Autonomous Vehicles (AVs) and the Capacity of Roads

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London, UCL, Great Britain
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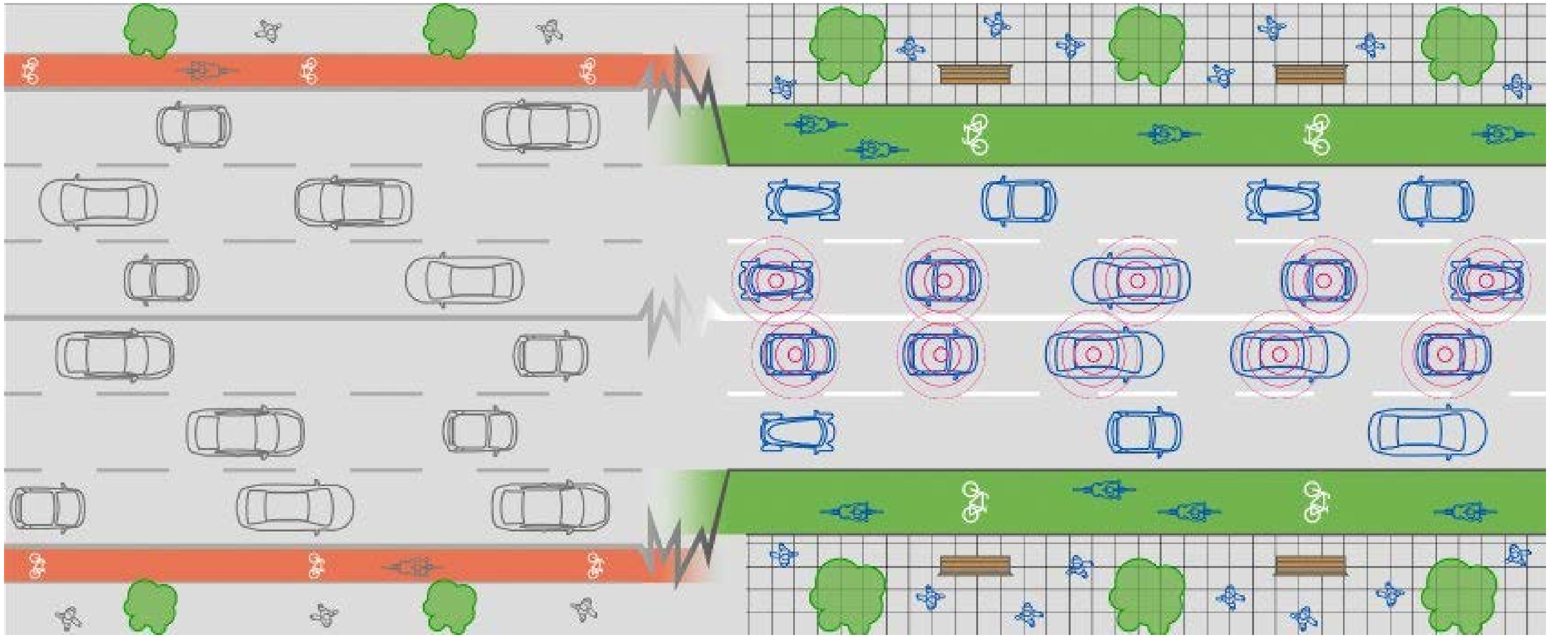
Will tell you three things today

- General: how transport systems might change
- General: a touch into ethics
- Main part: capacity

AVs – Why are they interesting?



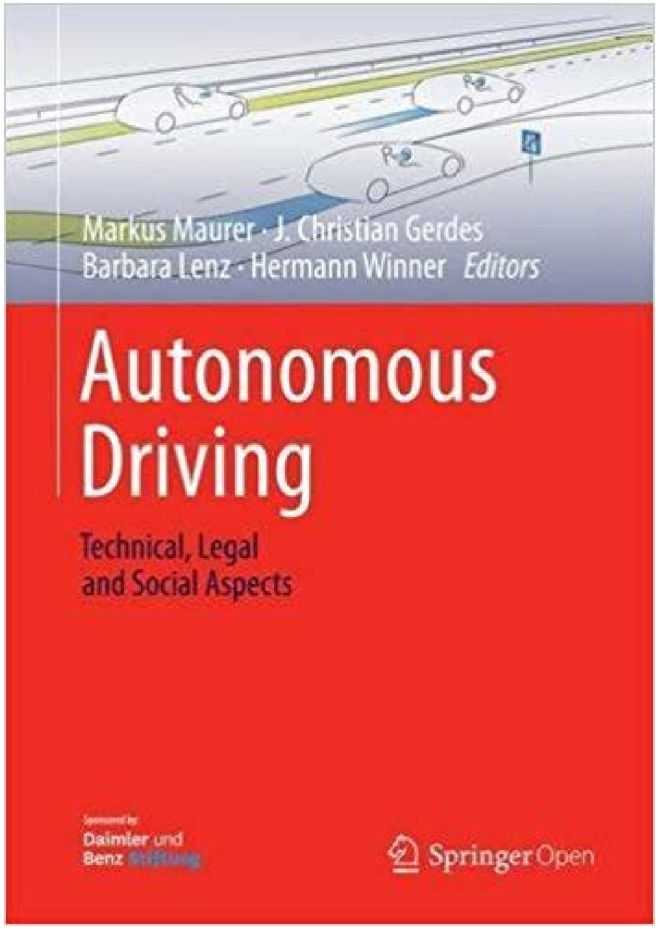
- It forces us think about the microscopic modelling of traffic flow
- And about better methods to do traffic management, now and in the future

http://www.spiegel.de/auto/aktuell/autonomes-fahren-chance-fuer-die-stadt-a-997393.html

Before…

- Let us nevertheless have a look at the other implications
- Many of them, see e.g. **the book:**
- http://www.springer.com/gb/book/9783662488454

- My pick today:
  - Future traffic: who will use an AV?
  - Ethics of AV



Many colleagues of mine…

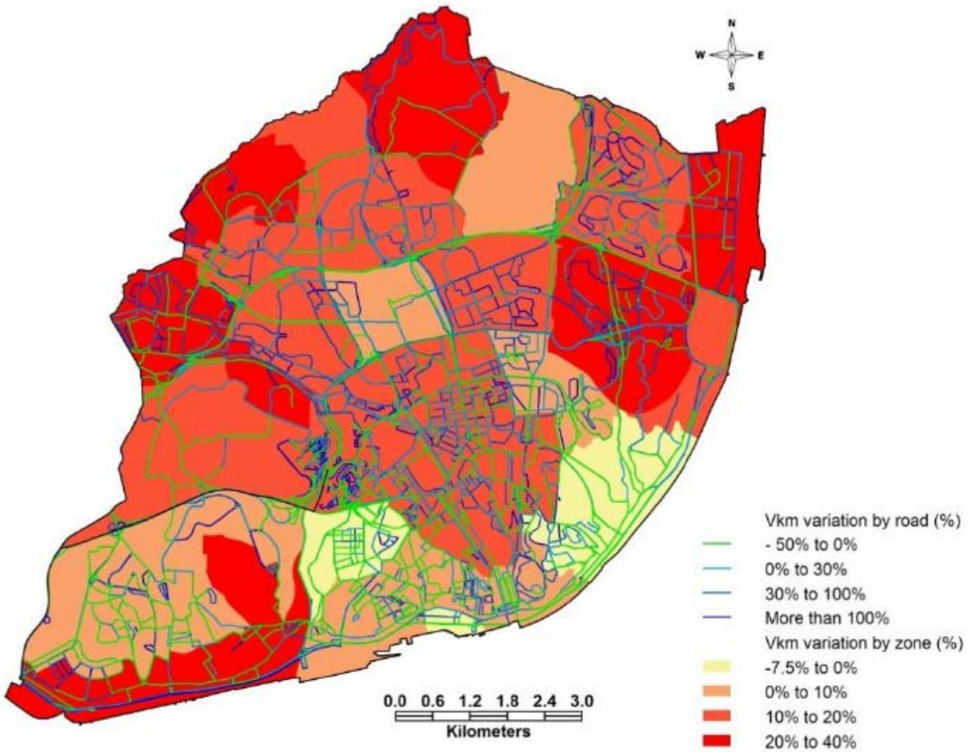
- Discuss another capacity, the occupation rate Θ of AV's
- Currently, $\Theta \approx 1.3$
- In speculations about the future, $0 \leq \Theta < 5$
- ($\Theta \rightarrow 0$: when in the office, you send your AV to retrieve your forgotten pencil)
- Careful studies: little will change, with a slight decline of Θ
- See e.g. http://www.ifmo.de/tl_files/publications_content/2016/ifmo_2016_Autonomous_Driving_2035_en.pdf

By 2035, we expect to see a moderate increase in vehicle-kilometres travelled by private cars – about 3% – as a result of the introduction of AVs. Assuming the maximum share of AVs in the private car fleet that is realistic, the upper bound of this increase is estimated at 9%.

More radical studies…

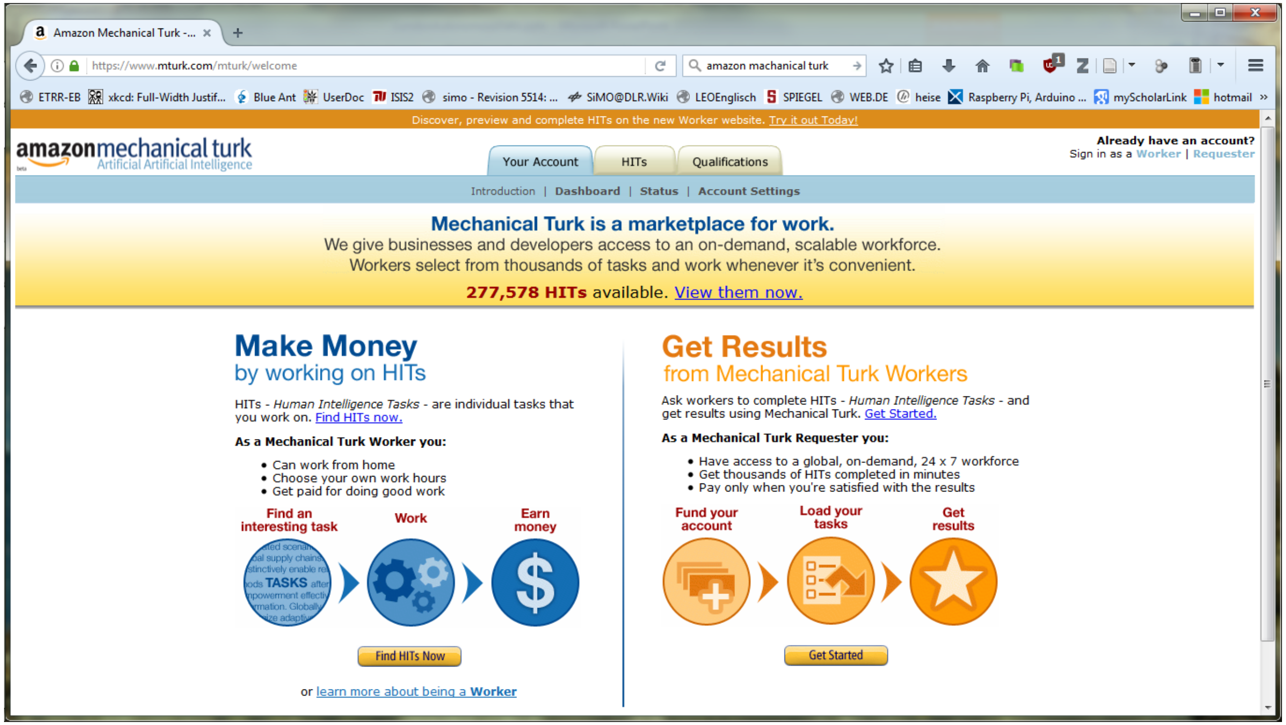
- Claim that AVs will change the entire transport system
- (The Lisbon study)
- A large amount of shared cars will create additional miles, but eliminate parking spaces
- Vehicles will travel more, but there will be less of them
- It may take a while until AV's become available, to actually test those predictions

Figure 5. **Spatial distribution of the variation of peak hour travel volumes for TaxiBot system in Lisbon** (weekday 8-9 a.m., TaxiBot plus high-capacity public transport scenario, vehicle-kilometres)

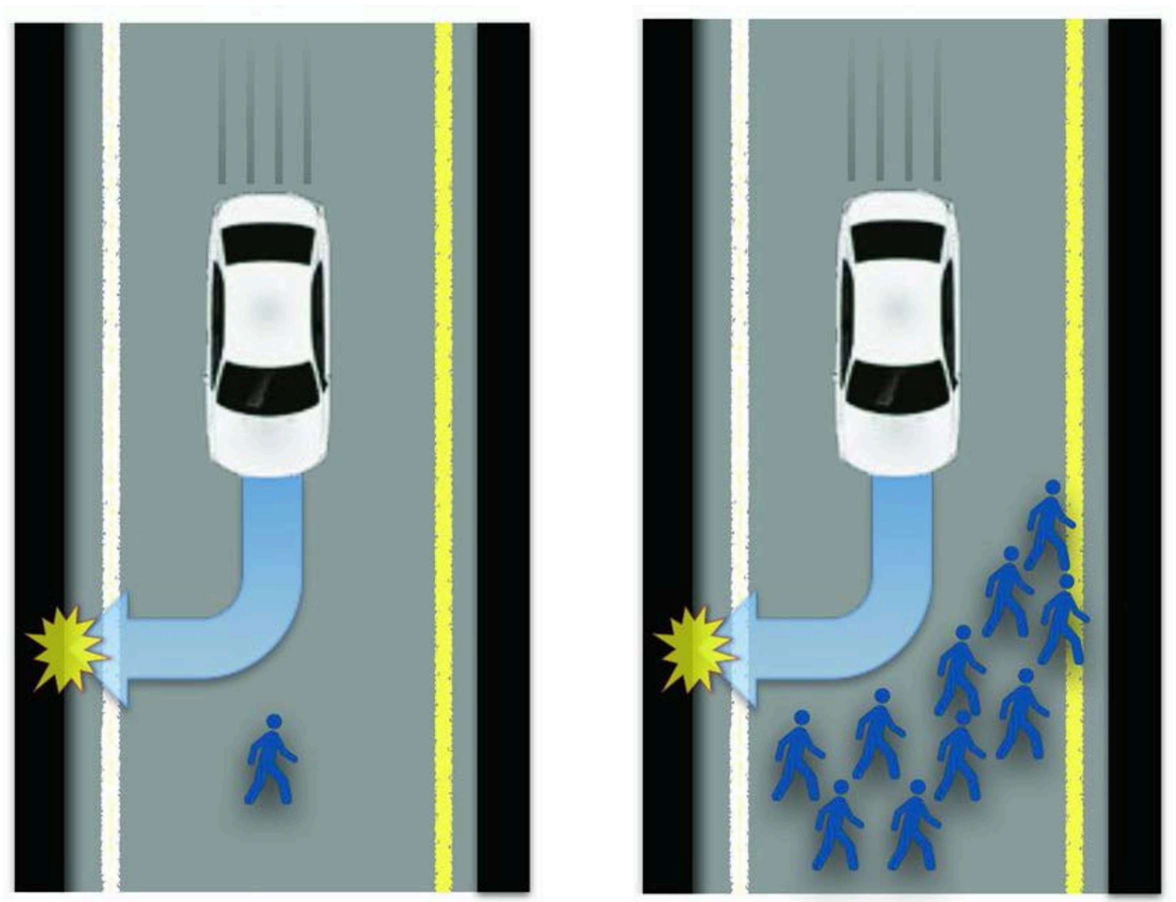


Ethics

- There are many variants of this…E.g., this study:
- J Bonnefon, A Shariff, I Rahwan: The social dilemma of autonomous vehicles, Science **352**, 1573-1576 (2016)
- $n = 1928$ people in autumn 2015 via Amazon's Mechanical Turk platform



Three scenarios
(involving imminent unavoidable harm)

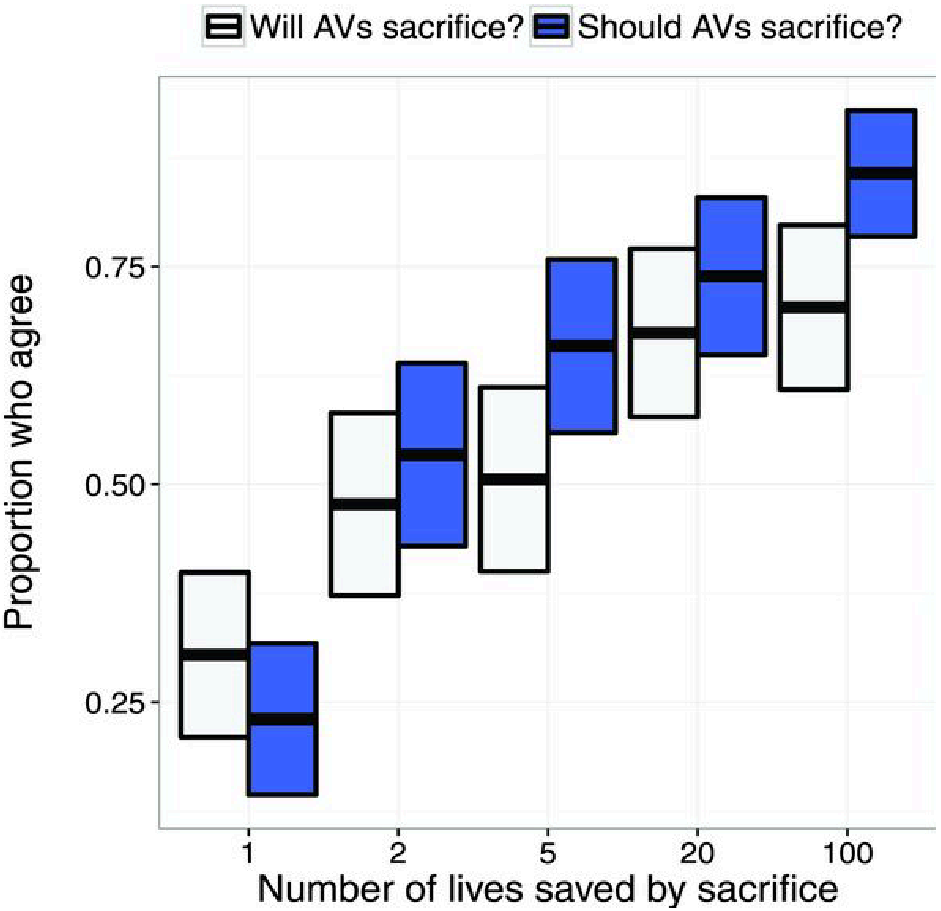


Jean-François Bonnefon et al. Science 2016;352:1573-1576

Published by AAAS

Greater good versus the life of the passenger ☺

- Participants prefer AVs programmed to kill their passengers for the greater good.
- (If more than five lives could be saved.)
- Boxes show 95% CI of mean.
- Ignore the “will sacrifice”



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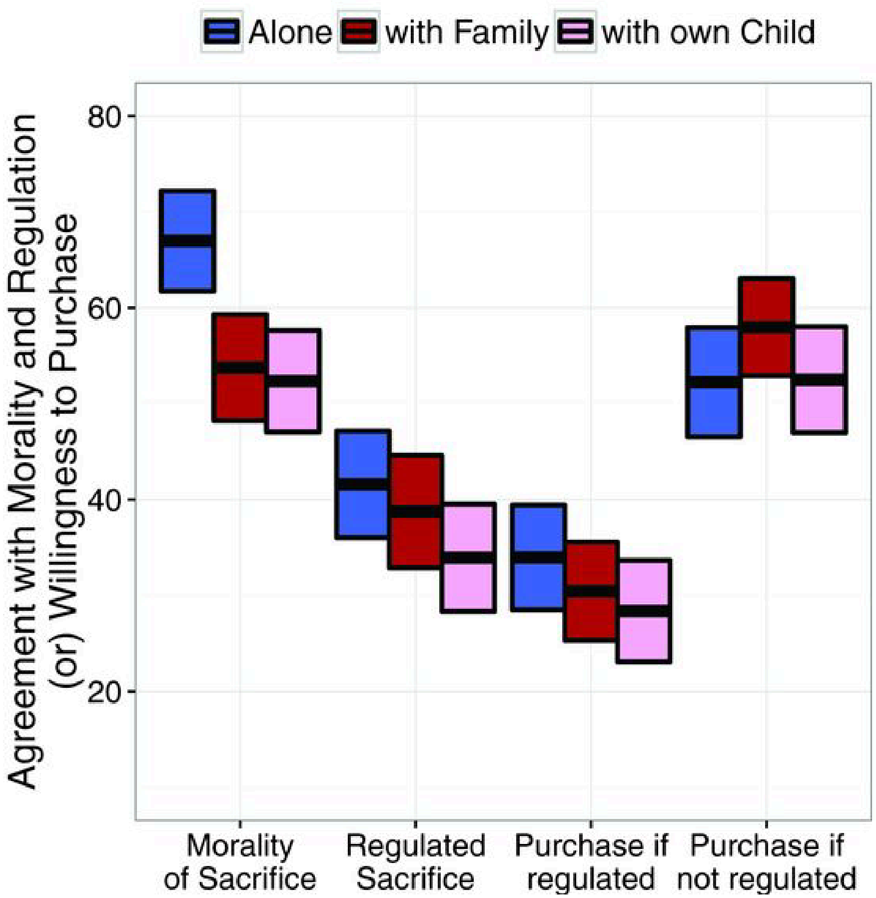
But “nobody” will buy those cars ☹

- Of course…
- Study is technically sound, but I think not too relevant
- And: do humans really make a moral decision in such a situation?

- Clearly: while humans eventually cannot, AVs can – so, at some point, discussion is needed



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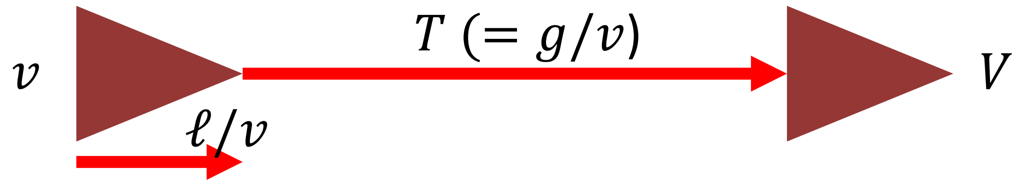
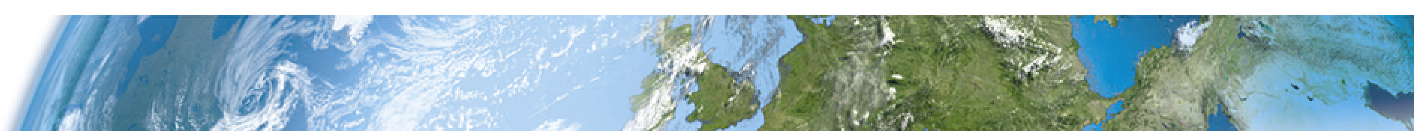
Capacity

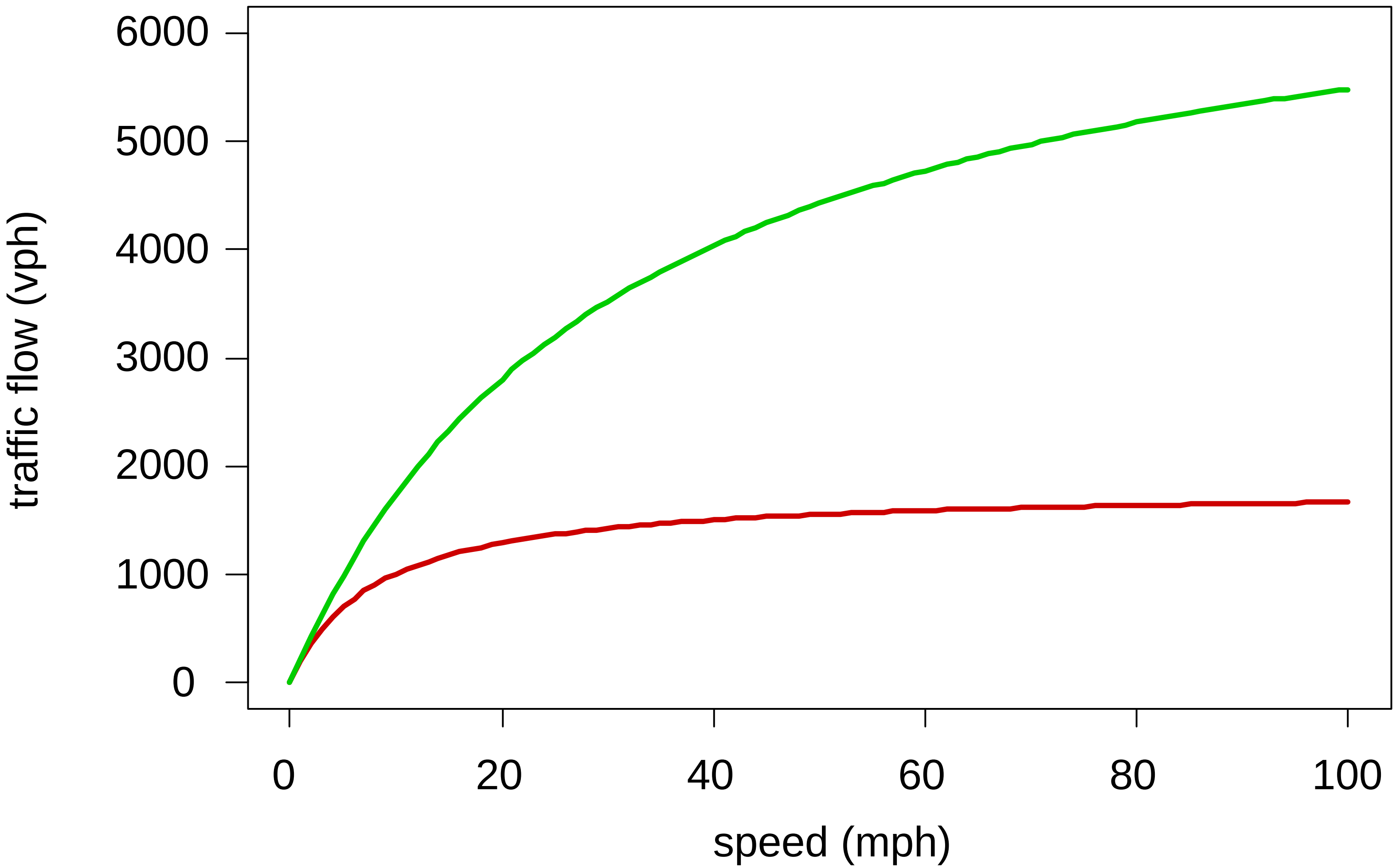
Introduction



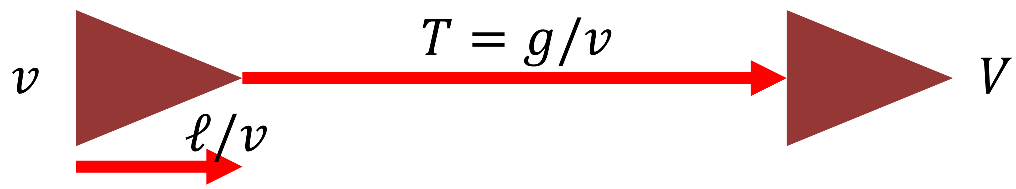
- Do autonomous vehicles (AV) increase the capacity Q of roads?
- Simple!
- If AV's have smaller net time headway T than human-driven ones, Q increases (Flow $q(v) = 1/\langle T + \ell/v \rangle$ and $Q = \max_v \{q(v)\}$)



Clearly: $q \to \frac{1}{T}$ for $v \to \infty$



Introduction



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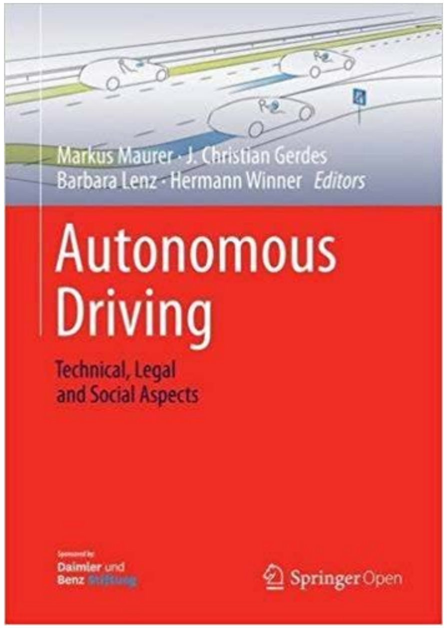
- Simple!
- If AV's have a smaller net time headway T than human-driven ones, Q increases (Flow $q = 1/\langle T + \ell/v\rangle$ and $Q = \max_v\{q(v)\}$)
- Here the discussion starts: what have we now, what is possible?
- There is a lot of work with inconclusive results.
- Some people argue that Q will go down (Markos P.)
- I have done work where I assumed it goes up
- I have done other work, where it goes down (not, I'm kidding)
- I will try to give some ideas here what to do to resolve this.

Introduction

- Let's start right-away: what have we now, what is possible?
- In the book project already mentioned, I had the pleasure to work with Hermann Winner, an expert on driver assistant systems
- $T = 0.3 \ldots 0.5$ s is technically possible for AV's
- But: what is human's T? Surprisingly difficult to answer!
- In countries with such rules: acceptable T's are around 2 s; in Germany: $T \leq 0.9$ s can be fined
- Come to this in a moment…



Introduction

- Looking at the headways was a static approach
- I missed: is a state with $q \approx Q$ stable?
- Obviously not, but why not?
- (Obviously: if it were stable, no jams would be present)

- Most likely cause of instability: the car-following process
- And the stability of the car-following process is a complicated issue, too
- Even less is known about it, empirically.
- Or better still: experimentally.
- The rest of this presentation will deal with these two issues

Headways, mostly empirical

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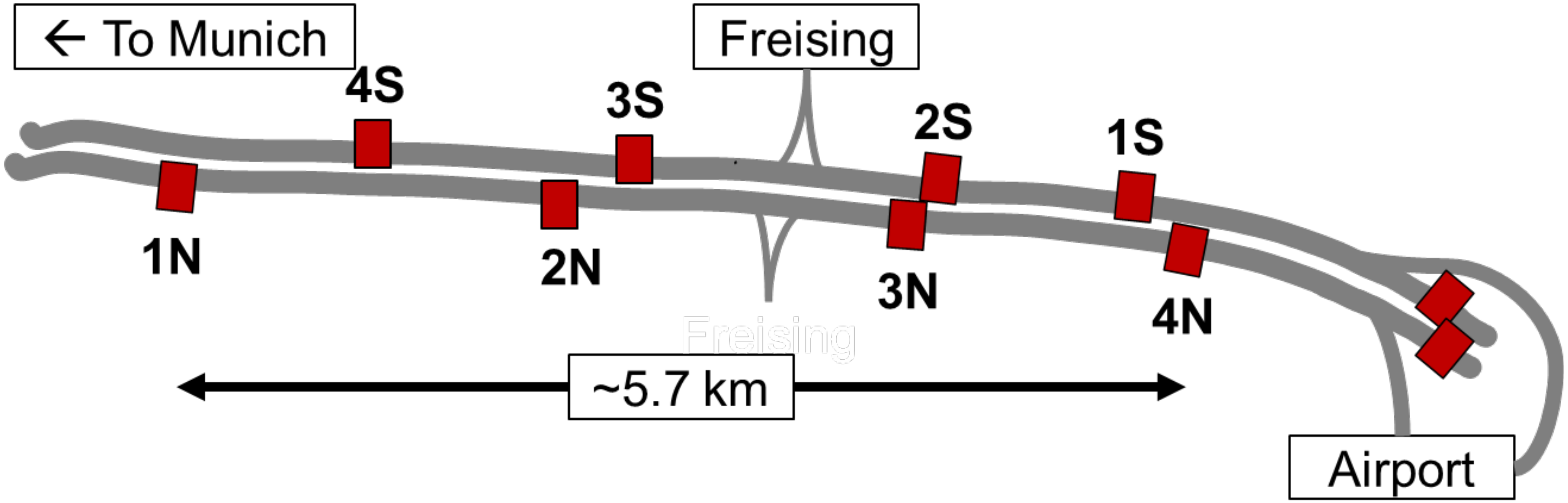
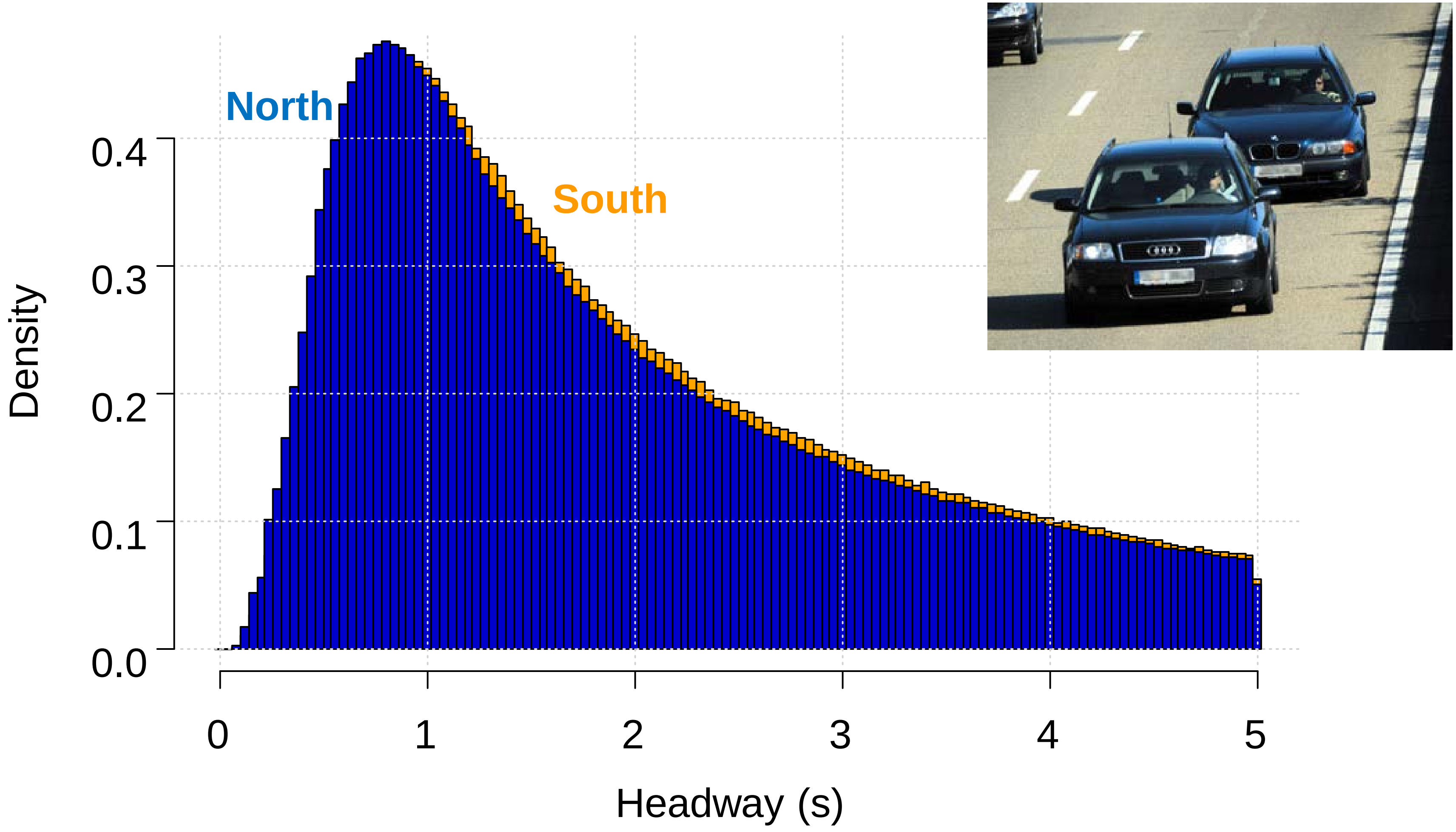
Data

- Today: look at single vehicle data from A 92 (Munich ←→ Airport)



- 28 loops at 2 × 5 sites recorded ~14 Mio data from Sep 2015
- What is the expected headway of a human driver?

The expected headway of a human driver?



More about data

- Quantiles of headway (in s):

Direction	Min	25%	Median	75%
North	0.06	1.08	2.11	4.5
South	0.02	1.15	2.19	4.53

- Maximum in distributions at $T = 0.8$ s (N) and $T = 0.92$ s (S)
- (We see: roughly 16 – 18 % of the drivers can be fined.)

- Similar & more results for other places & data-sets
- (Another story, not for today.)

More about data

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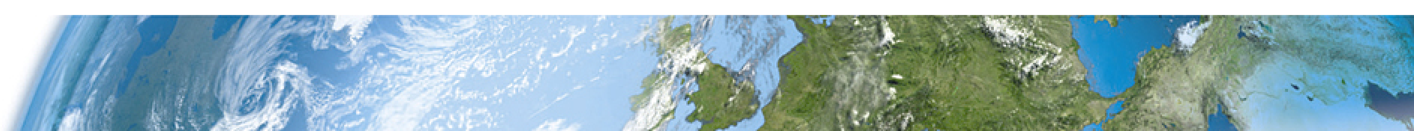
- Maximum in distributions at $T = 0.8$ s (N) and $T = 0.92$ s (S)
- (We see: roughly 16 – 18 % of the drivers can be fined.)
- Distribution is extremely left skewed, and one may assume that it consists of two different distributions:
  - E.g. a gamma distribution for large headways
  - Something different (GEV, inverse gamma,…) for small headways (interaction!)



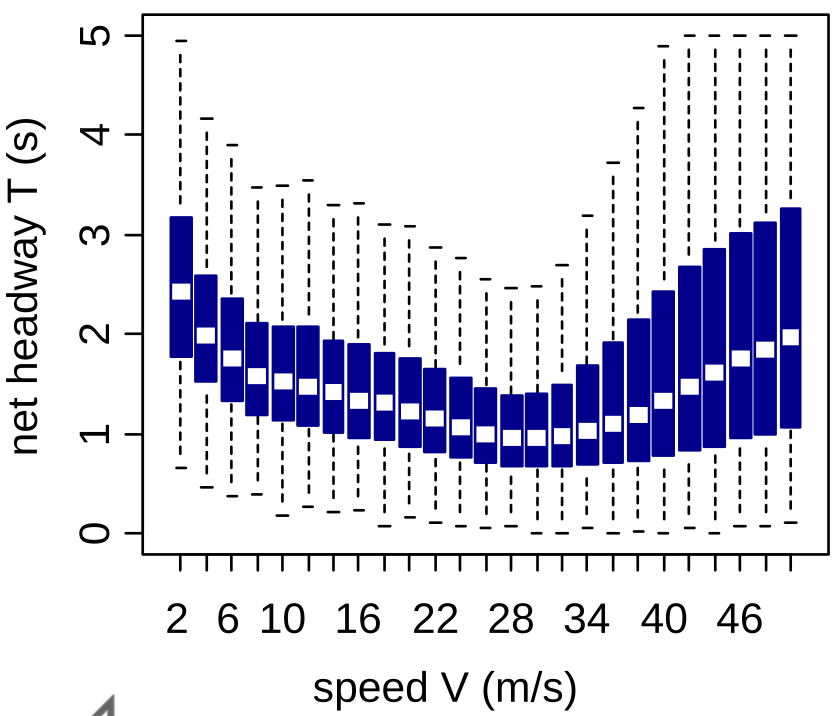
Back to the original question

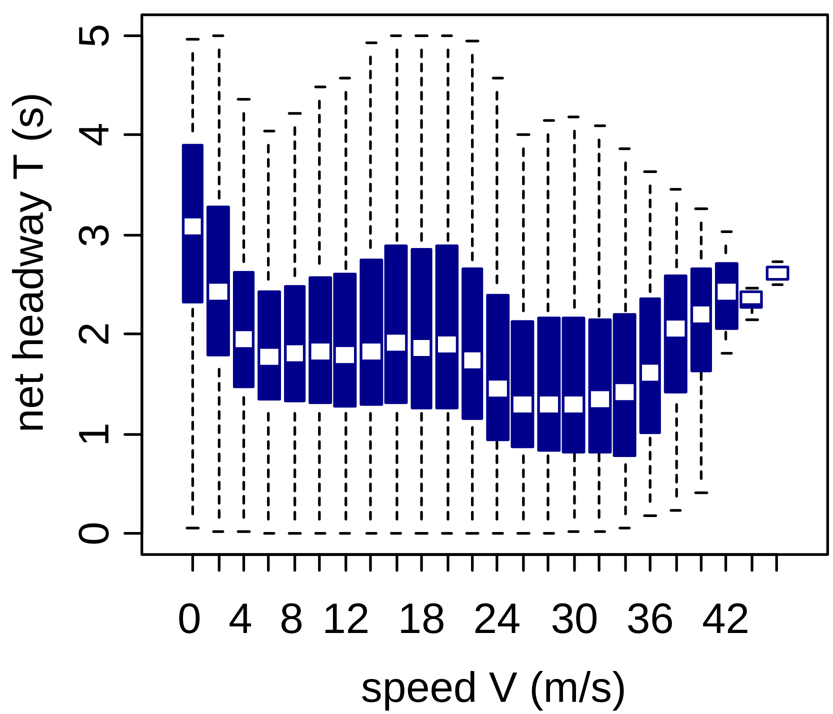
- What is the expected headway of a human driver?
- The maximum of the distribution?
- The median?

- And: the width of the distribution is not an effect of driver heterogeneity: even one driver displays the same width.

Comparing trajectory data with loop data

- Of course: no proof, just evidence.
  - Freeway loops (heterogeneous)
  - Trajectory data (homogeneous)





Back to the original question

- What is the expected headway of a human driver?
- The maximum of the distribution?
- The median?

- And: the width of the distribution is not an effect of driver heterogeneity: even one driver displays the same width.

- So far, my feeling is that it is an effect of the lead driver who does not drive with constant speed.
- But: this one typically has a lead driver themselve, so: there is a chance that it is self-generated

What will an AV do?

- If it is following another AV, it will for sure display a much smaller headway distribution
- …with a mean / median / mode that can be configured.
- If it is following a human driver…
- Who is fooling around with its speed,
- Then it must display a similar pattern as a human, hopefully with a smaller, but still not so small width.

- This hints at: eventually a range of mean headways with a chance to be smaller than the average human‘s; the same for the width of the distribution, and so for the “noise” in driving

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Stability

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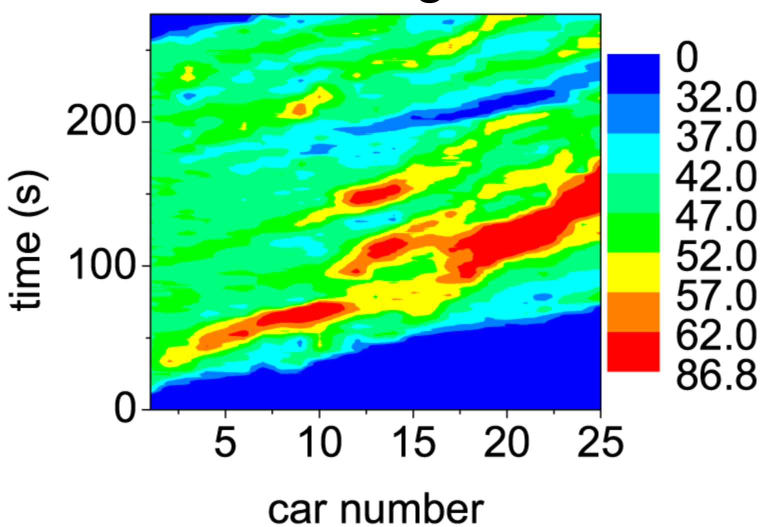
Stability – what is known?

- Old story: Gazis et al. performed first experiments in 1958
- The first model of instability: acceleration $a = \beta \Delta v(t - r)$ ➔ instability is due to reaction time r (Δv: speed difference)
- There have been many other experiments, e.g.
  - Vehicles in a circle (Bando, Sugiyama, Schadschneider,…)
  - Data I have used from a Japanese (Nakatsuji) experiment
  - From 2014: Jiang et al., 25 vehicles on a normal road



Jiang R, Hu MB, Zhang HM, Gao ZY, Jia B, et al. (2014) Traffic Experiment Reveals the Nature of Car-Following. PLoS ONE 9(4): e94351. doi:10.1371/journal.pone.0094351
http://journals.plos.org/plosone/article?id=info:doi/10.1371/journal.pone.0094351

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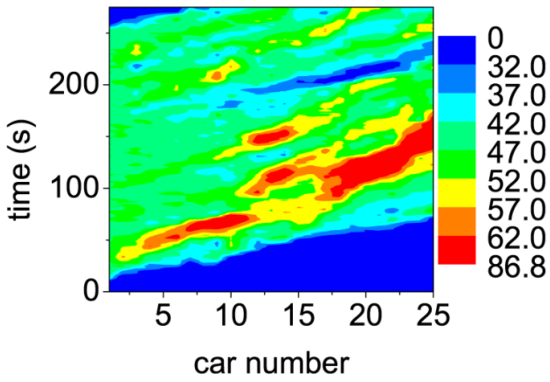
- There have been many other experiments, e.g.
  - Vehicles in a circle (Bando, Sugiyama, Schadschneider,…)
  - Data I have used from a Japanese (Nakatsuji) experiment
  - Quite recently: Jiang et al., 25 vehicles on a normal road

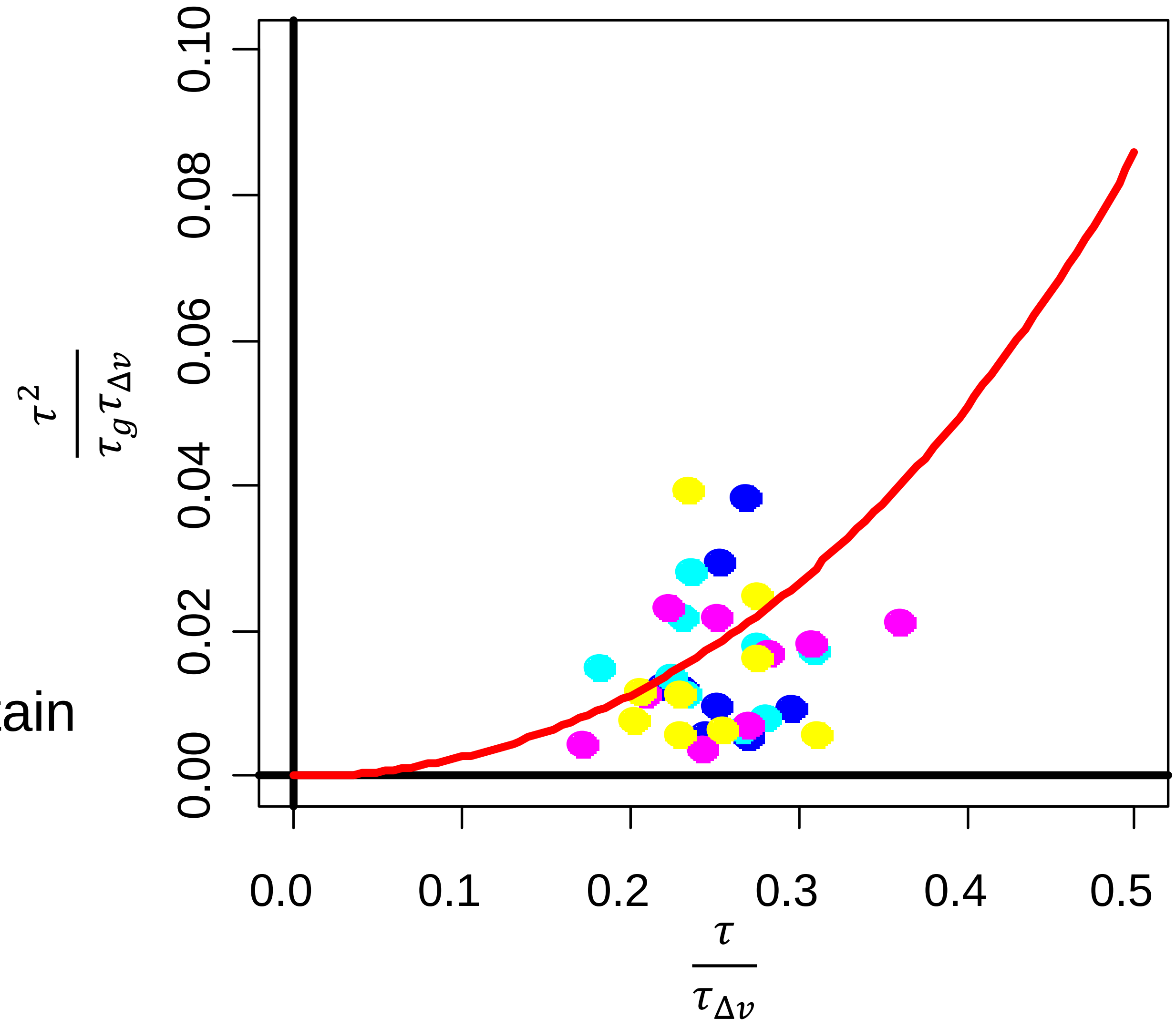
- They indicate, that car-following is unstable (sometimes)
- Let me add, that this is not guaranteed to happen



Real drivers…

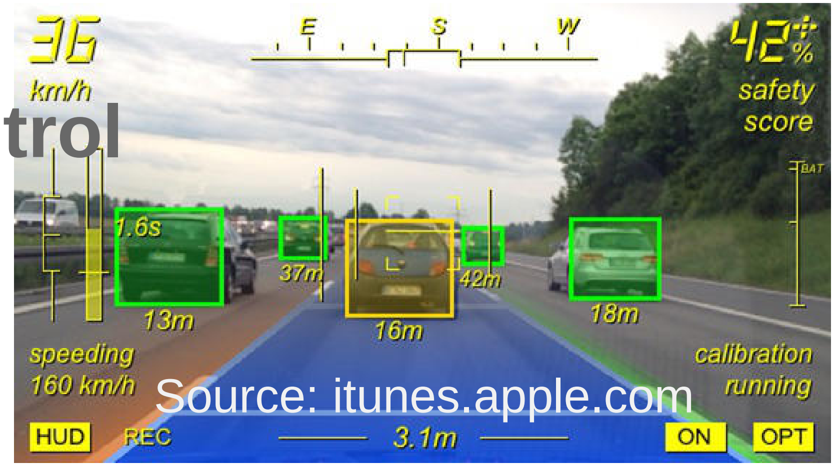
- Are at the boundary of stability
- (red line marks the boundary)
- Each dot is one driver in one experiment
- Fitting data to a certain model, then check stability

- Full story is in [1].



[1] PW, European Physical Journal B 84, 713-718 (2011)

ACC – Adaptive cruise control



Source: itunes.apple.com

- ACC's are light-weight AV's
- Configured to have a weak platoon instability [2].
- Work as a linear controller (some of them),
- $a = \left(\Delta v - (vT^* - g)/\tau_g\right)/\tau_{\Delta v}$
- g: net distance, v is speed, preferred headway T^*
- A linear car-following model (Helly's model);
- Platoon-stable if $\tau_{\Delta v} \leq T^* \left(1 + \frac{T^*}{2\tau_g}\right)$, where $\tau_{\Delta v}\tau_g \approx 20\ s^2$.
- $\tau_{\Delta v}\tau_g \approx 20$: comfort feature, makes jerk $\dot{a}$ and $|a|$ small enough

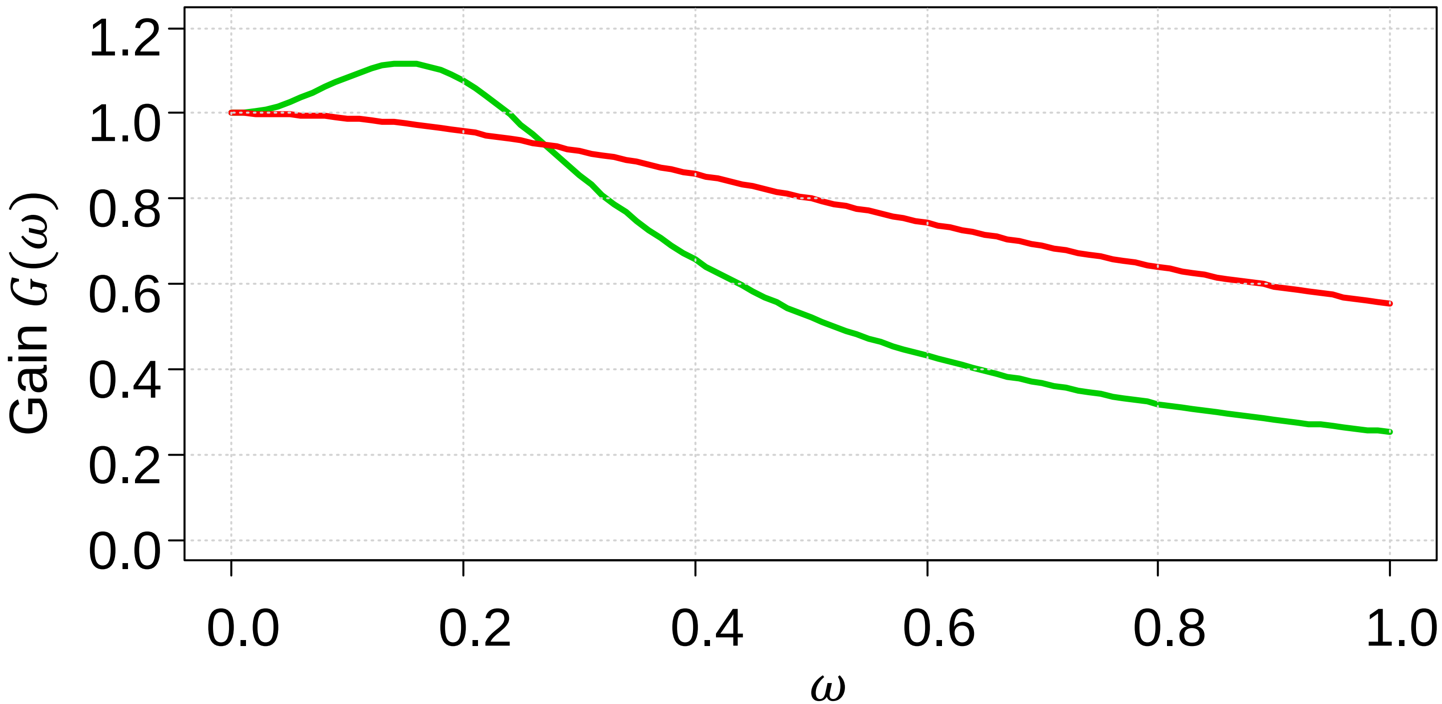
[2] Winner, H., Hakuli, S., Wolf, G.: Handbook Driver Assistant Systems (…) (2011) [in German]

Gain of the linear driver

$T^* = 1.5$ s and $\tau_{\Delta v}\tau_g = 20$ s

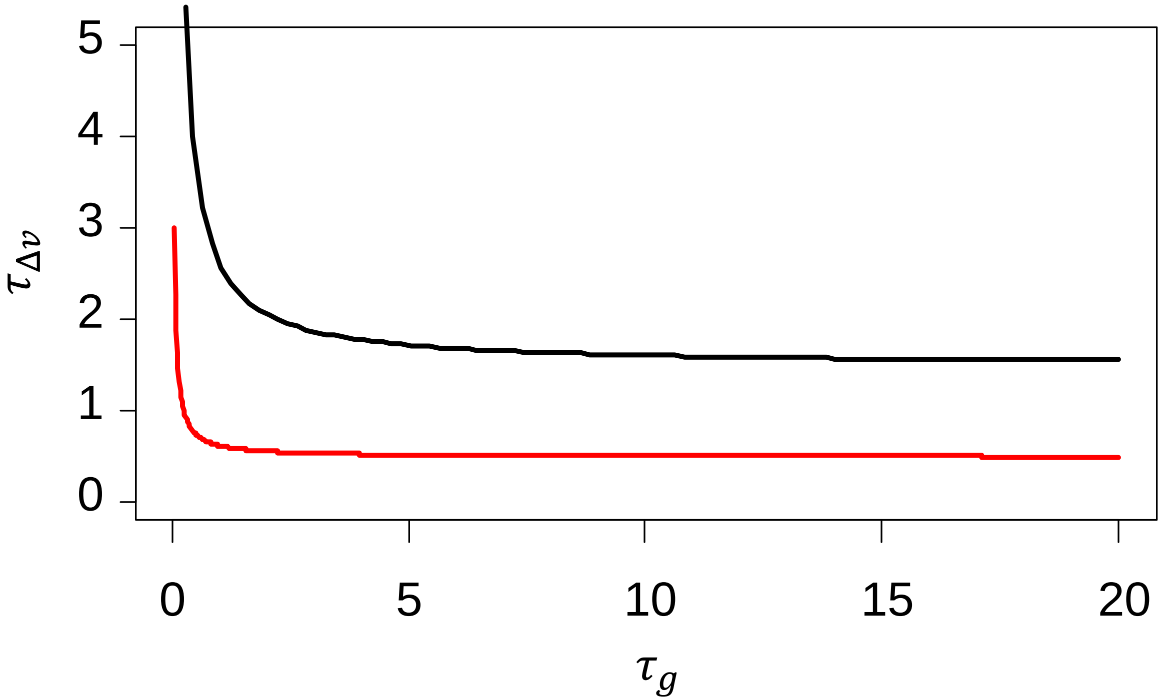
- Red: stable, $\tau_{\Delta v} = 1.5, \tau_g = 13.3$
- Green: unstable, $\tau_{\Delta v} = 4, \tau_g = 5$

$$G(\omega) = \left|\frac{a_{\text{follow}}(\omega)}{a_{\text{lead}}(\omega)}\right| \Longrightarrow a_{\text{follow}}(\omega) = G(\omega)\, a_{\text{lead}}(\omega)$$



Just for curiosity: Winner‘s 0.5 s…

- Lead to awfully small τ‘s; most likely, it does not work like this…
- But: humans do it all the time! 0.5 s occur regularly…
- Any idea about the how to?
- CACC and better anticipation
- May be, the anti-correlation in Δv?
- …



First set of conclusions

- (Have skipped a model for this.)
- In principle, large capacities can be reached, if T^* is small.
- Current ACC seem to have a comfort problem even if it were allowed to drive with $T^* = 0.5$ s
- Some of them have an anticipation problem: they are short-sighted, but with a great more detail than humans
- Sure: I do not have knowledge about what is currently under development
- Noisy acceleration is not important (for the model here)
- Stability may be an issue, though…

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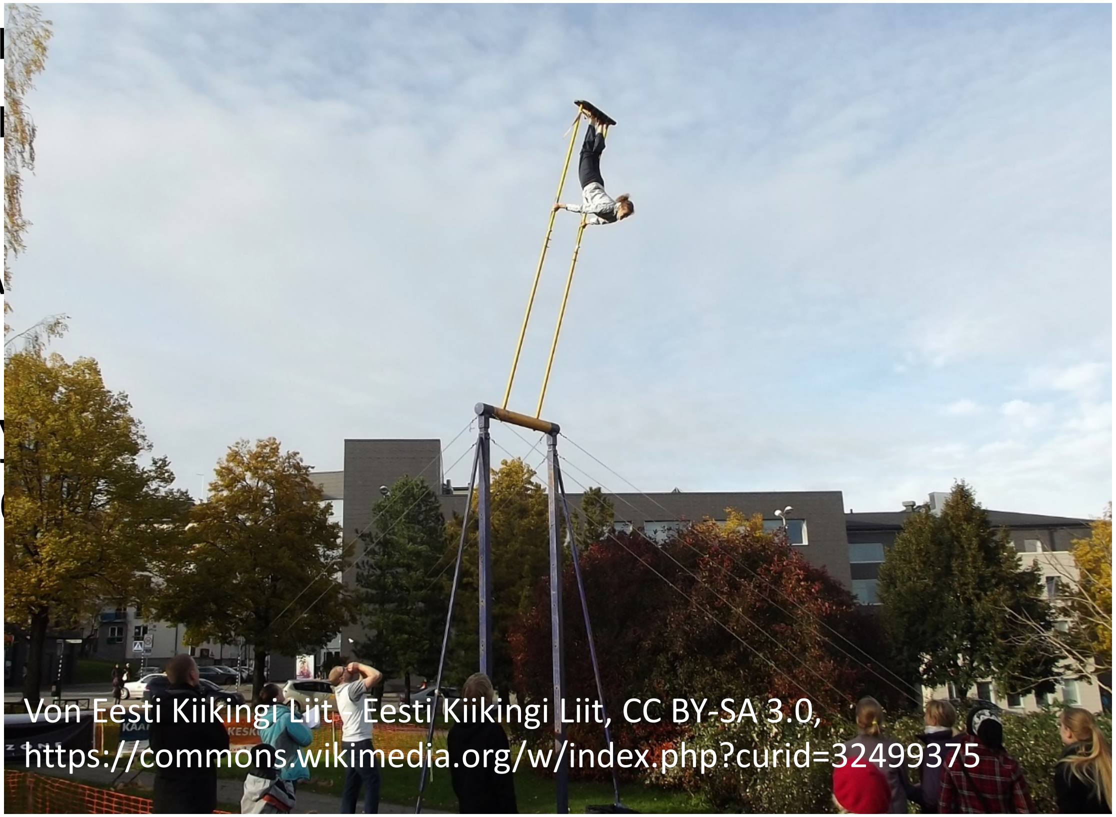
Speculation on stability

- My feeling: in real life, traffic flow is more stable than what we expect from our theories
- So, it seems, there is so
- For sure: co-operation a
- But may be, humans hav
- The AV model from a ph
  inhomogeneous, dampe
- Think of a swing!



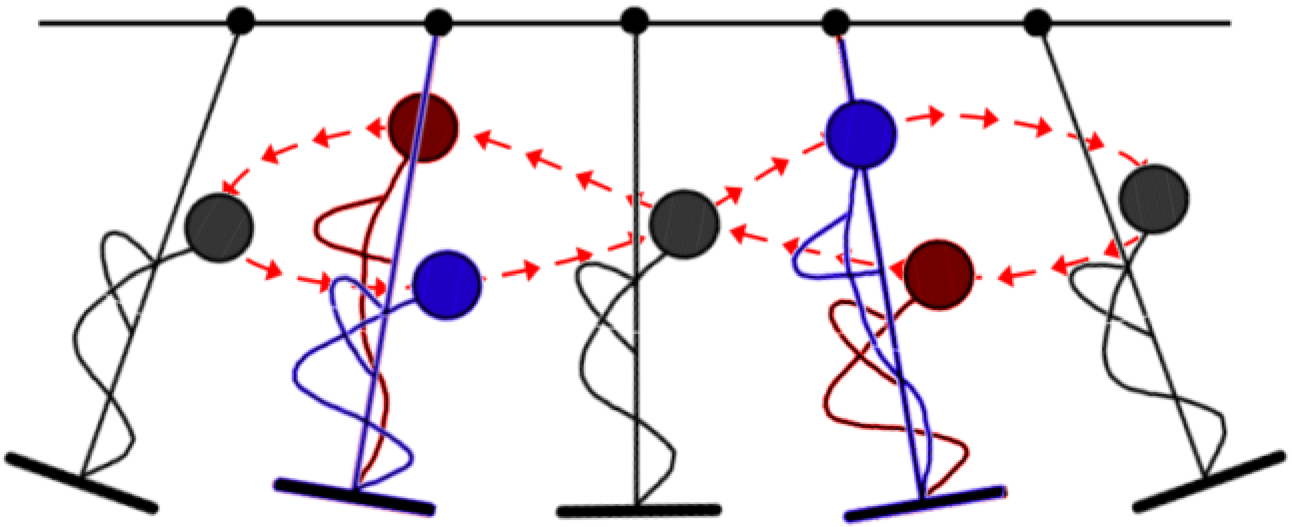
The tale of a swing: parametric resonance

- You all know this, the beautiful example of a human on a swing
- By changing the position on the swing, a human can pump energy into the oscillation, or she can release energy
- Do you know how it works?
  (Here: it changes $\tau_g \tau_{\Delta v}$ dynamically)
- In other words: humans may actively damp out oscillations, because almost all of us can use a swing.

Source: pixabay.com

The „trick“ is

- The swinging person changes her center of mass, therefore the length of the swing pendulum and so the frequency ω becomes time-dependent



http://energonauten.123v.net/joomla-2.5/jsmallfib_top/Exp/Exp_Param_Osz.htm

A beautiful example

Botafumeiro at the Cathedral of Santiago de Compostela

https://www.youtube.com/watch?v=2QFd_55El1I

Watch careful: they drag, when the botafumeiro is at the deepest point

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However…

- I have not the faintest idea how to show that this is true
- So it remains, so far, on the level of a nice idea

Source: pixabay.com