



Achieving Equilibrium for Dense, Integrated Vehicle Navigation

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Virtual



Strings

- Drone usage is forecast to be in 1000s
- String of aircraft en-route, on ground, studied recently
- String of cars on highways, studied since 1960s
- String in the sky and on the ground, similar issues:
 - Spacing (time, distance)
 - Stability
 - Scalability (num of vehicles)
 - Response Time (acceleration)
 - Sensors Accuracy
 - Communication (V2V, V2I)



Cruise Control Systems

- Adaptive Cruise Control (ACC)
- Cooperative Adaptive Cruise Control (CACC)
 - Considered the first step in automation
- Platooning – Vehicles traveling with a common goal, typically, increasing performance, cost (gas), space, time, etc.
- Platoon of heavy-duty vehicles on highways maintain a pre-set gap between the vehicles using V2V communication
- Platoon's performance depends on maintaining String Stability
- Aircraft en-route maintain a safe spacing, scheduled arrival time



String and String Stability

- What about the vehicles that are not part of a platoon?
- Gunter et al. assessed string stability of seven 2018 model year ACC equipped vehicles that are widely available in the US market and showed that none of the ACC are string stable
- These are some of motivations for this work
- We treat aircraft and cars the same, call them vehicles



Equilibrium – Definitions

- **String Stability:** Resilient to perturbation
- **Congested System:** When vehicles cannot move at their maximum allowed speed.
- **Equilibrium State:** When a set of n vehicles moving at a relatively constant speed and *uniform spacing* from each other in a congested system.
- **Steady State:** In non-congested system, when vehicles navigate at the maximum allowed speed at constant spacing from each other but potentially at different intervehicle spacing.



Achieving Equilibrium – Proposed Solution

The algorithm as executed by N_i , for all i :

while (true)

{

$d_{i-1,i}(t-1) = Loc_{i-1}(t-1) - Loc_i(t-1)$ // expected value $\geq d_{safe}$

$d_i(t) = \min((d_{i-1,i}(t-1) - d_{safe})/k, S)$ // expected value ≥ 0

$Loc_i(t) = Loc_{i-1}(t-1) + d_i(t)$, for all i // expected value $\geq d_{safe}$

}

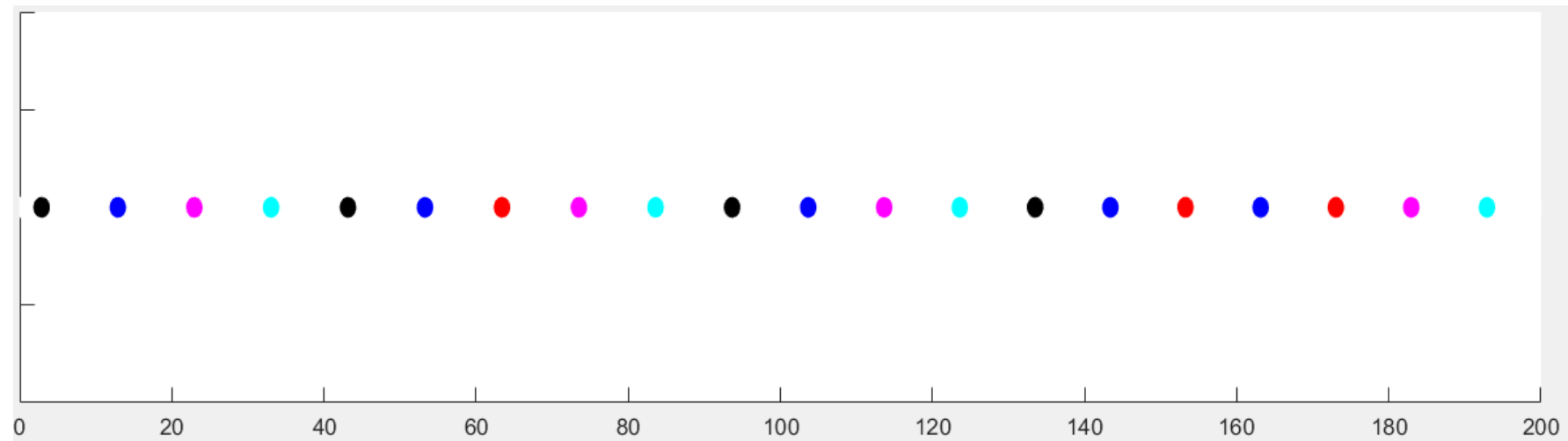
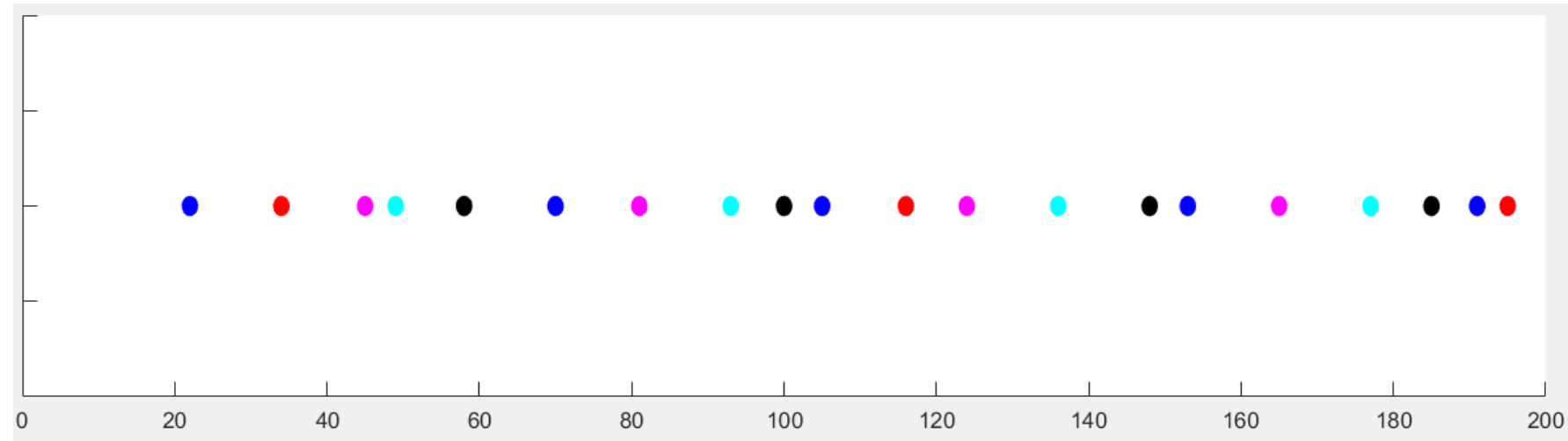
- Parameters are defined in the paper



Equilibrium

- Vehicles DO NOT:
 - Follow a leader in trying to match its speed as in a platoon,
 - Try to achieve or maintain a pre-specified intervehicle spacing,
 - Share their data with each other (no V2V communication),
 - Operate based on a time schedule, and
 - Have to be homogeneous.
- Vehicles DO:
 - Execute the algorithm,
 - Have sensors to determine their distance from the vehicle in front,
 - Adhere to a maximum speed limit set for the corridor, and
 - Only adjust their speed.

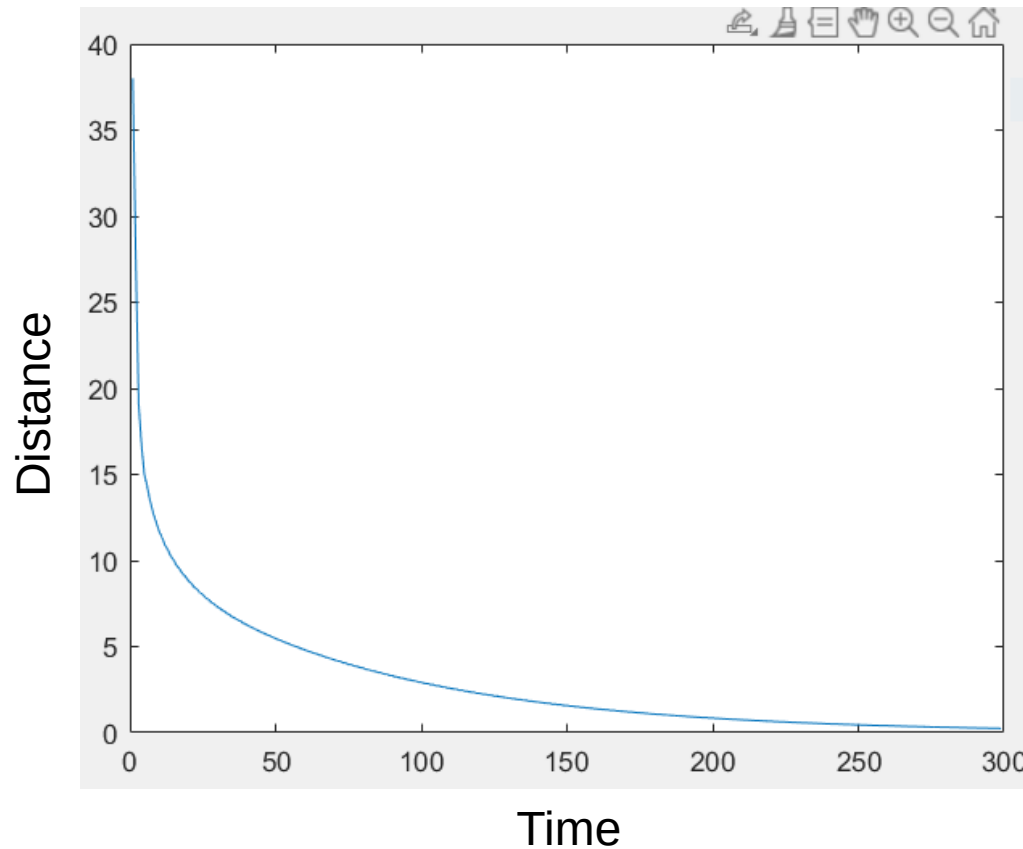
Simulation – from random start to equilibrium



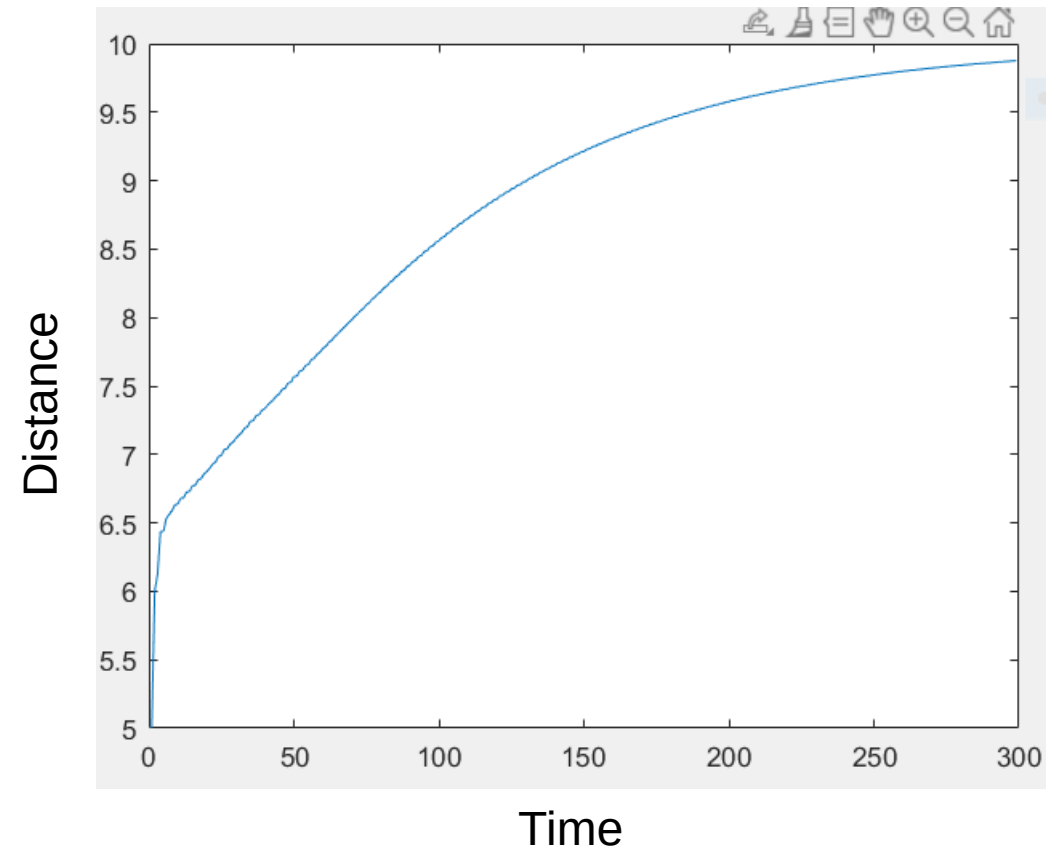
Simulation – from random start to equilibrium



Maximum intervehicle distances



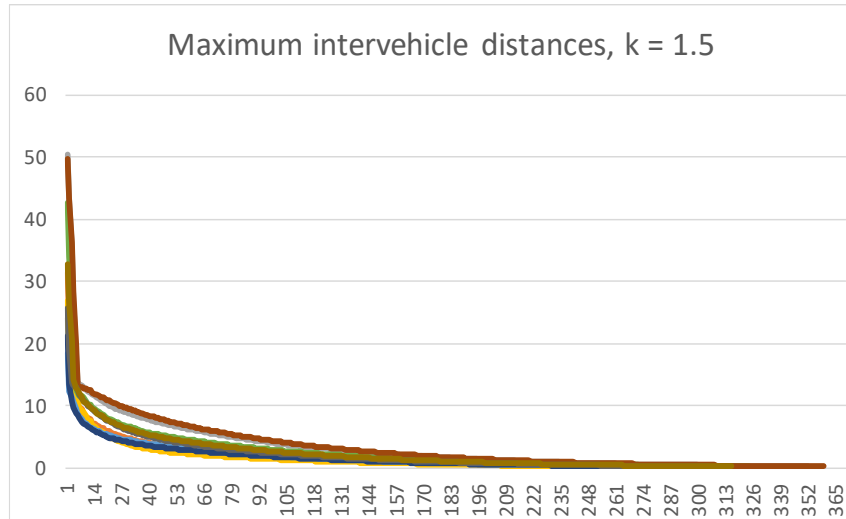
Distance to front vehicle



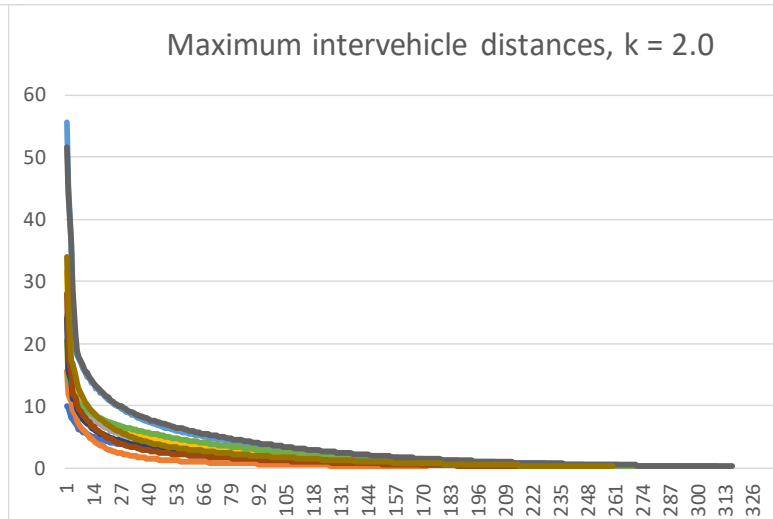
Simulation – Best average value, $k = 2$



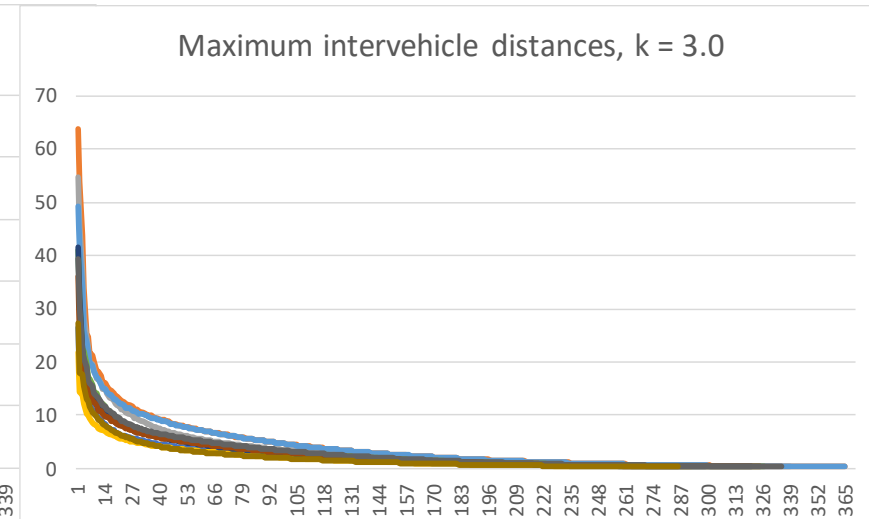
$k = 1.5$



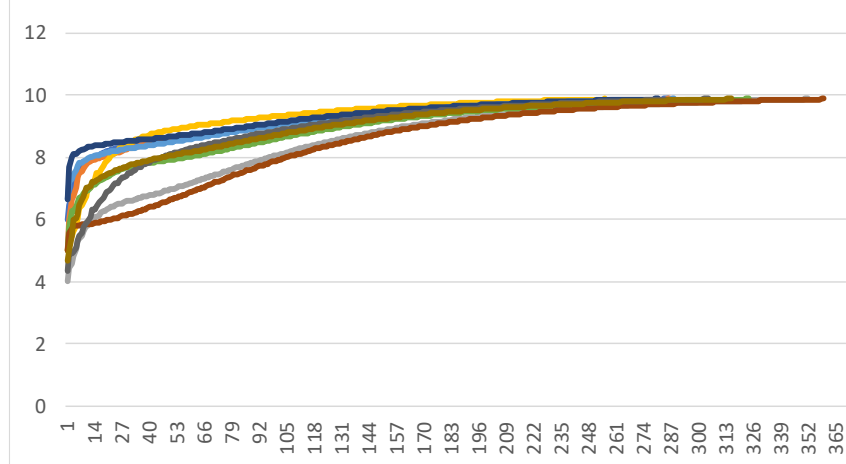
$k = 2.0$



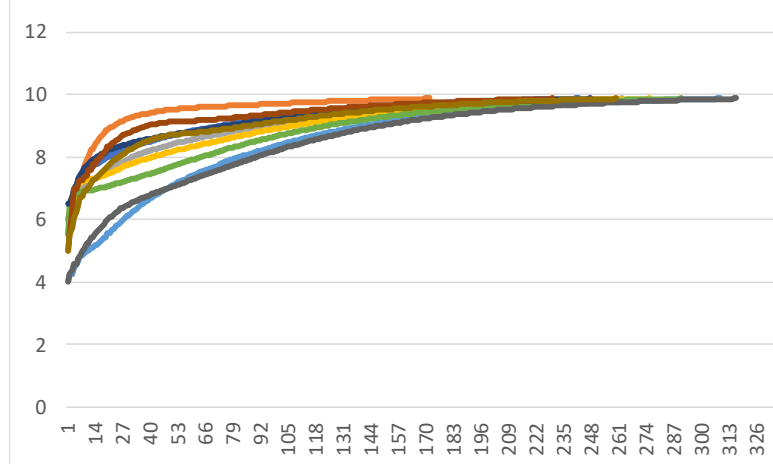
$k = 3.0$



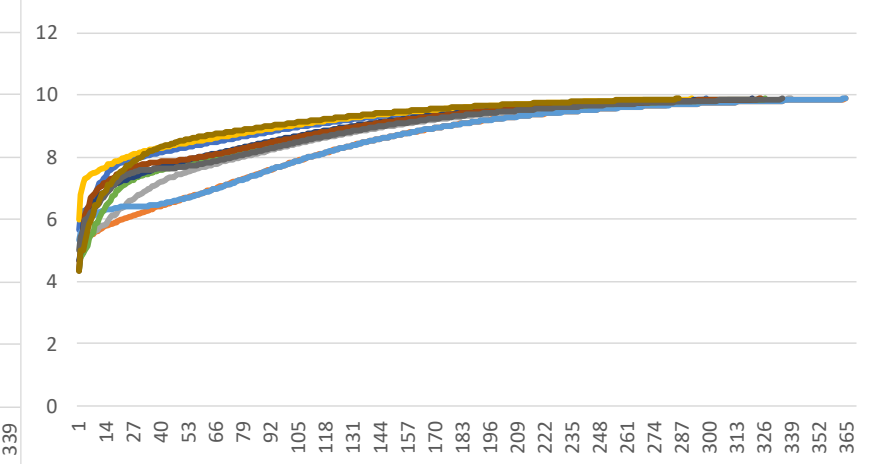
Distance to front vehicle, $k = 1.5$



Distance to front vehicle, $k = 2.0$



Distance to front vehicle, $k = 3.0$





Future Work

- This is a work in progress
- Analysis of the solution beyond steady and equilibrium states
- Determining the amount of time it takes for a given system to reach equilibrium is also left for future work
- Formal analysis of stability of the solution
- Expanding the model of the system and the vehicles to more accurately represent practical scenarios, i.e., acceleration



Questions?

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