How small can headways be in platoons of connected autonomous vehicles?

Yingyan Lou[1], Ph.D.
School of Sustainable Engineering and the Built Environment
Arizona State University

Key Words

Connected and autonomous vehicles, minimal headway, trajectory planning

Introduction

Connected and autonomous vehicle (CAV) technologies are currently being developed and road-tested at an unprecedented rate. The technologies have being applied to various transportation safety and mobility applications, and are expected to continue driving innovations in transportation. Platooning is one of many CAV mobility applications. While the concept of platooning is at least two decades old, CAV technologies have enabled new approaches such as cooperative adaptive cruise control (CACC), and have brought forth new optimism that inter-vehicle headways can be virtually infinitesimal due to a virtually nonexistent reaction time. This might be the case under stationary condition, or for a group of vehicles whose trajectories are planned ahead. However, it may not be achievable when vehicles with different initial states (position, speed, and acceleration) merge into a single platoon. This research aims to investigate the limit of vehicle headways in CAV platoons as a function of the initial states of a pair of leading and following vehicles.

The problem is essentially a trajectory planning problem, where not only vehicle headway after the platoon has been formed is of interest, but also during the platoon formation process. The trajectory planning problem is applicable to the following vehicle only, as we assume that the lead vehicle's trajectory is given and no further adjustment is allowed. This assumption is consistent with existing literature, where the use scenario involves a central controller that computes and manages trajectories of approaching vehicles on a first-come first-serve basis. Same as in [1], we focus on a simple case where only piece-wise linear speed profiles are considered for trajectory planning. Two headway criteria for platoon formation are explored: constant space headway and constant (instantaneous) time headway. The latter is often considered safer and more conductive to string stability in CACC [2]. The problem then boils down to whether a feasible trajectory of the following vehicle can be constructed or not, given the trajectory of the leading vehicle, so that the two vehicles will be the desired distance apart when the platoon is formed. In this study, a feasible trajectory for the following vehicle implies that 1) there is no collision between the two vehicles, and 2) all physical constraints (bounds of acceleration and velocity) are satisfied. Note that it is entirely possible that the headway at some time point during the platoon formation process is smaller than the desired value. In fact, this is deliberately allowed in order to explore the relationship among the desired headway, the vehicles initial states, and the physical constraints.

---

[1] Presenting author. Associate Professor, Yingyan.lou@asu.edu, 480-965-6361, 660 S. College Ave., Box 873005, Tempe, AZ 85287

For the constant space headway criteria, it is found that the target space headway could potentially be any value as long as the initial conditions of the two vehicles are favorable. On the other hand, when vehicles are required to maintain a minimum constant (instantaneous) time headway at all time, it is possible that they may not be able to achieve this minimum time headway as a platoon, even with favorable initial conditions. The minimum time headway will be reached at some point during the platoon formation process and the final (instantaneous) time headway between the two vehicles will be greater than the required minimum time headway.

Methodology and Results

In this work, we do not consider power-train control due to the nature of the trajectory planning problem—the planning horizon is sufficiently long to ignore lower-level vehicle dynamics. Our analysis is based on kinematic equations. Two variables are of interest: the velocity of the following vehicle, and the (space or time) headway. The goal of the trajectory planning problem is to achieve the desired headway when the velocities of the two vehicles are matched (not necessarily matched for the first time during the platoon formation process).

Constant Space Headway

We developed an algorithm to construct a feasible trajectory for the following vehicle that can achieve the target space headway when the platoon is formed. The algorithm first determines the sequence of actions as one of the five typical patterns characterized by the initial conditions of the two vehicles (see Table 1).

Table 1 Five Typical Patterns of Action Sequences based on Initial Condition

<table>
<tr><th></th><th>$v_F < v_L$</th><th>$v_F = v_L$</th><th>$v_F > v_L$</th></tr>
<tr><td>$s > \Delta$</td><td rowspan="2">Case I
• Accelerate to match speed ($v_F \uparrow$ to v_L, $s \uparrow > \Delta$)
• Accelerate to overshoot speed ($v_F \uparrow > v_L$, $s \downarrow > \Delta$)
• Decelerate to match speed and achieve desired space headway ($v_F \downarrow$ to v_L, $s \downarrow$ to Δ)</td><td>Case III
• Accelerate to reduce space headway ($v_F \uparrow > v_L$, $s \downarrow > \Delta$)
• Decelerate to match speed and achieve desired space headway ($v_F \downarrow$ to v_L, $s \downarrow$ to Δ)</td><td>Case IV
• Decelerate to match speed ($v_F \downarrow$ to v_L, $s \downarrow$)
○ If $s > \Delta$, go to Case III;
○ If $s = \Delta$, no action required;
○ If $s < \Delta$, go to Case II</td></tr>
<tr><td>$s = \Delta$</td><td>No action required.</td><td rowspan="2">Case V
• Decelerate to match speed ($v_F \downarrow$ to v_L, $s \downarrow < \Delta$)
• Go to Case II</td></tr>
<tr><td>$s < \Delta$</td><td colspan="2">Case II
• Decelerate to achieve desired space headway ($v_F \downarrow < v_L$, $s \uparrow$ to Δ)
• Go to Case I</td></tr>
</table>

In each of these cases, two common key processes emerge: matching speed and achieving desired space headway. The actions are similar in each process, but the primary objectives are different. The initial conditions determines which process takes priority. For example, if the two vehicles start with a small space headway (smaller than the desired value) that is deemed unsafe, then increasing space headway to achieve the desired value will be the imminent process the following vehicle engages. During this process, the velocity of the following vehicle could further deviate from that of the leading vehicle, which will then be adjusted after the space headway has at least reached the desired value. During the velocity adjustment, the space headway will vary, but could only be greater or equal to the desired space headway. The completion time of each process, as well as the value of the variable that is not the primary objective, can be computed analytically due to the adoption of a piece-wise linear velocity profile. Upon completion of each process, the conditions will be re-evaluated, and a new applicable pattern selected. The procedure repeats until a complete piece-wise linear velocity profile is constructed.

It can be observed that with favorable initial conditions (Case I and Case III), any desired space headway can be achieved without it being violated during the platoon formation process. However, when the initial conditions are not favorable (Case II, Case IV, and Case V), the desired space headway could be violated. This violation in fact provides insights into how small the final space headway can be. Given an absolute minimal value of space headway (to absorb sensor and power-train control disturbances), we could assign this value to the time point at which the space headway is the smallest during the formation process, can back calculate the final space headway when the platoon is formed.

Constant Time Headway

We consider a simple case for the constant time headway scenario, where two vehicles have the same initial speed but are relatively far apart. Suppose the following vehicle employs a triangle-shaped velocity profile (same sequence of actions as in Case III in Table 1), as this is the velocity profile that leads to the fastest platoon formation. We know from analysis in the constant space headway scenario that the desired space headway will not be violated in Case III. However, this is not the case for time headway.

We derived mathematical expressions of the time headway, as well as the change of time headway, as functions of time. It is found that the time headway is a piece-wise continuous function, whereas the change of time headway is not continuous at the point when the following vehicle switches from acceleration to deceleration. Moreover, it is worth noting that the time headway is a monotonically decreasing function before the switch, but a quadratic function after. This means that at some point before the velocities are matched, the desired time headway is violated. If we require the desired time headway be observed throughout the process, then the final time headway will be greater than the desired value. Analytical relationships between the final time headway and the initial conditions are developed for the simple case considered.

Conclusion

This research explores an important research question that has not received sufficient attention. How small the headways can possibly be in a CAV platoon has significant implication on the expected benefit of improved efficiency. This research investigates the limit of vehicle headways in CAV platoons as a function of the initial states of a pair of leading and following vehicles. Through kinematic analysis, we found that under constant space headway policy, the desired space headway can be achieved without the value being violated during the platoon formation process, if the initial conditions are favorable. However, with constant time headway policy, which is more advantageous when it comes to string stability, it may not be possible to achieve the desired time headway without violating it at some point during the platoon formation process, even if the initial conditions are favorable.

Note that we assume perfect information and power-train control with no delay or errors. The results, therefore, would provide a lower bound of vehicle headways in CAV platoons and thus an upper bound of possible capacity increase resulted from a specific platooning strategy.

References

[1] Zhou, F., Li, X., and Ma, J. (2017) Parsimonious shooting heuristic for trajectory design of connected automated traffic part I: Theoretical analysis with generalized time geography. *Transportation Research, Part B: Methodology*, 95, 394–420. doi:10.1016/j.trb.2016.05.007

[2] Zhou, J. and Peng, H. (2005) Range Policy of Adaptive Cruise Control Vehicles for Improved Flow Stability and String Stability. *IEEE Transactions on Intelligent Transportation Systems*, 6, 229–237.