# Two-vehicle Look-ahead Convoy Control Systems

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***Abstract*—The control system on each vehicle in a convoy requires information about the motion of preceding vehicles, in order to maintain stability and satisfy operating constraints. A two-vehicle look-ahead control strategy is proposed and investigated for the operation of a convoy, with the introduction of vehicle dynamics. Two control laws for this strategy are considered and compared. Simulation results illustrate the effect of the control strategy together with the vehicle dynamics and the response of the convoy to the presence of sudden short disturbances. They also show that the proposed control strategy can maintain string stability of the convoy system.**

*Keywords-**convoys; stability; disturbances; constraints; dynamics***

## I. INTRODUCTION

In recent years, there has been much research [1 – 7] on the coordinated operation of autonomous or semi-autonomous vehicles, so as to facilitate rapid transport with close spacing while avoiding the occurrence of collisions. The control strategy for this purpose depends both on the dynamics of the individual vehicles and on the information available to each controller. As the simplest possibility, each vehicle may be assumed to know only the relative position and velocity of the next one ahead, thereby minimizing information requirements but limiting achievable performance. More commonly, the motion of a particular vehicle, at the head of a convoy, is supposed to made known to all others, but this imposes significant communication requirements, as well as causing difficulty if convoys are to be merged. Here we wish to investigate the issue of how the availability of information is used by the proposed control strategy to achieve string stability, while introducing some different nature of the vehicles under consideration.

## II. REQUIREMENTS

For the convoy to operate satisfactorily, there are certain requirements to be satisfied. Firstly, not only must the motion of each vehicle be stable, but the system must also have the property [2 – 4] of string (or platoon) stability. This means that the effect of a disturbance, such as a sudden deceleration, has to be attenuated, preferably in a non-oscillatory manner, as it passes back along the convoy. Also, there will be constraints on the allowable values of some dynamical variables, particularly acceleration and jerk, either for the sake of comfort in a passenger vehicle or because of limitations on the propulsion systems, or both. Moreover, the system is required to function acceptably under all predictable conditions, including normal operating maneuvers as well as emergency circumstances. In this present study, we shall simulate the response of the convoy to changes in the motion of the two preceding vehicles, although for a more complete investigation the operations of merging and separation, which place further requirements on the control system, should also be considered. In addition, we shall also simulate the effect of the presence of sudden disturbances in the middle of the convoy.

## III. MODELLING

We are considering convoy operation in only one spatial dimension, as on a railway track, or a road where lane changes are not permitted. Thus, at time $t$, the position of $i$th vehicle (or some point on it) can be represented by the coordinate $x_i(t)$, its velocity by $v_i = \dot{x}_i$, its acceleration by $a_i = \dot{v}_i$ and so on. Another important variable is the inter-vehicular separation,

$$\varepsilon_i = x_{i-1} - x_i - L \tag{1}$$

where $L$ is the length of a vehicle (possibly including a desired spacing) and is assumed to be the same for each one. For simplicity, we are taking all the vehicles to be identical, although this assumption is neither entirely necessary to our discussion nor always satisfied in practice. On each vehicle, there will be a local controller, generating a signal denoted by $u_i$, which enters into the dynamical equations, in a way dependent upon the form of model assumed to be valid. Two forms of models can be considered. If we suppose that the control signal directly influences the force applied to the vehicle, which is modelled simply as an inertial mass, we obtain a model of the form

$$\dot{v}_i = f(v_i, u_i) \tag{2}$$

whereas, if the transmission from control signal to applied force is modelled as a first-order dynamic process, we have

$$\dot{a}_i = f(a_i, v_i, u_i) \tag{3}$$

where the function $f(\cdot)$, in either case, is generally nonlinear although a linear approximation may be adequate. When the system model is linear, we can conveniently solve it by the use of Laplace transforms, so that $V_i(s) = sX_i(s)$, $A_i(s) = sV_i(s)$, etc., with the conventional notation and customary assumption of zero initial conditions for the derivation of transfer functions. With nonlinear modeling, on the other hand, the analysis in general becomes much more difficult than in the linear case, as transfer functions are not available.

In this paper, we shall firstly use purely linear models for both the vehicle and the control system in deriving the appropriate transfer function. The basic control law is then modified with the addition of an integral term to minimize the spacing error, while improving the convoy response. Next, by recognizing that in reality vehicle does not respond immediately to speed changes, the vehicle dynamic model is used by representing the characteristics of the vehicle propulsion system with a simple lag system of some time constant.

## IV. CONTROL

The purpose of the control system is to maintain stable operation of the convoy, while satisfying any essential constraints on the variables, under all conditions which may be expected to occur. In normal operation, there will be some specification on the spacing, either in time or distance, between the vehicles, which the control system must enable to be satisfied, at least when the convoy is operating at a constant speed. All these requirements are potentially in conflict, and the ability of the control system to reconcile them depends on the nature and quantity of the information available to it. In our control strategy, each vehicle in the convoy obtains only the relative position and velocity of two vehicles in front of it, through measurements and/or communication links.

By way of further simplification, we consider only linear control laws, although there may well be advantages to be gained from the deliberate introduction [6] of nonlinearities, which is indeed to some extent unavoidable. For instance, if there is no vehicle within a certain distance ahead, the control system should operate so as to maintain a preassigned speed, rather than continue to accelerate or decelerate in accordance with the algorithm, which it would use if a preceding vehicle were detected. Consequently, the overall control scheme would be nonlinear at least in the sense of switching between different linear control laws at appropriate times.

## V. ANALYSIS

The simplest model with relevance to the problem is

$$\dot{v}_i = u_i \tag{4}$$

where the controller directly determines the acceleration of the vehicle.

In order to maintain a desired time separation (or headway) $h$ between successive vehicles, the control signal can be generated as

$$u_i = K_p(\varepsilon_i - hv_i) + K_v(v_{i-1} - v_i) \tag{5}$$

where $K_p$ and $K_v$ are constant gains.

The drawback with this strategy is that, in order to achieve close spacing by decreasing the headway $h$, we have to increase the gain $K_v$, potentially causing excessive acceleration demand. However, rather than relying on the supplementary information about the motion of the immediately preceding vehicle, we have proposed the control strategy that considers looking further ahead in the convoy [7]. If only relative positions and velocities are used, the control law will then have the form

$$u_i = \sum_{m=1}^{n} [K_{pm}(\delta_{im} - mhv_i) + K_{vm}(v_{i-m} - v_i)] \tag{6}$$

where

$$\delta_{im} = \sum_{l=0}^{m-1} \varepsilon_{i-l} = x_{i-m} - x_i - mL \tag{7}$$

assuming that information is available from up to $n$ vehicles ahead. Now using the simple dynamic model of (4), and taking Laplace transforms, we obtain the relation

$$X_i(s) = \sum_{m=1}^{n} G_m(s) X_{i-m}(s) \tag{8}$$

where

$$G_m(s) = \frac{K_{vm}s + K_{pm}}{s^2 + \sum_{r=1}^{n}[(K_{vr} + rhK_{pr})s + K_{pr}]} \tag{9}$$

It must, of course, be admitted that practical difficulties may limit how far it is feasible to look ahead, but at least $n = 2$ might be attainable. For this value of $n$, (6) is simplified to

$$\begin{aligned} u_i &= K_{p1}(\varepsilon_i - hv_i) + K_{p2}(\varepsilon_{i-1} - 2hv_i) \\ &\quad + K_{v1}(v_{i-1} - v_i) + K_{v2}(v_{i-2} - v_i) \end{aligned} \tag{10}$$

Taking Laplace transforms of (10) and using the constraints set in [7] gives a simplified overall response of

$$X_i(s) = \frac{K_{v1}X_{i-1}(s) + K_{v2}X_{i-2}(s)}{s + K_{v1} + K_{v2}} \quad (11)$$

In this case, the overall response is directly dependent on $K_p$'s and $h$, that is

$$K_{v1} + K_{v2} = \frac{(K_{p1} + K_{p2})}{(K_{p1} + 2K_{p2})h} \quad (12)$$

Further improvement can be made if integral terms are added into (10), where any instantaneous change in spacing with immediate preceding vehicle is smoothly eliminated, as shown in (13),

$$u_i' = u_i + K_{I1}\int(\varepsilon_i - hv_i) + K_{I2}\int(\varepsilon_{i-1} - 2hv_i) \quad (13)$$

Taking Laplace Transforms of (13) gives

$$X_i(s) = \frac{AX_{i-1}(s) + BX_{i-2}(s)}{s^3 + Cs^2 + Ds + K_{I1} + K_{I2}} \quad (14)$$

where,

$$A = K_{v1}s^2 + K_{p1}s + K_{I1}$$
$$B = K_{v2}s^2 + K_{p2}s + K_{I2}$$
$$C = K_{v1} + K_{v2} + (K_{p1} + 2K_{p2})h$$
$$D = K_{p1} + K_{p2} + (K_{I1} + 2K_{I2})h$$

Simplification of (14) can be obtained through pole-zero cancellation if and only if the following constraints are met,

$$K_{p1}^2 = 4K_{v1}K_{I1} \quad (15)$$

$$K_{p2}^2 = 4K_{v2}K_{I2} \quad (16)$$

$$(K_{p1} + K_{p2})^2 = 4(K_{v1} + K_{v2})(K_{I1} + K_{I2}) \quad (17)$$

$$[(K_{p1} + 2K_{p2})h]^2 = 4(K_{I1} + 2K_{I2})h \quad (18)$$

$$\frac{K_{p1}}{2K_{v1}} = \frac{K_{p2}}{2K_{v2}} = \frac{K_{p1} + K_{p2}}{2(K_{v1} + K_{v2})} = \frac{(K_{p1} + K_{p2})h}{2} \quad (19)$$

where all roots of (14) are maintained to be simple real roots. This leads to the same simplified overall response as in (11). The only difference is that in this case the overall response not only depends on $K_p$'s and $h$ but also on $K_I$'s, that is

$$K_{v1} + K_{v2} = \frac{(K_{I1} + K_{I2})}{(K_{I1} + 2K_{I2})h} = \frac{(K_{p1} + K_{p2})}{(K_{p1} + 2K_{p2})h} \quad (20)$$

Furthermore, it has been shown in [7] that the string stability of (11) can be achieved, which gives attenuation at all frequencies for both cases.

If the command signal does not determine the acceleration directly due to the dynamics of vehicle, we consider the model

$$\tau\dot{a}_i + a_i = u_i \quad (21)$$

for some time constant $\tau$, which represents the characteristics of vehicle propulsion system including the engine, transmission, tyres and wheels, and any other internal controllers. This time constant is incorporated in the simulation.

## VI. Simulation

To illustrate the effect of the control strategy considered in the last section, we present some examples of simulation results, which are based on a convoy of six vehicles, numbered from 0 to 5, where the lead vehicle (0) has a specified velocity profile. We consider the control given by equations (10) and (13), and use it onto the dynamic model of equation (21). Thus, in both cases, the relative positions and velocities of the next two vehicles ahead are used. The initial spacing between the front of each vehicle to the front of the next vehicle is set to 5 m. The length of a vehicle is taken to be 4 m, which is included in the initial spacing. The desired headway is set to $h$ = 1s and all of the vehicles are initially at rest. The lead vehicle then accelerates in two stages to a speed of 20 m/s, decelerates to 15 m/s, and accelerates again to 25 m/s, with the velocity changes following a smooth profile over the period of 150 s. The convoy maintains this steady speed thereafter.

To simulate the effect of disturbance in the convoy, vehicle 3 is put under sudden velocity dropped to 20 m/s at $t$ = 160 s for a few seconds, gains the convoy velocity of 25 m/s once the disturbance eases, increases speed slightly in order to catch-up with the convoy and gets back to the convoy speed once the desired convoy spacing between vehicles 2 and 3 is achieved. In the simulation results, we show the velocities and relative position of each vehicle, and the spacing between two adjacent vehicles.

### A. Case I

In this case, we use equations (1), (10) and (21), where $\tau$ = 0.2 s as suggested by [1] and the gains satisfy conditions set in [7]. There is a slight complication in the control law for the next to the leading vehicle. The control law needs to be modified because it has only one vehicle ahead of it instead of two. This is accomplished by simply setting the gains to zero which would otherwise be associated with the missing vehicle. The simulations were run for various sets of gains values within the conditions set and it appears that the gains of $K_{p1} = 0.4$, $K_{v1} = 0.16$, $K_{p2} = 0.425$ and $K_{v2} = 0.17$ give the best smooth response. The results are shown in Figures 1 to 3.

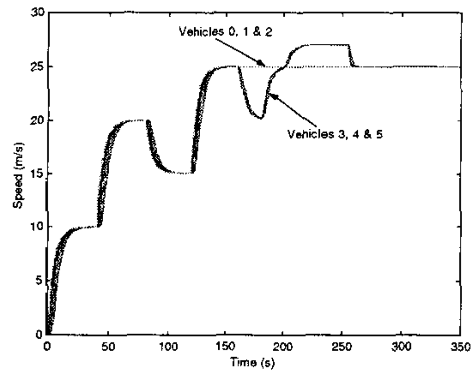


Figure 1. Speed for Case 1

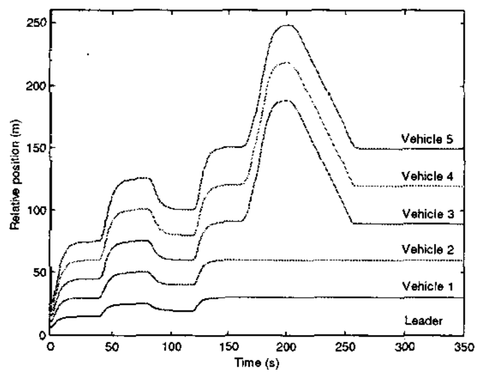


Figure 2. Relative position for Case 1

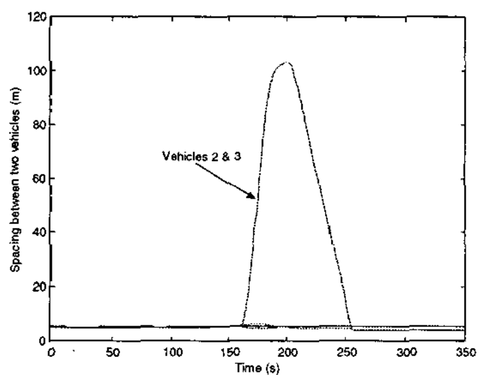


Figure 3. Spacing between vehicles for Case 1

### *B. Case 2*

For this case, we use equations (1), (13) and (21), where $\tau = 0.2$ s as before and the gains satisfy conditions (15) to (19). Again, the simulations were run for various sets of gains values within the conditions set above.

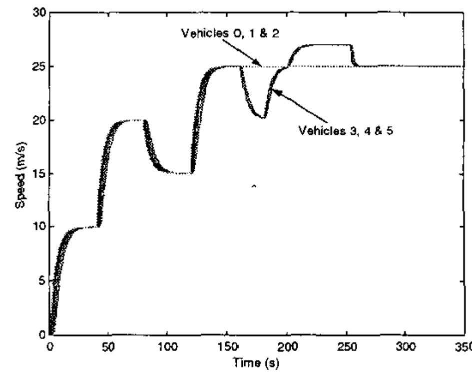


Figure 4. Speed for Case 2

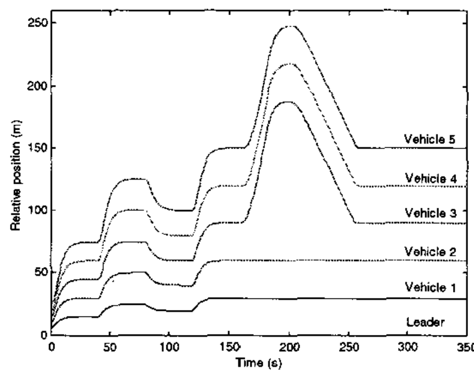


Figure 5. Relative position for Case 2

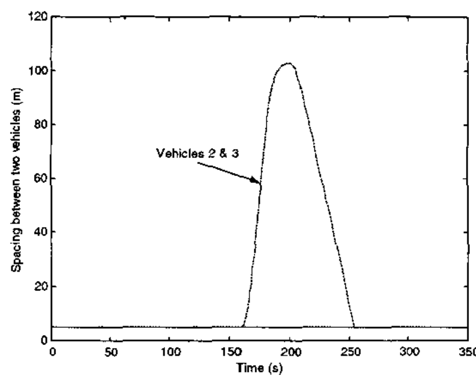


Figure 6. Spacing between vehicles for Case 2

It appears that the gains of $K_{p1} = 0.56$, $K_{v1} = 0.98$, $K_{I1} = 0.08$, $K_{p2} = 0.007$, $K_{v2} = 0.012$ and $K_{I2} = 0.001$ give the best similar response to that of Case 1. In this case, much better spacing between adjacent vehicles in the convoy is achieved especially after the merging maneuver. The results are shown in Figures 4 to 6.

## VII. Discussion

Results from the simulation for both cases considered above show that the convoy has achieved and maintained close vehicle follower. The first part of the simulation covers the time interval from 0 s to 150 s. This interval shows that all vehicles in the convoy, for Cases 1 and 2, are following the change in speed of the leader using the control law defined in equations (10) and (13), respectively, without any disturbance in the convoy. In both cases, changes in speed of the leading vehicle leads to respective changes in vehicle's speed and acceleration down the convoy. Furthermore, Figures 2 and 5 show that the spacing between two adjacent vehicles in the convoy is according to the time headway set. Small oscillation, with maximum value of less than 0.2 m, is observed during speed changes as shown in Figures 3 and 6.

The second part of the simulation covers the time interval from 150 s to 350 s, in which disturbance occurs for a few seconds on vehicle 3 at $t$ = 160 s. The convoy enters this interval at steady constant speed of 25 m/s. The change in the speed of vehicle 3, due to disturbance, can be seen in Figures 1 and 4 for both cases, respectively. The change subsequently effects vehicles 4 and 5, which automatically follow the new speed profile set by vehicle 3. Results in Figures 2 and 5 show that in the present of disturbance in the middle of the convoy, the affected vehicles down the convoy are able to maintain their safe inter-vehicle spacing and avoid unnecessary collision. Those figures also show the merging of the affected vehicles into the front group when the disturbance eases. It can be seen from those figures that the merging process of the second group terminates safely when the spacing between vehicles 2 and 3 is within the required inter-vehicle spacing at the current convoy speed.

Figure 6 shows that Case 2 gives better response at the end of the merging process when compared to the response of Case 1 in Figure 3. The main difference is the reduction of permanent spacing error between vehicles 2 and 3. While Case 1 cannot achieve the required spacing, Case 2 shows that the required spacing can be achieved by including the control law with an integral term (with appropriate tuning of gains).

Nevertheless, both cases given above show that the control laws proposed in equations (10) and (13) can react effectively (using the appropriate switching controller and gains tuning) to avoid collision down the convoy.

## VIII. Conclusion

We have proposed and investigated a two-vehicle look-ahead control strategy for the operation of a convoy system. Two types of control laws have been considered and compared. The proposed control laws have been applied to vehicle models with their dynamic characteristics represented by a time constant. From the comparison of the results in both cases above, the general performance appears to be similar in all examples considered. The choice of gains is important in achieving improvements, limiting the peak acceleration and/or enhancing the string stability of the system. In both cases considered, the proposed control laws can handle the disturbance, such as sudden decrease in vehicle's speed in the convoy, by reacting appropriately to the changes and at the same time avoiding collision. On the other hand, the control law in Case 2 appears to give better performance in reducing spacing error after the merging process, as compared to that in Case 1. Simulation results also show that the proposed control strategy can achieve string stability of the convoy system.

It should be noted, however, that we have only explored a very limited range of possibilities here, and much more may still be achievable within the same framework. In particular, constraints such as (15) to (19) are by no means obligatory, being introduced merely for simplicity and convenience. The issue of how much more could be achieved if they were removed is unclear and deserves exploration. It may be significant that further advances will require more deliberate introduction of nonlinearities, which in any event necessary in practice.

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