Novel Information Flow Topology for Vehicle Convoy Control

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Abstract. This paper analyzed a novel information flow topology (IFT) for vehicle convoy. The topology used two-vehicle look-ahead with an immediate rear-vehicle inclusive. Mass spring damper and Newton's second law were utilized to provide the behavior and basics for the vehicles motion respectively. The concept of homogeneous vehicle convoy and constant headway time (CHT) policy was in cooperated for the inter-vehicular spacing. The new IFT was compared with the conventional topology of the two-vehicle look-ahead to ascertain its improvement. The novel topology provides good inter-vehicular space of 0.42 m ahead of the conventional topology. Moreover, the proposed topology obeys the rate of change of speed throughout the vehicles journey than the conventional type. Low jerk of 0.44 ms^{-3} was achieved against 0.47 ms^{-3} of the conventional. Finally, the new topology is visible throughout the journey than the earlier, which discontinues after 117 s in all parameters.

Keywords: Jerk · Performance · Spacing · String-stability · Topology · Vehicle

1 Introduction

This paper focused to introduce a new version of information flow topology (IFT) of two-vehicle look-ahead and rear- vehicle. The concept of sting-stability would be used to tackle the issue of string instability in the convoy. String stability is the ability of the vehicle in the convoy to move without amplifying the errors of the lead vehicle downstream. In an effort to address this issue, researchers have been working on different techniques to maximize the usage of road transport to capacity and to enhance the safety and comfort of the road users. Levine and Athans [1] proposed the first mathematical model of a vehicle convoy system in the early 60 s. The study presented a system, in which the vehicle displacement and speed were regulated in a heavily dense convoy of possible number of vehicles moving in a single lane. The major features of the model includes; passengers comfort, safety measures, speed control and energy wastage. Moreover, Melzer and kuo [2] developed theory of linear systems for optimal regulation presented as a countably unlimited group of agents. The theory was used for an infinite size of string of vehicles. The shortcoming of the strategies is due to

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the used of centralized controller, in which each vehicle in the convoy has direct accessibility to all the state variables of the string. [3–5] reported IFT, in which only nearest neighbors were utilized in the topology. It was evident from the work that reduction in the number of utilized neighboring vehicles, leads to undesired convoy behaviors. The research work figures out the dependency of string stability to measurements of other vehicle (bi or unidirectional) within the convoy. Decentralized control for vehicle string strategies was investigated in [6] in which relative importance of different measurements were studied in the optimal control through minimization of the cost function.

More recently, number of convoy control methods where presented in real world for demonstration purposes, which include the Safe Road Trains for the Environment (SARTRE) in Europe [7], Intelligent Transport Systems (ITS) named Energy-ITS in Japan [8], and Grand Cooperative Driving Challenge (GCDC) in Netherlands [9] etc. The oldest convoy concentrates on the use of radar-based systems for sensing, which has limited communication exchange topologies [10]. The rapid growth in vehicle technology leads to the deployment of vehicle-to-vehicle (V2V) communications, like Dedicated Short Range Communications (DSRC) and Vehicular Adhoc Networks (VANET) [11] this however, permits more variety of topologies for convoy, such as the two-predecessor following and multiple-predecessor following configurations [10, 12] to achieve better convoy string stability. Due to the challenges that arise in different vehicle convoy information topologies [13], it is more preferable to take vehicle convoy systems as a group of dynamic systems, and to design an enhanced control strategy. Sudin and Cook [14] came up with an improved vehicle convoy strategy, were two-vehicle look-ahead control strategy was utilized to achieve string stability. Oncu et al. [15] examined the influence of convoy uniform delay and sampling-hold on string stability. Bernardo et al. [16] proposed techniques to analyse vehicle convoy string stability issues with more emphasis on dynamic network control. Wang et al. [17] studied the effect of time varying network architectures on convoy using discrete-time Markov chain.

All these makes the IFT a challenging control problem. There is the need for an enhanced and more realistic IFT; hence the interest of this paper is basically on the development of a novel IFT of homogeneous vehicle convoy system. Section 2 of this paper describes the mathematical modelling of the proposed topology. An analysis on the new IFT is shown in Sect. 3. Section 4 concludes on the obtained results.

2 Materials and Methods

MATLAB R2013b platform was used for both modelling and implementation in this paper. The proposed work used the assumption of a homogeneous convoy because it eases the investigation in various mathematical presentations of convoys [13, 18]. Furthermore, it has been proved in other researches that non-homogeneity does not instantly give an enhancement on experiment in the performance of the string [19]. Linear dependent spacing policy was utilized due to its simplicity to use; it as well reveals efficient and interesting results and also insight in some cases [3]. These encourage the selection of linear dependent spacing policy among the most confronting spacing policies; constant spacing (CS) which is the fixed time spacing policy and constant headway time (CHT) policy. The CS provides fixed inter-vehicular spacing that is independent of speed of the vehicles [20, 21]. It has been reported by [22] that such spacing policy suffers a lot to string instability due to the minimal inter-vehicular spacing used and hugely depends on V2V communication [23, 24]. The CHT is speed dependent, which was utilized in this work due to its ability to remain linear in nature [25]. This gives a greater chance to fully utilize the linearity involved and achieve one of the human driving habit [26]. Hence the speed dependent policy CHT is proposed as against the CS, which is prone to collusion. The mathematical modelling is presented in the subsequent sub-heading. The two-vehicle look-ahead and rear-vehicle formulation for the IFT is discussed in this section. The technique used is based on the fact that a driver can have much control of his/her vehicle if the driver has access to monitor the rear vehicle in addition to the two vehicles in front of him/her. The IFT for the control strategy is to simulate the human driving behaviour in a real convoy scenario, in which the following vehicle do not only relay on the information received from the preceding vehicle or leading vehicle but also the rear vehicle. The rear vehicle is necessary because of safety in the convoy, which is the primary function of mirrors in vehicle. This is to give adequate respond time for the control vehicle to changes in the leader, predecessor and rear vehicle's speed to avoid front and rear collusion and to enable passengers comfort. The strategy is designed to eliminate string instability in the convoy system. Therefore the new IFT to mimic human driving habit for safe convoy is proposed.

The novel topology of the two-vehicle look-ahead and rear-vehicle is presented in Fig. 1, while the Eq (1) presents the strategic equation derived from Fig. 1.

$$\begin{aligned} m\ddot{x}_i = K_{p1}(x_{i-1} - x_i) + K_{v1}(\dot{x}_{i-1} - \dot{x}_i) + K_{p2}(x_{i-2} - x_i) + K_{v2}(\dot{x}_{i-2} - \dot{x}_i) \\ + K_{p3}(x_{i+1} - x_i) + K_{v3}(\dot{x}_{i+1} - \dot{x}_i) \end{aligned} \tag{1}$$

where: m is the vehicle mass, x_i, x_{i-1}, x_{i-2} and x_{i+1} are the instantaneous positions of the i-th, (i − 1)-th, (i − 2)-th and (i + 1)-th vehicle respectively along the X-axis, $\dot{x}_i$, $\dot{x}_{i-1}$, $\dot{x}_{i-2}$ and $\dot{x}_{i+1}$ are the correspoing velocities of the vehicles, $\ddot{x}_i$ is the acceleration of the i-th vehicle, $K_{p1}, K_{p2}, K_{p3}, K_{v1}, K_{v2}$ and K_{v3} are the constants.

The control signal $(\mathcal{U}_i)$ has direct influence on the force applied to the vehicle, which was modelled as initial mass [14].

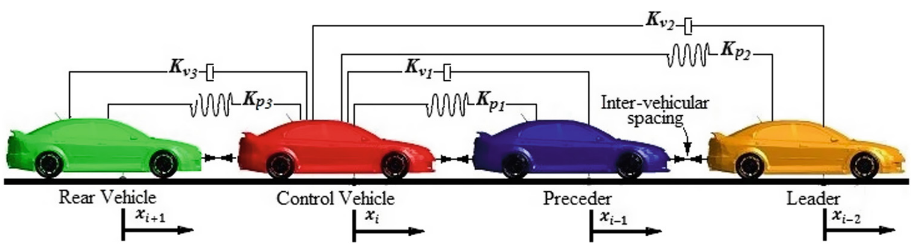

Fig. 1. Representation of the proposed control strategy.

$$\ddot{x}_i = f(\dot{x}_i, \mathcal{U}_i) \tag{2}$$

The simplified model related to the problem can be expressed as in Eq. (3):

$$\ddot{x}_i = \mathcal{U}_i \tag{3}$$

Hence, considering the fact that the following (i-th) vehicle has no influence on the three ((i − 1)-th, (i − 2)-th and (i + 1)-th) vehicles, Eq. (4) is obtained as:

$$\begin{aligned}\mathcal{U}_i = K_{p1}(x_{i-1} - x_i) + K_{p2}(x_{i-2} - x_i) + K_{p3}(x_{i+1} - x_i) + K_{v1}(\dot{x}_{i-1} - \dot{x}_i) \\ + K_{v2}(\dot{x}_{i-2} - \dot{x}_i) + K_{v3}(\dot{x}_{i+1} - \dot{x}_i)\end{aligned} \tag{4}$$

Equation (4) provides the control strategy of the two-vehicle look-ahead and rear vehicle using fixed spacing policy. [20–22, 27] reveal that the effect of string instability continues with such spacing policy. It is clear that different convoy speed required different inter-vehicular spacing [14]; this is to give enough time for the control vehicle to respond to changes in the leader, predecessor and rear vehicles' speed to avoid collusion. Hence, a more promising policy is required. Due to the fact mentioned here, the speed dependent policy is employed in this model. After incorporating the spacing policy CHT in the model equation, it yields to an improved control signal equation as presented in Eq. (5):

$$\begin{aligned}\mathcal{U}_i = K_{p1}(x_{i-1} - x_i - h\dot{x}_i) + K_{p2}(x_{i-2} - x_i - 2h\dot{x}_i) + K_{p3}(x_{i+1} - x_i - h\dot{x}_i) \\ + K_{v1}(\dot{x}_{i-1} - \dot{x}_i) + K_{v2}(\dot{x}_{i-2} - \dot{x}_i) + K_{v3}(\dot{x}_{i+1} - \dot{x}_i)\end{aligned} \tag{5}$$

where: $h\dot{x}_i$ is the speed dependent spacing from the adopted spacing policy. As the convoy speed increases, the inter-vehicular spacing increases and vice versa. When the vehicles in the convoy are moving with steady speed, it is assumed that the inter-vehicular spacing between the leader vehicle (x_{i-2}) to the control vehicle (x_i) is twice that of the rear vehicle (x_{i+1}) to the control vehicle or that of predecessor vehicle (x_{i+1}) to the control vehicle.

The realized strategy of the vehicle is based on the signals received from the two-vehicles ahead and one-rear. Hence Eq. (5) can be re-written as [28]:

$$\mathcal{U}_i = \sum_{m=1}^{n} \left[k_{pm}(\delta_{im} - mh\dot{x}_i) + k_{vm}\{(\dot{x}_{i-m} - \dot{x}_i) + (\dot{x}_{i+m} - \dot{x}_i)\}\right] \tag{6}$$

where,

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

Taking the Laplace transformation of Eq. (6) gives:

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

Equation (8) yields,

$$s^2X_i = K_{p1}(X_{i-1} - X_i - hsX_i) + K_{p2}(X_{i-2} - X_i - 2hsX_i) + K_{p3}(X_{i+1} - X_i - hsX_i) \\ + K_{v1}s(X_{i-1} - X_i) + K_{v2}s(X_{i-2} - X_i) + K_{v3}s(X_{i+1} - X_i) \tag{9}$$

Re-arranging for X_i from Eq. (9) gives,

$$X_i = \frac{(K_{v1}s + K_{p1})X_{i-1} + (K_{v2}s + K_{p2})X_{i-2} + (K_{v3}s + K_{p3})X_{i+1}}{s^2 + [K_{v1} + K_{v2} + K_{v3} + (K_{p1} + 2K_{p2} + K_{p3})h]s + K_{p1} + K_{p2} + K_{p3}} \tag{10}$$

Further re-arranging Eq. (10) and reducing to a single pole system results to the following,

$$X_i = \frac{K_{v1}\left(s + \frac{K_{p1}}{K_{v1}}\right)X_{i-1} + K_{v2}\left(s + \frac{K_{p2}}{K_{v2}}\right)X_{i-2} + K_{v3}\left(s + \frac{K_{p3}}{K_{v3}}\right)X_{i+1}}{s^2 + (K_{p1} + 2K_{p2} + K_{p3})hs + K_{v1}\left(s + \frac{K_{p1}}{K_{v1}}\right) + K_{v2}\left(s + \frac{K_{p2}}{K_{v2}}\right) + K_{v3}\left(s + \frac{K_{p3}}{K_{v3}}\right)} \tag{11}$$

Hence:

$$X_i = \frac{K_{v1}\left(s + \frac{K_{p1}}{K_{v1}}\right)X_{i-1} + K_{v2}\left(s + \frac{K_{p2}}{K_{v2}}\right)X_{i-2} + K_{v3}\left(s + \frac{K_{p3}}{K_{v3}}\right)X_{i+1}}{s[s + (K_{p1} + 2K_{p2} + K_{p3})h] + K_{v1}\left(s + \frac{K_{p1}}{K_{v1}}\right) + K_{v2}\left(s + \frac{K_{p2}}{K_{v2}}\right) + K_{v3}\left(s + \frac{K_{p3}}{K_{v3}}\right)} \tag{12}$$

Several ways have been proposed by researchers to guarantee string stability to their developed control strategies [29]. To achieve stable string stability and reduce the complexity of the control law, the pole and zero cancellation is proposed. This aimed at reducing Eq. (12) to a single pole system (linear equation). To linearize Eq. (12) the pole and zero cancellation technique was used through the following constraint.

$$\frac{K_{p1}}{K_{v1}} = \frac{K_{p2}}{K_{v2}} = \frac{K_{p3}}{K_{v3}} = (K_{p1} + 2K_{p2} + K_{p3})h \tag{13}$$

This result to the simplification of Eqs. (12) to (14) as:

$$X_i = \frac{K_{v1}X_{i-1} + K_{v2}X_{i-2} + K_{v3}X_{i+1}}{s + K_{v1} + K_{v2} + K_{v3}} \tag{14}$$

Equation (12) is first order and the poles of the equation are on the left hand side of the s-plane since K_{v1} to K_{v3} are all positive. This implies that the mathematical model of the two-vehicle look-ahead and rear-vehicle system of Eq. (5) is string stable with respect to the constraint of Eq. (13) as shown in Eq. (14). Hence, the system response of the convoy depends to h and $K_p's$ as seen from Eq. (15).

$$K_{v1} + K_{v2} + K_{v3} = \frac{K_{p1} + K_{p2} + K_{p3}}{\left(K_{p1} + 2K_{p2} + K_{p3}\right)h} \quad (15)$$

2.1 Modelling Procedure

The model was built on MATLAB R2013b platform following the derived control strategy Eq. (5). The Simulink representation of the strategy is represented on Fig. 2. The model uses the CTH policy to provide the speed dependent spacing policy were the inter-vehicular spacing depends on the speed of the leader, predecessor and rear vehicles collectively. The novel topology with the adopted policy provides adequate spacing, minimises the chance of collusion and guaranteed stable string within the convoy.

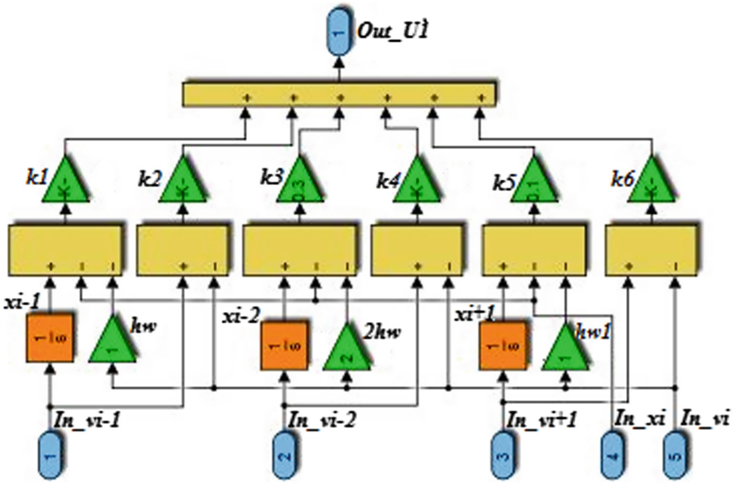

Fig. 2. Single car control strategy for the proposed convoy.

The control strategy was implemented in Fig. 2 and cascaded with a vehicle design by Sudin and Cook [14] to enable test the new topology with that of [14].

The top-level of the proposed model was shown in Fig. 3. This shows identical vehicles arrangement, were vehicle_1–4 represents the set of homogeneous vehicles in the order of leader, predecessor, control vehicle (vehicle_3) and rear vehicle respectively. The main input block in Fig. 3 provides the input speed to the independent vehicles in the convoy, initial position block gives an arbitrary position of each vehicle within the convoy, while position compare block compares the displacement of each vehicle with the control vehicle. This deliberate design provides a new knowledge in vehicle convoy IFT with more realistic human driving habit.

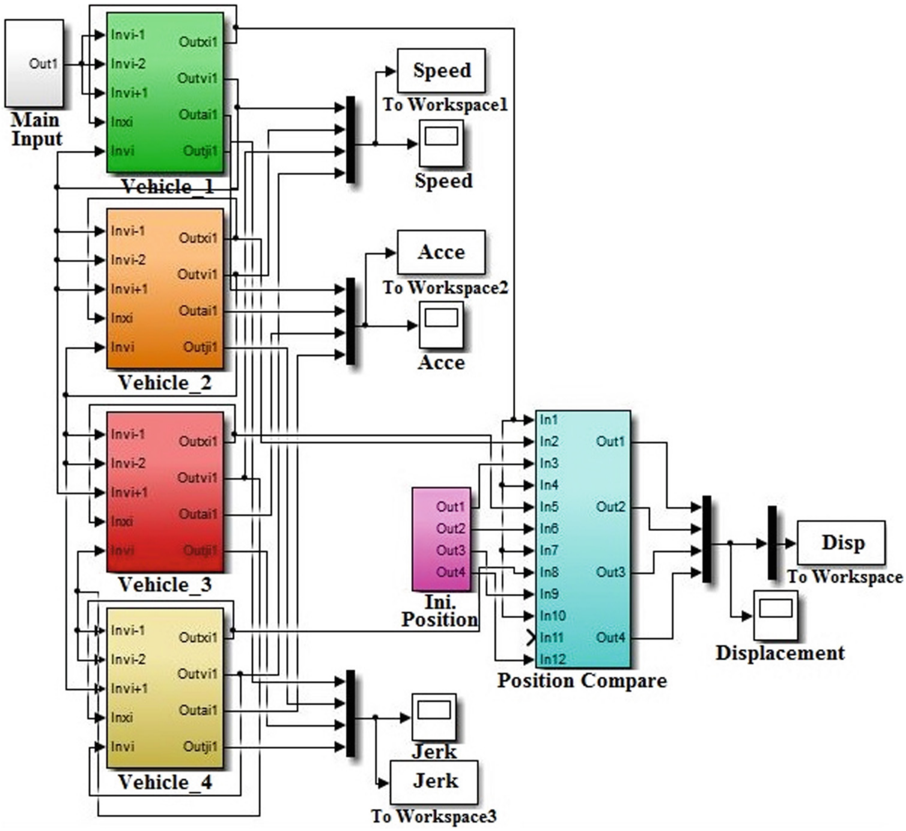

Fig. 3. Centralized control strategy for the proposed convoy.

3 Results and Analysis

The outcomes of the simulation of the proposed model were presented in this section and are used to compare with that of [14] to justify the improvements achieved with respect to the new topology. The model Eq. (5) was tested using the poles and zeros cancellation technique where proper cancellation was conducted with high convoy stability. The following simulations give an inside on the new topology as compare to that of Sudin and Cook [14].

Figure 4 shows a variable spacing of the proposed topology, where equal spacing was achieved among the vehicles with respect to any variation in speed of the vehicles. This indicator gives an improved and string stable IFT than that of Fig. 5. The new topology permits a smooth and free running of the vehicle over a period of 160 s of test with peak spacing of 150 m. This speed dependent policy gives a wider range of inter-vehicular spacing of maximum of 37.5 m apart; it also permits the control vehicle to react to sudden changes in speed of the other vehicles. As seen in Fig. 4, the maximum spacing from the new topology prevents collusion among the stream of the vehicle due to wide spacing apart when the vehicle accelerated and vice versa.

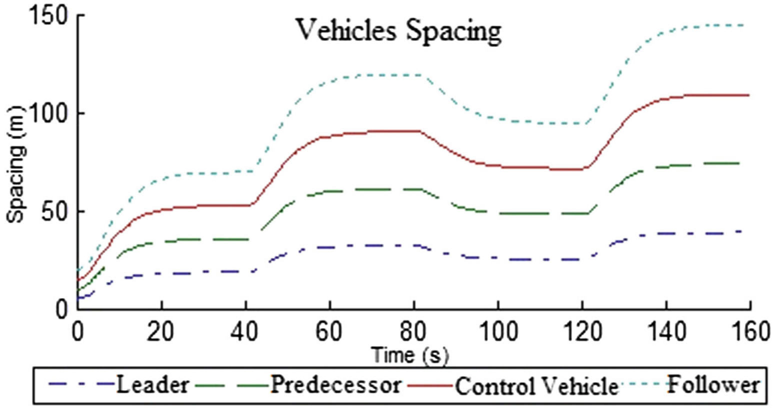

Fig. 4. Spacing of the proposed convoy control strategy.

Figure 5 shows the spacing achieved of the conventional two-vehicle look-ahead topology. The strategy uses CHT but has the following short comings of, chattering habit as seen for the first 70 s and with maximum spacing of only 33.3 m apart, which indicated the possibility of collusion among the vehicles on high speed. This topology runs for 160 s but was only visible for the first 115 s and truncated for the last 45 s due to the ill condition of the approach, which limits the study on its properties.

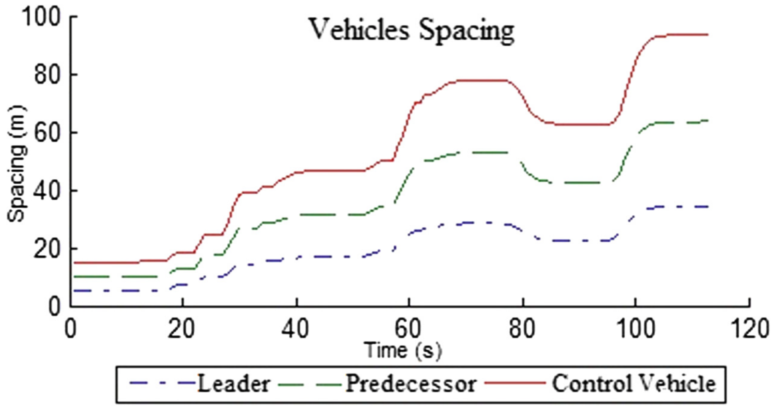

Fig. 5. Spacing of the two-vehicle look-ahead convoy control strategy.

Figure 6 reveals how the control vehicle of the proposed topology closely tracks the path of the leader, predecessor and follower vehicle speeds without collusion. This shows the ability of the control vehicle to depend hugely on the acceleration, deceleration and constant speed of the neighbouring vehicles within the convoy as compared to Fig. 7.

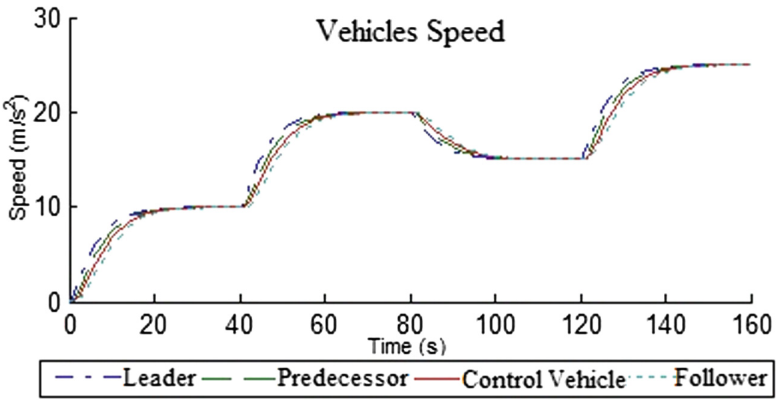

Fig. 6. Speed of the proposed convoy control strategy.

Figure 7 shows the lapses in the speed of the conventional against the novel topology. The speed is affected by the chattering effect within the first 70 s this shows an unrequired variation in speed, which caused an overlap in speed among the vehicles even at low speed of 30 ms^{-1}. Moreover, the convoy runs for 160 s but was only visible for 115 s due to the ill condition of the model, hence no account for the remaining 45 s is known.

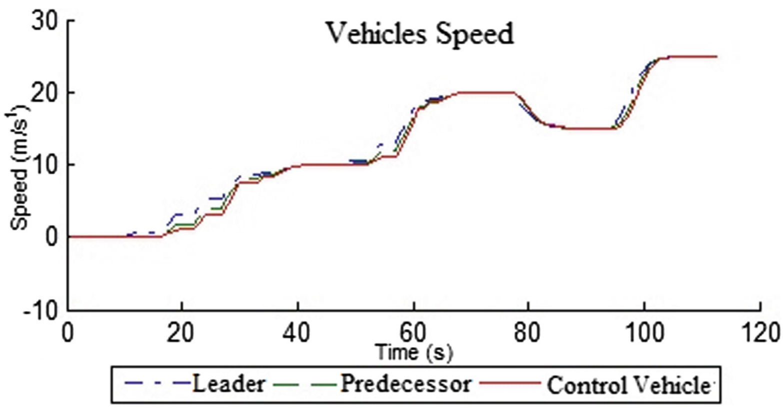

Fig. 7. Speed of the two-vehicle look-ahead convoy control strategy.

Figure 8 presents the acceleration of all the vehicles in the new topology. The rate of change of velocity in the control vehicle is maintained at maximum acceleration of 0.92 ms^{-2}, which is below the acceptable acceleration of 2 ms^{-2} [30]. The control vehicle's acceleration is between that of the predecessor and the follower, no single place where the control vehicle's acceleration overlaps that of other vehicles. This shows proper control of acceleration as compared to the conventional Fig. 9.

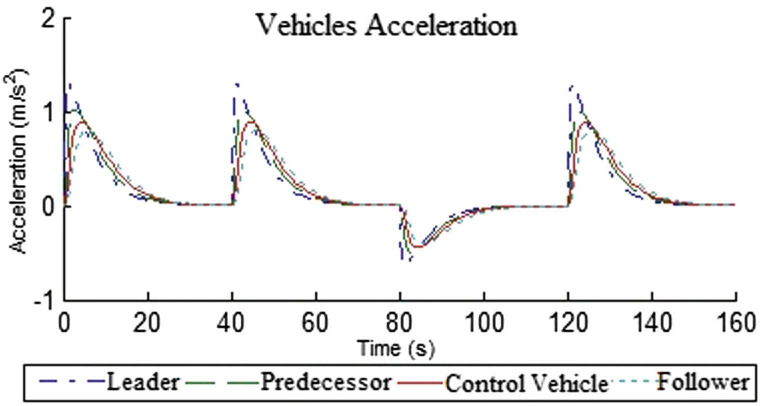

Fig. 8. Acceleration of the proposed convoy control strategy.

It is evidence that inconsistent acceleration is observed in Fig. 9. The control vehicle was controlled at a maximum acceleration of 1.0 ms^{-2}, which is however outstanding. The bone of contention to this acceleration is the chattering phenomena at the first 70 s of the journey and was discontinued at 115 s only during a journey of 160 s, moreover, the maximum acceleration of the control vehicle in Fig. 9 was high (1.0 ms^{-2}) as compared to the proposed topology (0.92 ms^{-2}). This slight difference in control vehicle acceleration in both cases has reasonable consequence on the final control vehicle's jerk, on which the overall passenger's comfortability depends.

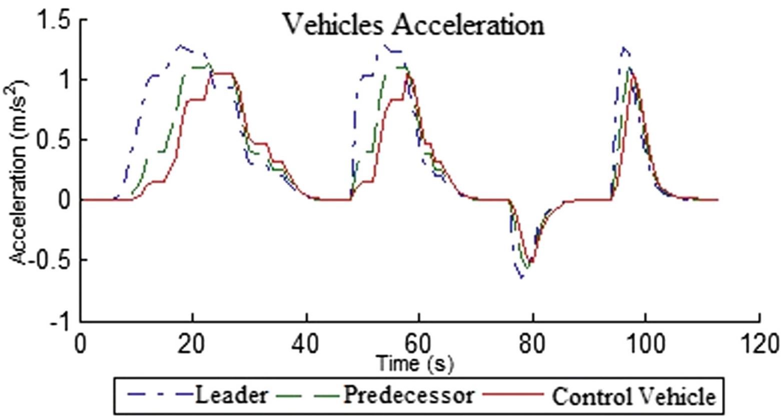

Fig. 9. Acceleration of the two-vehicle look-ahead convoy control strategy.

The smaller the jerk, the more comfortable is the vehicle and vice versa. The jerk of the control vehicle was found from Fig. 10 as 0.44 ms^{-3}, which is pretty well below the maximum accepted jerk of 5 ms^{-3} [31]. This 0.44 ms^{-3} proved that the control vehicle would be comfortable for passengers [14] compared to that of Fig. 11.

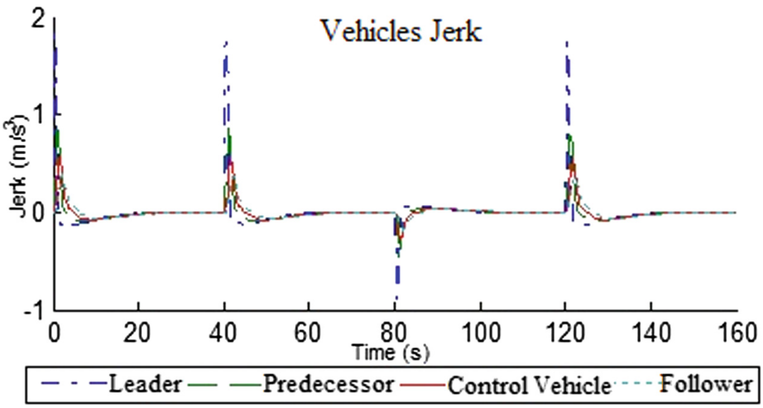

Fig. 10. Jerk of the proposed convoy control strategy.

The simulation result of Fig. 11 shows fast response with undesirable jerk of 0.47 ms^{-3}. The undesired oscillation produced in the simulation is due to the fact that small oscillation occurs as the vehicle is trying to settle down at its final speed in the two-vehicle look-ahead topology. The jerk is higher than that of the proposed topology with value of 0.03 ms^{-3}. This difference in jerk in addition to the oscillation would leads to passenger's discomfort.

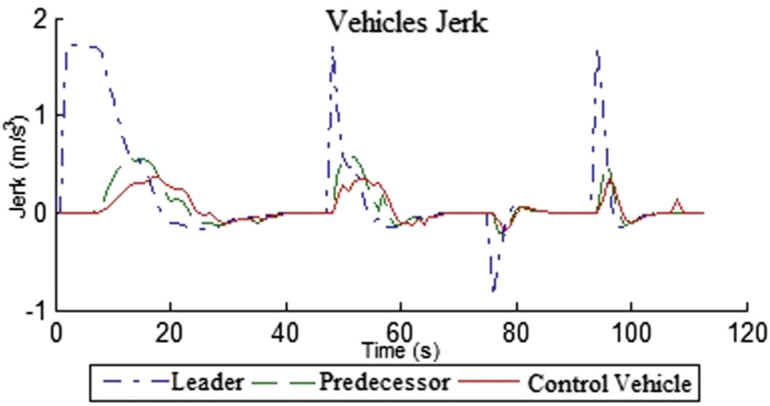

Fig. 11. Jerk of the two-vehicle look-ahead convoy control strategy.

4 Conclusions

The new topology gives an improved performance on the inter-vehicular spacing with no chattering effect and is visible throughout the journey. The spacing for the four vehicles is spread equally over distance of 150 m, i.e. 37.5 m apart. Sufficient inter-vehicular spacing of 37.5 m apart was achieved as against 33.3 m of the conventional topology. The large spacing of 37.5 m permits the control vehicle to react to any change in speed of the neighbouring vehicles within the convoy. The speed of the control vehicle is well arranged without an overlap as compared to that of the two-vehicle look-ahead, which was overlapped at some points within the journey. The overlap in speed results to collision of the vehicles. Rate of change of velocity is low on the control vehicle (0.92 ms^{-2}) as compared to that on the conventional topology (1.1 ms^{-2}). The lower the rate of changes of velocity, the better the control vehicle's jerk [14]. A jerk of 0.44 ms^{-3} was realised in the proposed topology as compared to that of the conventional topology (0.47 ms^{-3}). The low jerk provides passengers comfortability throughout the journey.

The proposed IFT is strictly based on centralized control, where the behaviour of each independent vehicle of the convoy is determined by a given input speed. The control vehicle used the collective behaviours of the neighbouring vehicles and make decisions on its movement and position. The novel topology prevents collusion, enhanced passengers comfort and improved the overall convoy's string stability.

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