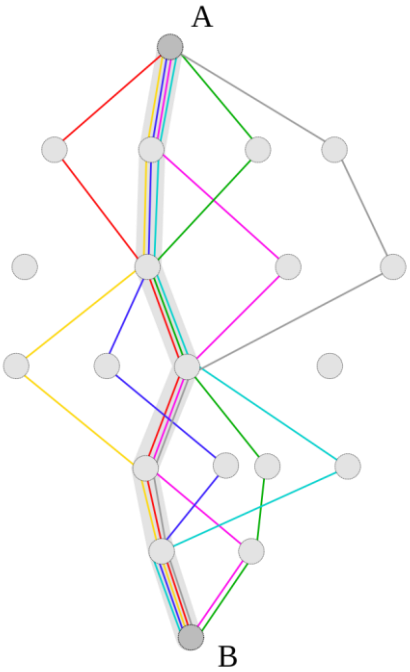
A practical implementation for pheromone-based traffic congestion reduction(?)

Fabrice Saffre

03/02/2023 **VTT – beyond the obvious**

The (old) core idea (1/2)

- Ground-dwelling social insects (mainly ants and termites) use chemicals to mark their environment and communicate useful information to each other (about where to find food, what's the safest path back to the nest etc.)
- Basically: an ant that finds a possible route to a desirable goal (say a drop of sugary water) marks it with an attractive pheromone and, when the conditions are right, the response to and amplification of this signal by other ants allow the colony to identify the best out of multiple options (e.g., find the shortest path)
- Famously, this kind of positive feedback can inform the efficient design of networks and solve other related NP-complete problems
- Hence the success of Ant Colony Optimisation (ACO) heuristics in operational research.



The (old) core idea (2/2)

- So it has long been proposed that a “reverse-ACO” approach (where the pheromone is repulsive instead of attractive) could help reduce traffic congestion
- In short: when an (artificial) ant’s path on the way to its goal is blocked (e.g., because too many others are using the same route and queues have formed), it releases a “frustration” signal that acts as a repellent, incentivising followers to try another itinerary
- This has been shown to work quite well in simulation (including with realistic traffic patterns on actual road networks)[1]
- There’s only one problem: in practice, cars cannot physically mark the asphalt or “sniff” the road ahead!
- So, it is usually hypothesised that the corresponding dynamics take place inside a numerical representation of the environment, a Digital Twin (DT) in which the cars’ avatars can deposit and detect the presence of a “virtual” pheromone.

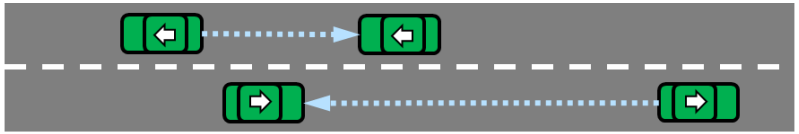
(1) Ho, Mun Chon, et al. "An improved pheromone-based vehicle rerouting system to reduce traffic congestion." *Applied Soft Computing* 84 (2019): 105702.

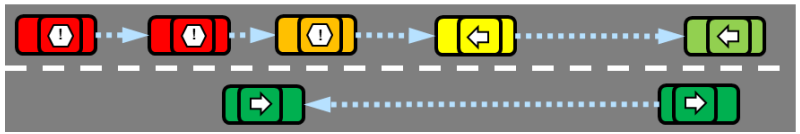
There is another way

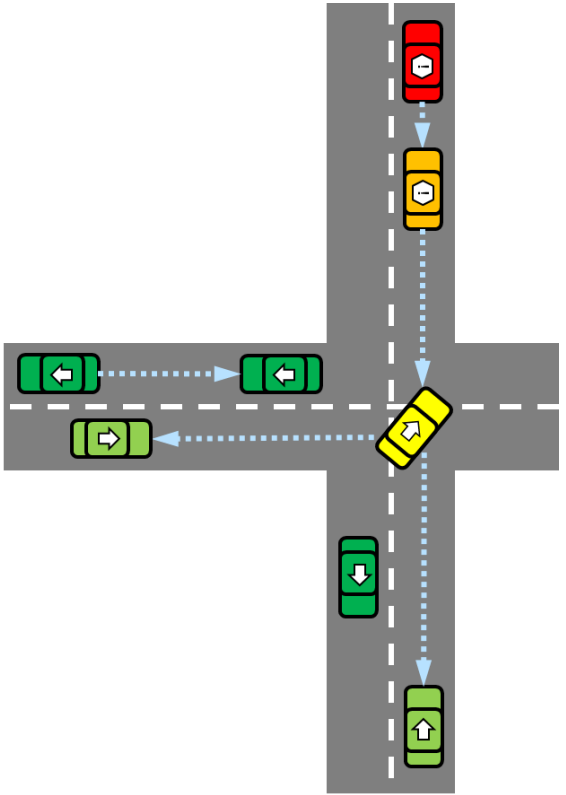
- Is such a Digital Twin the most practical option?
  - It has to be hosted somewhere and operated by someone, which could bear a significant infrastructure and operational cost
  - For such a scheme to work, all vehicles must stay connected to the central DT, to read/write information (“virtual” pheromone) in real-time
  - It is obviously a single point of failure, subject to faults and cyber attacks
- We could perhaps substitute a “gossip-based” system in which the vehicles’ onboard computers collectively host a distributed Digital Twin, interacting only through local, peer-to-peer (P2P) communication
- Such an alternative design would more closely follow the swarm intelligence paradigm, with all the associated advantages:
  - More robust to all forms of disruptions (accidental or malicious)
  - More resource-efficient (no dedicated infrastructure needed, no additional load on communication networks)
  - Infinitely scalable (every new participant brings their own computational power).

Implementation

- The basics are the same as in reverse ACO:
  - Whenever a vehicle cannot move toward its goal, it releases a repellent
  - This “virtual” pheromone diffuses through space and decays over time
- However, the signal doesn’t diffuse between neighbouring cells in some abstract representation, it does so from every vehicle toward its nearest “upstream” neighbour(s)

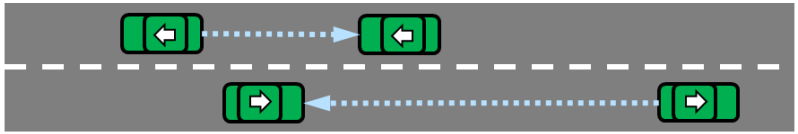


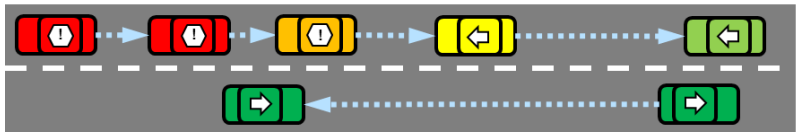


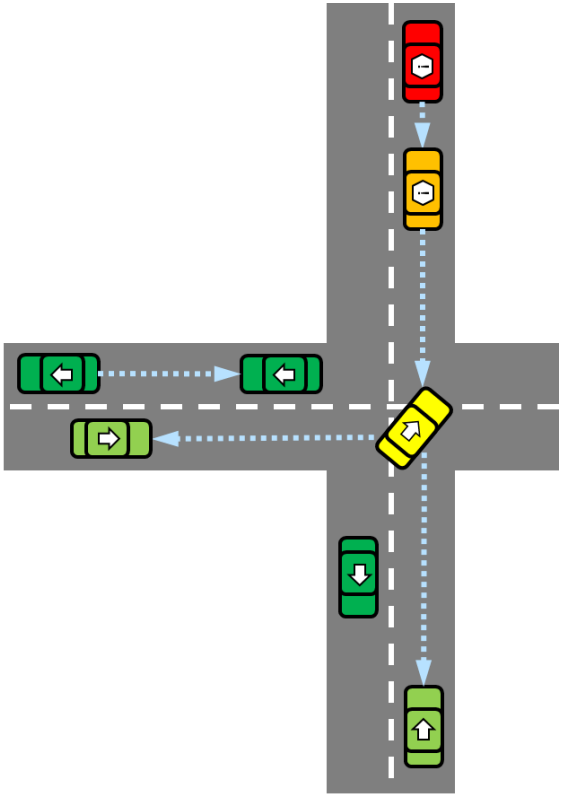


Implementation (cont'd)

- The pheromone only exists in the form of a number ("quantity") stored in the memory of each vehicle
- A tuneable amount is "transferred" to and received from nearby peers according to simple rules (it diffuses upstream from each vehicle's location, in every direction of travel)
- The signal decays at a tuneable rate to avoid unwanted long-term memory effects.

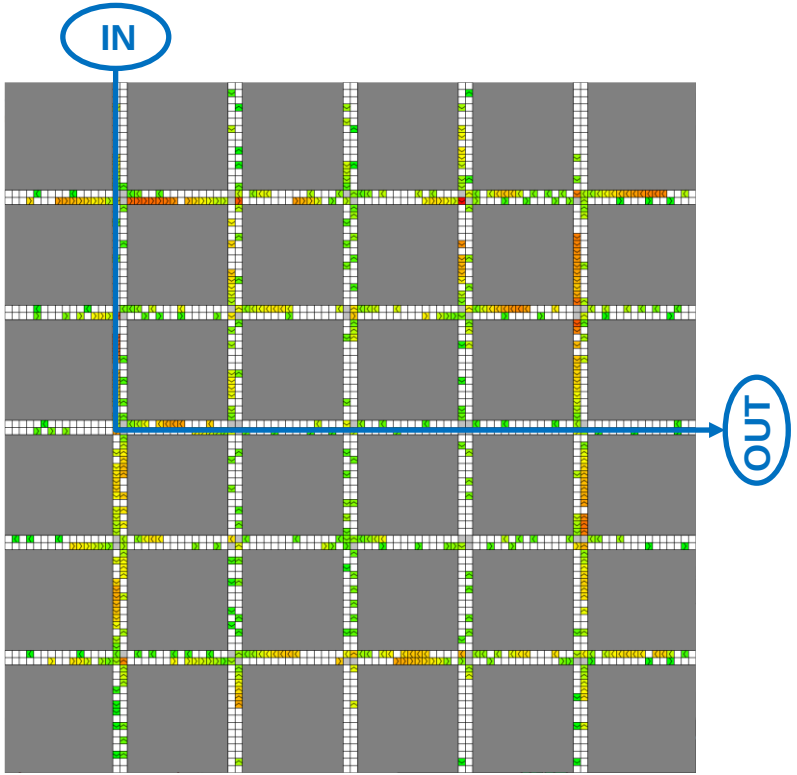






Testing the idea

- Monte Carlo simulation of a “Manhattan-style” road networks (6x6 blocks of identical size: 5 “streets”, 5 “avenues”)
- Vehicles enter the system from one of the 20 “entry gates” and are heading for one of 14 “exit gates” (the two are never on the same axis, i.e., every journey involves at least one 90° turn)
- For practical reasons, the numerical experiment uses a discrete representation of space (vehicles occupy one cell at a time and “hop” from one to the next in the direction of movement)
- But information propagates from vehicle to vehicle, according to the previously described rules (empty cells contain no pheromone data)
- Only shortest paths between entry and exit are legal (no detours allowed)



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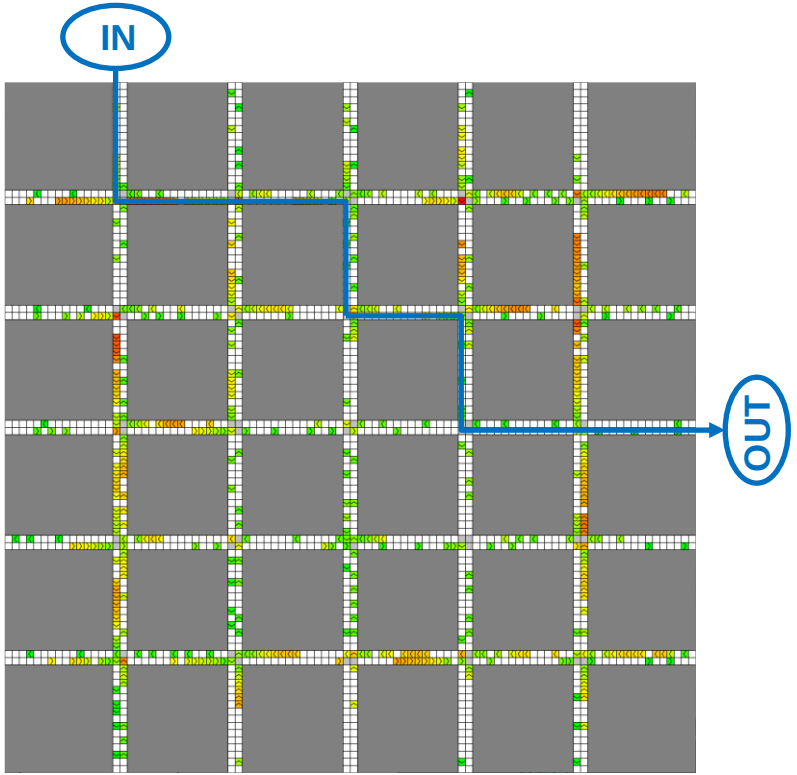

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Decision-making

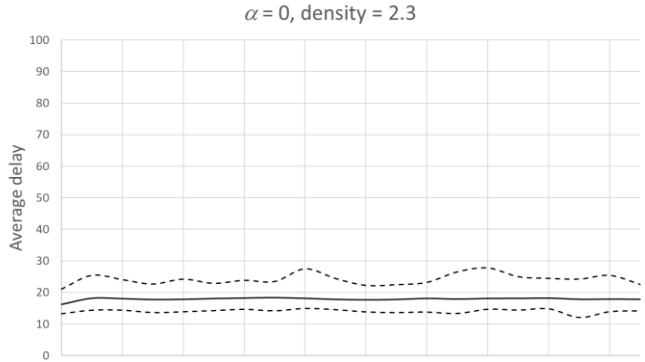
- Congestion avoidance is based exclusively on local decision-making by individual vehicles (no central planning or explicit coordination)
- As per the shortest path rule, upon reaching a crossing, only two situations are possible:
  - The exit is on the same horizontal or vertical axis as the vehicle, in which case there is only *one* valid option
  - The exit is not on the same axis, in which case there are *two* (continue straight or make a turn)
- In the second case, a choice is made based on the pheromone signal intensity broadcasted by the next car ahead in each direction:

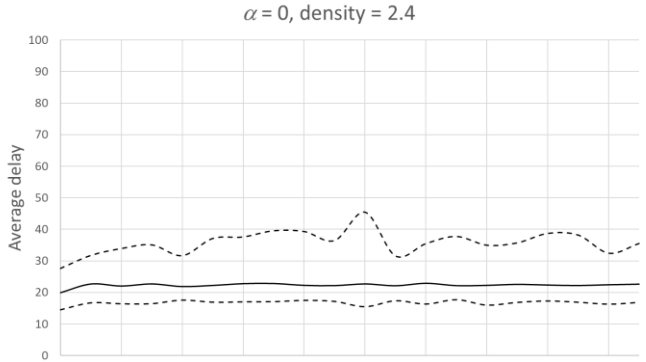
$$w_1 = \frac{1}{(1+x_1)^\alpha} \qquad w_2 = \frac{1}{(1+x_2)^\alpha}$$

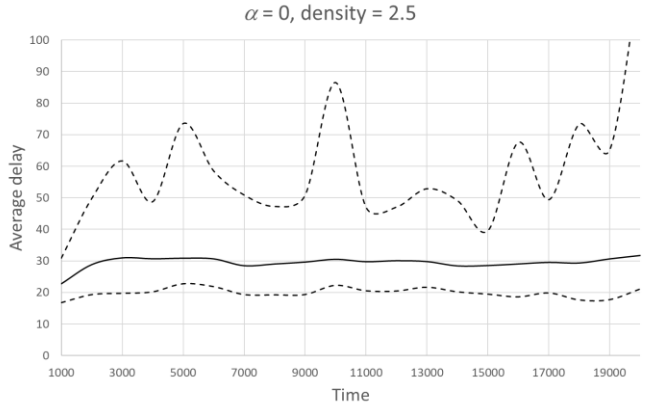
$$P_1 = \frac{w_1}{w_1 + w_2} \qquad P_2 = 1 - P_1$$

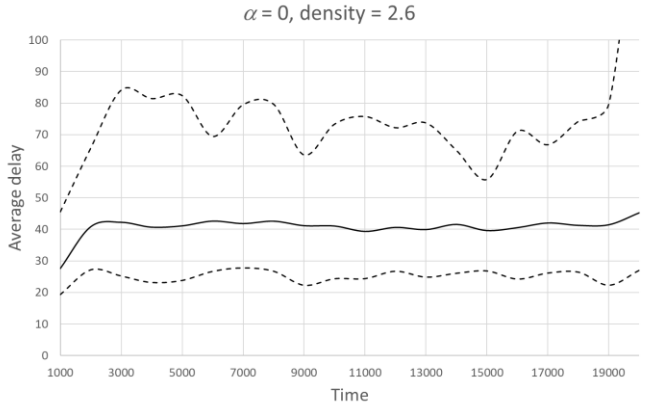
- NB: the higher α, the more the difference between x_1 and x_2 is amplified (for $\alpha = 0$, $P_1 = P_2 = 0.5$ and the choice is always random).

Test results (benchmark, $\alpha = 0$)

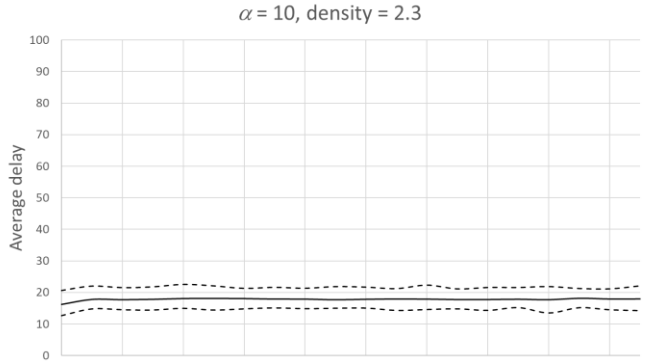


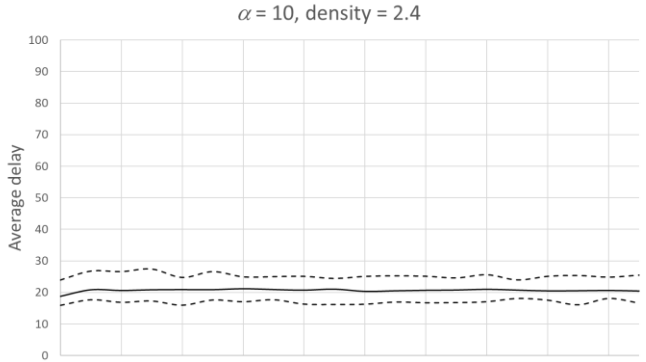


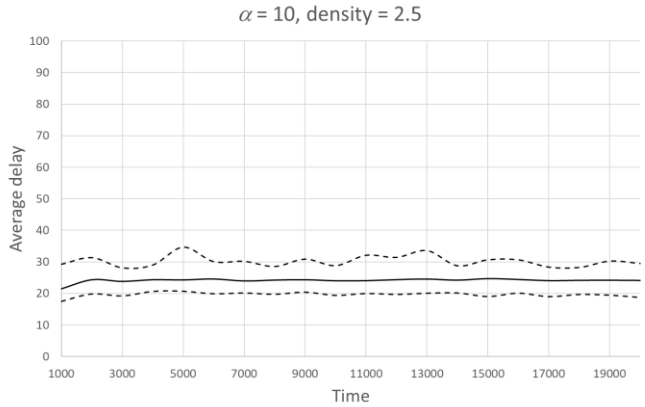


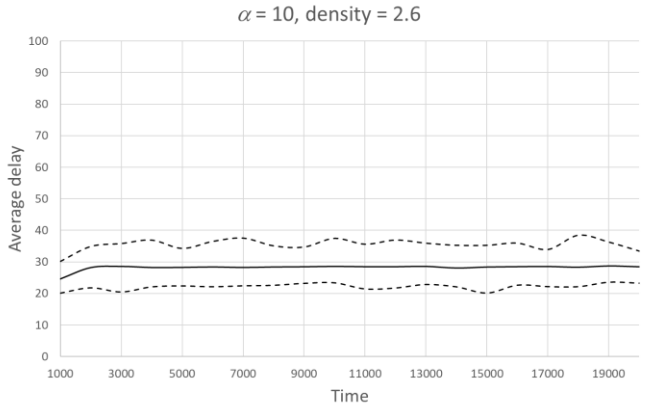


Test results ("all-or-nothing", $\alpha = 10$)









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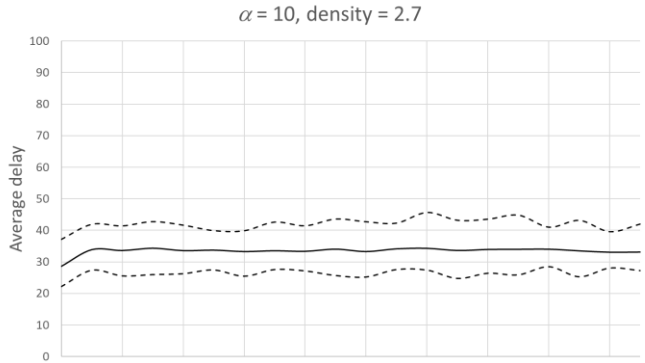
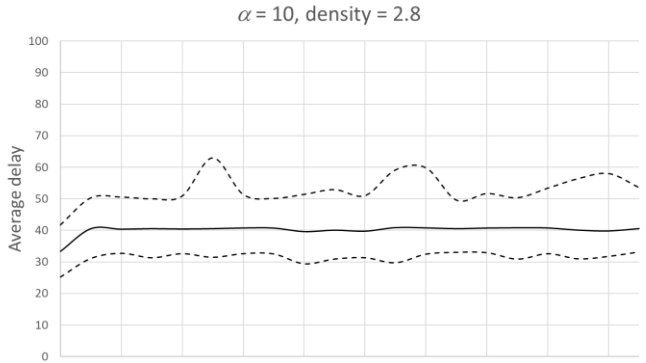
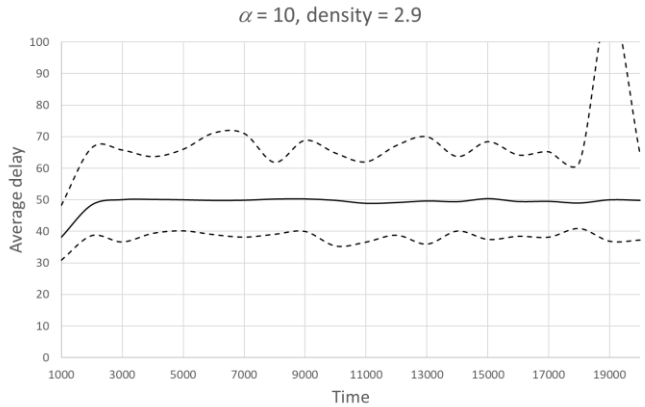
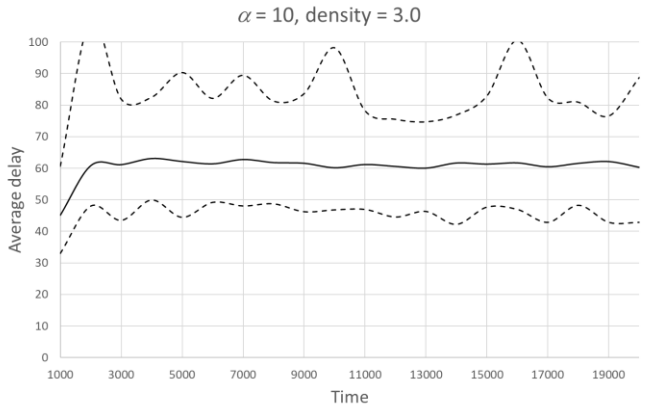
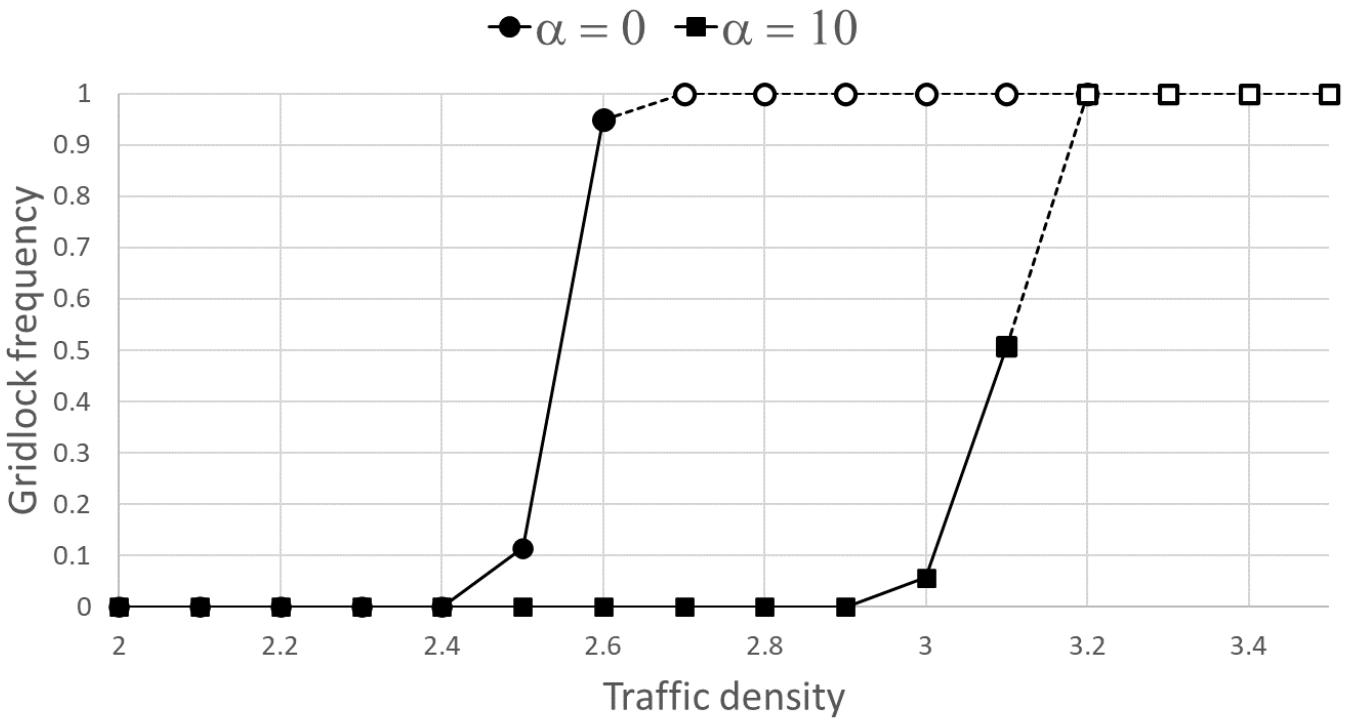








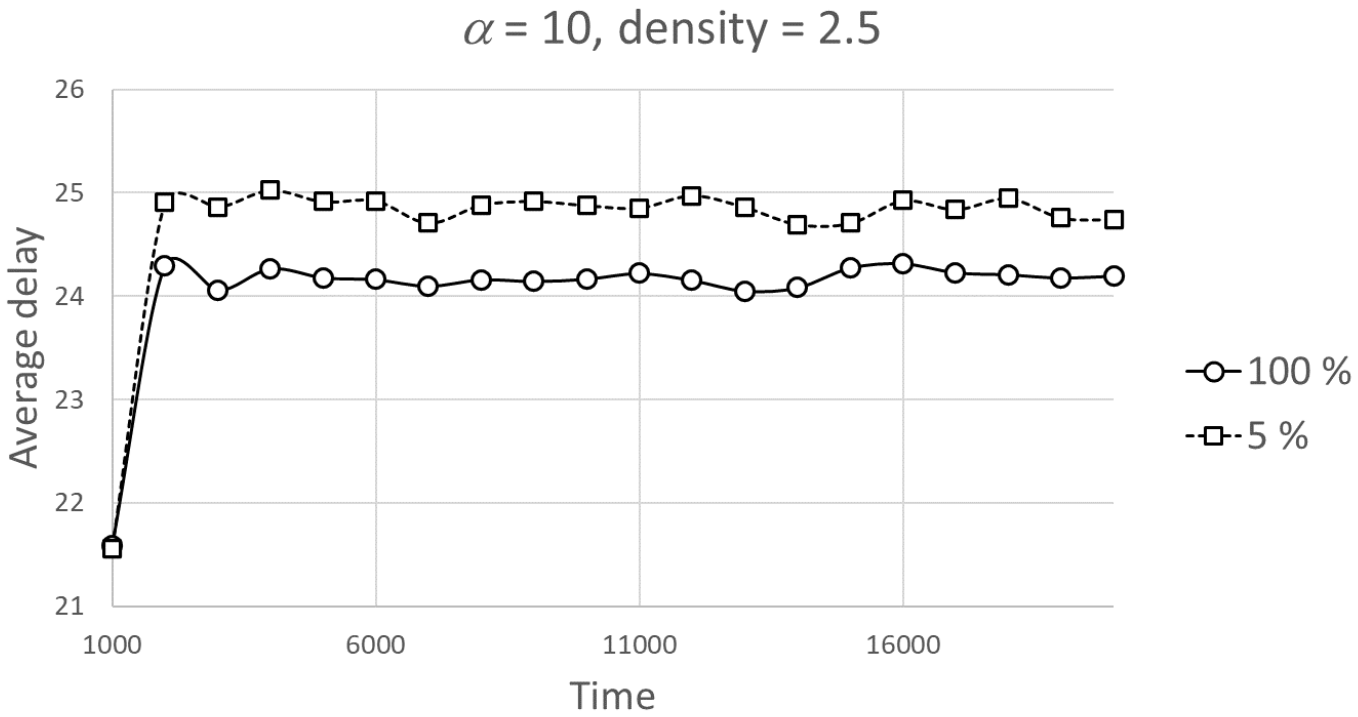
Test results (“Gridlock”)



Reality check

- Q: how plausible is it that gossiping self-driving “ant-cars” will be able to collectively orchestrate their itineraries to minimise congestion in the foreseeable future?
- A: not very!
- *However*, the good news is: results suggest that, if just 5% of all vehicles are taking part in such a scheme, you can already reap most of the benefits
  - This is surprising but perhaps not as weird as it seems...
  - Traffic congestion is a highly nonlinear phenomenon (e.g., the sudden transition from fluid traffic to gridlock can be described as a phase transition)
  - This means that small changes *can* have a big impact
- Furthermore, self-driving cars are not strictly necessary (a change of itinerary could be suggested to the human driver via the GPS screen)
- Convincing one major manufacturer to implement this idea could conceivably be enough to see positive effects and could be good publicity (“*SwarM*erc®”?)

Test results (variable participation)



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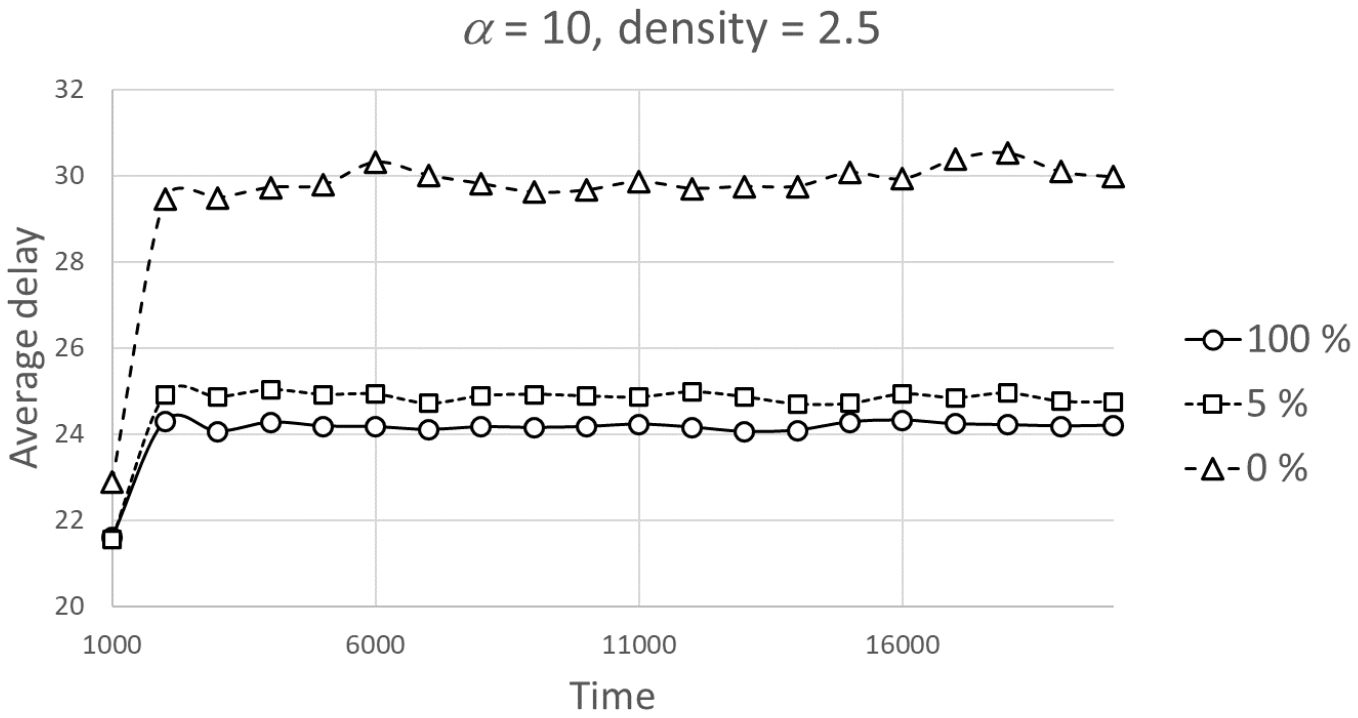

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Fabrice Saffre
fabrice.saffre@vtt.fi
+358 40 187 7817

@VTTFinland

www.vtt.fi