ComNets
Institute of Communication Networks
TUHH

Robust Communication for Networked Control Systems

ITG FG 5.2.4 Workshop "Vehicular Communication", Aachen

Daniel Plöger, Hamburg University of Technology

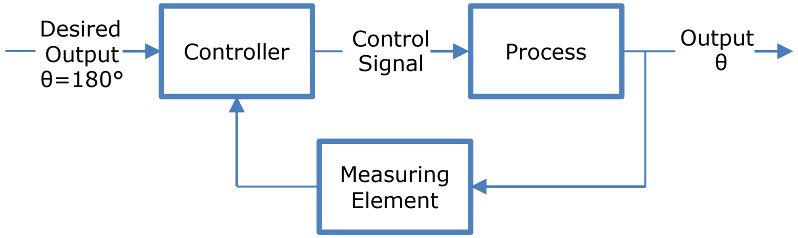
Agenda

1. Introduction to Networked Control Systems

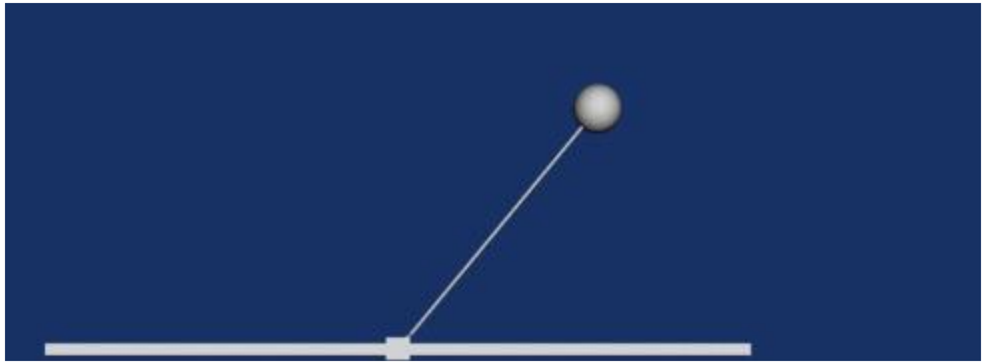
2. Cooperative Adaptive Cruise Control Research for Platooning at TUHH

3. Platoon string stability and vehicle collision analysis

Control Systems



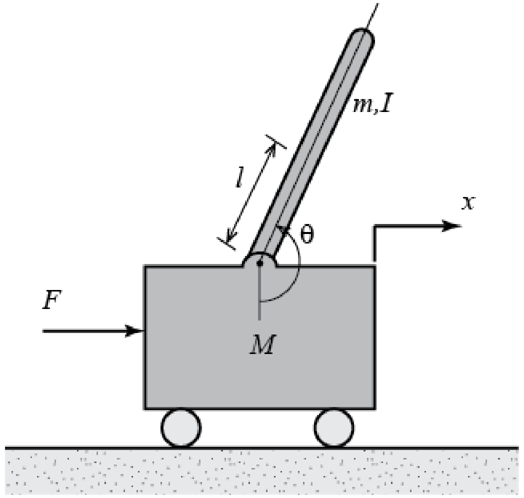
Control System



Inverted pendulum: *How stable is the system with the control design of choice?*

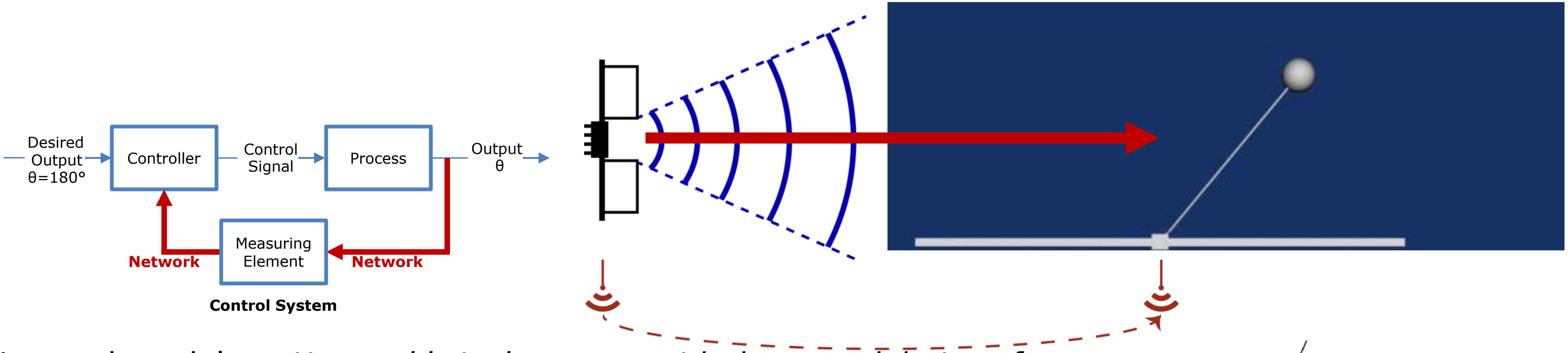
Good performance is achieved if the pendulum stays in a balanced equilibrium.

- Classic problem in dynamics and control theory.



Bill Messner, Dawn Tilbury. *Control Tutorials*. University of Michigan, *http://ctms.engin.umich.edu [Online; accessed 21-February-2018]*

Networked Control Systems (NCS)

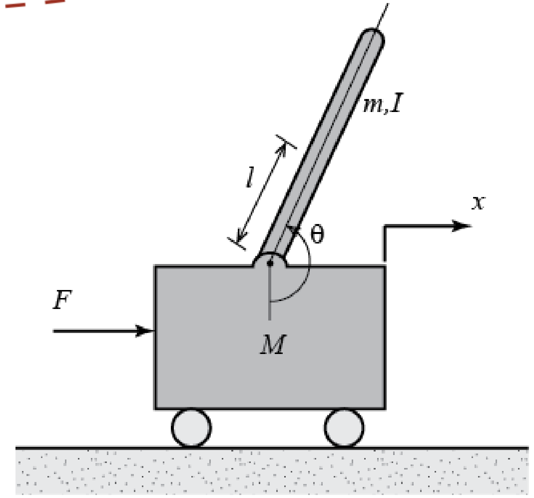


Inverted pendulum: *How stable is the system with the control design of choice?*

Good performance is achieved if the pendulum stays in a balanced equilibrium.

- Classic problem in dynamics and control theory.

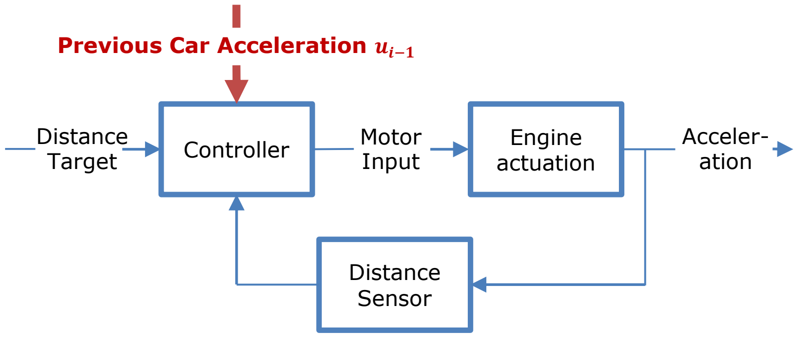
What happens if the feedback information is transmitted via an unreliable channel?



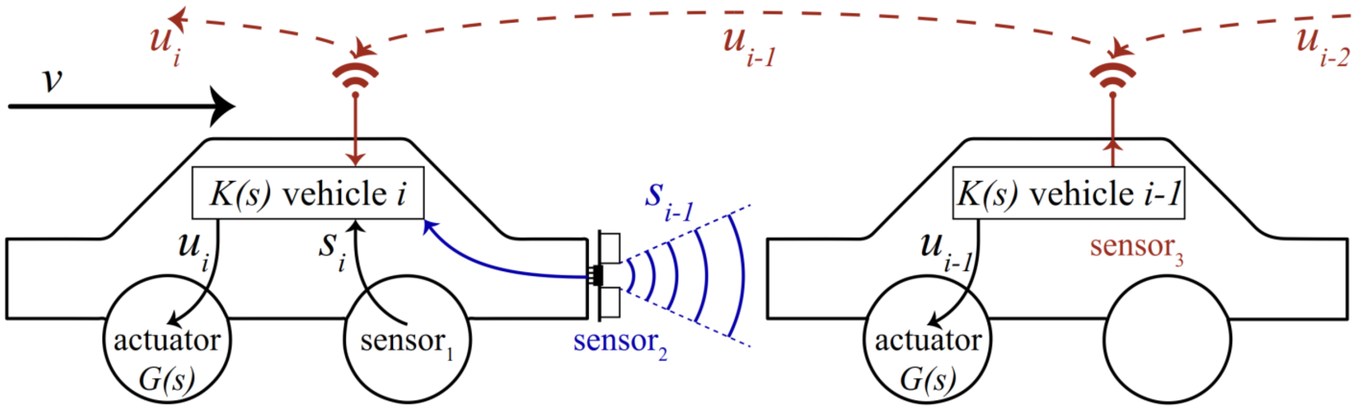
Bill Messner, Dawn Tilbury. *Control Tutorials*. University of Michigan, *http://ctms.engin.umich.edu [Online; accessed 21-February-2018]*

Cooperative Adaptive Cruise Control (CACC)

ComNets
Institute of Communication Networks
TUHH

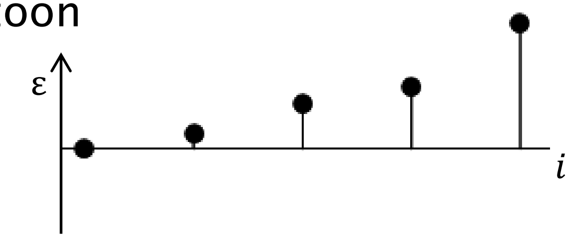


Cooperative Adaptive Cruise Control System (CACC)



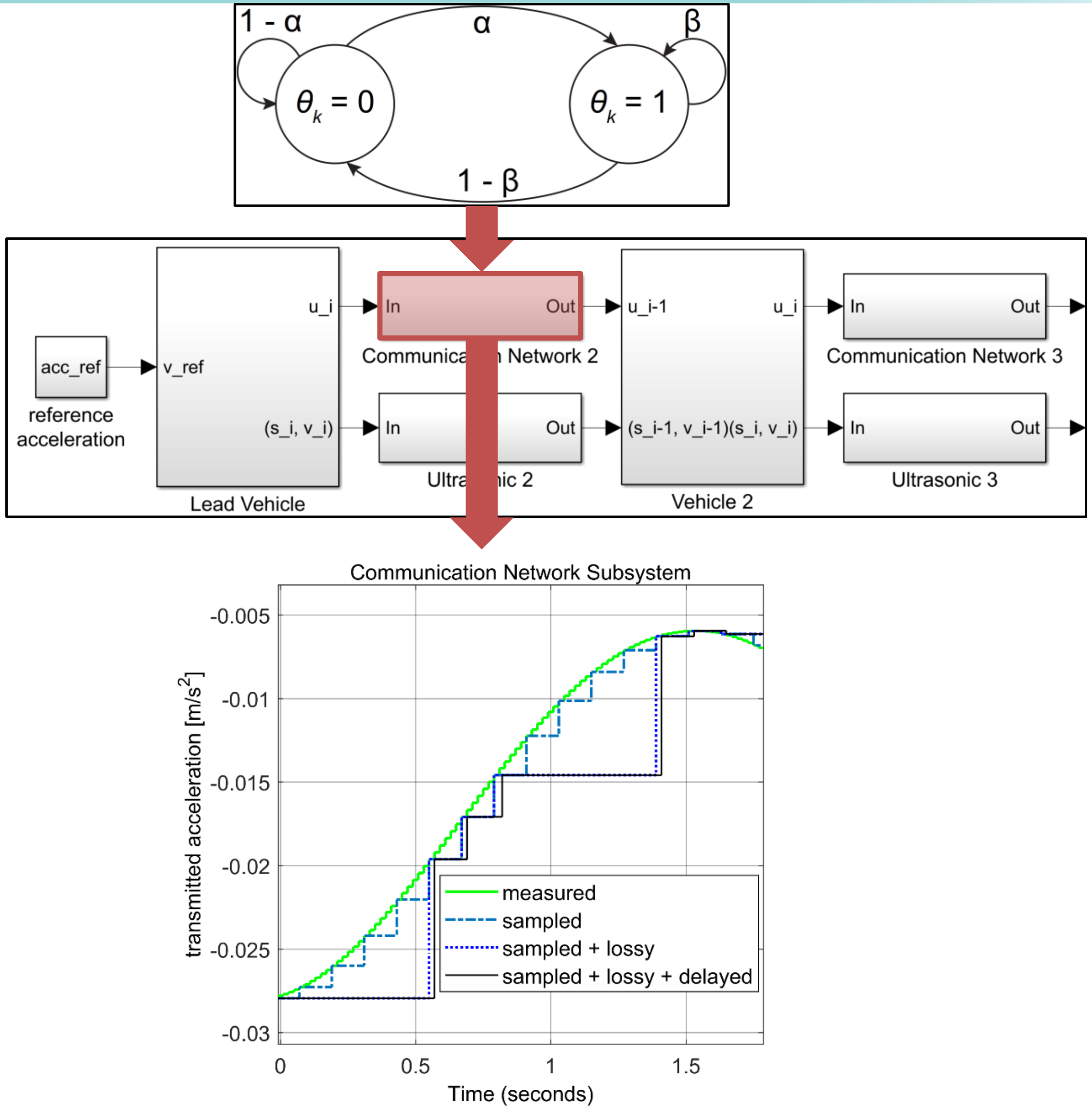
Autonomous platooning has a more complex performance analysis:

- Prevent vehicle collision
- Prevent amplification of errors ε_i along the platoon



- ➢ What is the worst acceptable radio channel in terms of **delay**, **collisions**, **burst errors**?
- ➢ Is communication required to be **synchronized**?
- ➢ How often are status updates needed?
- ➢ What is the minimum **required distance**?
- ➢ How **aggressive** must the controller act?

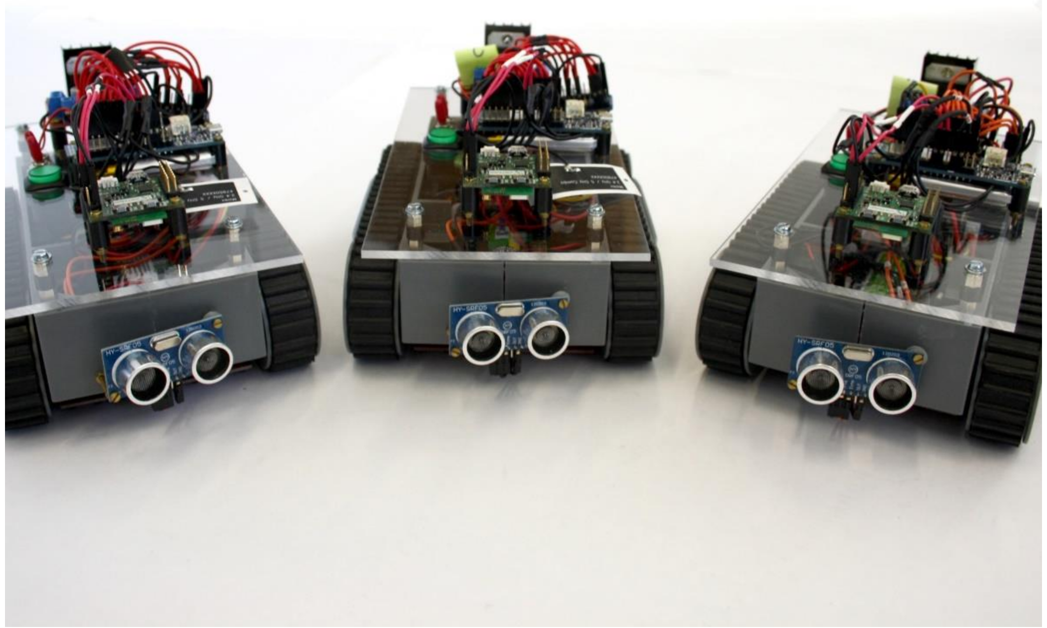
CACC Research at TUHH



Requirements are analyzed by **simulation** and **real world experiments**.

Subject of research: universal performance targets.

Not subject of research: specific protocols or systems such as *5G*, *IEEE 802.11p*



Performance Metrics: String Stability

Platoon **string stability**:

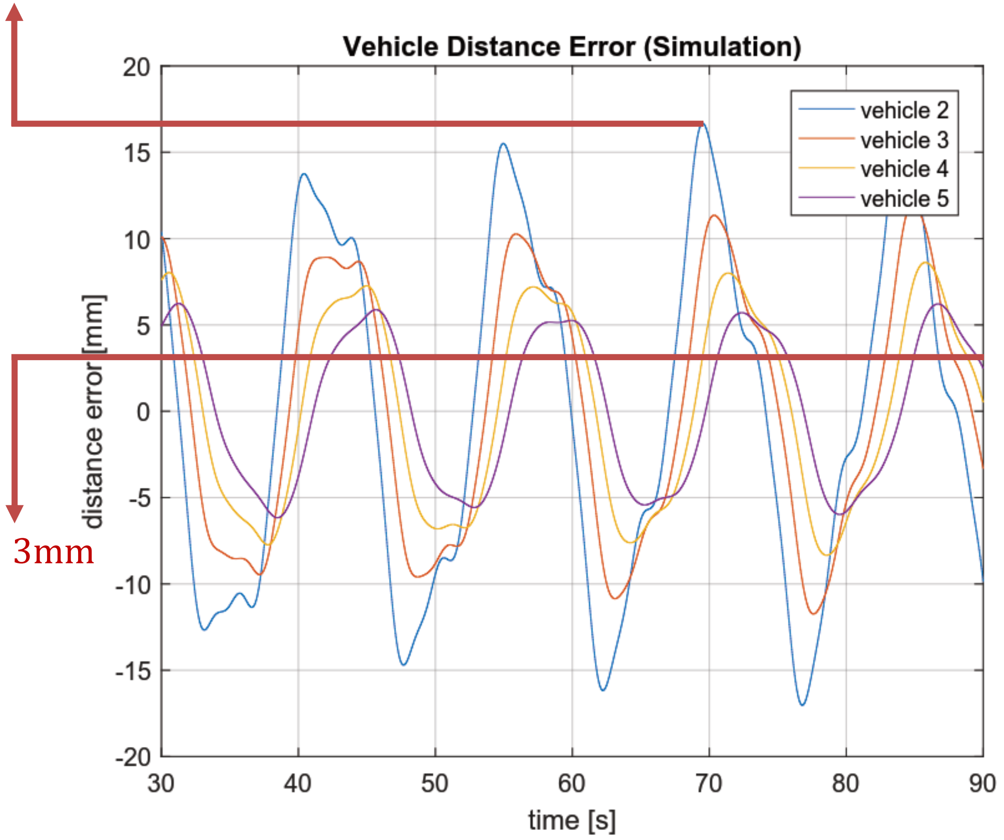
$\|\varepsilon_{i+1}\|_p \leq \|\varepsilon_i\|_p$, ε_i = distance error of the i^{th} vehicle.

Validity of definition depends on the ***p*-norm** used on the errors along the time vector T:

1. String stability in a **strong** sense:
   - $\|\varepsilon_i\|_\infty = \max_{1 \leq j \leq T} |\varepsilon_{i,j}|$.
2. String stability in a **weak** sense:
   - $\|\varepsilon_i\|_1 = \sum_{j=1}^{T} |\varepsilon_{i,j}|$.

➢ String stability is given if the **vehicle distance error** attenuates along the platoon.

$\|\varepsilon_2\|_\infty = 17\text{mm}$



$\frac{\|\varepsilon_2\|_1}{T} = 3\text{mm}$

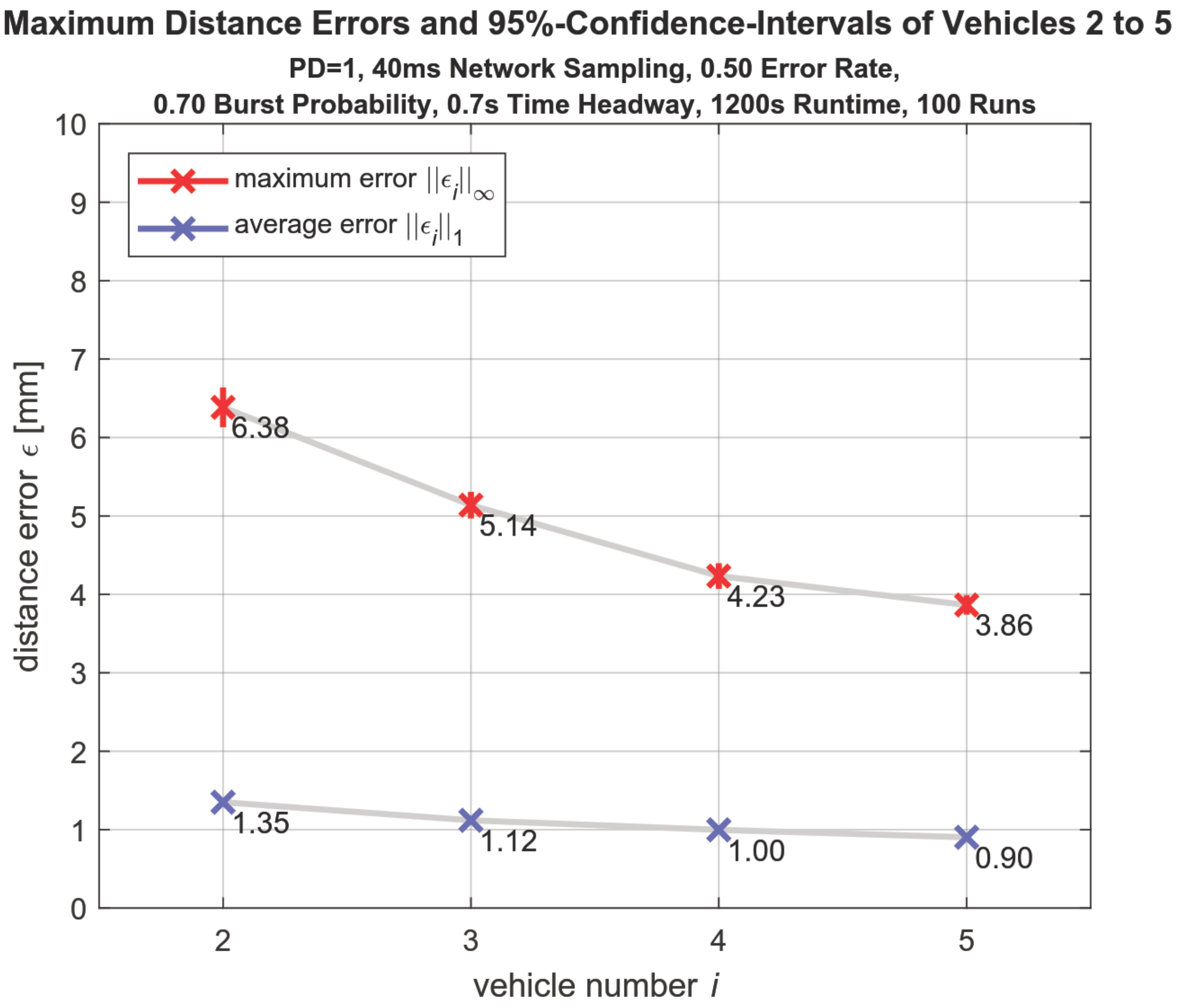
Performance Metrics: Vehicle Collisions

ComNets
Institute of Communication Networks
TUHH

Both definitions ensure **declining distance errors** when propagating along the vehicles, but do they prevent **vehicle collisions**?

The maximum error states that the risk of collision of **succeeding** platoon members decreases.

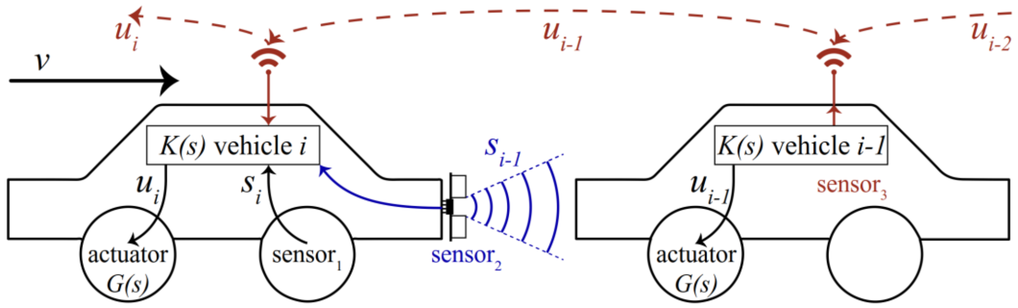
What is its statement about the risk of collision of the **first** vehicle?

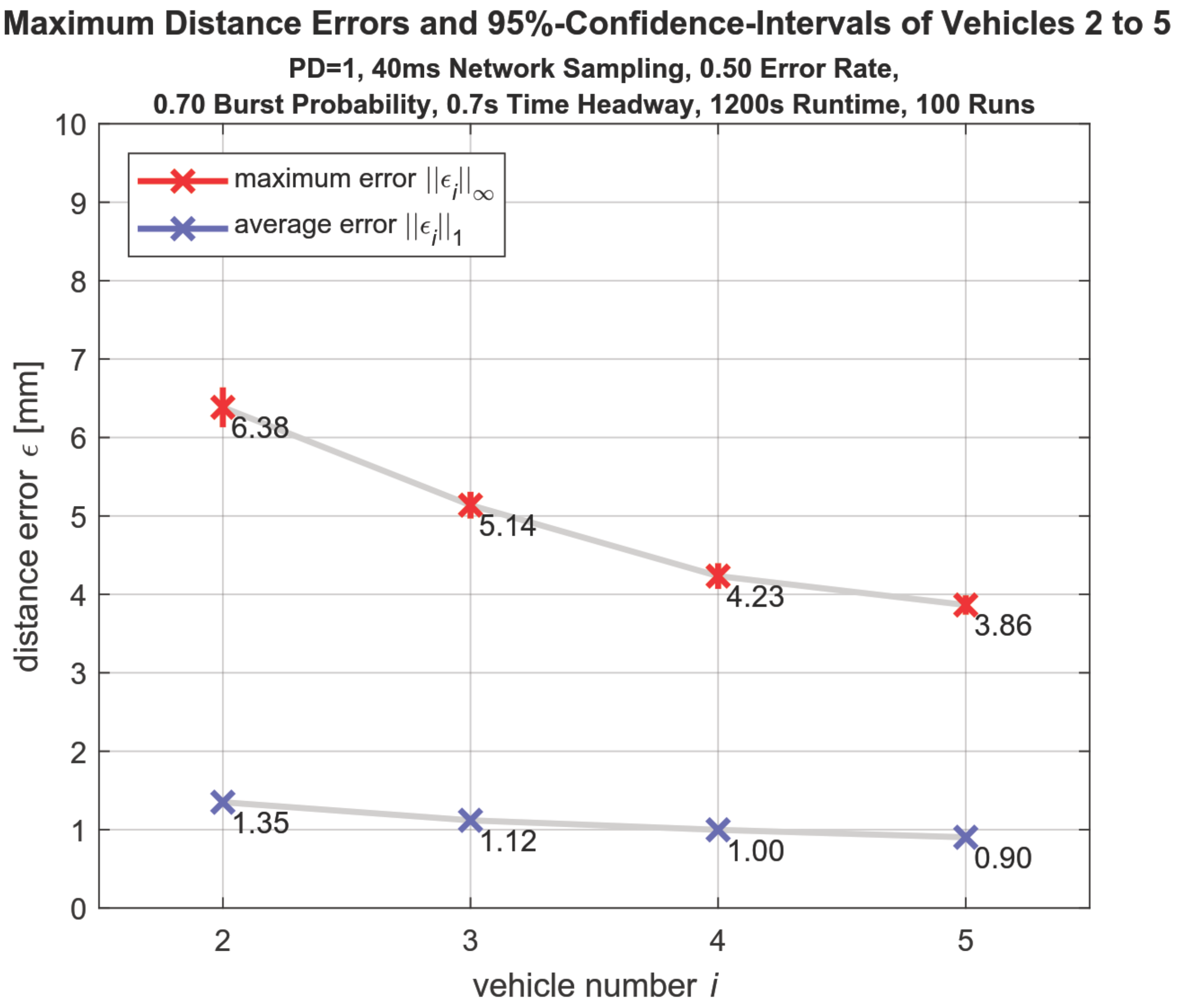


Excursion: Spacing Policy

Controller uses a **time headway spacing policy**

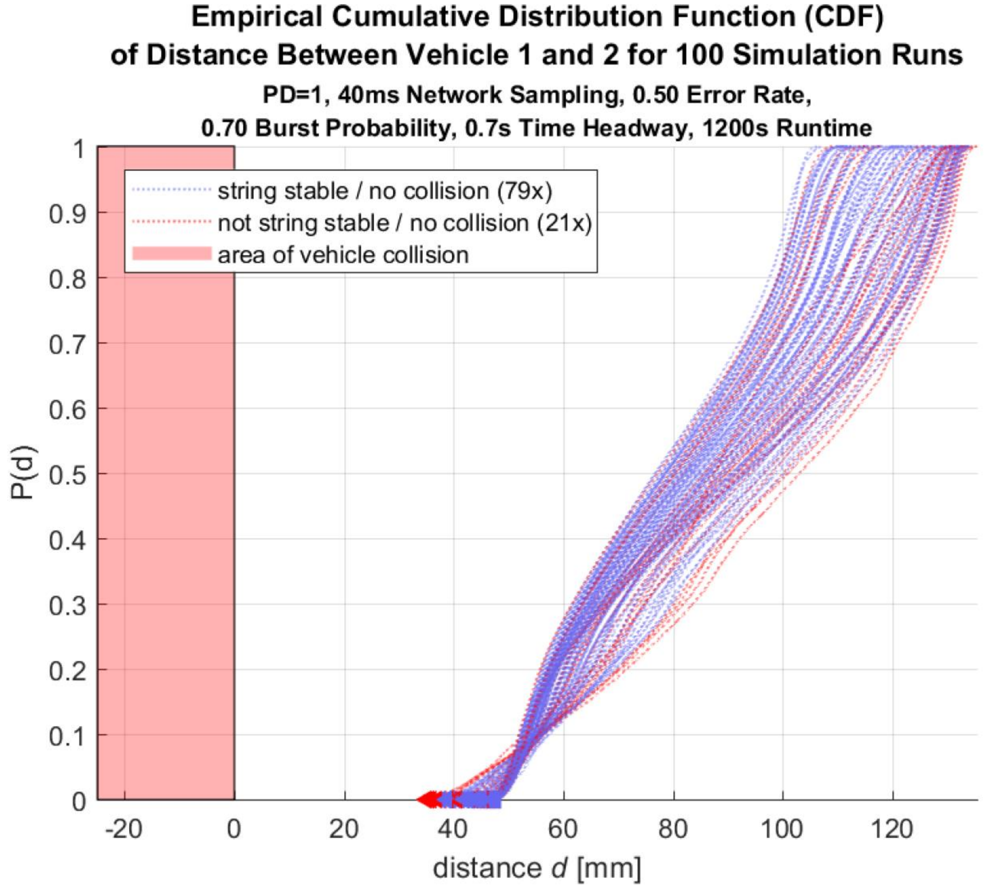
- The desired distance $d_{r,i}(t)$ of vehicle i is dependent on a constant distance r, a time headway h and the vehicle velocity $v_i(t)$.
- $d_{r,i}(t) = r + hv_i(t), \quad 2 \leq i \leq m.$
- Let's assume $r = 0$ to analyze the **risk of collision** within the platoon.



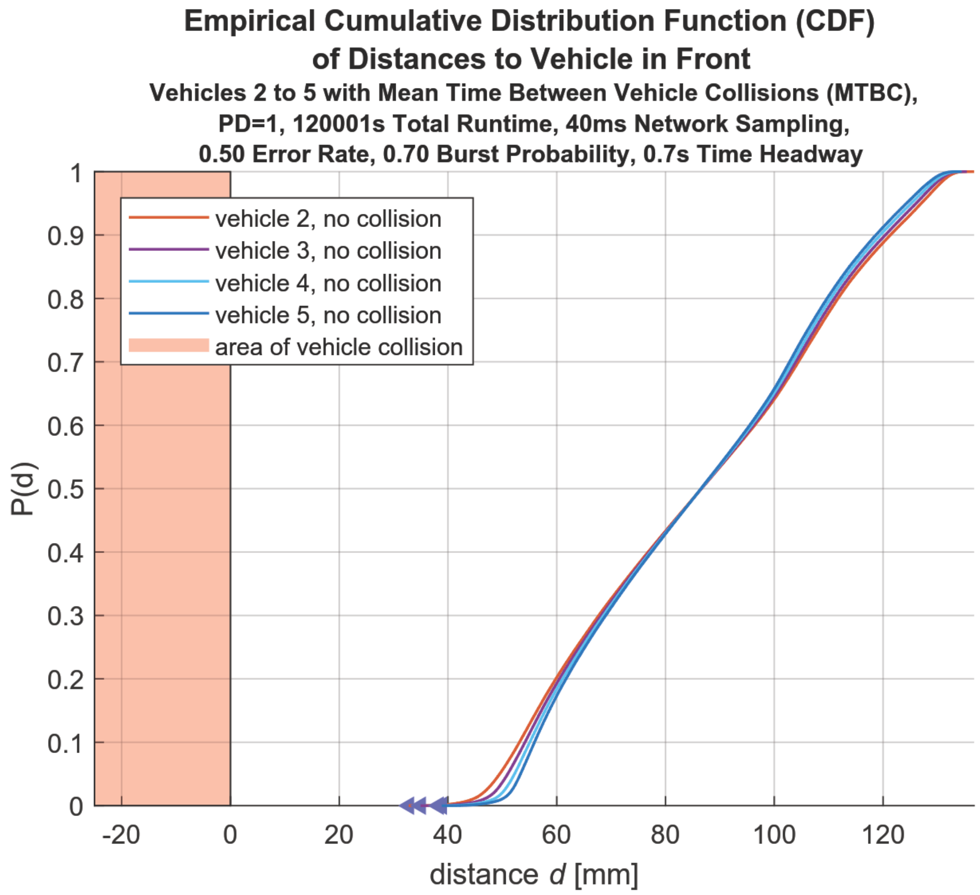


Stable Platoon
Examination of Collision

- Variable distance of string-stable platoon keeps platoon **collision-free**.
- Some **instable** events happen in an overall **stable** platoon.



- Distribution of small distances **shrinks** for succeeding vehicles.

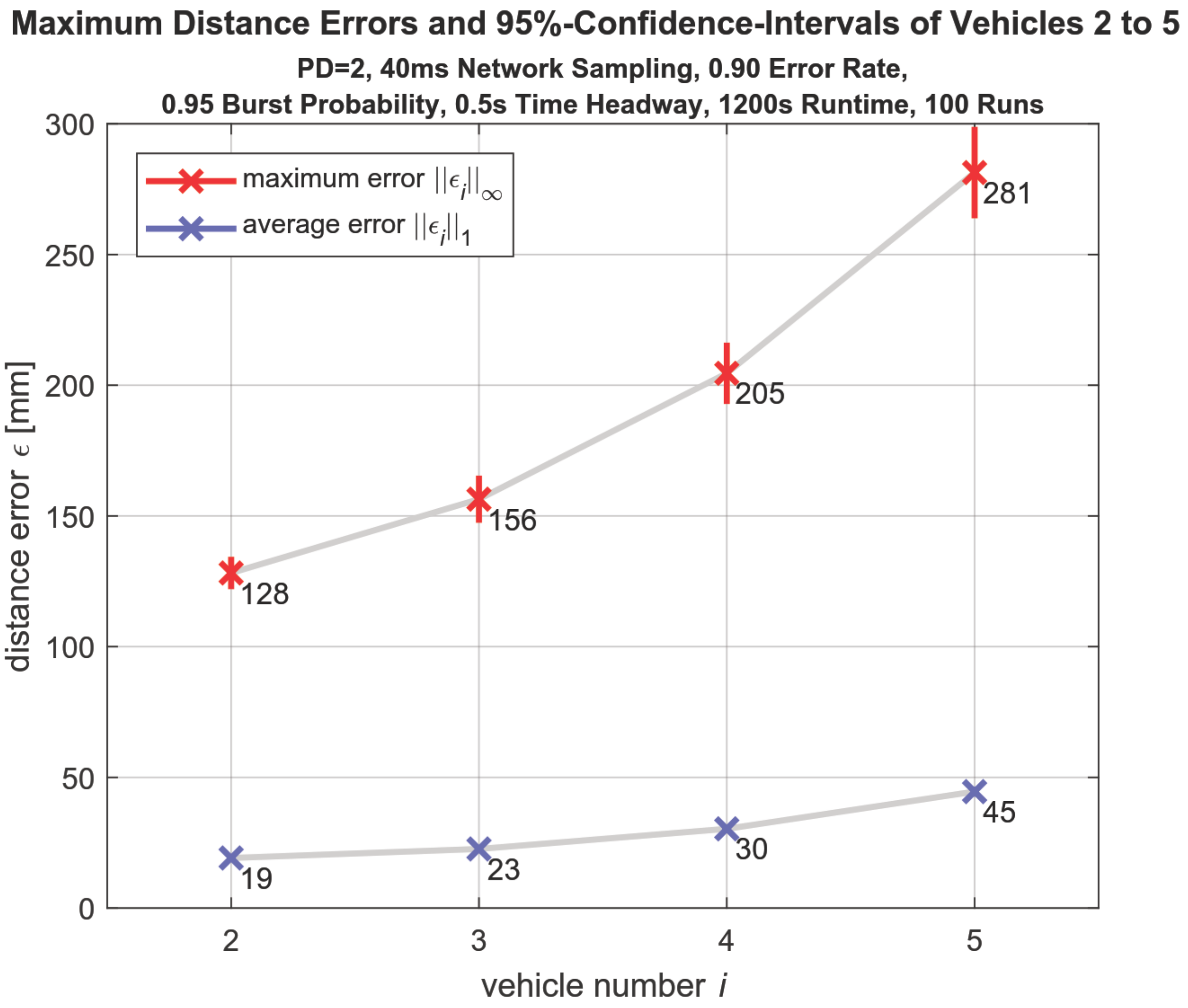


Scenario 2: Instable Platoon

ComNets
Institute of Communication Networks
TUHH

Previous stable platoon stays collision-free.

How does this instable platoon perform?

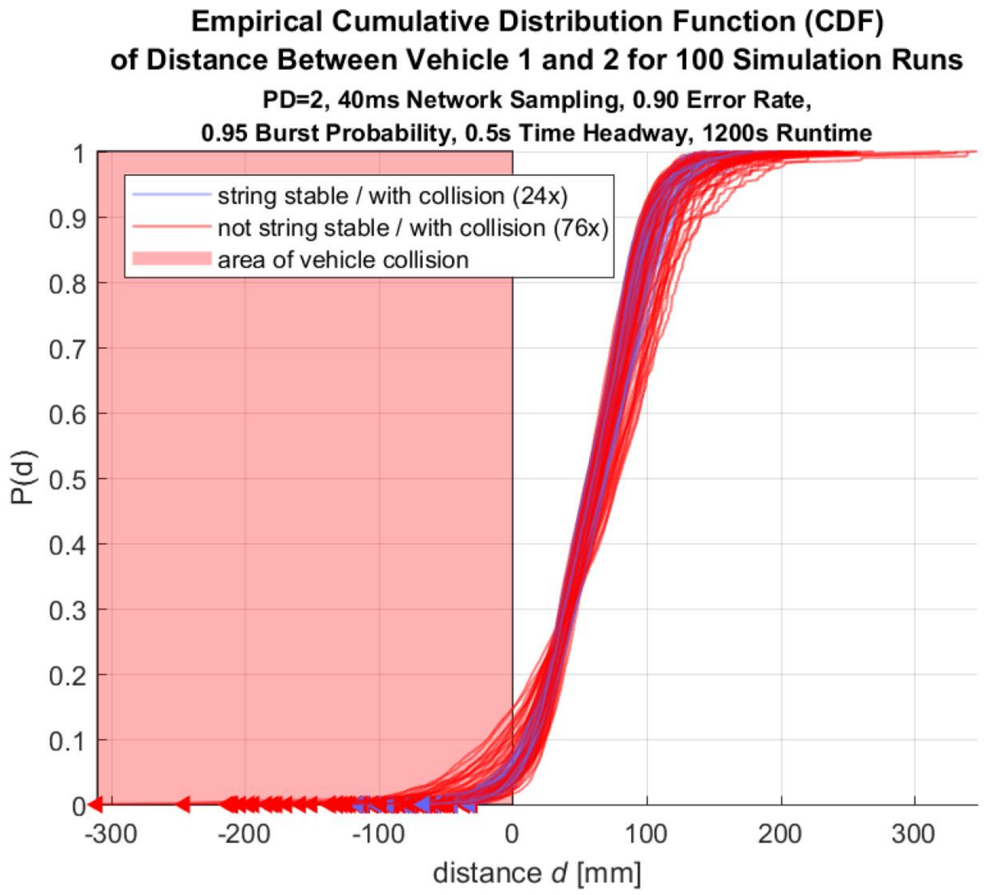


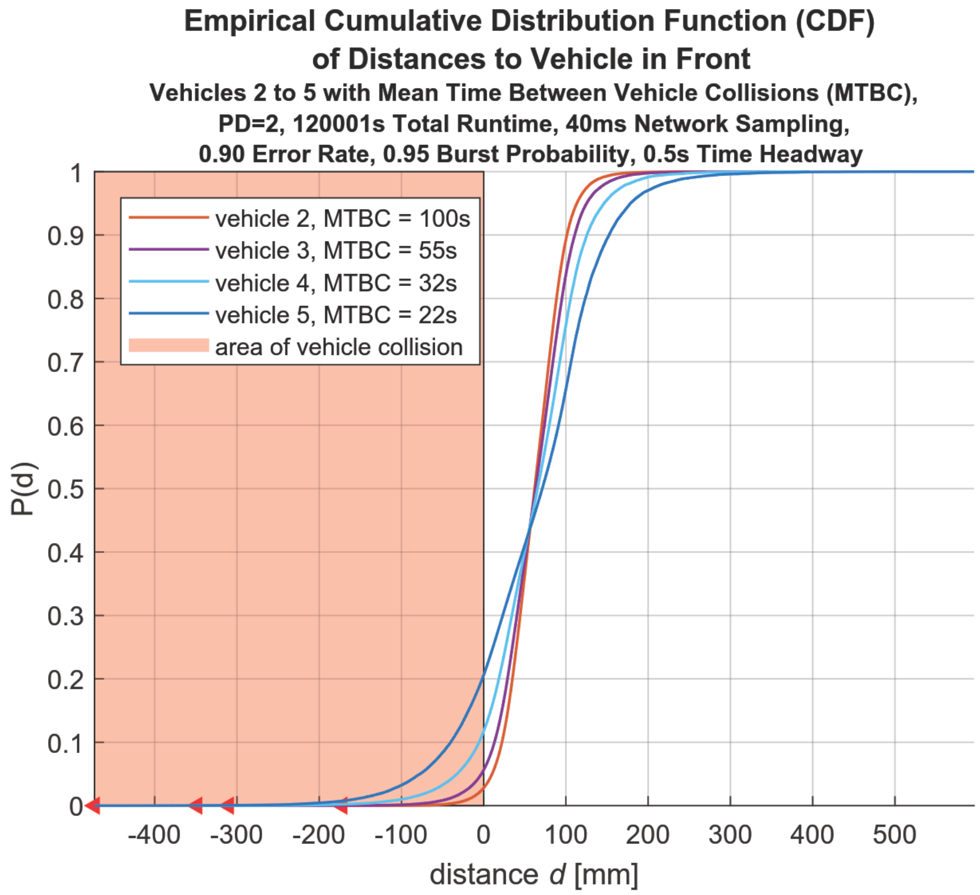
Instable Platoon
Examination of Collision

ComNets
Institute of Communication Networks
TUHH

- Collisions occur in all simulation runs.
- Some **stable** events happen in an overall **instable** platoon.

- Distribution of small distances **grows** for succeeding vehicles.





Scenario 3: Uncertain Stability

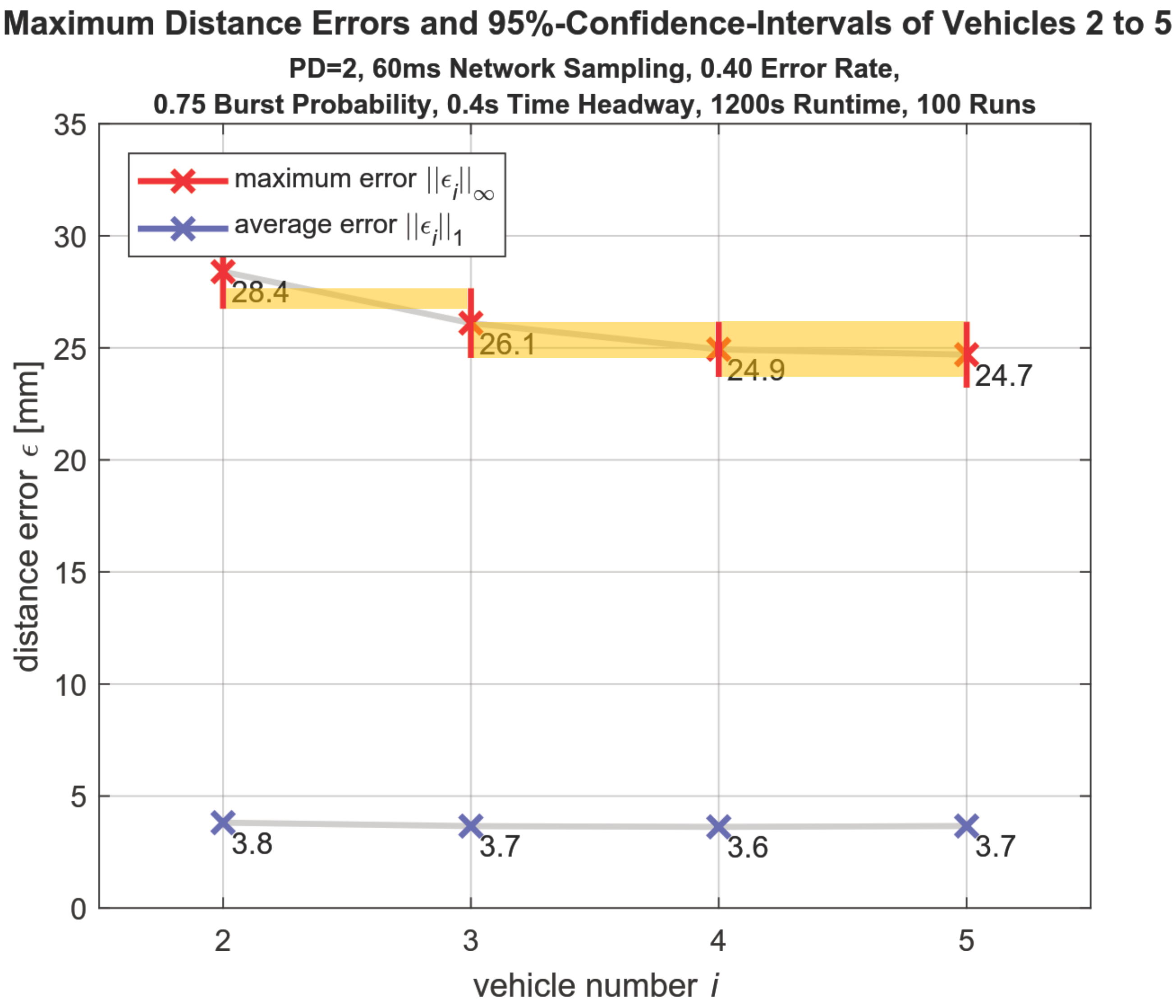
ComNets
Institute of Communication Networks
TUHH

Means of the distance errors appear to be stable.

But confidence intervals overlap

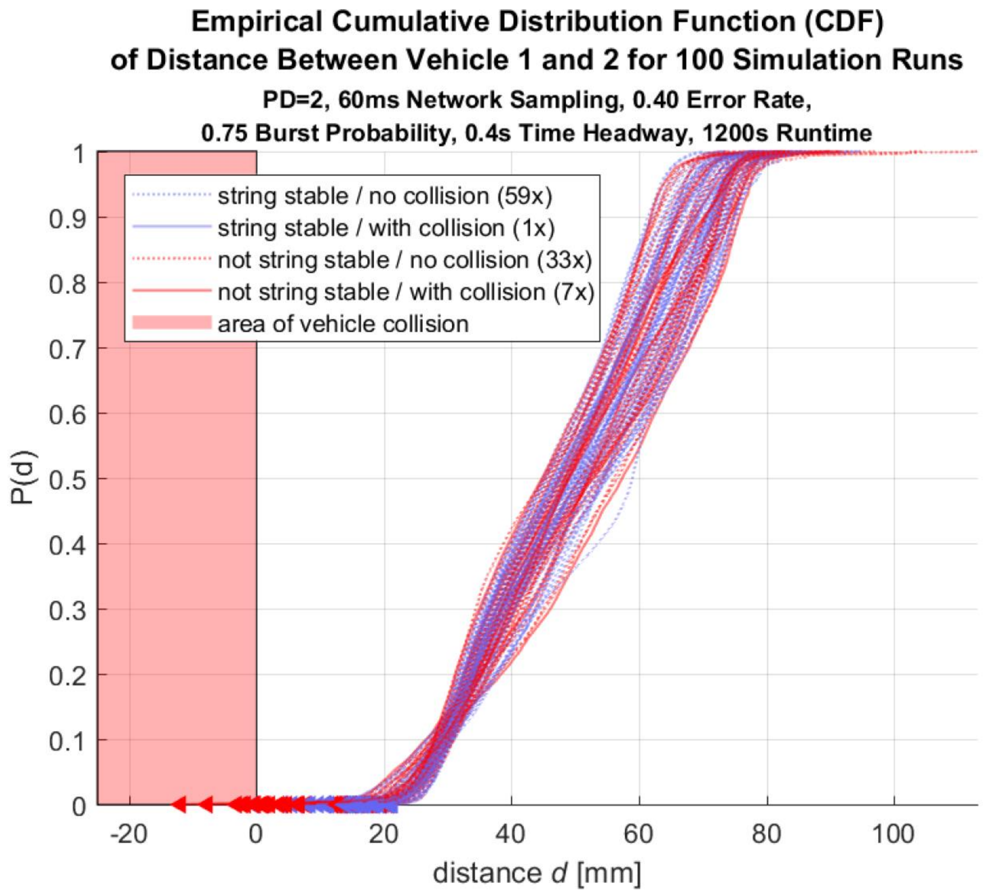
- ➢ No knowledge about **true error mean ratio** between vehicles.

What is the implication for the collision?

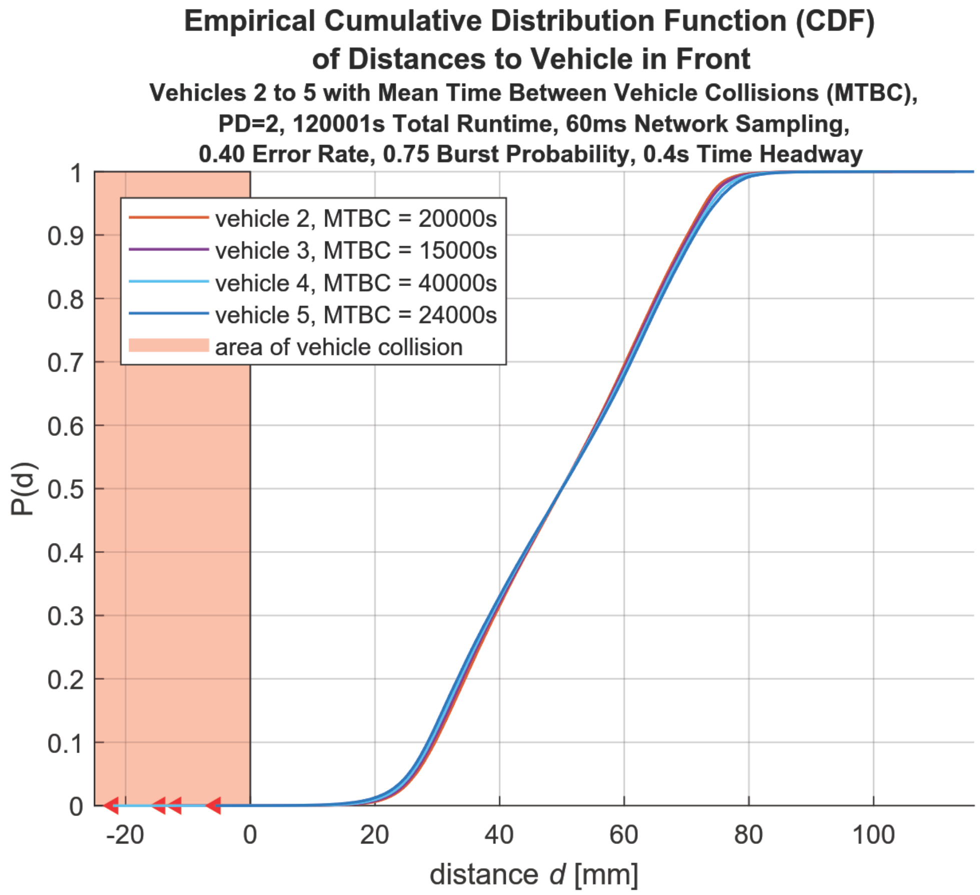


Uncertain Stability
Examination of Collision

- **Stable** and **instable** events happen at once.
- In at least one event, a string-stable simulation run has a vehicle collision.



- Distribution of small distances are **mixed up** between succeeding vehicles.

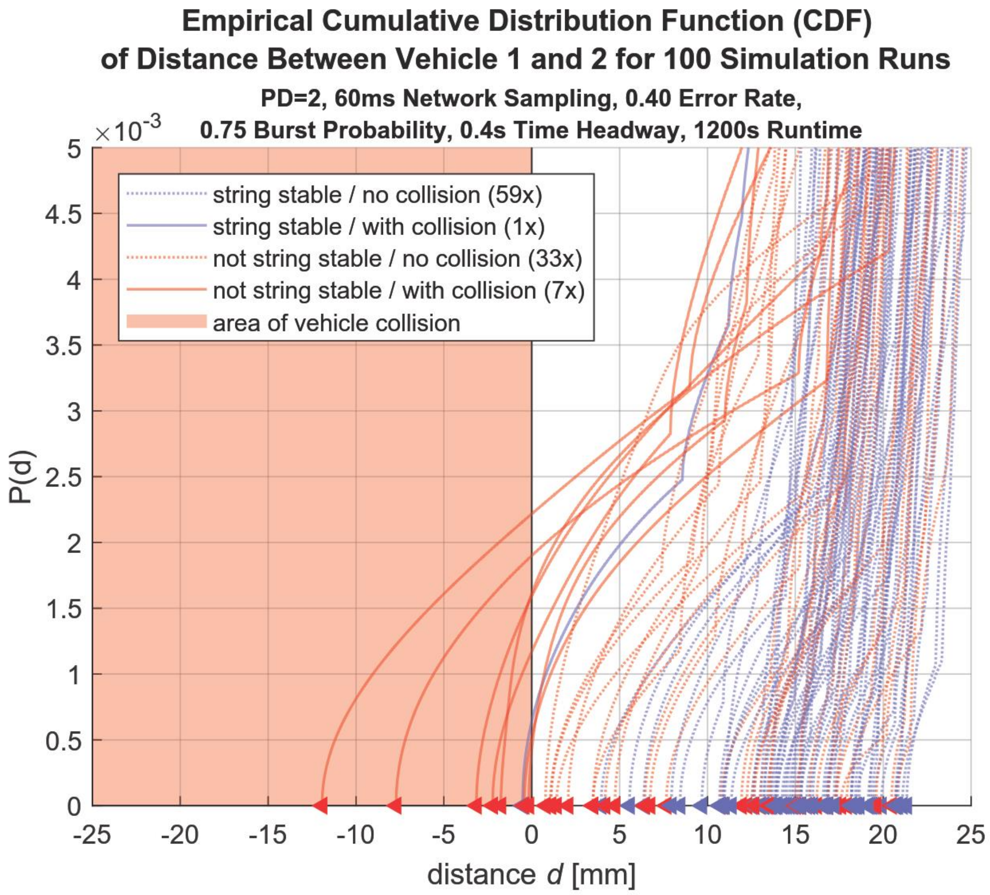


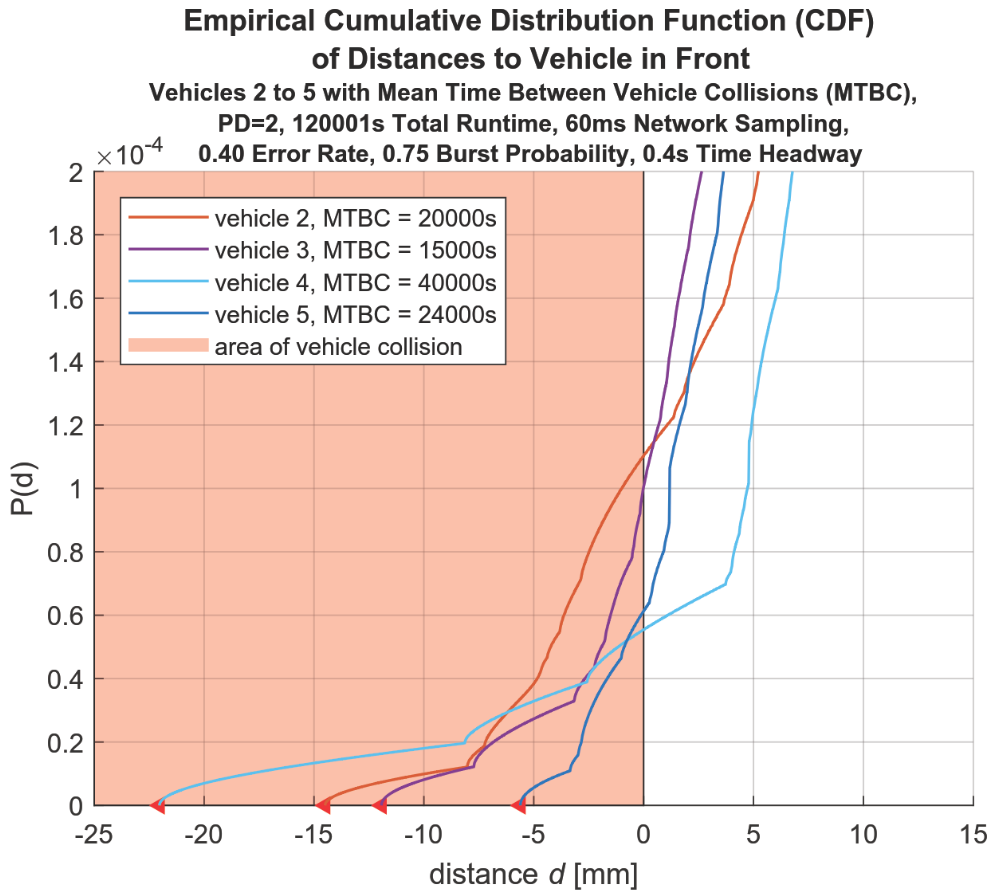
Uncertain Stability
Examination of Collision

ComNets
Institute of Communication Networks
TUHH

- **Stable** and **instable** events happen at once.
- In at least one event, a string-stable simulation run has a vehicle collision.

- Distribution of small distances are **mixed up** between succeeding vehicles.





Conclusion

String-stable and **collision-free** platoons are *not* inherently connected with each other.

String stability does *not* guarantee collision-free platoons.

But: a string-stable platoon *without* collisions between the first vehicles guarantees **collision-free succeeding vehicles**.

Next steps:

- Evaluate significance of **rare events** of collisions.
  - ➢ Enables more valid statements about collision probability in border cases.
- **Real-world experiments** may eliminate unpredictable influences on radio link quality, motor and vehicle behavior, and other factors.

Thank you for listening!

Questions?