Investigating Attacks on Vehicular Platooning and Cooperative Adaptive Cruise Control (CACC)

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ITS

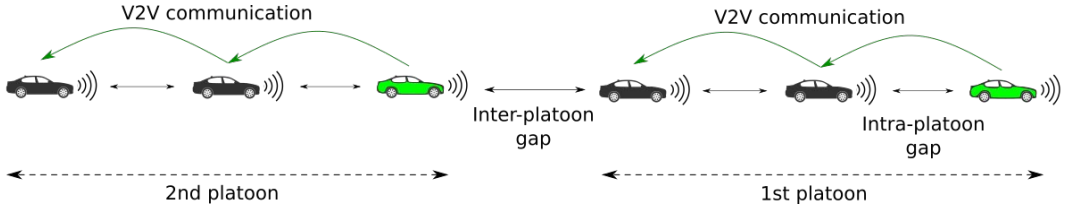
- Components
  - Vehicles
  - Road Side Units
  - Service Centers

- Cooperative Awareness Message (CAM)
  vs
  Decentralized Environmental Notification Message (DENM)
  - DIfferent dissemination frequencies
  - Different goals

- Applications[1,2]
  - Road safety
  - Traffic efficiency

Platooning

- Properties
  - Intra-platoon gaps
  - Inter-platoon gaps
  - Platoon size



- Vehicular Public Key Infrastructure[3]
  - Beacon validation
  - Identity management

- CACC controllers
  - Constant Vehicle Spacing
  - Constant Headway Time

Radar Measurements: R V2V Communication: Top precedence:

Controller	Policy	Predecessor			Leader			Topology
		d	s	a	p	s	a	
ACC	CTH	R	R					-
PATH	CVS	R	R					PL Following
Consensus	Both	R						PL Following
Flatbed	CVS	R	R					PL Following
Ploeg	CTH	R	R					Predecessor Following

Problem Statement

Investigating attacks on vehicular platooning and its maneuvering capabilities with the goal of decreasing its efficiency and degrading the formation stability.

- What is the effect of falsification attacks when perpetrated during a maneuver?
- How is the platoon's stability affected by attacks originating from within, regardless of position?
- What is the severity of the attacks' induced collisions?
- Can misbehavior detection function in such a scenario?

Novelty

- Attacks during platoon maneuvering
  - Middle-Join
  - Exit
- Systematic review of attacks
  - Combined kinematic properties - positive and negative injections
  - Different platoon speeds - all positions
- Evaluation of Flatbed
  - Jamming
  - Falsification attacks

Contributions

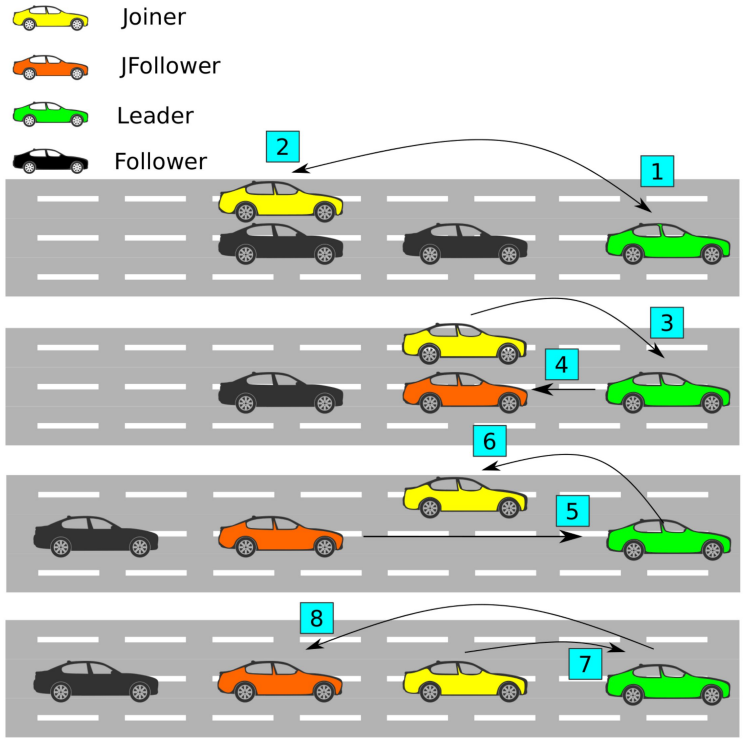
- Maneuvers
  - Support all controllers in a Join
  - Support dynamic positioning in a Join
  - Faster Exit

- Unified Attack Framework
  - Attacker(s) position
  - Attack type and payload
  - Maneuvering

- Tools Used
  - Plexe-Veins[6]: Platoon network simulator
  - OMNeT++[8]: Event Simulation Framework
  - SUMO[7]: Urban Mobility Simulator

Join Protocol

A. Approach (1-2-3)
   a. Join index
   b. Reach position
B. Increase Gaps (4-5-6)
   a. Increase policy margins (JFollower)
   b. Maintain position(Joiner)
      i. Threshold
      ii. Abort
C. Join Formation (6-7-8)
   a. Change lane
   b. Update formation
   c. Update policy margins



System Model

- Assumptions
  - Same vehicle characteristics (engine, brakes, car length)
  - All vehicles have valid pseudonyms
  - Cars on the road know the platoon leader

- Adversary Model
  - Internal member or Leader Attacker
  - Only CAM and DENM falsifications allowed
  - Collusion between misbehaving vehicles

Attacks

- Simple attacks
  - Replace nominal value with a malicious one
  - Always falsified with the same value
  - Position, Speed, Acceleration
- Gradual attacks
  - Relative values
  - Increase by step
  - Limit range of values
- Smart attacks
  - Relative values - increase by step
  - Falsify one property - relate the rest based on kinematic equations
  - Stricter limits
- Jamming attack
  - Drop all packets

Simulation setup

Configuration	Attack Values	Attack Position	Maneuver
JammingDetail	[30-35] s	1	[no,Join,Exit]
PosInjectionAttack	[3, 5, 7, 9, 11] m	[0,2]	[no,Join,Exit]
SpeedInjectionAttack	[-50, 0, 50, 100, 150] km/h	[0,2]	[no,Join,Exit]
AccInjectionAttack	[-30, -10, 0, 10, 30] m/s^2	[0,2]	[no,Join,Exit]
GradualPosFalsificationAttack	[-10,40] m	[0,2]	[no,Join,Exit]
GradualSpeedFalsificationAttack	[-10,17] m/s	[0,2]	[no,Join,Exit]
GradualAccFalsificationAttack	[-10,10] m/s^2	[0,2]	[no,Join,Exit]
SmartPosFalsificationAttack	[-10,10] m	[0,2]	[no,Join,Exit]
SmartSpeedFalsificationAttack	[-10,10] m/s	[0,2]	[no,Join,Exit]
SmartAccFalsificationAttack	[-10,10] m/s^2	[0,2]	[no,Join,Exit]

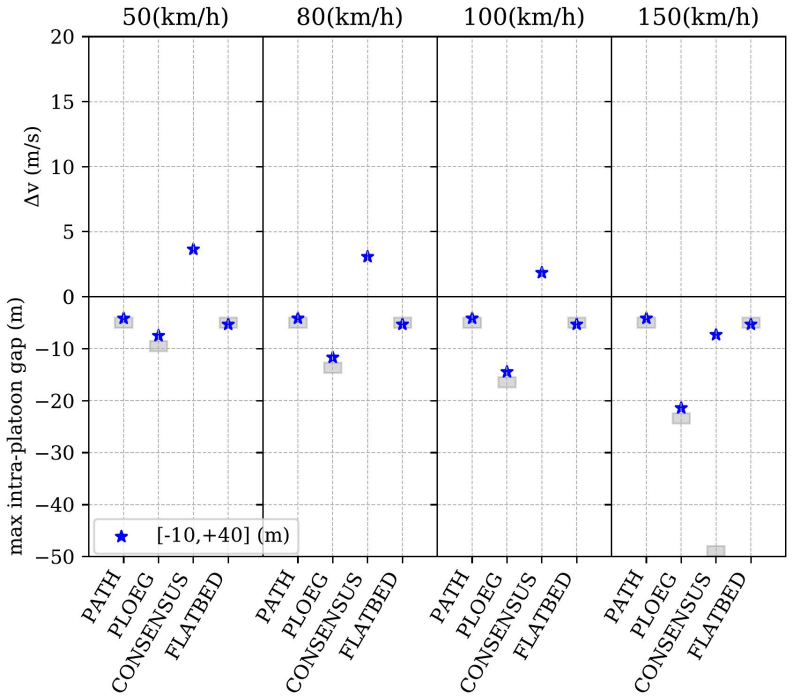
Property	Value
Controller	PATH, Ploeg, Consensus, Flatbed
Spacing	5m, 0.5s, 0.8s, 5m
Platoon Length	6 / 7 (Join)
Leader speed	50, 80, 100, 150 kmph
Sensors	ϵ_p^{V2V} = 1 m, ϵ_s^{V2V} = 0.1 m/s, ϵ_a^{V2V} = 0.01 m/s^2 ϵ_p^{RAD} = 0.1 m, ϵ_s^{RAD} = 0.1 m/s

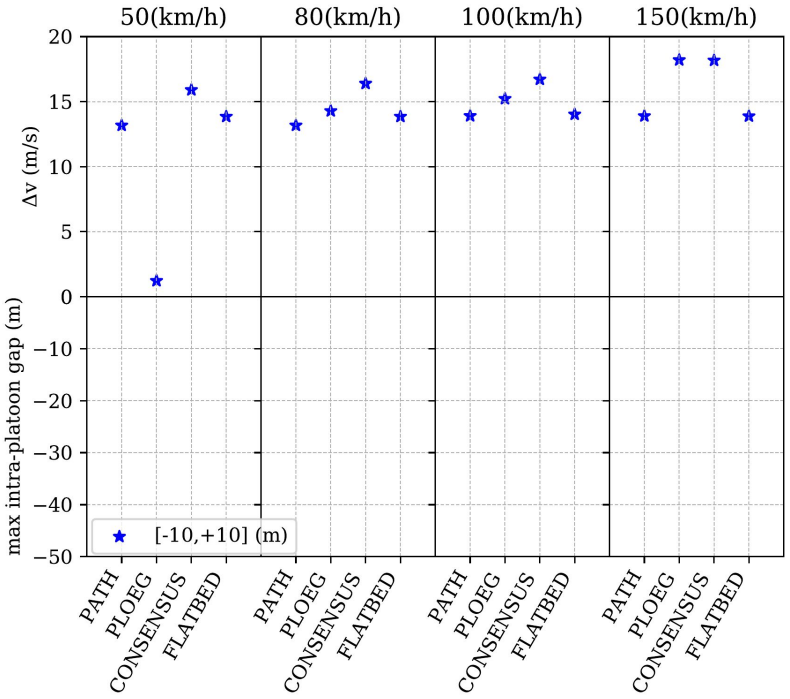
General Parameters	Value
Simulation length	120s
Warm-Up period	30s
Area Size	5 KM x 50 M (4 lanes)
Repetitions	10
Carrier Frequency	5.89 GHz
Max TX Power	100mW
Physical Layer Bitrate	6Mbps
Sensitivity	-94dBm
Thermal Noise	-95dBm
Physical Layer Propagation Delay	true
Network Layer Propagation Delay	true

Metrics

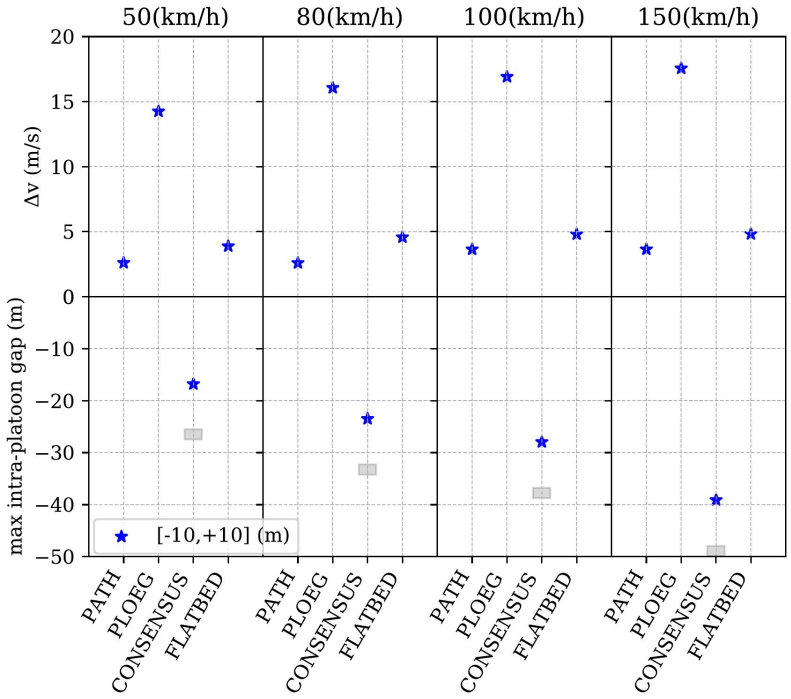
- Controllers behavior
  - Distance between each vehicle
  - Speed, Acceleration, Controller Acceleration, Position
- Platoon instability
  - Nominal gaps
  - Maximum error distance from nominal gaps
- Collision Severity
  - ΔV between colliding cars

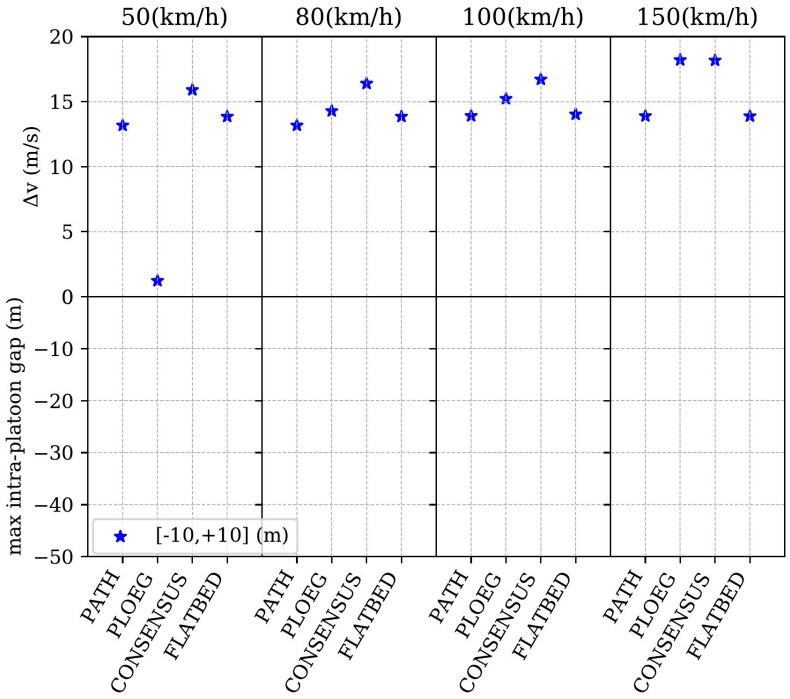
Gradual vs Smart Pos Leader Attack



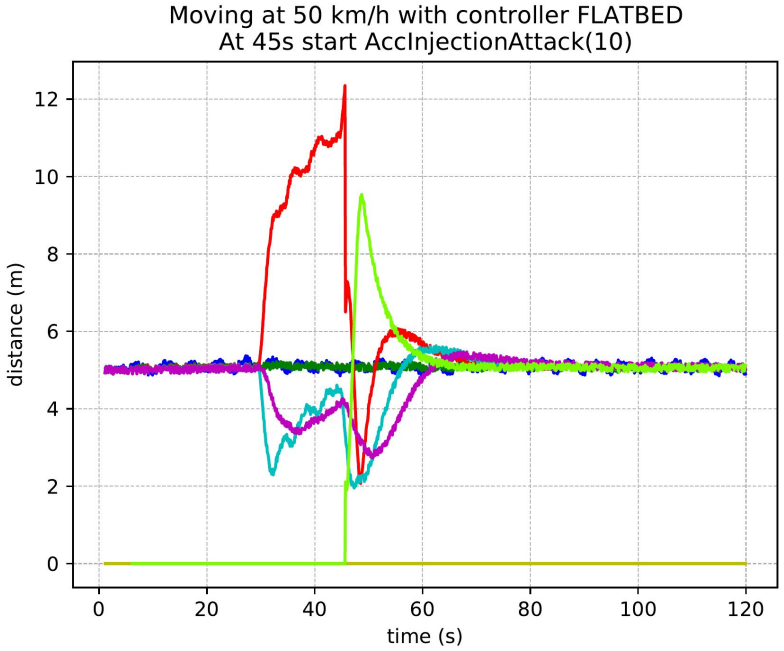


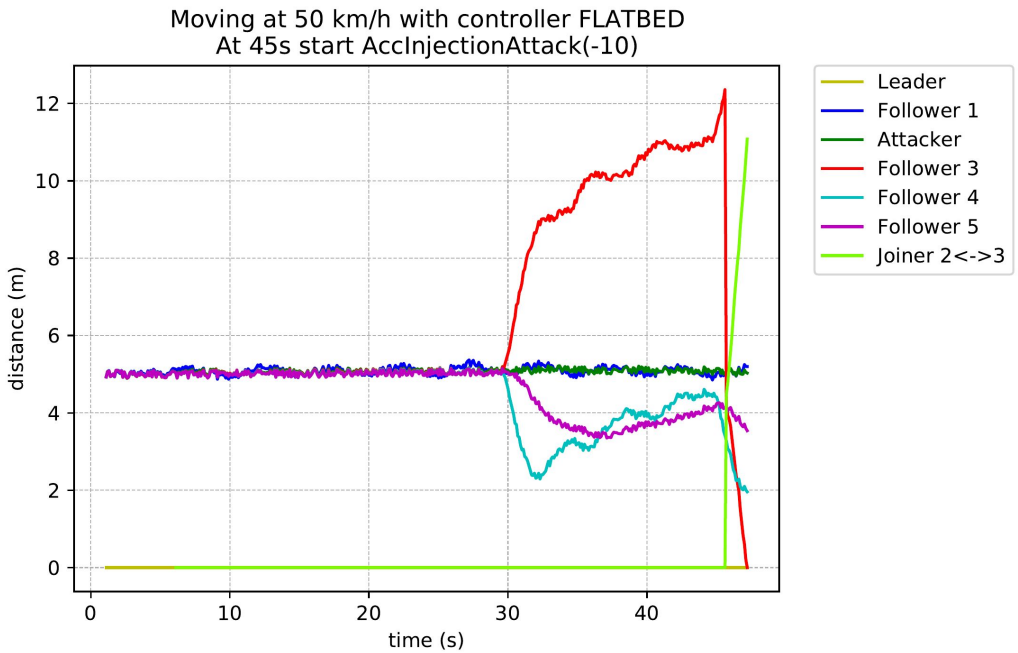
Smart Pos: Follower vs Leader





Acceleration Attack - Flatbed Join





Hitmap

Attack		No Maneuver				Join Maneuver				Exit Maneuver			
		50 (km/h)	80 (km/h)	100 (km/h)	150 (km/h)	50 (km/h)	80 (km/h)	100 (km/h)	150 (km/h)	50 (km/h)	80 (km/h)	100 (km/h)	150 (km/h)
Position (m)	PATH	-	-	-	-	-	-	-	-	-	-	-	-
	Consensus	LF {3,5,7,9,11}	LF {3,5,7,9,11}	LF {3,5,7,9,11}	LF {3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}	{3,5,7,9,11}
	Flatbed	-	-	-	-	-	-	-	-	-	-	-	-
	Ploeg	-	-	-	-	-	-	-	-	-	-	-	-
Speed (km/h)	PATH	LF {-50,0}	LF {-50,0} F +50	LF {-50,0,50}	LF {-50,0,50,100}	{-50,0}	{-50,0,50}	{-50,0,50}	{-50,0,50,100}	{-50,0}	{-50,0,50}	{-50,0,50}	{-50,0,50,100}
	Consensus	L {100,150}	L 150	L 150	-	-	-	-	-	-	-	-	-
	Flatbed	L {100,150}	L {100,150}	L 150	-	{-50,0}	{-50,0}	{-50,0}	{-50,0,50,100}	-	-	-	-
	Ploeg	-	-	-	-	-	-	-	-	-	-	-	-
Acceleration (m/s^2)	PATH	F {-30,-10}	F {-30,-10}	F {-30, -10}	F {-30, -10}	{-30,-10}	{-30,-10}	{-30,-10}	{-30,-10}	{-30,-10}	{-30,-10}	{-30,-10}	{-30,-10}
	Consensus	-	-	-	-	-	-	-	-	-	-	-	-
	Flatbed	-	-	-	-	-	-	-	-	-	-	-	-
	Ploeg	LF {-10,-30}	LF -30	LF -30	LF -30	-30	-30	-30	{10,30}	-30	-30	-30	{10,30}
Gradual Position (m)	PATH	-	-	-	-	-	-	-	-	-	-	-	-
	Consensus	LF -10/+40	LF -10/+40	-	-	-10/+40	-10/+40	-	-	-10/+40	-10/+40	-	-
	Flatbed	-	-	-	-	-	-	-	-	-	-	-	-
	Ploeg	-	-	-	-	-	-	-	-	-	-	-	-
Gradual Speed (m/s)	PATH	LF {-10/+17}	LF {-10/+17}	LF {-10/+17}	LF {-10/+17}	-10/+17	-10/+17	-10/+17	-10/+17	-10/+17	-10/+17	-10/+17	-10/+17
	Consensus	L -10/+17	L -10/+17	L -10/+17	L -10/+17	-	-	-	-	-	-	-	-
	Flatbed	L -10/+17	L -10/+17	L -10/+17	L -10/+17	-	-	-	-	-	-	-	-
	Ploeg	-	-	-	-	-	-	-	-	-	-	-	-
Gradual Acceleration (m/s^2)	PATH	F -10/+10	F -10/+10	F -10/+10	F -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
	Consensus	-	-	-	-	-	-	-	-	-	-	-	-
	Flatbed	-	-	-	-	-10/+10	-	-	-10/+10	-	-	-	-
	Ploeg	LF -10/+10	LF -10/+10	LF -10/+10	LF -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
Smart Position (m)	PATH	F* -10/+10	F* -10/+10	F* -10/+10	F* -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
	Consensus	L -10/+10	L -10/+10	L -10/+10	L -10/+10	-	-	-	-	-	-	-	-
	Flatbed	F -10/+10	F -10/+10	F -10/+10	F -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
	Ploeg	L -10/+10	LF -10/+10	-10/+10	LF -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
Smart Speed (m/s)	PATH	F -10/+10	F -10/+10	F -10/+10	F -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
	Consensus	L -10/+10	L -10/+10	-	-	-	-	-	-	-	-	-	-
	Flatbed	L -10/+10	L -10/+10	L -10/+10	L -10/+10	-10/+10	-	-	-	-	-	-	-
	Ploeg	LF -10/+10	LF -10/+10	L -10/+10	L -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
Smart Acceleration (m/s^2)	PATH	F -10/+10	F -10/+10	F -10/+10	F -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10
	Consensus	-	-	-	-	-	-	-	-	-	-	-	-
	Flatbed	L -10/+10	L -10/+10	L -10/+10	L -10/+10	-	-	-	-	-	-	-	-
	Ploeg	LF -10/+10	LF -10/+10	LF -10/+10	LF -10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10	-10/+10

Remarks

- Controllers
  - Consensus - most resilient
  - CVS - susceptible to jamming during acceleration
- Attacks on Maneuvers
  - Exit: minimal differences
  - Join:
    - Denied entry
    - CVS susceptibility
- Attack potency comparison
  - Follower better than Leader - no maneuver scenarios
- Kalman Filter
  - Detects Attacks
  - 100% False positives during maneuvering

Future Work

- Maneuvers
  - Security & Privacy of current maneuvers?
  - Susceptible to smarter attacks?
    - Selective jamming
    - False controller dissemination
- Colluding attackers
  - Easier/Harder to detect?
  - Leader + Follower? Two middle-formation leavers?
- Defense mechanisms
  - Misbehavior detection models?
  - Can they detect all the attacks?
  - Actual cost (cpu) of deploying them?
- Evaluate more realistic scenarios
  - Different lengths, engine capabilities

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Appendix

1. Controller Comparison
2. Jamming
3. Kalman Filter
4. Intelligent Attacks
    a. Gradual Acceleration
    b. Smart Acceleration + Details
    c. Gradual Speed
    d. Smart Speed + Details
5. Maneuvers
    a. Acceleration - Join
    b. Gradual Acceleration - Join
    c. Gradual Speed Denied Entry - Join
    d. Smart Speed - Join
    e. Smart Position - Join
    f. Smart Position - Exit
    g. Acceleration - Exit
    h. Without Abort Crashes
6. Speed

Controller Comparison

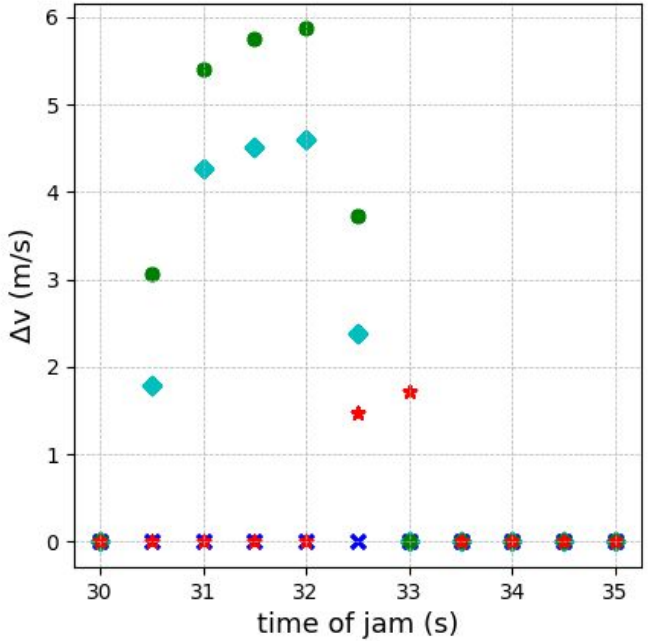
- Effective combined attacks
  - Ploeg - Acceleration
  - Consensus - Position
  - Flatbed - Speed
- Instability
  - Minimal difference Simple vs Gradual (1st table)
  - Consensus on combined attacks
- Crashes
  - Consensus is resilient
  - Ploeg always crashes

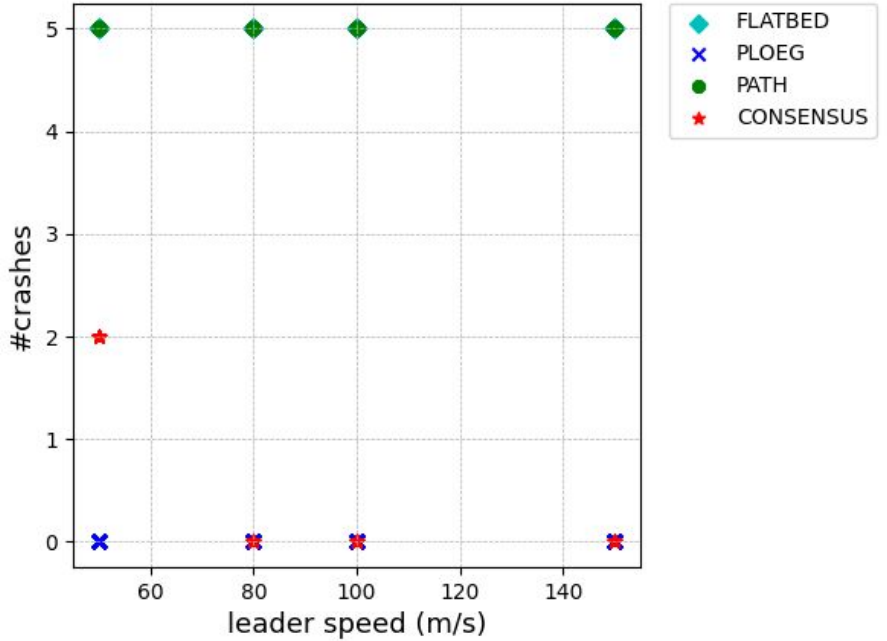
Controller	Simple			Gradual			Combined		
	P	S	A	P	S	A	P	S	A
PATH	100	—	20	100	—	—	—	—	—
Ploeg	100	100	20	100	100	—	—	—	—
Consensus	—	75	100	—	75	100	—	—	20
Flatbed	100	—	68.75	100	—	62.5	—	—	75

Controller	Simple			Gradual			Combined		
	P	S	A	P	S	A	P	S	A
PATH	—	1.47	10	—	—	—	—	—	—
Ploeg	—	—	20	—	—	—	—	—	—
Consensus	—	19.11	—	43.75	—	—	75	87.5	75
Flatbed	—	77.95	20	—	75	25	—	68.75	—

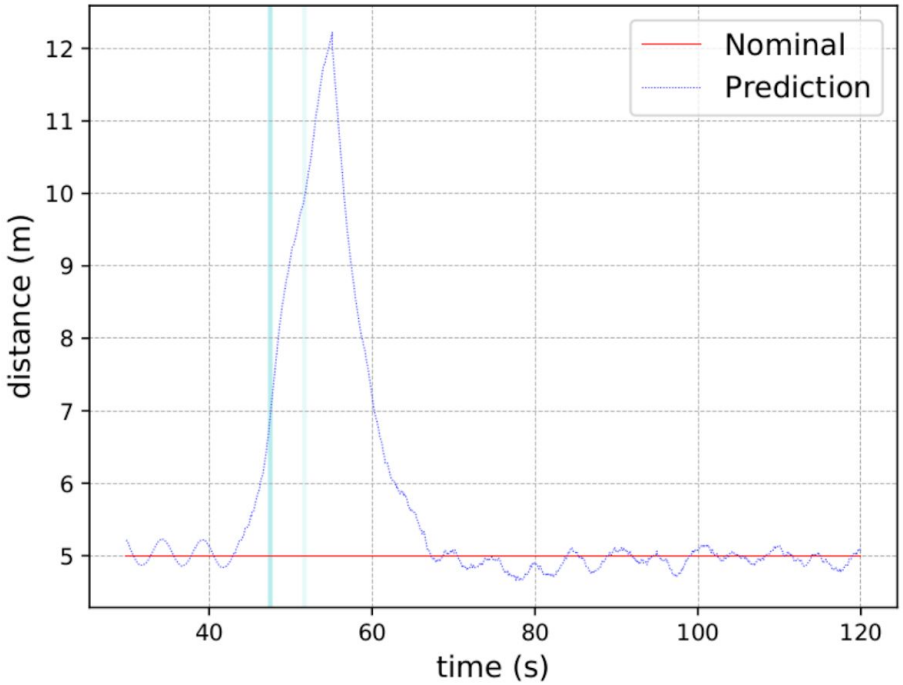
Controller	Simple			Gradual			Combined		
	P	S	A	P	S	A	P	S	A
PATH	—	98.53	70	—	100	100	100	100	100
Ploeg	—	—	60	—	—	100	100	100	100
Consensus	100	5.88	—	56.25	25	—	25	12.5	—
Flatbed	—	22.05	11.25	—	25	12.5	100	31.25	25

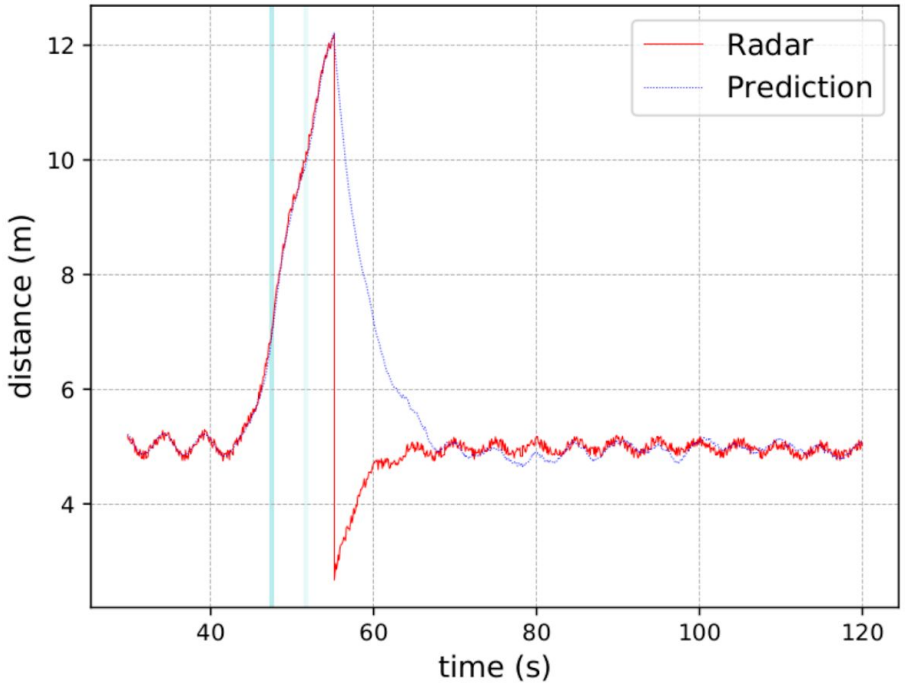
Jamming


Δv (m/s)
time of jam (s)
0
1
2
3
4
5
6
30
31
32
33
34
35


#crashes
leader speed (m/s)
0
1
2
3
4
5
60
80
100
120
140
FLATBED
PLOEG
PATH
CONSENSUS

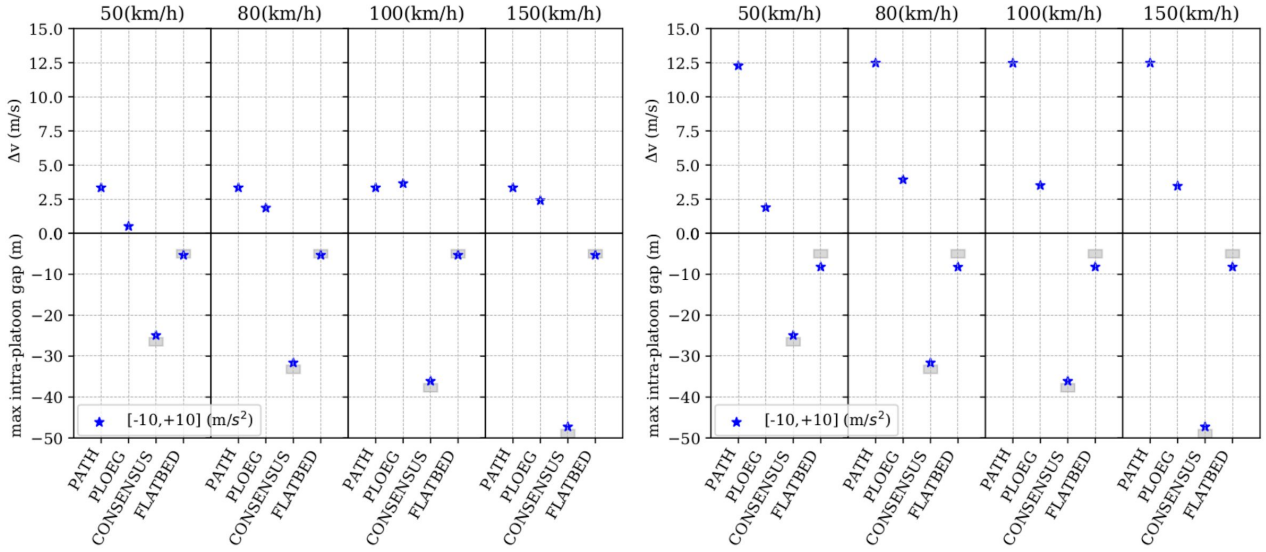
Kalman Filter Comparison: V2V - Radar





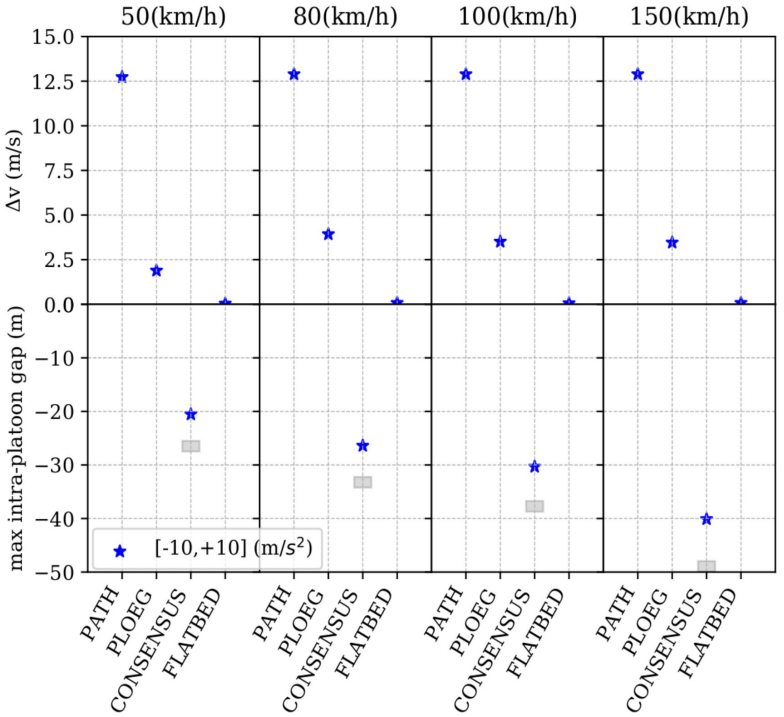
Gradual Acceleration: Follower vs Leader Attacker

- Rear vs Front Collision
  - PATH Follower is Better
  - Ploeg 50 km/h is Better

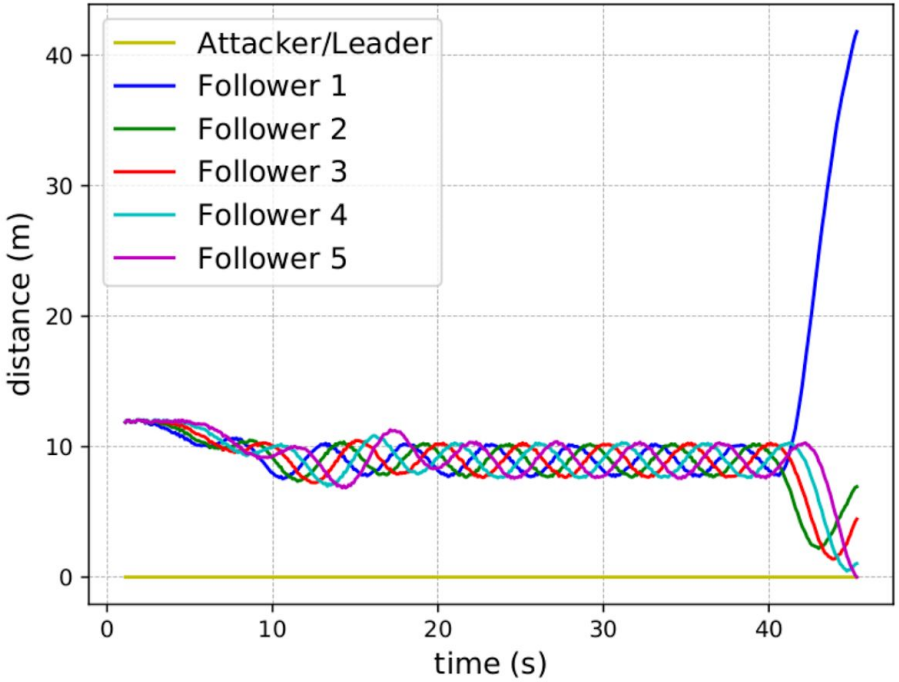


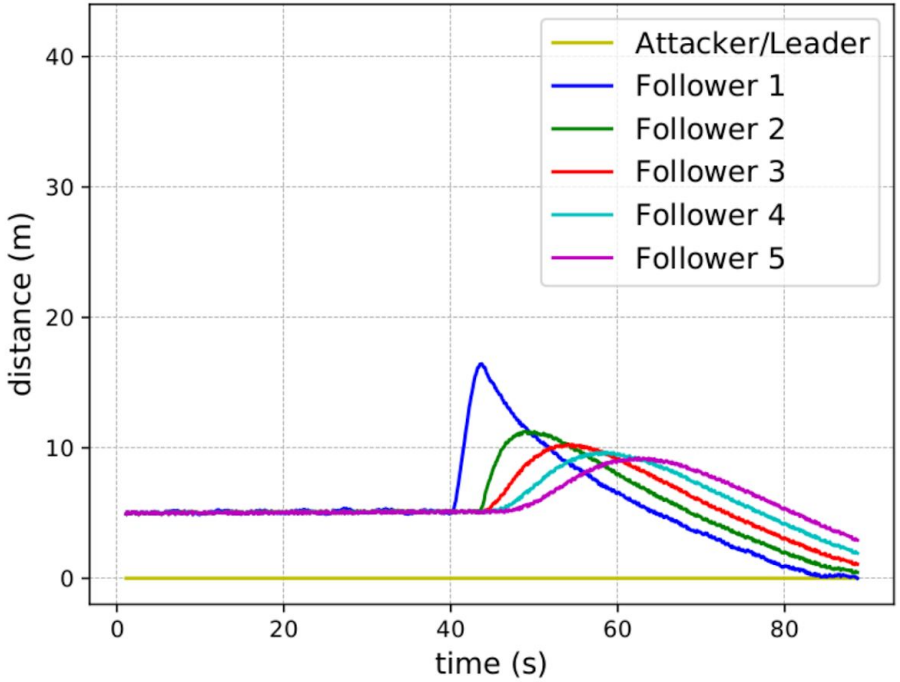
Leader Smart Acceleration

- Follower
  - Similar to Gradual Acceleration
- Leader
  - Flatbed closes the distance very slowly
  - Acceleration attack improves the least



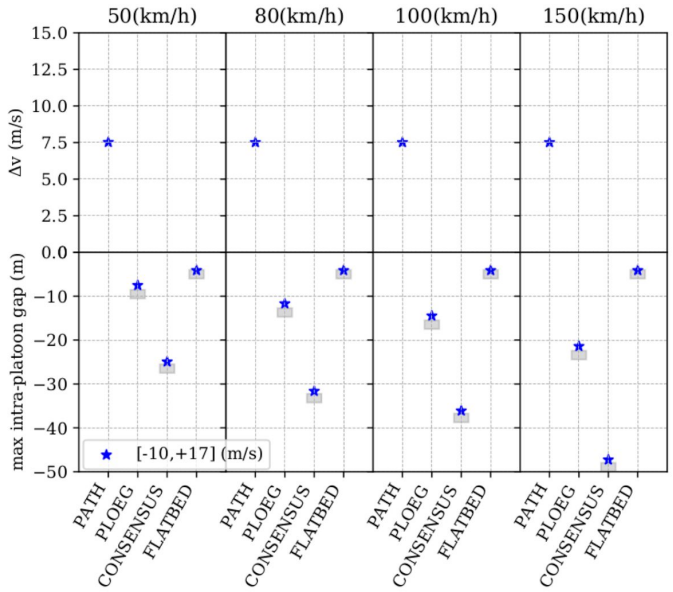
Smart Acceleration: Ploeg vs Flatbed

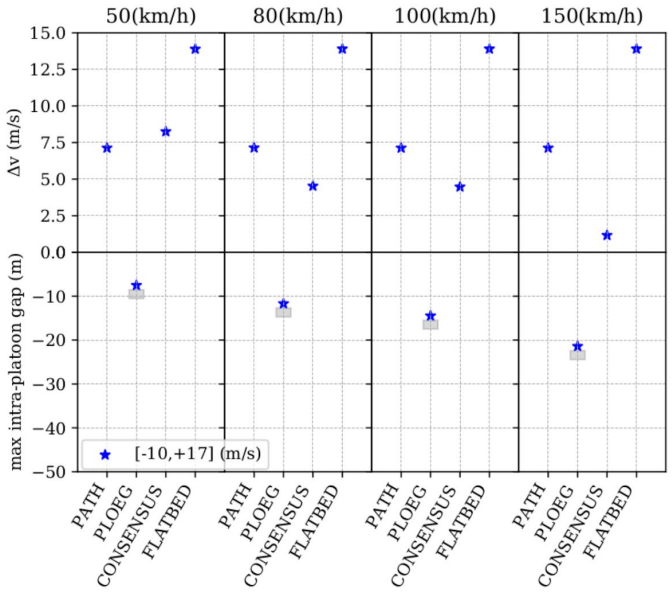




Gradual Speed: Follower vs Leader

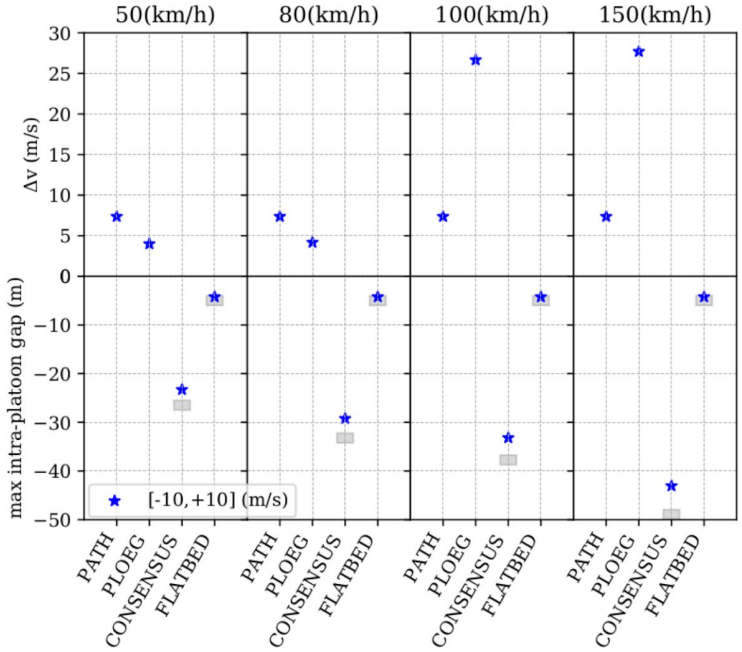
- Consensus
  - Increasingly Smaller difference between current speeds (thus gaps) and falsified speed

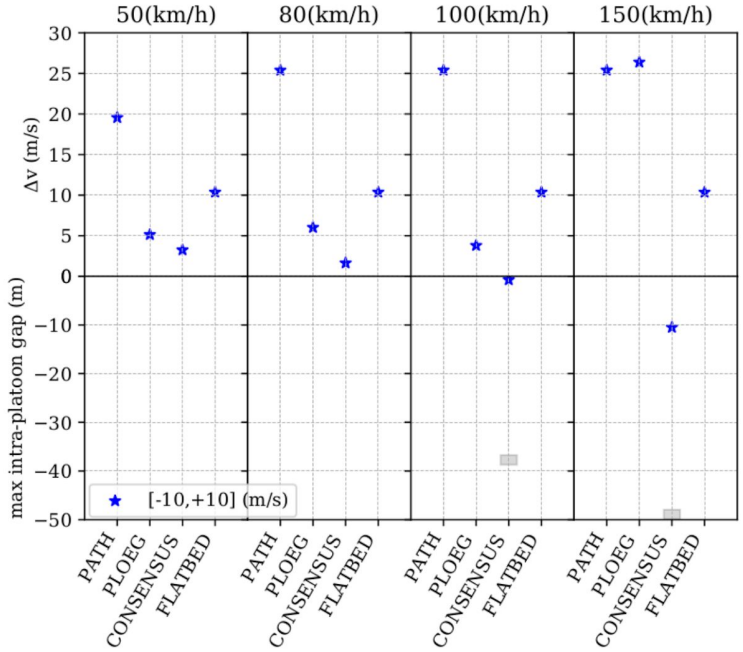




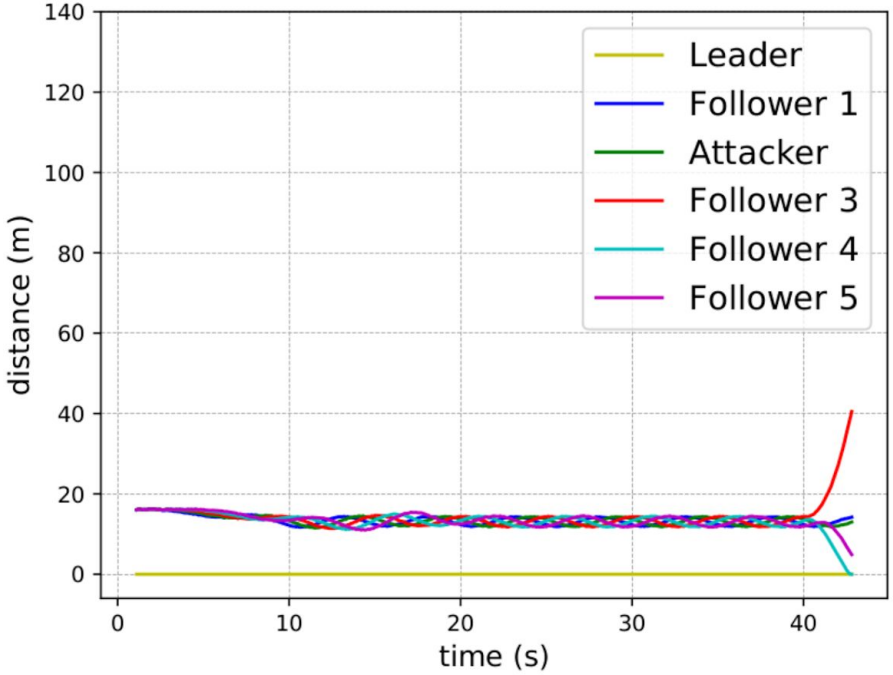
Smart Speed: Follower vs Leader Attacker

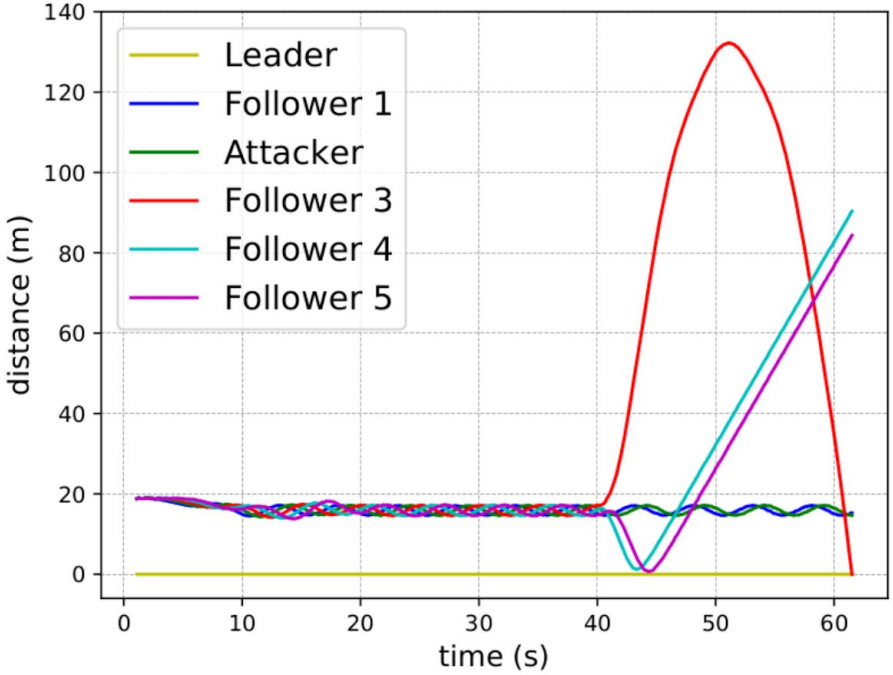
- PATH/Ploeg: Rear vs Front Collision
- Consensus: Bigger speed => Bigger gaps





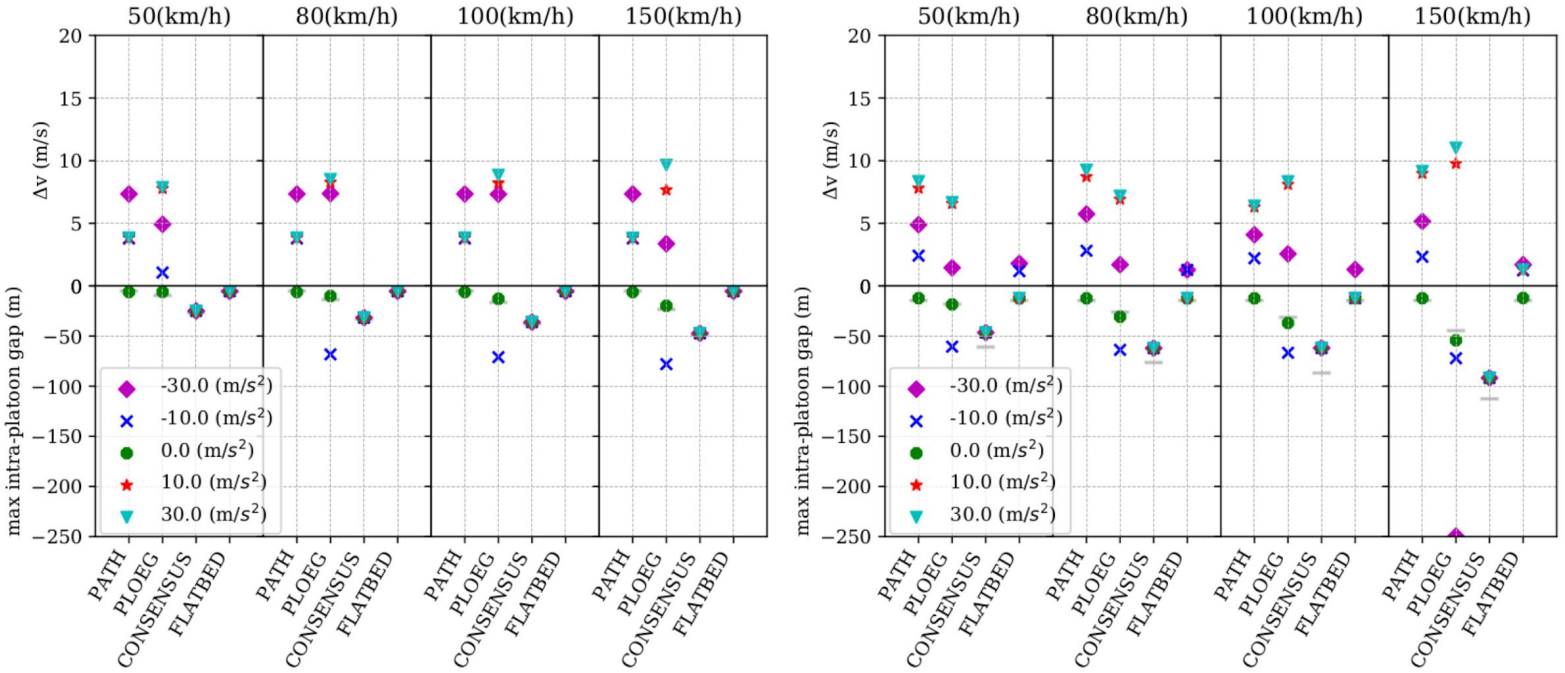
Smart Speed Ploeg 80 vs 100 km/h



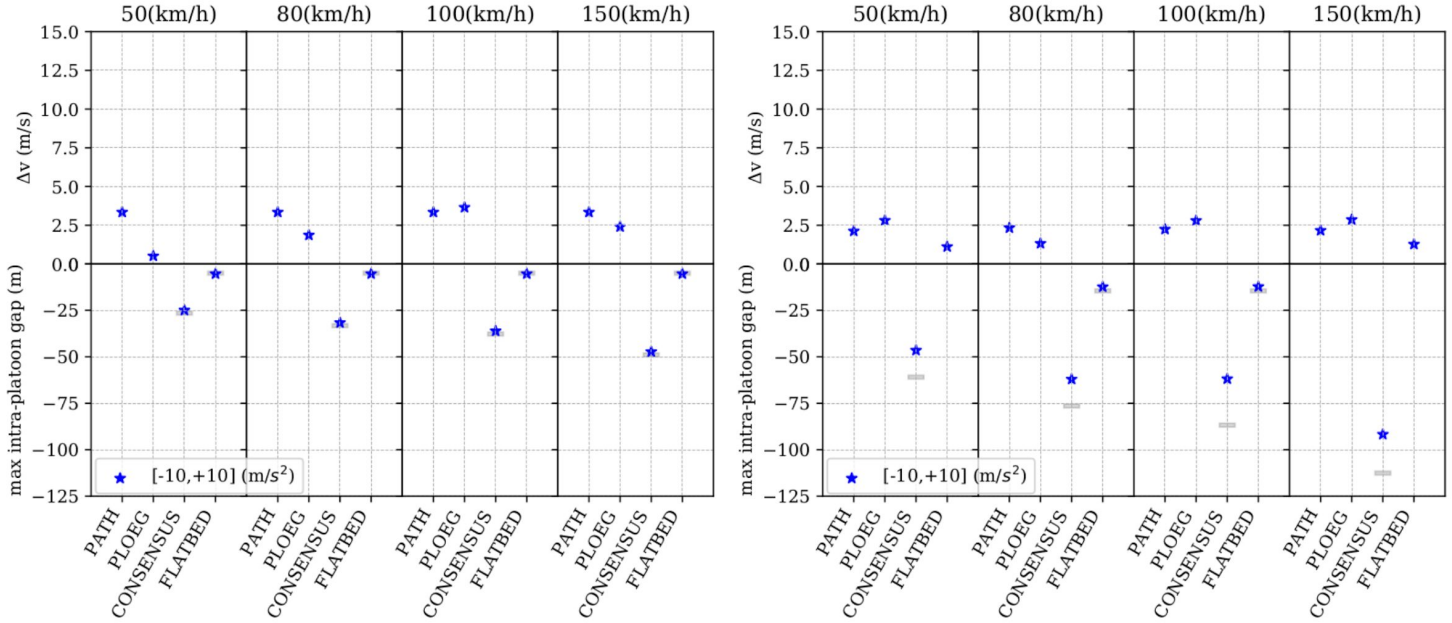


Acceleration: Static vs Join

- PATH: Positive values => better crashes (due to bigger gaps)

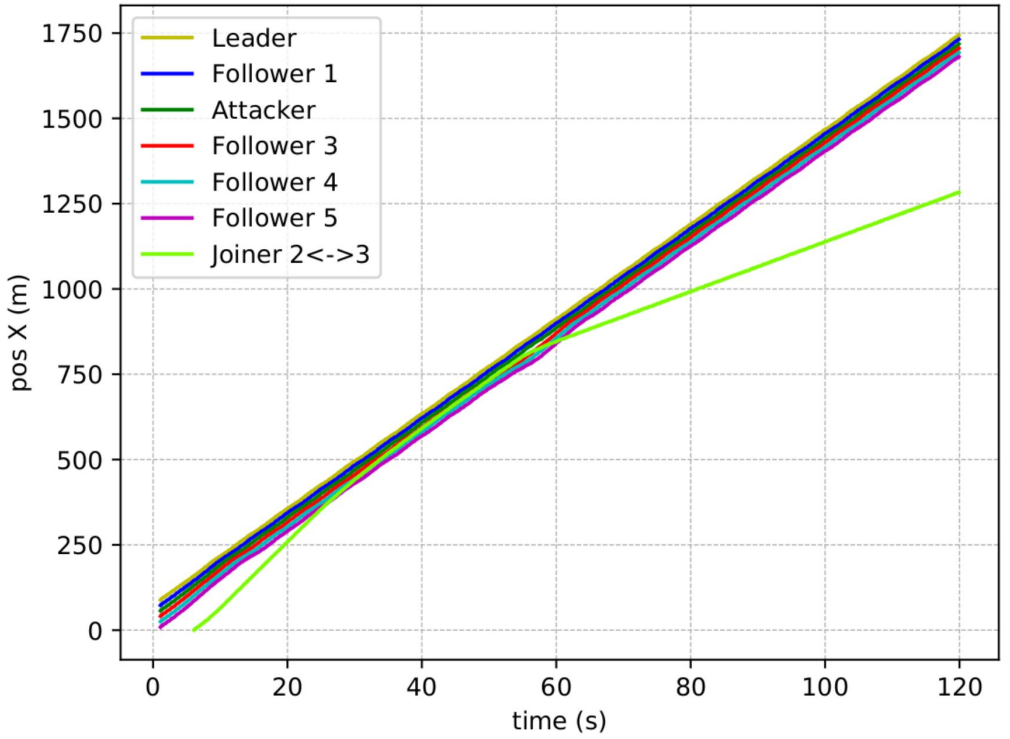


Gradual Acceleration: Static vs Join

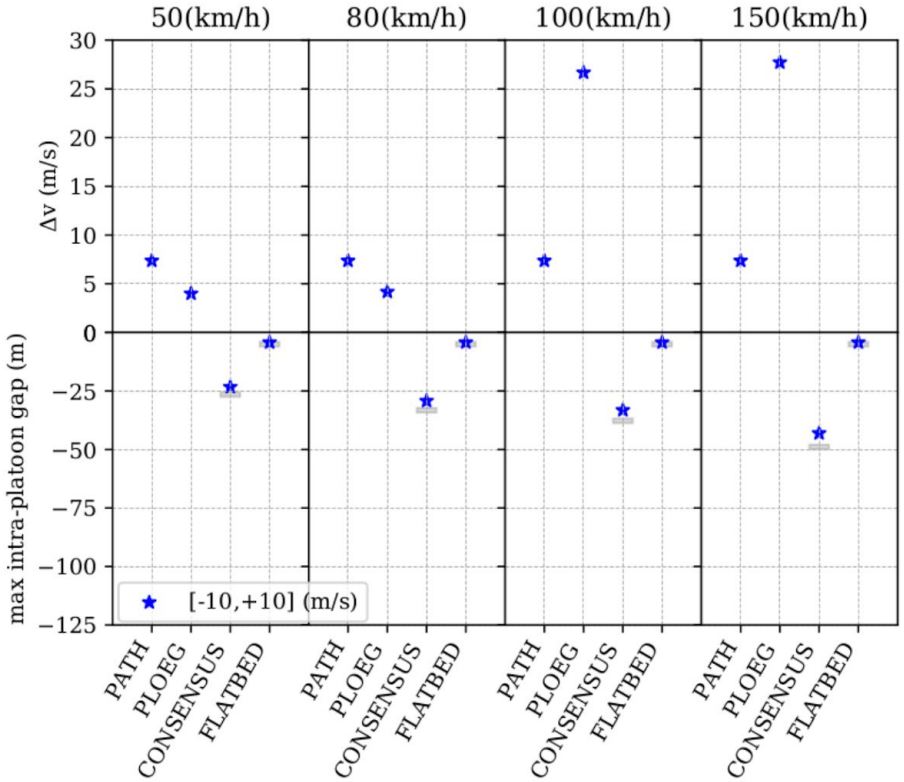


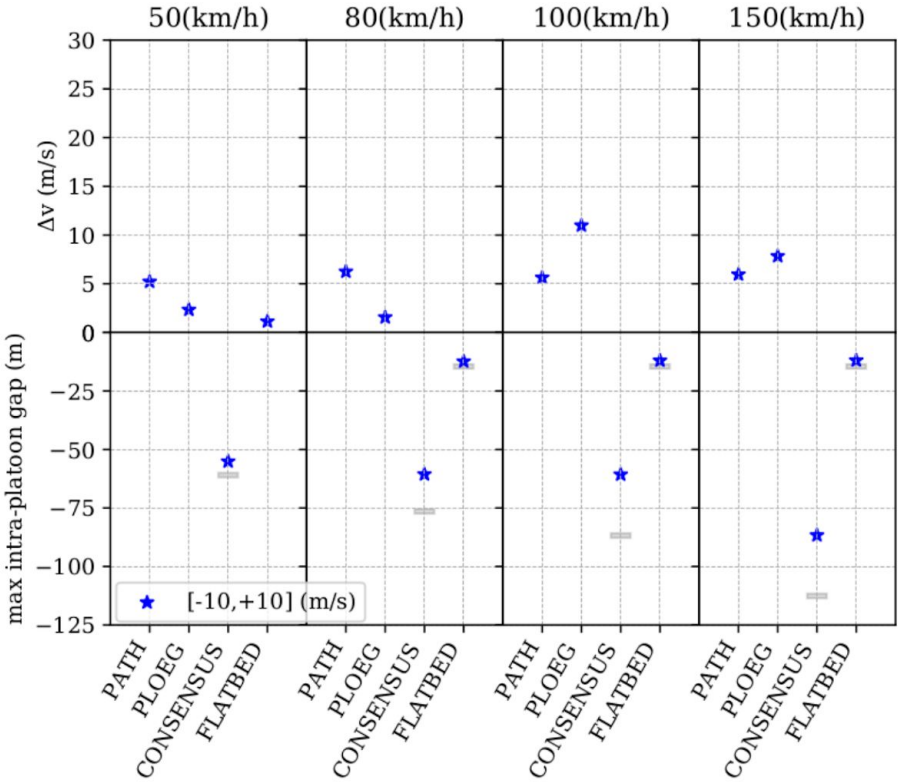
Gradual Speed Entry Denial: Ploeg

- Ploeg ignores speed data
- The Joiner does not
- Entry is aborted

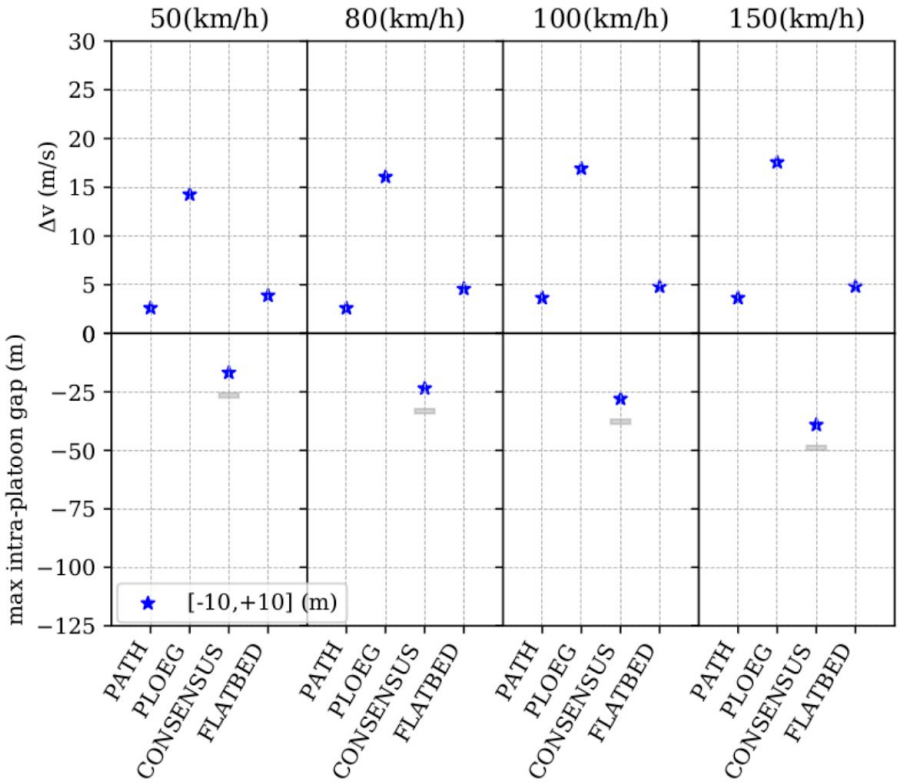


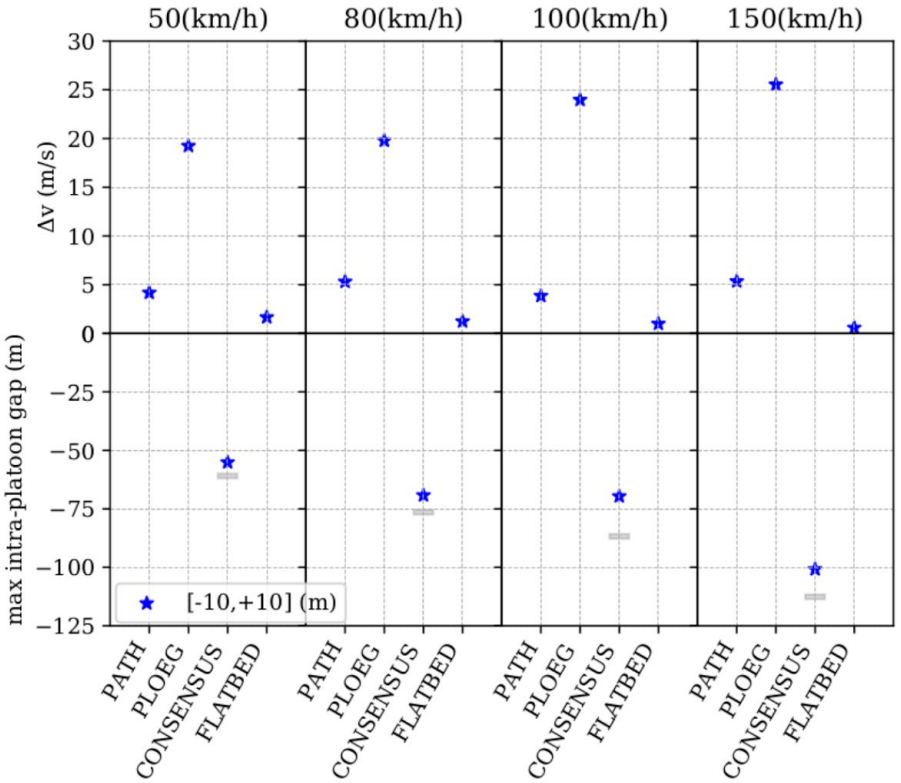
Smart Speed: Static vs Join



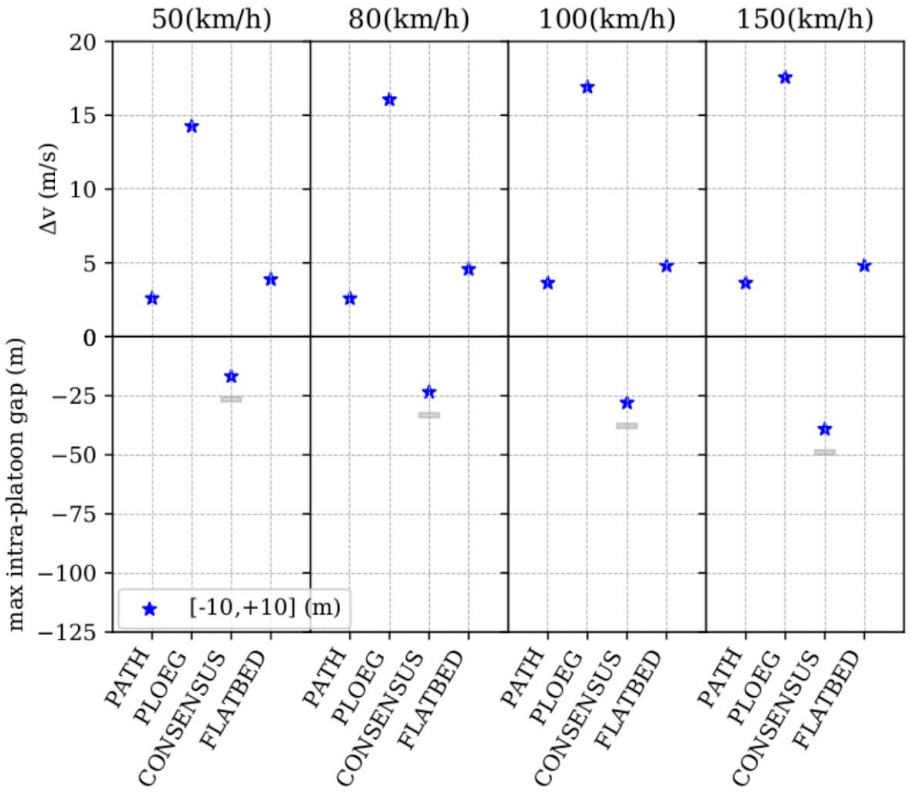


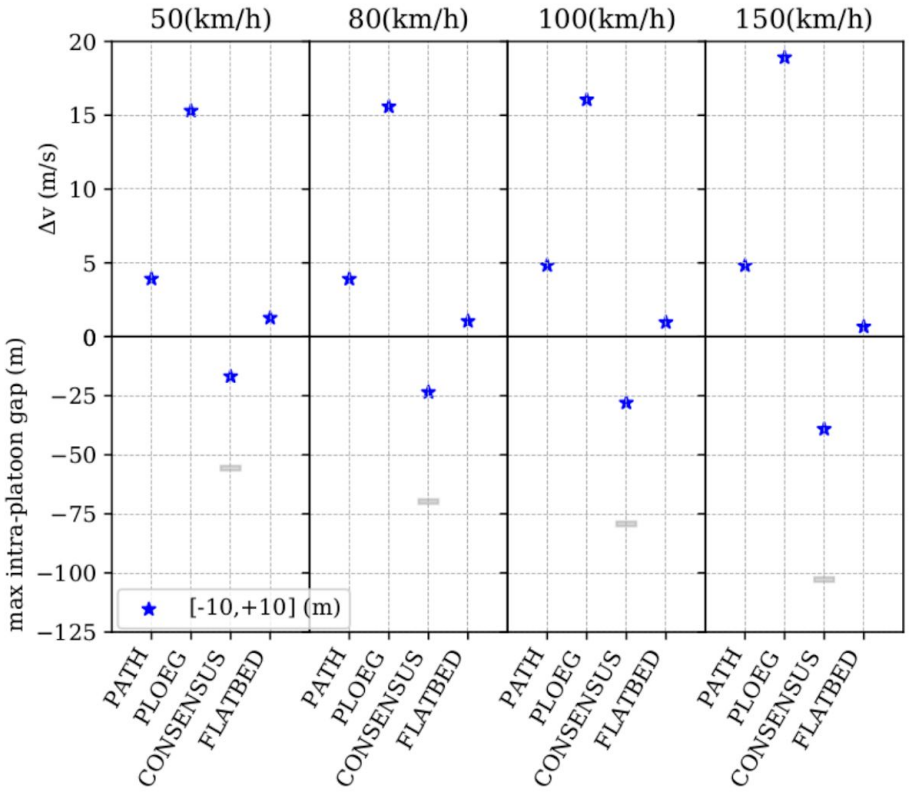
Smart Position: Static vs Join



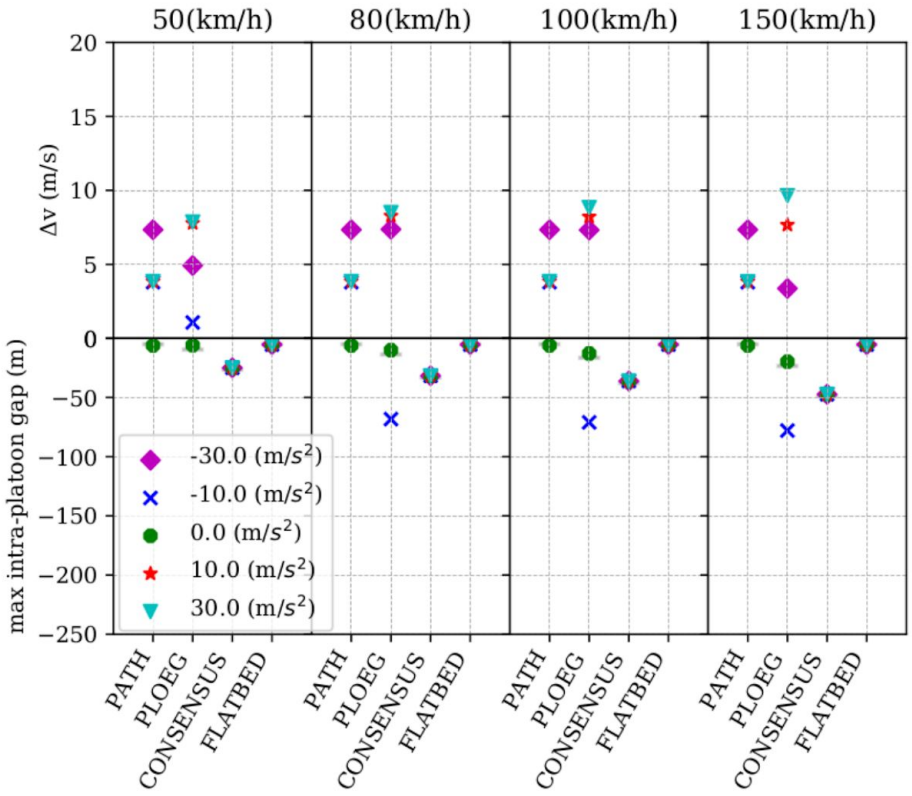


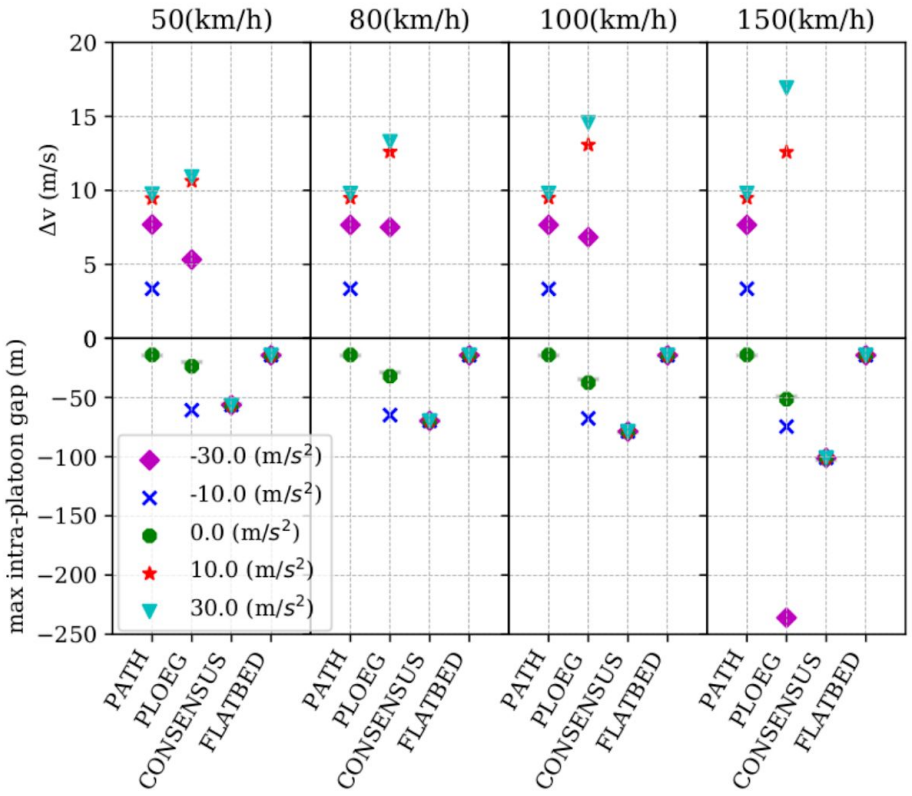
Smart Position: Static vs Exit



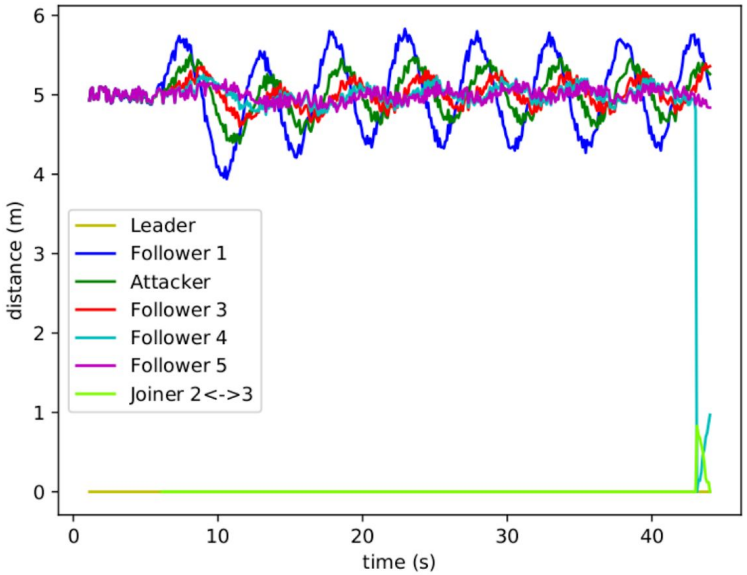


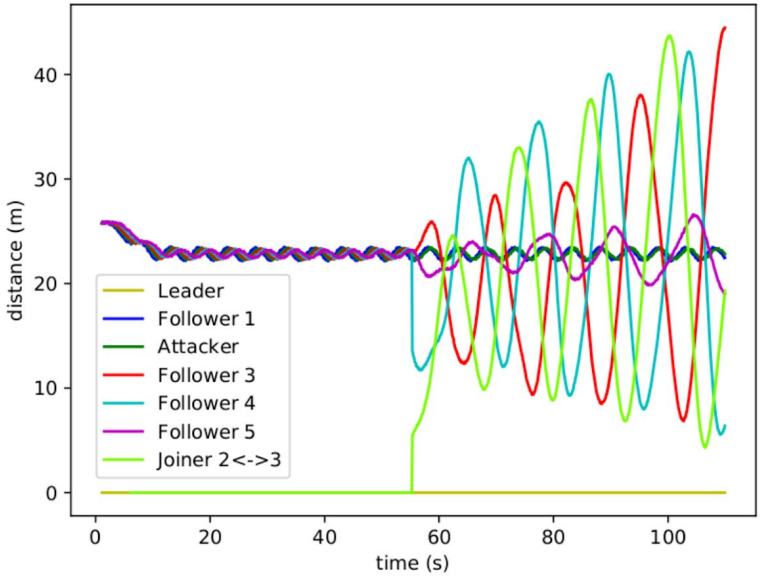
Acceleration: Static vs Exit



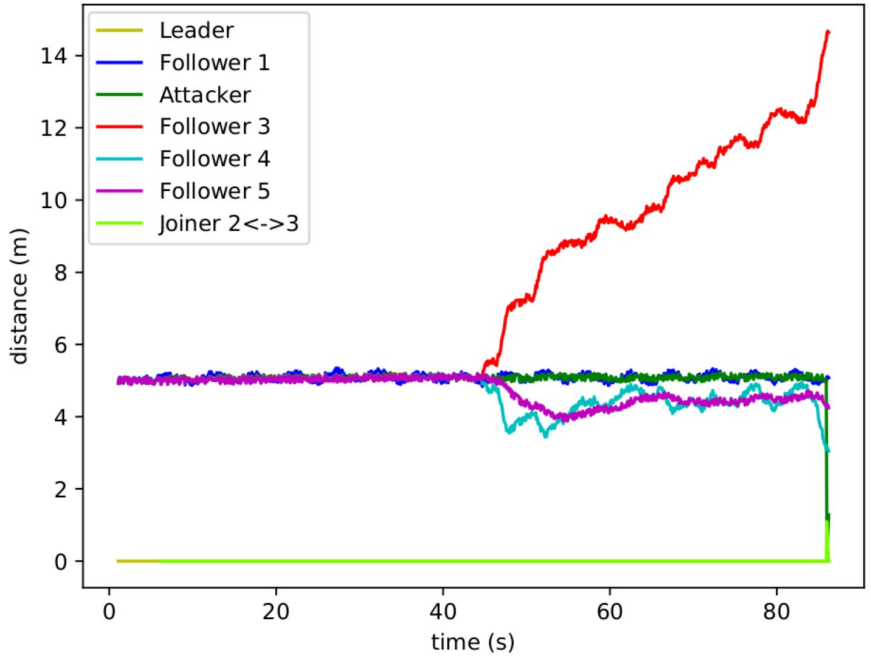


Join at Later Position: PATH vs Ploeg

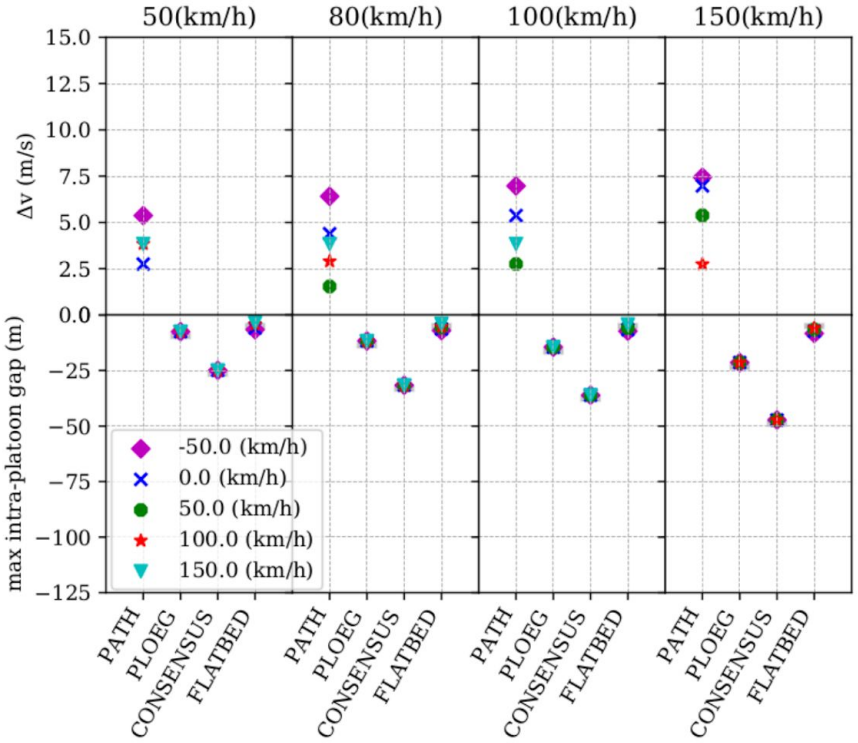


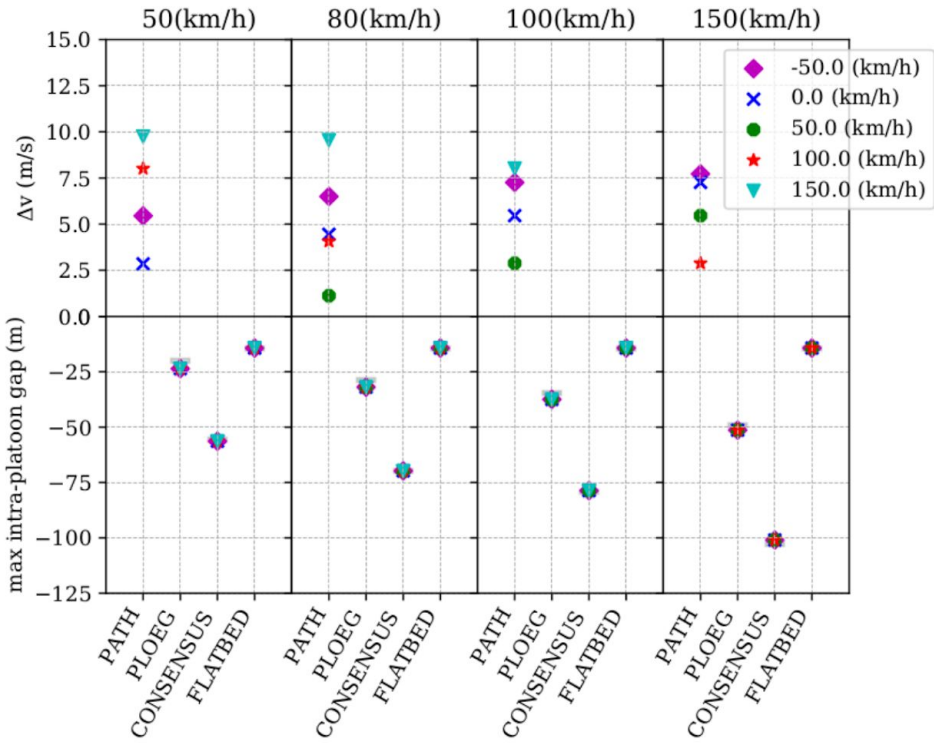


Join at Earlier Position: Flatbed



Speed Exit


50(km/h)
80(km/h)
100(km/h)
150(km/h)
Δv (m/s)
max intra-platoon gap (m)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−25
−50
−75
−100
−125
PATH
PLOEG
CONSENSUS
FLATBED
-50.0 (km/h)
0.0 (km/h)
50.0 (km/h)
100.0 (km/h)
150.0 (km/h)


50(km/h)
80(km/h)
100(km/h)
150(km/h)
Δv (m/s)
max intra-platoon gap (m)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−25
−50
−75
−100
−125
PATH
PLOEG
CONSENSUS
FLATBED
-50.0 (km/h)
0.0 (km/h)
50.0 (km/h)
100.0 (km/h)
150.0 (km/h)