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Application of Command Shaping to a Convoy of Ground Vehicles

Chad A. Henderson, Matthew G. Feemster, *Member, IEEE* and Michael J. Robertson

Abstract— **This paper documents the effect that command shaping has on the inter-vehicular spacing performance of autonomous convoys. The control method is based only on distance measurements between vehicles in the platoon. The lead vehicle's longitudinal controller was developed to follow a given velocity. The follower vehicles maintain the desired spacing using distance measurements to the preceding and following vehicles. Three overall control schemes were experimentally tested: PD control without lead vehicle velocity information, PD control with lead vehicle velocity information and PID control without lead vehicle velocity information. In all cases adding command shaping led to improved performance. This approach leads to more physically realizable controller efforts for the follower vehicles and helps maintain and improve string stability.**

I. INTRODUCTION

AUTOMATED vehicle convoys have been proposed as an alternative to human drivers in private, commercial and military convoys. These platoons of autonomous vehicles are able to safely reduce the spacing between vehicles, which would increase the throughput of a given stretch of road and therefore increase overall driving effectiveness of traffic patterns.

There are currently two different types of control approaches: point-follower control and vehicle-follower control [1]. Point-follower control requires communication between the vehicle and the roadway, whereas vehicle-follower control requires inter-vehicular communication. The point-follower control method has been shown to be a very simple and effective method when dealing with a platoon of a given number of vehicles. However when the number of vehicles in the platoon may vary, vehicle-follower control has proven to be the most valuable method.

Since in most real-life scenarios where autonomous vehicle convoys would be used there would be platoons of varying lengths, it is obvious that the vehicle-follower control shows the most potential. There have been numerous studies looking into the control challenges presented by using the vehicle-follower model. Chien and Ioannou [2] demonstrated it was impossible to design a stable constant vehicle spacing convoy using only the spacing to and velocity of the preceding vehicle. However, it has been shown that a vehicle-follower control strategy can be stable if the follower vehicle has access to either: 1) information about both the vehicles immediate predecessor and the lead vehicle of the platoon [3,4]; or 2) information about both the vehicle's immediate predecessor and follower [5].

Yanakiev and Kanellakopoulos [6] were the first to develop a mass-spring-damper system to model an autonomous vehicle convoy. It was this research that inspired the investigation of the effect of command shaping on autonomous platoon vehicles.

Miller [7] demonstrated that varying a convoy's velocity or separating distances using command shaping is possible while still maintaining a stable system. This paper will compare the performance of a PD controller without lead vehicle velocity information, PD controller with lead vehicle velocity information and a PID controller without lead vehicle velocity information and document the effects command shaping has on the overall convoy performance. The efficacy of the command shaping approach is verified in experiment on a three member convoy.

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C. A. Henderson was with the Systems Engineering Department, United States Naval Academy. He is now an Ensign in the United States Navy.

M. G. Feemster is with the Systems Engineering Department, United States Naval Academy, Annapolis, MD 20402 USA (e-mail: feemster@usna.edu).

M. J. Robertson is with the Systems Engineering Department, United States Naval Academy, Annapolis, MD 20402 USA (corresponding author, phone: 410-293-6188; fax: 410-293-2215; e-mail: mroberts@usna.edu).

II. COMMAND SHAPING

There have been many attempts to control unwanted vibrations in systems. One more recent and successful attempt was developed by O.J.M. Smith [8]. In his attempt he separated a given input step into two steps of smaller magnitude, the second step being delayed by a one-half period of vibration of the system. This type of shaper was also very sensitive to modeling errors. This process is demonstrated in Fig: 1.

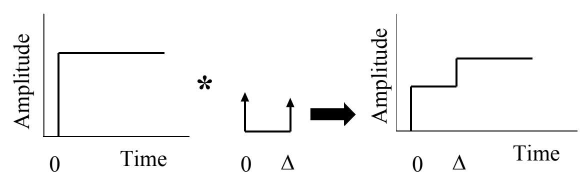

Fig: 1 Input Shaping Example

The amplitudes and time locations of the impulses are determined by solving a set of constraint equations that attempt to limit the unwanted dynamic response of the system. The constraint equations are usually categorized as 1) residual vibration constraints, 2) robustness constraints, 3) impulse constraints and 4) time-optimality.

The constraint on vibration amplitude can be expressed as the ratio of residual vibration amplitude with shaping to that without shaping. The vibration from a series of impulses is divided by the vibration from a single impulse to get the percentage vibration:

$$V(\omega,\zeta) = e^{-\zeta\omega t_n} \sqrt{[C(\omega,\zeta)]^2 + [S(\omega,\zeta)]^2} \quad (1)$$

where,

$$C(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i} \cos\left(\omega\sqrt{1-\zeta^2}\, t_i\right) \quad (2)$$

and

$$S(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i} \sin\left(\omega\sqrt{1-\zeta^2}\, t_i\right) \quad (3)$$

If $V(\omega,\zeta)$ is set equal to zero at the modeling parameters, (ω_m,ζ_m), then a shaper that satisfies (1) is called a Zero Vibration (ZV) shaper.

In order to make input shaping work well on most real systems, the constraint equations must ensure that there is robustness to modeling errors. Singer and Seering developed a form of robust input shaping by setting the derivative with respect to the frequency of the residual vibration, Equation (1), equal to zero. The resulting shaper is called a Zero Vibration and Derivative (ZVD) shaper [9]. The improved robustness can be seen by plotting a shaper's sensitivity curve– amplitude of vibration vs. modeling error. Fig: 2 shows an example of a sensitivity curve.

In Fig: 2, a 5% residual vibration is considered to be the acceptable level. Using this as the standard level, a ZV shaper has an insensitivity of 0.06. This means that the shaper limits the residual vibration below the tolerable limit for $\omega_{\text{actual}} = \omega_{\text{model}} \pm 3\%$. The ZVD shaper created has an insensitivity of 0.28. The price paid for this increase in robustness is the increase in shaper duration (Δ in Fig: 1). The ZV shaper's duration is on the order of 1/2 the period of vibration while the ZVD's duration is on the order of 1 period of vibration.

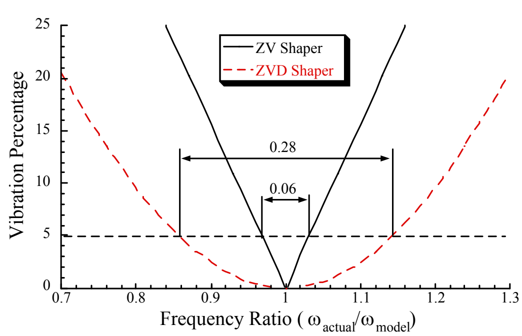

Fig: 2 Sensitivity Plot

III. AUTOMATED VEHICLE CONVOY MODEL

The model consists of a three-vehicle platoon where each vehicle is assumed to have a 1st order response given by

$$G(s) = \frac{b}{(s+b)} = \frac{\Omega(s)}{\Omega_c(s)} \quad (4)$$

where $\Omega(s)$ represents the vehicle's longitudinal velocity and $\Omega_c(s)$ denotes the commanded forward velocity. The model of (4) assumes the vehicle can be modeled as a lumped parameter, linear time-invariant model.

Remark: In the subsequent experiments, a low-level, PI velocity controller will be executed on each convoy vehicle in order to produce the designated structure of (4).

While acceleration and braking profiles, and transmission and drive train dynamics have significant effects on vehicle performance, they are ignored here in order to focus on the controller development and evaluation. The lead vehicle is the only vehicle with access to the desired velocity. The follower vehicles have access to the distance to the preceding vehicle as well as the distance to the immediate follower. The last vehicle will receive the distance from the preceding vehicle as well as the distance to a virtual following vehicle whose distance is always equal to the desired spacing [5]. A PI control is used to maintain the lead vehicle at the desired velocity and a PD controller is utilized for the follower vehicles to maintain the desired distance between it and the preceding/following vehicle. These controllers are explicitly given by

$$u_1 = K_{p1}(v_d - v_1) + K_{i1}\int (v_d - v_1)dt \quad (5)$$

and

$$u_i = K_{pi}(x_{i+1} - x_i - x_{i-1} - x_{vsi}) + K_{di}(\dot{x}_{i+1} - \dot{x}_i - \dot{x}_{i-1}) \quad (6)$$

where v_d is the desired velocity and x_{vsi} i is the desired spacing between vehicles i and $i+1$.

Command shapers have been developed to filter real-time changes in desired velocity to reduce settling time to the new velocities and reduce the overall actuation needed to reach the desired state. One of the first applications of command shaping on automated convoys was focused on reducing actuator effort in heavy truck platoons, but the study did not focus on results with respect to velocity tracking and/or inter-vehicular spacing [10]. In this paper, the command shaper is designed to eliminate the "vibration" in the velocity and position of the follower vehicles. The only place reference commands enter the systems is in the desired velocity sent to the lead vehicle, so this is where the command shaper is located. The shaped commands must first pass through the velocity control loop of the lead vehicle. This does little to change the vibration-reducing effectiveness of the command shapers.

IV. EXPERIMENTAL RESULTS

In order to demonstrate the efficacy of including Command Shaping in an interspacing control algorithm, an experimental convoy consisting of three vehicles was utilized. The convoy vehicle selected for the verification of the control algorithm was a custom, two drive wheel, non-holonomic robot constructed by the Systems Engineering Department (see Fig: 3)

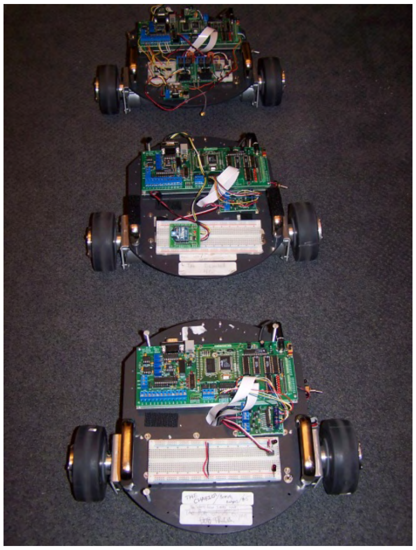

Fig: 3: Three member convoy

Each vehicle was equipped with a Rabbit 2000 micro-processor for execution of the control calculations and a wireless XBee serial modem for receiving information from a base PC station. Rather than utilize an odometry method for estimation of the vehicles' position (each vehicle motor is equipped with a 5000 $(count / rev)$ optical encoder), the VICON motion capture system [11] was employed to provide precision position feedback measurement. In order for the VICON system to uniquely identify the position and heading of each vehicle, a distinctive pattern of spherical, infrared reflectors (retro-reflective fiducials) was arranged on top of each vehicle. The measured global position and heading of each convoy member was measured within the VICON system's field of view (approximately a $3 \times 3(m)$ work environment - see Fig: 4) and subsequently sent to the MATLAB software environment for serial broadcasting of the position and heading of each convoy member via the wireless XBee modem.

Remark: Each convoy member receives the position of each vehicle; therefore, the interspacing distances d_{21} and d_{23} can be easily calculated.

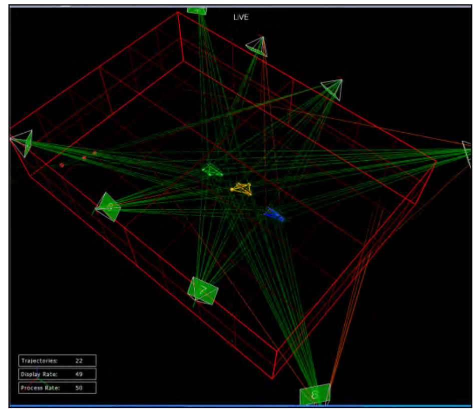

Fig: 4: Convoy pose via VICON measurement system

In order to promote straight-line tracking of the convoy, a low-level velocity/heading controller was implemented. The vehicle's measured its initial heading and subsequently adjusted the difference in wheel velocities to maintain that commanded initial heading.

Remark: With utilization of the VICON capture system, it is not essential for the vehicles to maintain a straight profile (*i.e.*, each vehicle directly behind the other). Previous experimental test-beds utilized infrared/ultrasonic sensors mounted on the front/rear of the vehicle to measure interspacing distance which mandated that the vehicles maintain a somewhat straight motion so as to remain within the sensor's field of view. To account for this ability, the interspacing distance between the i^{th} and j^{th} vehicle was calculated as follows

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_j - y_i\right)^2} \qquad (7)$$

Clearly, the potential exists for a latter convoy member to pass the lead vehicle and still achieve the control objective due to the unsigned nature of (7); however, the initial alignment of the vehicles in a straight-line coupled with execution of the low-level heading control precludes this from happening during experimental trials. The interspacing velocity signal was calculated using a backwards difference algorithm applied to d_{ij}.

A. *Experiment #1*

For each set of experiments. the lead vehicle was commanded to guide the convoy forward at a velocity of $0.3048\ (m/\sec)$ for $10.0\ (\sec)$ and then commanded to zero velocity. The convoy vehicles were set to maintain a desired interspacing distance of $D = 0.5\ (m)$. For this experimental set, the base interspacing control was executed as a proportional derivative (PD) algorithm with proportional/derivative gains K_p and K_d, respectively as shown in Table 1. In addition, the base velocity the lead vehicle was not shared with convoy members.

	K_p	K_d	Command Shaping	Lead vehicle velocity shared
LG PD	0.5	0.05	No	No
HG PD	2.0	0.05	No	No
HG PD + CmdShp	2.0	0.05	Yes	No

Table 1: Experimental test matrix #1

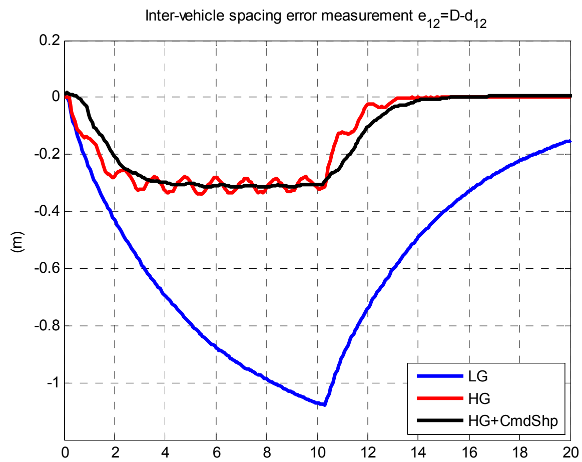

Fig: 5: Inter-vehicle spacing error $e_{12} = D - d_{12}$

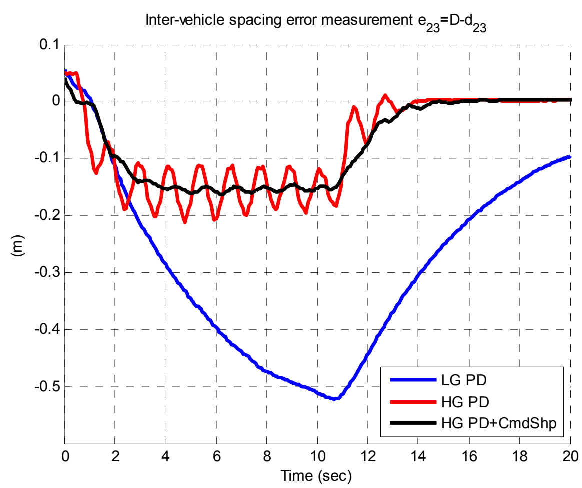

Fig: 6: Inter-vehicle spacing error $e_{23} = D - d_{23}$

As observed in Fig: 5 and Fig: 6, the low PD gain experiment with base velocity of the lead vehicle NOT known (LG PD) amongst the convoy members resulted in the presence of steady state error (SSE) in the inter-spacing distances d_{12} and d_{23} while the lead vehicle was in motion. In an effort to improve SSE, a higher proportional gain value K_p was selected which resulted in reduced tracking error yet manifested unwanted oscillations. To attenuate these oscillations while maintaining improved SSE performance, the high gain PD inter-spacing controller was augmented with Command Shaping (HG PD+CmdShp) as shown in Fig: 5 and Fig: 6. However, the observed bias in the tracking error still persists.

B. *Experiment #2*

In an effort to eliminate the constant inter-vehicle spacing tracking error observed in the results of Experiment #1, the lead vehicle's commanded forward velocity was shared among. Table 1 summarizes the experiments performed.

	K_p	K_d	Command Shaping	Lead vehicle velocity shared
LG PD	0.5	0.05	No	Yes
HG PD	2.0	0.05	No	Yes
HG PD + CmdShp	2.0	0.05	Yes	Yes

Table 2: Experimental test matrix #2

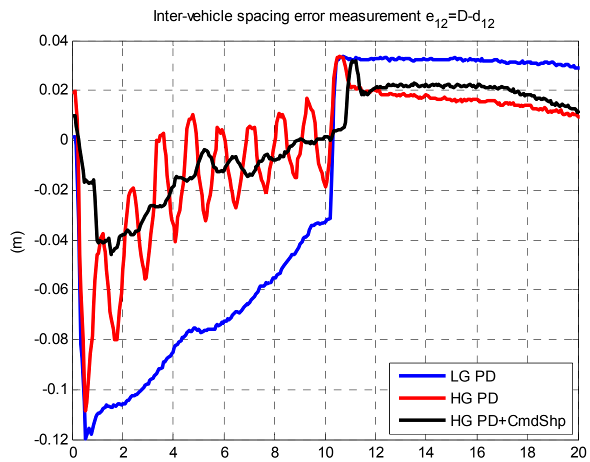

Fig: 7: Inter-vehicle spacing error $e_{12} = D - d_{12}$

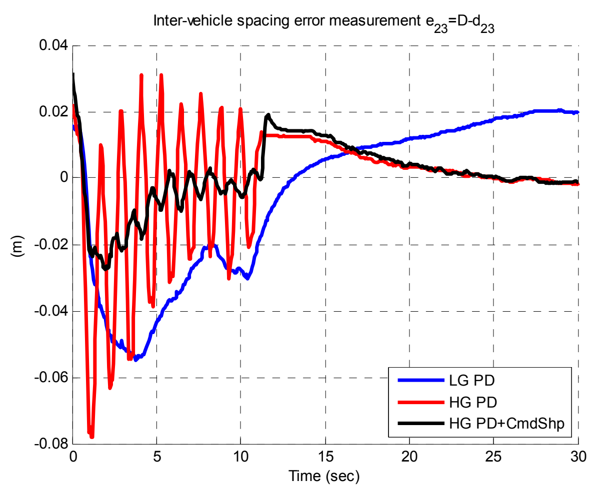

Fig: 8: Inter-vehicle spacing error $e_{23} = D - d_{23}$

The low PD gain value experiment (LG PD) of Fig: 7 and Fig: 8 augmented with the lead vehicle's base velocity command allowed for convergence to the desired interspacing distance D, yet in a somewhat sluggish manner. As a result, the higher PD gain values of experiment #2 (HG PD) improved the transient results; however, noticeable oscillations were the by product. In order to address this issue, a command shaper was employed to reduce the lightly damped, 1.125 Hz oscillation seen in the convoy's spacing response. Using [9] and the estimate of the natural frequency and damping ratio, the following shaper was used to modify the lead vehicle's velocity command (see Fig: 11)

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} 0.2908 & 0.4969 & 0.2123 \\ 0 & 0.445 & 0.89 \end{bmatrix} \quad (8)$$

With the addition of the Command Shaping algorithm (HG+CmdShp), the improved transient results is maintained while the undesirable oscillations are attenuated as observed in the responses of Fig: 7 and Fig: 8.

C. *Experiment #3*

The sharing/broadcasting of the lead vehicle's commanded velocity in Experiment Set #2 is not feasible or practical for fielded solution; therefore, the previous PD interspacing algorithm was augmented with an integral term (PID) in order to reduce the steady state inter-vehicular spacing seen during the move. Table 2 shows the gains used in this experiment set.

	K_p	K_d	K_i	Command Shaping	Lead vehicle speed shared
(LG PID)	1.8	1.7	0.1	No	No
(HG PID)	4.1	3.4	0.5	No	No
(HG PID+CMD)	4.1	3.4	0.5	Yes	No

Table 3: Experimental test matrix #3

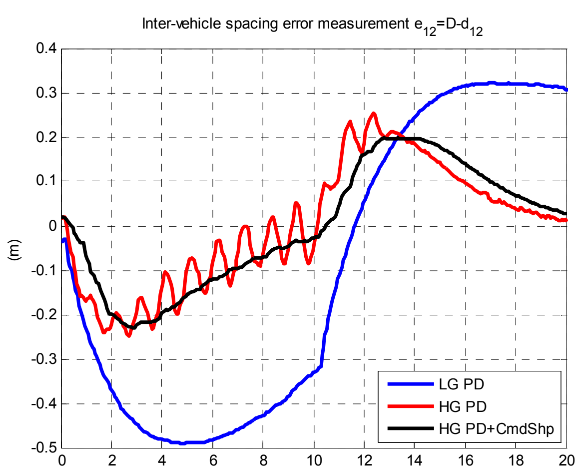

Fig: 9: Inter-vehicle spacing error $e_{12} = D - d_{12}$

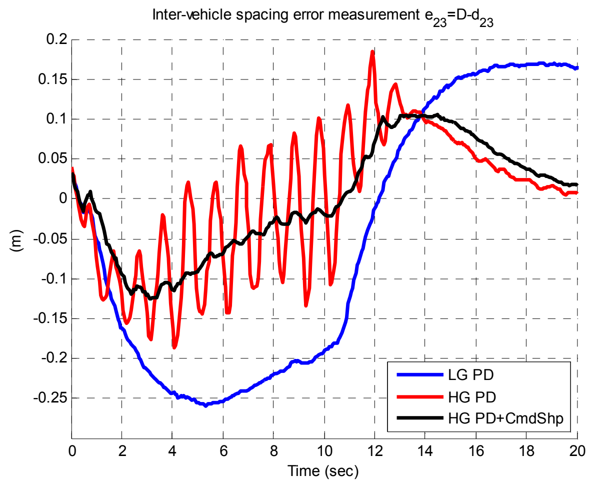

Fig: 10: Inter-vehicle spacing error $e_{23} = D - d_{23}$

As observed in Fig: 9 and Fig: 10, the low PID gain experiment exhibits slow convergence to the desired inter-spacing distance of $0.5(m)$. The transient performance is improved by increasing the values of the PID gains; however, oscillatory behavior is once again observed. By using the following command shaper,

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} 0.2908 & 0.4969 & 0.2123 \\ 0 & 0.5006 & 1.012 \end{bmatrix} \quad (9)$$

the oscillations observed as a results of other HG PD controllers are attenuated (see Fig: 9 and Fig: 10).

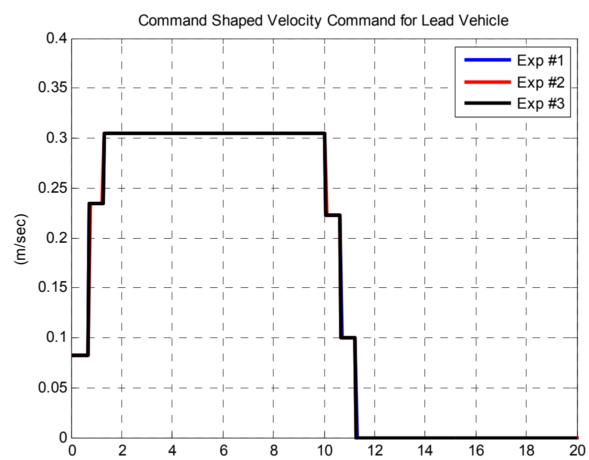

Fig: 11: Command Shaped forward velocity command for lead vehicle

Fig: 11 displays the Command Shaped velocity signal for the lead vehicle across Experiments #1 through #3. Though one expects approximately similar shaped input commands for Experiments #1 and #2 (since the HG PD values are identical), it is interesting to note that the PID Command Shaped velocity command signal for the lead vehicle, is similar to that of Experiments #1 and #2 even though the control gains are significantly different.

V. Conclusions

This paper demonstrates the feasibility of utilizing PD and PID convoy control algorithms using only distance/velocity measurements to the preceding and following car. Selection of the controller gains (PD or PID) alone could not match the performance of controller gains with the addition of Command Shaping. In addition, the controller performance was verified experimentally on a three member convoy. Future work includes integration of Command Shaping algorithms to improve formation control performance of a convoy of autonomous vehicles (move away from straight line propagation).

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