Dissipation of Stop and Go Waves via Control of Autonomous Vehicles

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***Abstract*—This paper presents a comprehensive study on addressing traffic waves caused by human driving behavior. Innovative strategies leveraging autonomous vehicles (AVs) and Lagrangian controllers are proposed to reduce fuel consumption, enhance traffic flow, and revolutionize traffic control. The study investigates the dynamics of traffic waves and explores solutions including intelligent transportation systems, optimized signal timings, and advanced control techniques. Experimental results demonstrate the effectiveness of Lagrangian controllers, incorporating the "slow-in, fast-out" approach, in reducing fuel consumption, excessive braking, and velocity standard deviation. The use of Follower Stopper control and PI saturation control demonstrates promising results on the ring road experiment conducted. The paper demonstrates that one autonomous vehicle programmed using these controllers is sufficient to dampen the traffic waves.**

***Index Terms*—Traffic Waves, Lagrangian Control, Autonomous Vehicles, Follower Stopper Control, PI Saturation Control**

I. INTRODUCTION

The article focuses on the problem of traffic waves, particularly stop-and-go waves, that arise as a result of human driving behavior. Previous works by Sugiyama et al. have shed light on the emergence of these waves in experiments without infrastructure bottlenecks or lane changes, but a solution for dampening them was not provided. The authors aim to address this gap by proposing strategies to reduce fuel consumption, enhance traffic flow, and revolutionize traffic control through the utilization of autonomous vehicles (AVs) and simple control techniques. By tackling the issue of traffic waves, the article seeks to contribute to more efficient and sustainable transportation systems.

Traffic waves, also referred to as traffic congestion or traffic jams, occur when a line of vehicles on a road slows down or comes to a halt, causing a ripple effect that propagates backward through the traffic flow. These waves can be triggered by various factors such as high traffic volume, accidents, road construction, traffic signal timing issues, and driver behavior. The occurrence of "phantom traffic jams" or "jamitons" highlights the ability of traffic waves to emerge even in the absence of specific obstacles. Such situations often start with a single driver abruptly braking, prompting subsequent drivers to react by slowing down or stopping as well. This chain reaction amplifies and spreads through the traffic, leading to a wave-like pattern of congestion. Traffic waves not only frustrate drivers but also result in slower travel speeds, increased travel times, and inefficiencies within the transportation system. Researchers have extensively studied traffic flow dynamics and developed mathematical models to understand and predict the emergence and propagation of traffic waves. The aim is to find effective measures to mitigate congestion and improve traffic management strategies. Various approaches include intelligent transportation systems, optimized traffic signal timings, enhanced road infrastructure, promotion of public transportation, encouragement of carpooling, and the implementation of traffic management techniques like ramp metering and variable speed limits. Furthermore, advancements in autonomous vehicles and vehicle-to-vehicle communication systems hold the potential to significantly reduce traffic waves in the future.

In the field of traffic management, a small percentage of vehicles, typically ranging from 3 to 5 percent, have the capability to estimate traffic conditions across large road networks. These vehicles serve as key sources of information for monitoring and analyzing traffic flow, allowing for a better understanding of congestion patterns and potential bottlenecks. Additionally, a limited number of Lagrangian controllers are employed to dampen traffic waves. These controllers utilize strategies such as the "slow-in, fast-out" approach, which aims to eliminate traffic jams by encouraging smoother and more consistent traffic flow. However, despite various efforts, the literature currently lacks a comprehensive solution for effectively dampening wave-like patterns known as stop-and-go waves, which naturally occur due to the behavior of human drivers. To address this challenge, researchers have explored jam-absorbing strategies based on Newell's car-following theory, with the setup proposed by Sugiayama et al [5]. serving as a significant reference point. The search for innovative approaches to wave dampening remains an ongoing area of research in traffic management. [1]

The main contributions of the authors are identified as follows:

- Designing and executing a series of ring-road experiments to demonstrate that an intelligently controlled autonomous vehicle can dampen stop-and-go waves.
- Presenting two distinct control strategies: a fixed average velocity control algorithm called FollowerStopper and a proportional-integral (PI) controller with saturation. These strategies aim to reduce fuel consumption and improve traffic flow.

- Conducting three experiments labeled A, B, and C to evaluate the effectiveness of the control strategies and comparing the results.
- Showing that the Lagrangian control approach, where a single autonomous vehicle controls the flow of human-controlled vehicles around it, can lead to substantial reductions in velocity standard deviation, excessive braking, and fuel consumption.
- Highlighting the potential impact of Lagrangian actuators, such as AVs or trained human drivers, in controlling traffic flow without the need for centralized interventions or dedicated actuation infrastructure.

The authors have successfully addressed the problem of dampening stop-and-go waves caused by human driving behavior through the use of autonomous vehicles and simple control strategies. They designed and executed ring-road experiments, presented different control strategies, and compared the results. The experiments demonstrate that the Lagrangian control approach can significantly reduce fuel consumption and improve traffic flow. The main contributions stated by the authors align with what they have achieved in the paper. They have provided evidence of the benefits of Lagrangian actuators, specifically autonomous vehicles, in controlling traffic flow. The control strategies presented, such as the FollowerStopper and PI controller with saturation, effectively dampen traffic waves and lead to improved traffic dynamics.

II. State-of-the-art Methods

The authors discuss a few implemented methods for traffic management which we will discuss in this section. Newell's car-following theory is a model used in transportation engineering to describe how a driver adjusts their speed to the vehicle ahead. The theory proposes that drivers maintain a headway, or space between vehicles, that is a linear function of their speed. This theory helps predict how disruptions like sudden braking or obstacles can lead to traffic jams by disrupting the flow of traffic.

Jam-absorbing strategies based on Newell's theory aim to mitigate the formation of traffic jams. These might involve increasing headway during congestion or the use of adaptive cruise control systems that adjust speed based on the vehicle ahead. However, while these strategies can help alleviate traffic congestion, they cannot completely prevent it due to the complex nature of traffic flow, influenced by various factors including road conditions and driver behavior.

Next, we have the Variable Speed Advisory (VSA) and Variable Speed Limits (VSL) which are two approaches used in traffic control to manage and regulate traffic flow based on real-time conditions. These methods involve adjusting the posted speed limits or providing speed recommendations to drivers to optimize traffic efficiency and safety. [3]

1) Variable Speed Advisory (VSA): VSA is a system that provides drivers with real-time speed recommendations based on prevailing traffic conditions. It utilizes sensors and data collection devices installed along roadways to monitor traffic flow, weather conditions, and other relevant factors. The collected data is then processed to calculate appropriate advisory speeds, which are communicated to drivers through dynamic message signs or in-vehicle displays. The purpose of VSA is to guide drivers to adopt speeds that align with the current traffic conditions, promoting smoother traffic flow and reducing congestion.

2) Variable Speed Limits (VSL): VSL is a technique where the posted speed limits are dynamically adjusted to match the actual traffic conditions. Similar to VSA, VSL relies on data collection devices to monitor traffic flow, congestion levels, and other parameters in real time. Based on the collected data, algorithms determine the optimal speed limits for a specific road segment or stretch. These speed limits are then updated on electronic signage along the roadway. The goal of VSL is to ensure that the posted speed limits reflect the current traffic conditions, improving traffic flow, and safety, and reducing the risk of accidents.

Benefits and Applications:

- VSA and VSL offer several benefits in traffic control. By dynamically adjusting speed recommendations or limits, these approaches can:
- Enhance Safety: VSA and VSL help in adapting driving speeds to match the prevailing traffic conditions, reducing the risk of accidents and promoting safer driving practices.
- Improve Traffic Flow: By optimizing driving speeds based on real-time conditions, VSA and VSL can minimize stop-and-go traffic patterns, smooth out traffic flow, and mitigate congestion.
- Increase Efficiency: By encouraging drivers to adopt speeds that are appropriate for the current traffic conditions, VSA and VSL can improve overall traffic throughput, reduce travel times, and enhance fuel efficiency.
- Adapt to Changing Conditions: VSA and VSL have the flexibility to respond to changing weather conditions, incidents, work zones, or other factors that may impact traffic flow. The speed recommendations or limits can be adjusted accordingly to accommodate these changes.

The next section talks about the setup for the ring road traffic management experiment.

III. Experimental Setup and System Dynamics

The experiment is set up as shown in the flowchart below. The drivers are instructed as:

- Drive as if you were in rush hour traffic.
- Do not pass the car ahead.
- Do not hit the car ahead.
- Drive safely at all times.
- Do not tailgate.

The experiment flow is given in the flowchart in Fig 2

The experiment consists of 20 vehicles along with one autonomous vehicle on the ring road. Each vehicle affects the vehicle behind it and is affected by the autonomous vehicle's

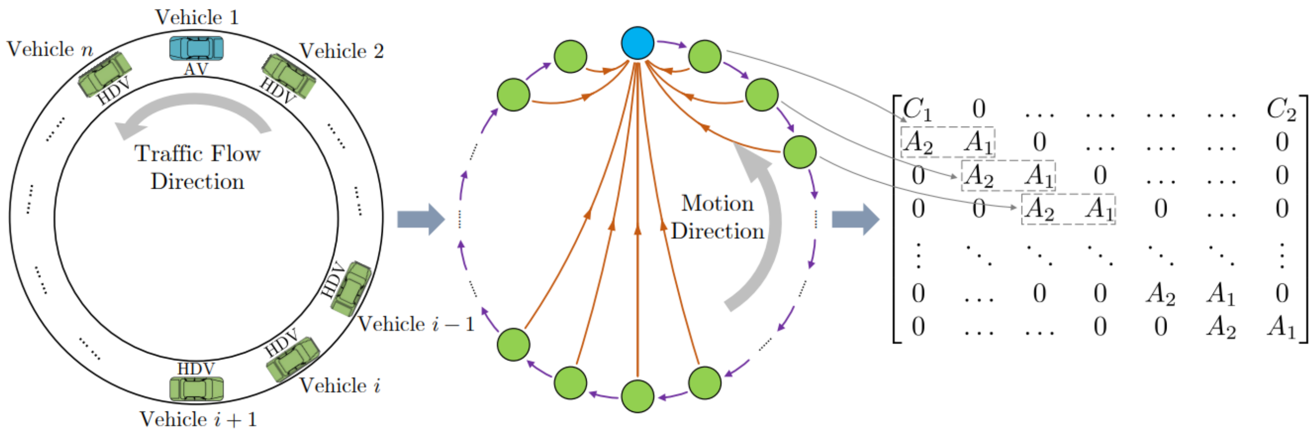
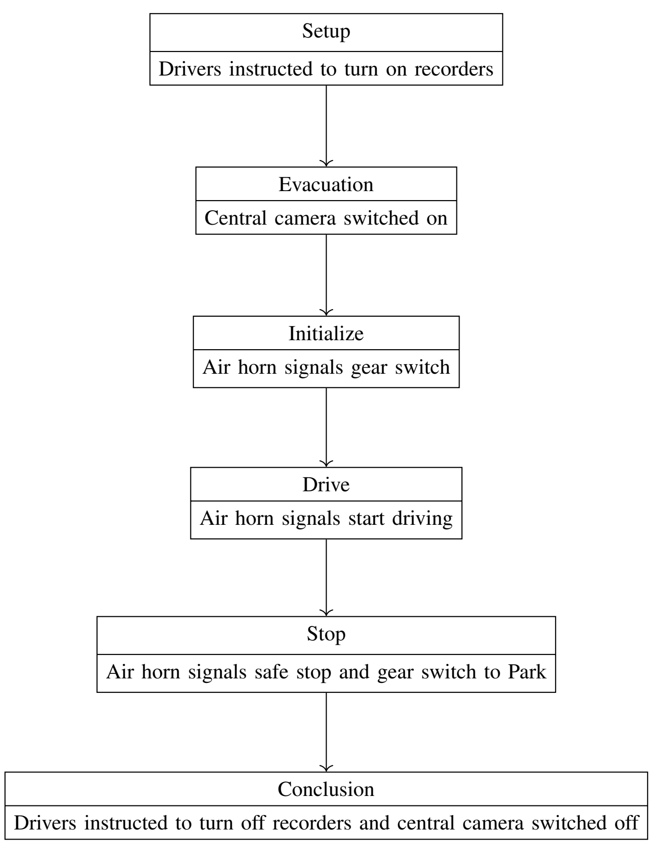


Fig. 1: System Dynamics. The blue agent is the autonomous vehicle and the rest are the human-driven vehicles with specific instructions given to the drivers. [2]

Fig. 2: Experiment Flowchart



behavior. The dynamic equations representing the gap between two vehicles, and their relative velocities are given below:

$$\begin{aligned}
&\dot{v}_i(t) = F\left(s_i(t), \dot{s}_i(t), v_i(t)\right) \\
&\begin{cases} \dot{\tilde{s}}_i(t) = \tilde{v}_{i-1}(t) - \tilde{v}_i(t) \\ \dot{\tilde{v}}_i(t) = \alpha_1 \tilde{s}_i(t) - \alpha_2 \tilde{v}_i(t) + \alpha_3 \tilde{v}_{i-1}(t) \end{cases} \\
&\alpha_1 = \frac{\partial F}{\partial s}, \alpha_2 = \frac{\partial F}{\partial \dot{s}} - \frac{\partial F}{\partial v}, \alpha_3 = \frac{\partial F}{\partial \dot{s}}
\end{aligned} \tag{1}$$

Here, $s_i(t)$, the relative velocity between its own and its preceding vehicle $s_i'(t)$, and its velocity $v_i(t)$. Given the observed behavior of real drivers, it is expected that the acceleration will increase under the following conditions: when the spacing between vehicles increases, the velocity of the ego vehicle decreases, or the velocity of the preceding vehicle increases. Based on these assumptions, we can consider that $\alpha 1 > 0$, $\alpha 2 > \alpha 3 > 0$. The dynamics can be modeled as state space representation as given below:

$$\begin{gathered}
\dot{x}(t) = Ax(t) + Bu(t) \\
A = \begin{bmatrix} C_1 & 0 & \dots & \dots & 0 & C_2 \\ A_2 & A_1 & 0 & \dots & \dots & 0 \\ 0 & A_2 & A_1 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & 0 & A_2 & A_1 & 0 \\ 0 & \dots & \dots & 0 & A_2 & A_1 \end{bmatrix}, B = \begin{bmatrix} B_1 \\ B_2 \\ B_2 \\ \vdots \\ B_2 \end{bmatrix} \\
C_1 = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}, C_2 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\end{gathered} \tag{2}$$

Each of A1, A2, B1, B2, C1, and C2 is a block matrix as given below. The states of the system are the gaps between neighboring vehicles and the relative velocities. The above-given state space models accurately the ring road experiment with one autonomous vehicle and the rest human-driven vehicles. The first row in the A matrix denotes the AV properties. Thus the controller can be directly applied to this dynamic system. Note, the system is stabilizable only when:

$$\alpha_2^2 - \alpha_3^2 - 2\alpha_1 \geq 0 \tag{3}$$

The 3 tables below explain how the 3 experiments were executed Table 1: A :: Follower Stopper control Table 2: B :: Human driven control - similar to experiment A Table 3: C :: PI Saturation control

In the next section, we discuss the algorithms used for traffic management, namely, Follower Stopper control and PI Saturation control.

TABLE I: Experiment A Events

Time (seconds)	Event Description
79	First traffic wave observed
126	FollowerStopper wave-dampening controller activated
126	Desired velocity set to 6.50
222	Desired velocity changed to 7.00
292	Desired velocity changed to 7.50
347	Desired velocity changed to 8.00
415	Desired velocity reduced to 7.50
463	Human driver resumes control
567	Experiment ended

TABLE II: Experiment B Events

Time (seconds)	Event Description
55	First traffic wave observed
112	Wave-dampening control activated with a desired velocity of 6.25 m/s (14 mph)
202	Desired velocity increased to 7.15 m/s (16 mph)
300	Desired velocity maintained at 7.15 m/s (16 mph)
409	Experiment ended

IV. Follower Stopper Controller

A follower-stopper controller is used in traffic management to mitigate congestion and dampen traffic oscillations. It is designed to regulate the speed and spacing of vehicles in a traffic stream by dynamically adjusting the acceleration and deceleration of individual vehicles. The goal is to maintain a more stable and smooth flow of traffic, reducing the occurrence of stop-and-go waves that contribute to congestion.

The follower-stopper controller operates by monitoring the behavior of the vehicles in the traffic stream and calculating appropriate acceleration or deceleration commands for each vehicle. It uses information such as the speed, position, and relative spacing between vehicles to make these decisions. When a vehicle approaches too closely to the one ahead, the controller triggers a deceleration command to ensure a safe and comfortable separation distance. On the other hand, if the spacing between vehicles becomes too large, the controller applies an acceleration command to encourage smoother traffic flow. By continuously adjusting the speed and spacing of vehicles, the follower-stopper controller aims to prevent the propagation of traffic disturbances and minimize the amplification of congestion. The controller update equations and the control law for command velocity are given below:

$$\Delta x_k = \Delta x_k^0 + \frac{1}{2d_k}\left(\Delta v_-\right)^2, \quad \text{for } k = 1,2,3 \tag{4}$$

TABLE III: Experiment C Events

Time (seconds)	Event Description
161	Traffic wave appears
218	PI controller with saturation wave damping activated
413	Experiment ended

$$v^{\text{cmd}} = \begin{cases} 0 & \text{if} \quad \Delta x \leq \Delta x_1 \\ v\frac{\Delta x - \Delta x_1}{\Delta x_2 - \Delta x_1} & \text{if } \Delta x_1 < \Delta x \leq \Delta x_2 \\ v + (U - v)\frac{\Delta x - \Delta x_2}{\Delta x_3 - \Delta x_2} & \text{if } \Delta x_2 < \Delta x \leq \Delta x_3 \\ U & \text{if } \Delta x_3 < \Delta x. \end{cases} \tag{5}$$

$$v = \min\left(\max\left(v^{\text{lead}}, 0\right), U\right) \quad \Delta v_- = \min(\Delta v, 0) \tag{6}$$

where, $\Delta x0k$: $\Delta x - \Delta v$ phase intercept and dk is the deceleration rate.

V. PI Saturation Controller

The PI saturation controller is a control strategy utilized in traffic management to regulate the acceleration and deceleration of vehicles based on the saturation limits derived from the speed of the lead vehicle. The controller aims to maintain the desired speed and spacing between vehicles, preventing excessive acceleration or deceleration that could lead to abrupt changes in traffic flow. By incorporating a proportional-integral (PI) control approach, the controller continuously monitors the speed of the lead vehicle and adjusts the acceleration or deceleration commands accordingly. The saturation limits, which define the maximum and minimum speeds that the controller can apply, are dynamically calculated based on the speed of the lead vehicle. This ensures that the follower vehicles do not exceed safe speed thresholds or fall below an acceptable lower limit, thereby promoting a more consistent and stable traffic flow. By considering the lead vehicle speed and adapting the control actions, the PI saturation controller provides an effective means of traffic management to optimize traffic performance and enhance road safety. The updated equations for the PI saturation controller are given below:

$$\begin{aligned} v^{\text{target}} &= U + v^{\text{catch}} \times \min\left(\max\left(\frac{\Delta x - g_l}{g_u - g_l}, 0\right), 1\right) \\ v_{j+1}^{\text{cmd}} &= \beta_j\left(\alpha_j v_j^{\text{target}} + (1-\alpha_j) v_j^{\text{lead}}\right) + (1-\beta_j) v_j^{\text{cmd}} \\ \alpha &= \min\left(\max\left(\frac{\Delta x - \Delta x^{\text{s}}}{\gamma}, 0\right), 1\right) \\ \beta &= 1 - \frac{1}{2}\alpha \end{aligned} \tag{7}$$

Here, α and β represent the weights. α is between 0 and 1 and denotes how fast the system converges and β shows how well the system can adapt to sudden changes in behavior. gu and gl denote the minimum and maximum permissible gap between two vehicles.

VI. Low Level Controller

The CAT Vehicle employs a sophisticated multi-mode controller to translate commanded velocity into precise gas and brake signals. The controller utilizes separate gains for acceleration and braking, implemented as proportional-integral-derivative (PID) modes, allowing for adaptable control actions based on the vehicle's operating conditions. The gains are determined through systematic system identification, involving the comprehensive analysis of the vehicle's response to different stimuli. This optimization process ensures the controller's optimal performance and responsiveness, enabling efficient and smooth control over acceleration and deceleration, and contributing to enhanced efficiency and reliable operation in various driving scenarios. The integration of advanced control strategies and optimization techniques showcases the CAT Vehicle's potential for advancements in autonomous driving and intelligent transportation systems. The low-level control equations are:

$$a_{j+1} = \begin{cases} h_1\left(v_j, v_j^{\mathrm{cmd}}\right) & \text{if } v_j^{\mathrm{cmd}} - v_j > -0.25\frac{\mathrm{m}}{\mathrm{s}} \\ h_2\left(v_j, v_j^{\mathrm{cmd}}\right) & \text{if } v_j^{\mathrm{cmd}} - v_j \leq -0.25\frac{\mathrm{m}}{\mathrm{s}} \\ 0 & \text{otherwise} \\ a_{j+1} \in [-100, 100] \end{cases} \tag{8}$$

where, when a $<$ 0 the brake is depressed, and a $>$ 0 the accelerator is depressed. The h1 controller accelerates to and maintains the desired reference speed and the h2 controller performs rapid speed reduction via the brake.

The results of the three experiments are given in Figure. 3. Wave start (WS) and Controller active (CA) are given for various metrics of evaluation of the three algorithms (follower stopper, human-driven controller, and the PI saturation) such as Standard deviation in the velocity, Fuel consumption, Braking, and throughput which is the number of vehicles passing through an area of the ring track in a certain given time. It can be seen that for the follower stopper control, the autonomous vehicle successfully manages to reduce the standard deviation in the velocity by 80.8% and reduces the overall fuel consumption by 42.5%. Using this controller, a 14.1 % increase in the throughput is observed as well. Controllers B and C perform well but have lower performance as compared to the follower-stopper controller in the above performance metrics.

VII. Simulations and Results

The dataset for the paper was found online the plots were regenerated from the dataset for all the experiments. The figure below shows how the position of each vehicle changes throughout the experiment. The waves start occurring as soon as the experiment is started and no control is active and dampens soon after the control action is started. Figure 4 shows the experiment conducted by the authors. The graph illustrates the velocity of the vehicles plotted against time. Several noteworthy findings obtained from the experiment are highlighted in the graph. The red lines represent the average velocity of the vehicles over time. The initial phase of the experiment, comprising the first 80-90 time steps, serves as the starting point. Notable observations are scarce in this section, as the forward stopper controller remains inactive. Consequently, waves with high amplitude begin to form around the 100-time step mark. In the subsequent portion of the graph, the forward stopper controller is engaged for the autonomous vehicles, programmed to maintain a desired velocity of 6.5 m/s. As a result, the waves gradually start to dampen, exhibiting a decrease in both amplitude and frequency. To evaluate the performance of the controller, the desired velocity is incrementally increased by 0.5 m/s. It is at a velocity of 7 m/s that the controller demonstrates optimal performance by yielding the highest damping effect. In this section, the waves nearly disappear. This process of incrementally increasing the desired velocity continues until it reaches 8 m/s. Subsequently, the desired velocity is reduced back to 7.5 m/s before the controller is deactivated. At this point, wave formation reemerges, resembling the initial inactive phase of the controller at the start of the experiment.

The simulation is performed in Python and the files are attached to the GitHub repo (check footnote). Figure 7 illustrates the simulation with the following parameters: Stopping distance: 50, Max speed: 5, Stopping speed: 0. It is observed, Figure 6a that as the stopping distance decreases, the wave becomes more prominent, and the convergence becomes slower. The output plot displays the performance of the follower-stopper controllers in the simulation. In this scenario, the vehicles come to a stop when the gap between them is less than the stopping distance. Conversely, they accelerate to the maximum speed when the gap exceeds the stopping distance. As a result, we observe fluctuations in the speed, oscillating between the stopping speed and the max speed, until the plot eventually converges and all vehicles reach the maximum command velocity. At this stage, all the vehicles are evenly spaced on the track and converge at the same velocity.

Figure 8 presents the same simulation, but with different parameters: Stopping distance: 80, Max speed: 2, Stopping speed: 0. In this case, the convergence is significantly faster compared to the previous simulation, see figure 6b. Therefore, it is evident that adjusting the stopping distance and stopping velocity based on the specific conditions is necessary to achieve a faster convergence rate.

Note, that all the agents show similar performance but it is not clearly visible in the velocity plot at the agent 10's plot covers all the other plots.

VIII. Conclusion

In conclusion, autonomous vehicles (AVs) have the potential to solve traffic problems by effectively regulating the flow of vehicles on the road. However, it is important to note that if AVs are poorly designed or implemented, they can actually contribute to congestion rather than alleviate it. While the system of AVs is stabilizable, it is not fully controllable. The uncontrollable mode of AV operation, characterized by stable spacing due to the ring structure, ensures a consistent flow of vehicles. Even a small percentage of 3-5% of AVs can significantly impact and regulate traffic patterns. In experimental scenarios, effective controllers such as Follower Stopper control have demonstrated superior throughput compared to alternatives such as ramp metering, variable speed limit, and PI Saturation control. These findings highlight the potential of AVs to revolutionize traffic management and pave the way for efficient transportation systems in the future. In short, the authors have successfully demonstrated the aim of the paper

[0]https://github.com/Prathamesh-Saraf/Autonomous-Vehicle-Traffic-Dampening

Exp.	Velocity st. dev. (m/s)			Fuel consumption (ℓ/100km)			Braking (events/veh/km)			Throughput (veh/hr)		
	WS	CA	%	WS	CA	%	WS	CA	%	WS	CA	%
A	3.31	0.64	-80.8	24.6	14.1	-42.5	8.58	0.12	-98.6	1827	2085	+14.1
B	2.36	1.19	-49.5	21.8	17.0	-22.1	9.50	2.27	-76.2	1828	2008	+9.8
C	3.85	1.74	-54.7	29.0	20.9	-28.1	9.66	2.47	-74.4	1755	1711	-2.5

Fig. 3: Controller performance and statistics

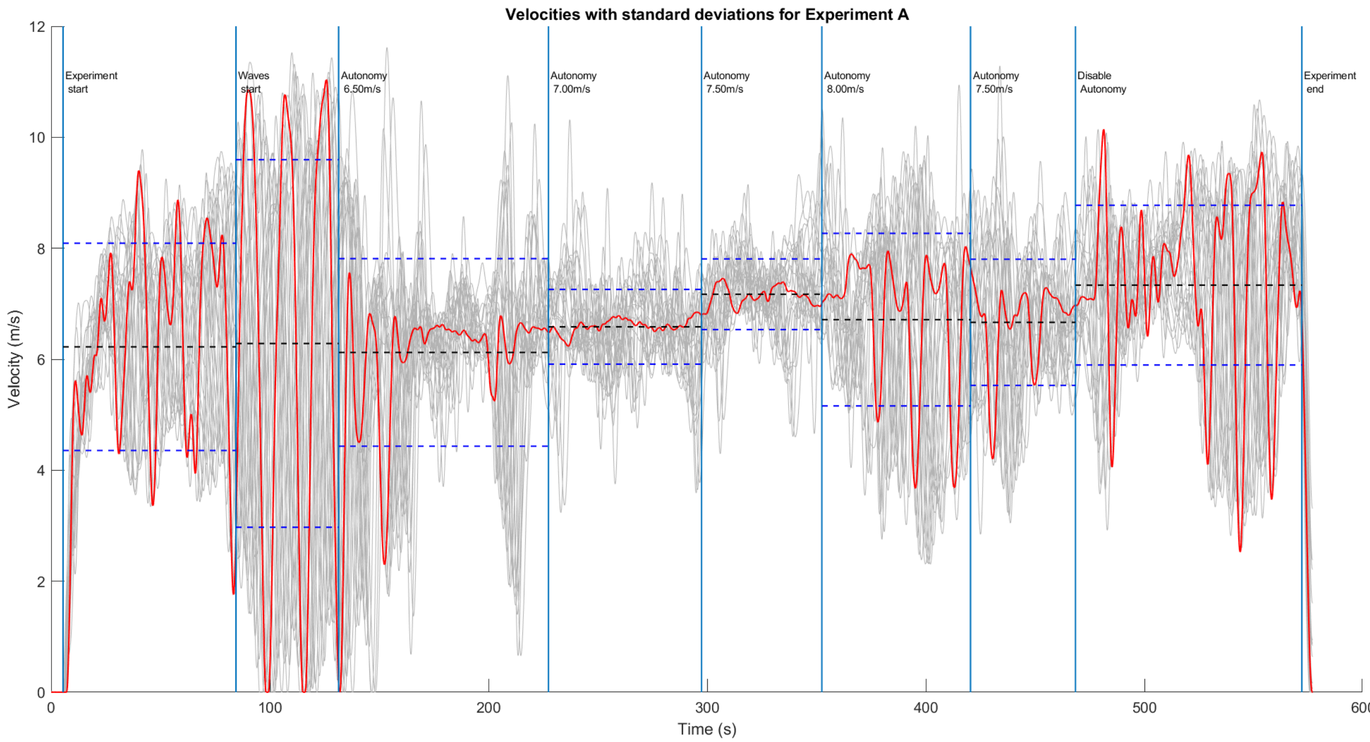


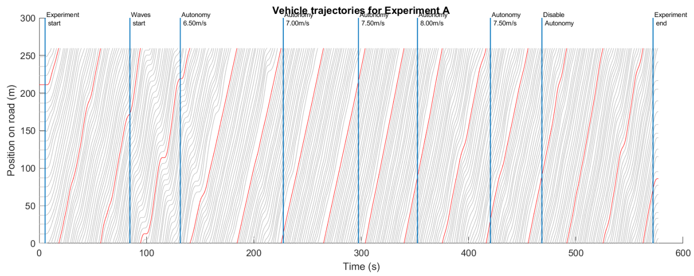
Fig. 4: Vehicle velocities and standard deviations over time for experiment A: Follower Stopper controller

and show how thee proposed controllers can dampen the traffic waves.

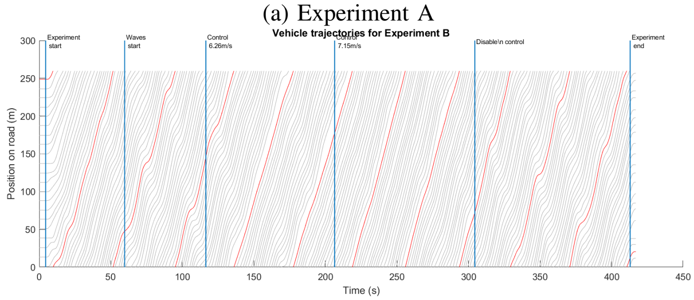
IX. Future Work and Unanswered Questions

The ring road experiment system possesses stabilizability but lacks controllability. It exhibits an uncontrollable mode that represents a stable spacing pattern resulting from the ring road structure. In this mode, vehicles maintain a consistent distance, contributing to stable traffic flow. However, certain scenarios, particularly lane changes on multi-lane freeways, can trigger the emergence of stop-and-go waves. When vehicles change lanes, they create gaps in the lane they vacate, which help in dampening waves. However, if these gaps become too large, they may encourage more frequent lane changes, thereby reducing their overall effectiveness in wave dampening. It is important to conduct further experiments and research to assess the viability of employing Lagrangian actuators on urban freeways and to consider the impact of traffic waves in non-highway environments, such as regular roads and intersections.

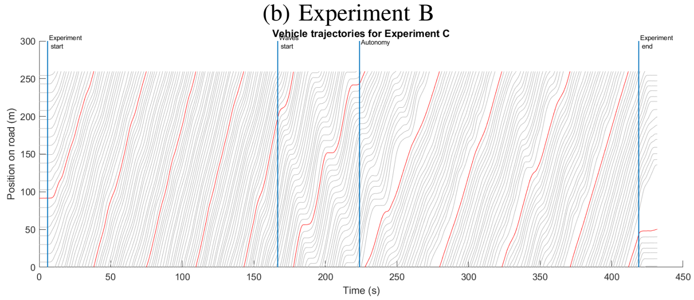
It should be noted that poorly designed or implemented control systems for autonomous vehicles can contribute to the formation of traffic jams. Inefficient autonomous vehicle control can lead to suboptimal acceleration and deceleration patterns, resulting in irregular traffic flow and congestion. To address this issue, it is essential to refine and optimize autonomous vehicle control strategies to ensure smooth and efficient traffic movements. By developing robust control algorithms and enhancing the coordination among autonomous vehicles, traffic congestion and the occurrence of stop-and-go waves can be mitigated, leading to improved overall traffic flow and reduced congestion-related problems.



(a) Experiment A

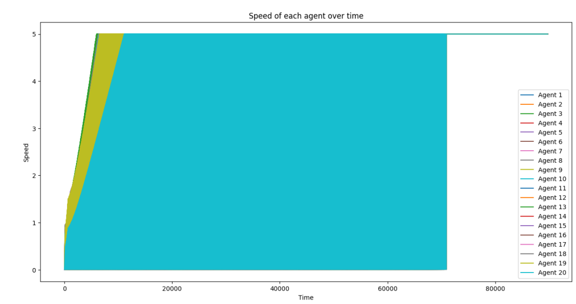


(b) Experiment B

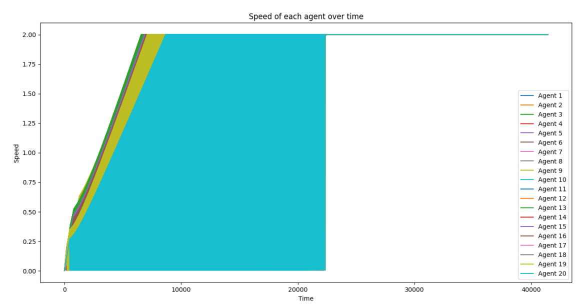


(c) Experiment C

Fig. 5: Vehicle positions over time



(a) Stopping distance: 50, Max speed: 5, Stopping speed: 0



(b) Stopping distance: 80, Max speed: 2, Stopping speed: 0

Fig. 6: Vehicle velocities over time

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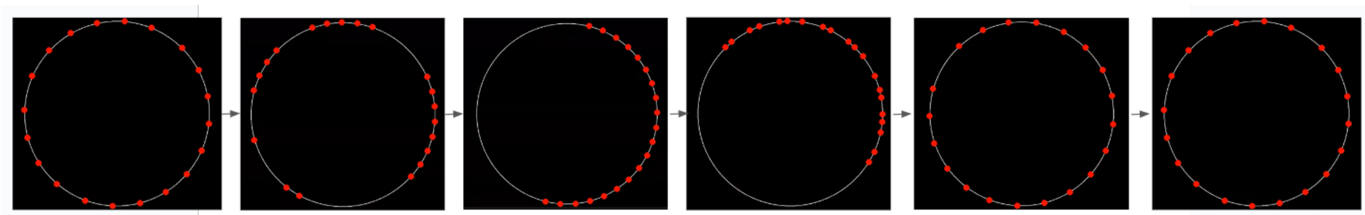

Fig. 7: Stopping distance: 50, Max speed: 5, Stopping speed: 0. The span shots taken at t = 0, 5, 15, 45, 120, 200 secs

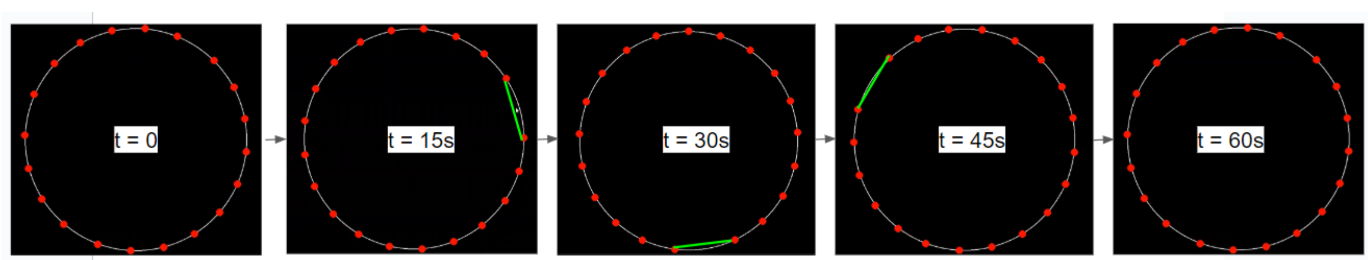

Fig. 8: Stopping distance: 80, Max speed: 2, Stopping speed: 0. The span shots taken at t = 0, 15, 30, 45, 60 secs