic wave attenuation was not achieved as expected on simulations) during the 22 cars experiment. The controller's ability to mimic human reasoning given uncertain circumstances is advantageous when planning for unknown situations, but not enough to operate in crowded scenarios without a improved reactive design associated to acceleration profiles after deceleration. Effectiveness of fuzzy logic based systems relies heavily on the attenuation of the rules, so a better understanding on parameters that affect the propagation of traffic waves is required to improve controller design in the future and make velocity-based car-following control more beneficial tool to handle traffic situations in systems including autonomous elements.

VII. Future Research

Our findings show that further Having tested the controller in real stop-and-go traffic situations and finding that the acceleration was too slow, further research into increasing the acceleration rate is necessary. The current design limited how fast an acceleration the controller could request in order to maintain comfortable accelerations. However, further research could be conducted to find an optimal balance between an effective and a comfortable acceleration rate for the passengers.

It will also be necessary to create a steering controller that accompanies the controller discussed in this paper and calculates the appropriate steering angle. To simulate multiple vehicles driving in a circle, the current controller changes the steering angle from 0 radians to a set steering angle for both the preceding vehicle and the autonomous vehicle and places them on a circle of a certain radius. However, there are turns of various angles on highways. Every turn will not require the same steering angle. Therefore, the controller will need to be improved so that it can calculate the steering angle that is needed at the moment. This steering controller could be created using a fuzzy logic approach similar to the approach used in this paper. The sets and rules described above can be refined and expanded to include scenarios in which the steering angle changes.

There may also be some speed limitations for the controller discussed in this paper. The controller was only tested for speeds up to approximately 20 mph. These speeds are fine for stop-and-go traffic. However, the controller can still be tested for higher speeds so that the controller can be used in scenarios other than stop-and-go traffic and can potentially compensate for variations in the speed of the vehicles on the road. This improvement should reduce the amount of slowing down that vehicles on the road will undergo and has the potential to prevent traffic jams from occurring in the first place.

After these changes are made or accounted for, people should consider using this controller on the road.

Acknowledgment

The authors would like to thank Matt Bunting, Shumo Cui, Maria Laura Delle Monache, and Raphael Stern, for allowing us to and assisting us in testing our controller in their infinite traffic loop test.

Research for Haulcy and Hamilton was supported by the National Science Foundation and the Air Force Office of Scientific Research, under awards IIS-1262960 and CNS-1253334, titled "NSF: REU Site: The Cognitive and Autonomous Test (CAT) Vehicle." For Sprinkle, Bhadani, Seibold, Work, and Piccoli under awards NSF CNS-1446435, 1446690, 1446702, 1446715, "Control of Vehicular Traffic Flow via Low Density Autonomous Vehicles."

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