Lecture 09: Car-Following Models Based on Driving Strategies

- 9.1 Motivation
- 9.2 Gipps' Model
- 9.3 Intelligent Driver Model
- 9.4 Derivatives of the Intelligent Driver Model
- 9.5 Models for Adaptive Cruise Control
- 9.6 Human-Driver Car-Following Models

9.1 Motivation

The *plausibility criteria* of the last lesson and model completeness are necessary but not sufficient for a realistic simulation. Additional requirements for **car-following models (CF models)** include

- No accidents $\Rightarrow$ not satisfied by the OVM
- The accelerations $\dot{v}$ and braking decelerations have to be physically possible, e.g. $-9\,\mathrm{m/s^2} \le \dot{v} \le 4\,\mathrm{m/s^2}$ $\Rightarrow$ not satisfied by the OVM, Newell's micromodel, or the CA models
- Furthermore, CF models should reflect a "normal" comfortable driving style in normal situations, e.g., $|\dot{v}| < 2\,\mathrm{m/s^2}$ depending on the driving style $\Rightarrow$ distinguish between emergency and normal driving
- For highly dynamic situations such as approaching a red traffic lights/standing vehicles, anticipation according to elementary kinematics (e.g., the minimum stopping deceleration $b_{\text{kin}} = v^2/(2s)$) is necessary $\Rightarrow$ incorporate some driving strategy
- The model parameters should reflect distinct aspects of the driving style

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9.2 Gipps' model

The **Gipps model** explicitely satisfies the kinematics in highly dynamic situations

$$v(t+T) = \min\left[v_{\text{free}}, v_{\text{safe}}\right]$$

- The free-acceleration part obeys, e.g., $v_{\text{free}} = \min(v(t) + aT, v_0)$ with acceleration a or some more complicated acceleration profile.
- The safe speed is based on following heuristic *worst-case scenario* where a minimum gap s_0 should be kept at all times:
  - The leader suddenly brakes at deceleration b_l to a full stop,
  - the follower brakes at deceleration b after a reaction time T. For extra safety, another "brake hitting time" ϑ is assumed (somewhat inconsequential),
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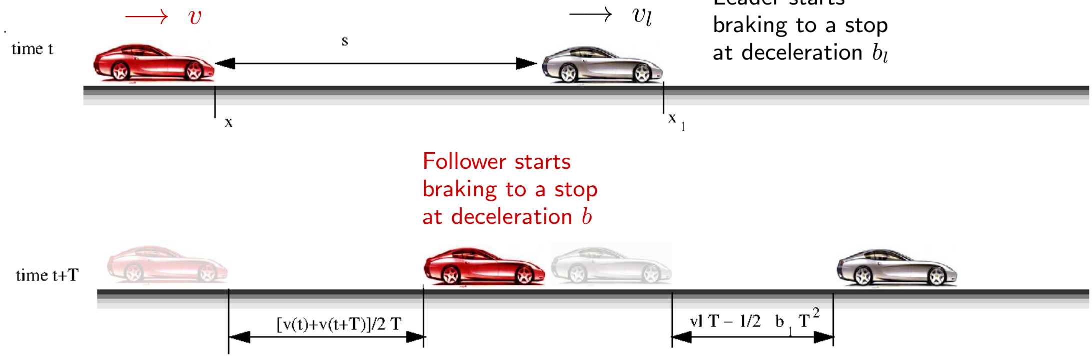

Follower starts braking to a stop at deceleration b

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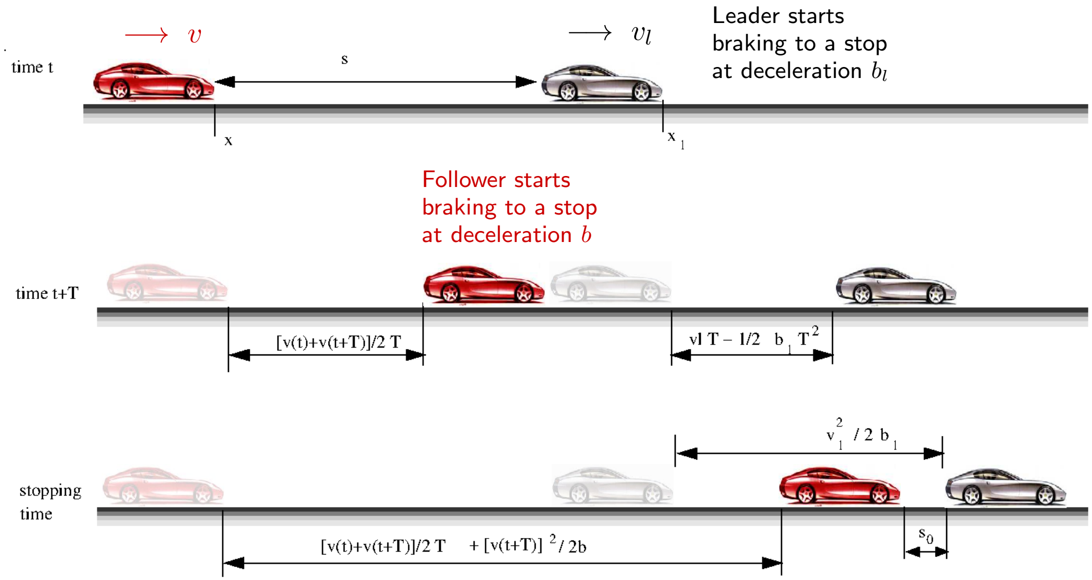

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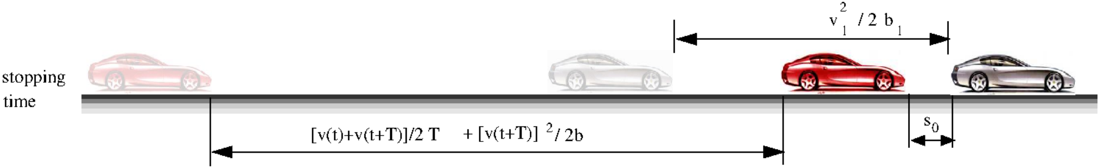

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$$x^{\text{stop}} - x = \frac{v(t) + v_{\text{safe}}}{2} T + v_{\text{safe}} \vartheta + \frac{v_{\text{safe}}^2}{2b}$$

$$x_l^{\text{stop}} - x_l = \frac{v_l^2}{2b_l}$$

$$s_0 \stackrel{!}{=} s_{\text{stop}} = s + (x_l^{\text{stop}} - x_l) - (x^{\text{stop}} - x)$$

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Assume a "brake hitting time" $\vartheta = T/2 \Rightarrow$ quadratic equation

$$v_{\text{safe}}^2 + 2bT v_{\text{safe}} + bvT - v_l^2 \frac{b}{b_l} - 2b(s - s_0) = 0$$

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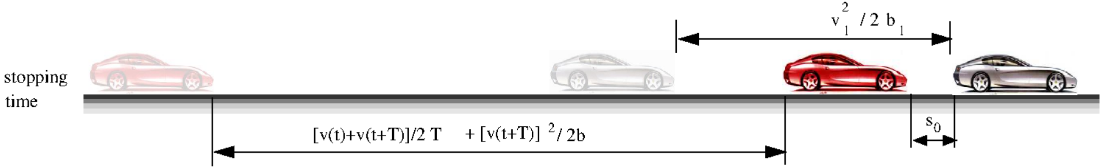

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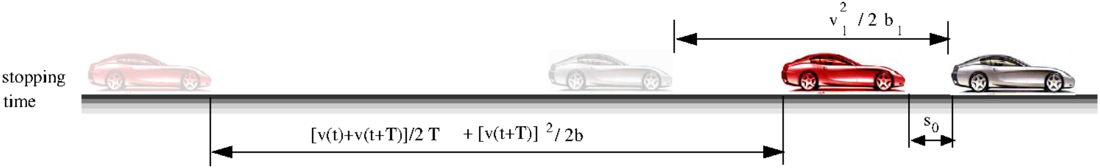

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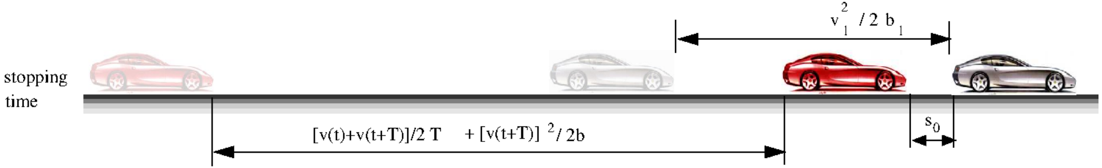

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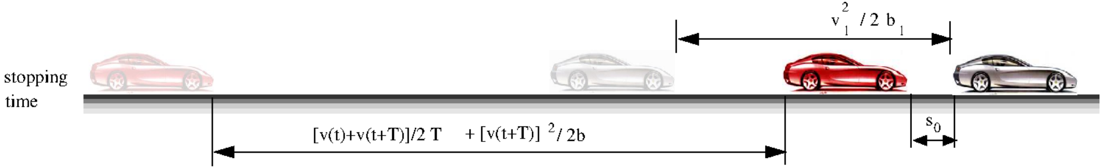

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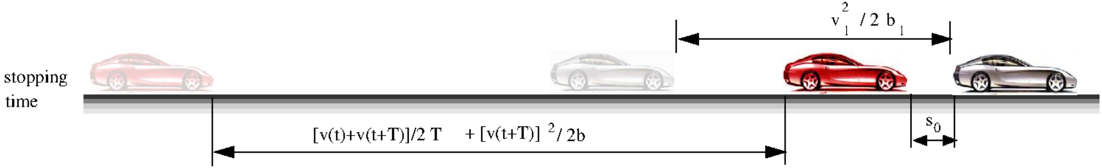

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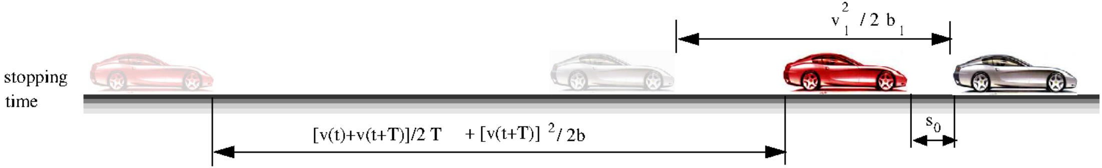

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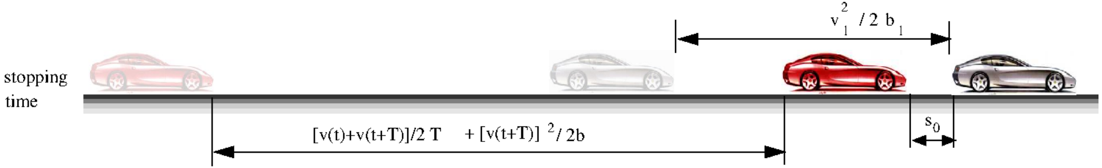

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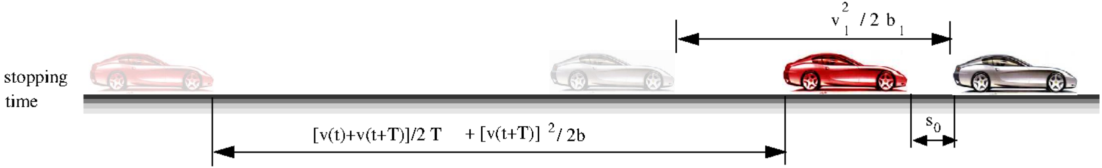

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The simplified Gipps model

The simplified version makes following assumptions:

- Constant acceleration a in the free-flow regime until reaching the desired speed v_0
- No acceleration is assumed during the reaction time T and the brake hitting time ϑ is zero. So, these assumptions just calculate the speed which *would* prevent a crash in the worst case if it were adopted instantaneously and held constant during T. Hence, the *reaction distance* of the follower is simply given by $\Delta x_{\text{react}} = v(t)T = v_{\text{safe}}T$
- The leader and the follower have the same braking capabilities $b_l = b$

This leads to following quadratic equation:

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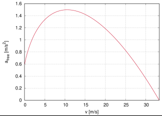
The final Gipps models

$$v(t+T) = \min\left[v + a_{\text{free}}(v)T, v_{\text{safe}}(s, v, v_l)\right] \quad \text{Full Gipps Model}$$

$$a_{\text{free}}(v) = 2.5a\left(1 - \frac{v}{v_0}\right)\sqrt{0.025 + \frac{v}{v_0}},$$



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The model is for general brake hitting times ϑ. For the standard value $\vartheta = T/2$, simplify $b(T/2 + \vartheta) \to bT$

$$v(t+T) = \min\left[v + aT, v_0, v_{\text{safe}}(s, v_l)\right] \quad \text{Simplified Gipps Model}$$

$$v_{\text{safe}}(s, v_l) = -bT + \sqrt{b^2T^2 + 2b(s - s_0) + v_l^2}$$

Freeway parameters: $v_0 = 35\,\text{m/s}$, $a = b = b_l = 1.5\,\text{m/s}^2$, $T = 1.1\,\text{s}$, $\vartheta = T/2$, $s_0 = 2\,\text{m}$

City parameters: just reduce the desired speed v_0

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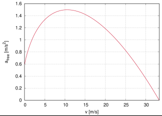

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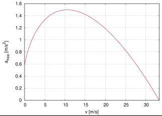

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The final Gipps models

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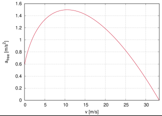
$$a_{\text{free}}(v) = 2.5a\left(1 - \frac{v}{v_0}\right)\sqrt{0.025 + \frac{v}{v_0}},$$



$$v_{\text{safe}}(s, v, v_l) = -b(T/2 + \vartheta) + \sqrt{b^2(T/2+\vartheta)^2 + 2b(s - s_0) + v_l^2 \frac{b}{b_l} - vbT}$$

The model is for general brake hitting times ϑ. For the standard value $\vartheta = T/2$, simplify $b(T/2 + \vartheta) \to bT$

$$v(t+T) = \min\left[v + aT, v_0, v_{\text{safe}}(s, v_l)\right]$$ **Simplified Gipps Model**

$$v_{\text{safe}}(s, v_l) = -bT + \sqrt{b^2T^2 + 2b(s - s_0) + v_l^2}$$

Freeway parameters: $v_0 = 35\,\mathrm{m/s}$, $a = b = b_l = 1.5\,\mathrm{m/s^2}$, $T = 1.1\,\mathrm{s}$, $\vartheta = T/2$, $s_0 = 2\,\mathrm{m}$
City parameters: just reduce the desired speed v_0

Homogeneous steady state and fundamental diagram of the Gipps models I: Free-flow regime

Unlike the past CF-models, the Gipps model(s) do not have an explicit fundamental diagram (FD) given by the OV function $\Rightarrow$ must be calculated by assuming a **stationary steady state**:

- **Stationarity**: $\frac{\mathrm{d}}{\mathrm{d}t} = 0$, so $v(t+T) = v(t)$
- **Homogeneity**: $\frac{\mathrm{d}}{\mathrm{d}x} = 0$, so $v_l(t) = v(t)$

Free-flow regime:

$$v(t+T) = v(t) \;\Rightarrow\; a_{\text{free}}(v) = 0 \;\Rightarrow\; v = v_0$$

Does the free-flow Gipps model include any interactions in the free-flow regime?

No, not any! strict separation of regimes by the min-function!

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Homogeneous steady state and fundamental diagram of the Gipps models II: Interaction regime

Here, the second part of the min-function applies:

$$v(t+T) = v = v_{\text{safe}} = v_l$$

$$v = -b(T/2+\vartheta) + \sqrt{b^2(T/2+\vartheta)^2 + 2b(s-s_0) + v^2\frac{b}{b_l} - vbT}$$

$$\left(v + b(T/2+\vartheta)\right)^2 = b^2(T/2+\vartheta)^2 + 2b(s-s_0) + v^2\frac{b}{b_l} - vbT$$

Quadratic equation for $v_e(s)$ or linear equation for $s_e(v)$:

$$s_e^{\text{Gipps}}(v) = s_0 + vT + v\vartheta + \frac{v^2}{2b}\left(1 - \frac{b}{b_l}\right)$$

Shape of the FD for the special case of the simplified Gipps model?

$s_e = s_0 + vT \Rightarrow$ triangular FD

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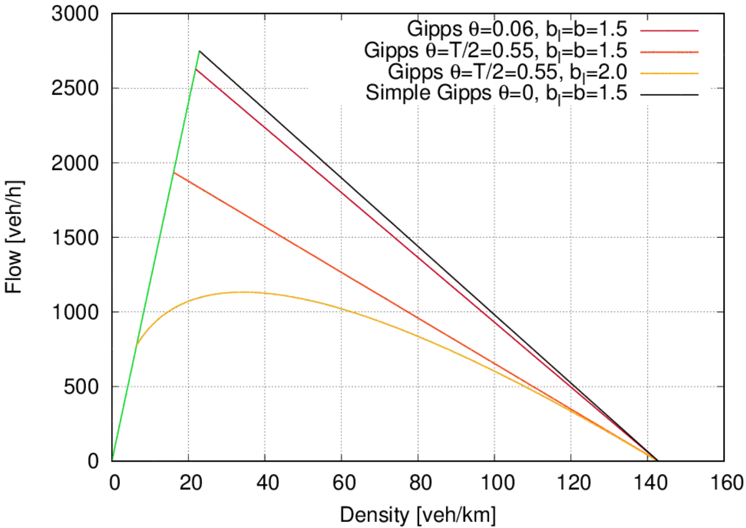
Fundamental diagram of the Gipps model variants



The Drivers of the Gipps model become more defensive

- with increasing reaction time T and brake hitting times ϑ
- with increasing implied leader deceleration b_l

? Why traffic becomes unstable for $b_l < b$?

! Since the follower thinks he/she can brake harder than the leader. Along the whole string of vehicles ...

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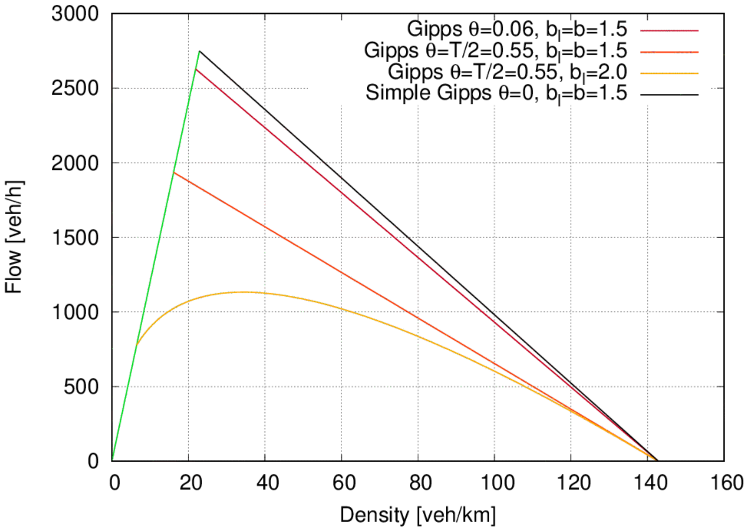

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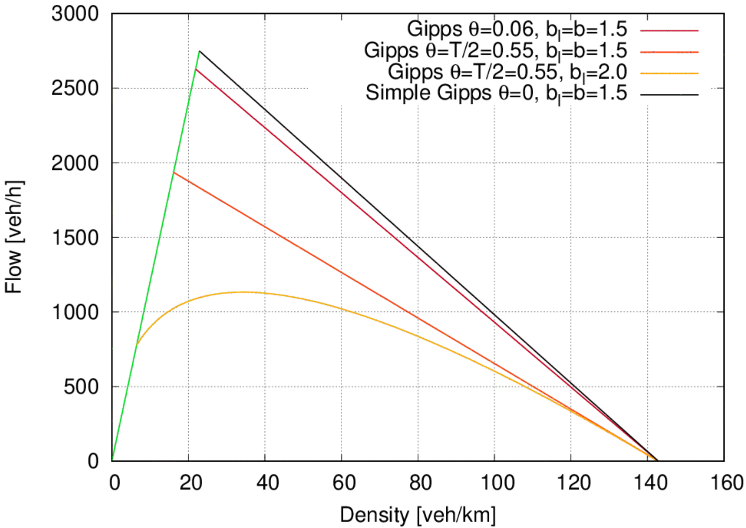

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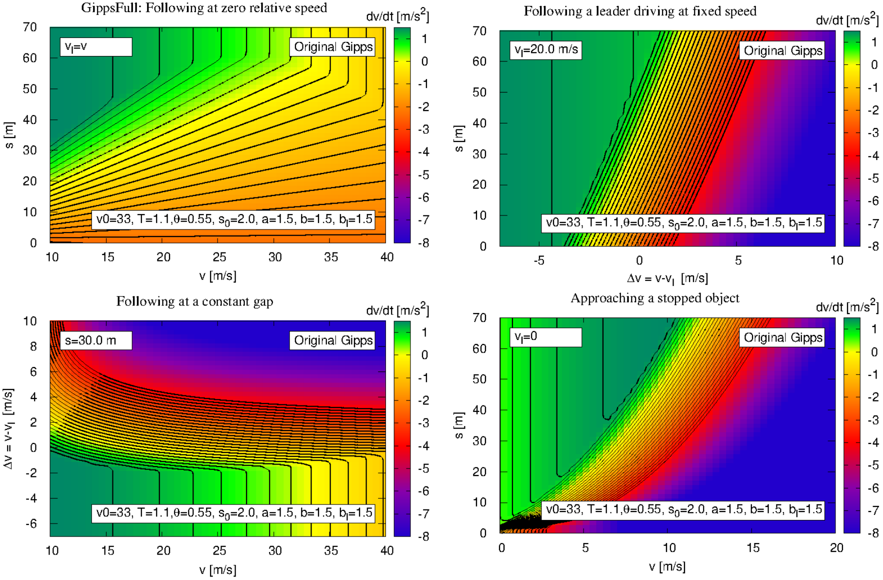
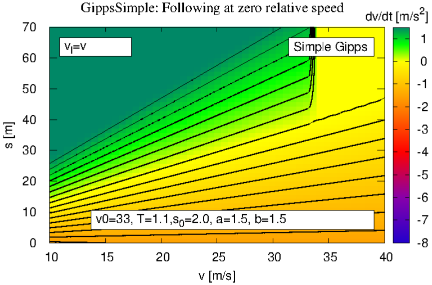
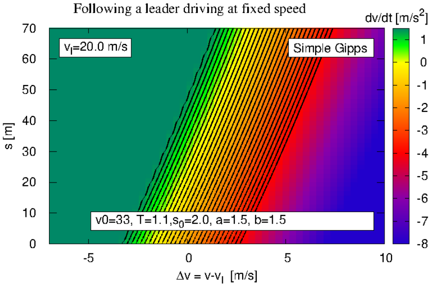
Gipps model acceleration function

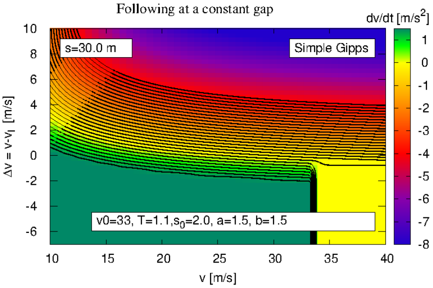


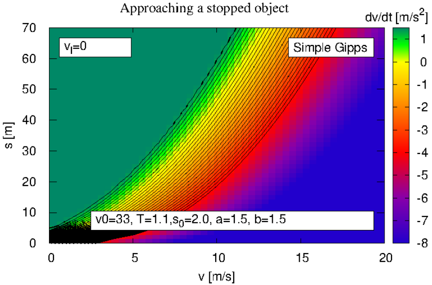
⇒ accGippsSimple

Simplified Gipps model acceleration function







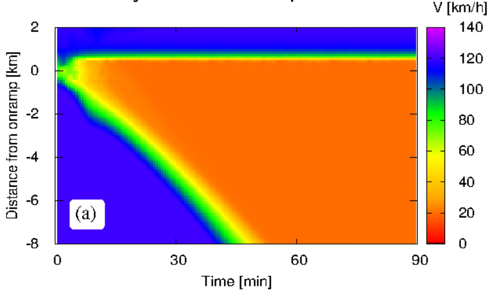


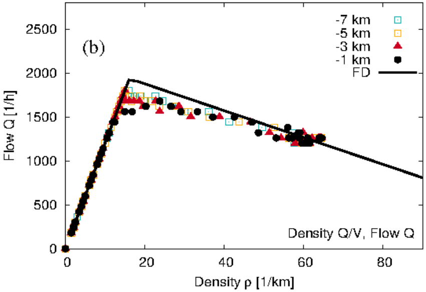
⇐ accGipps

⇒ accIDM

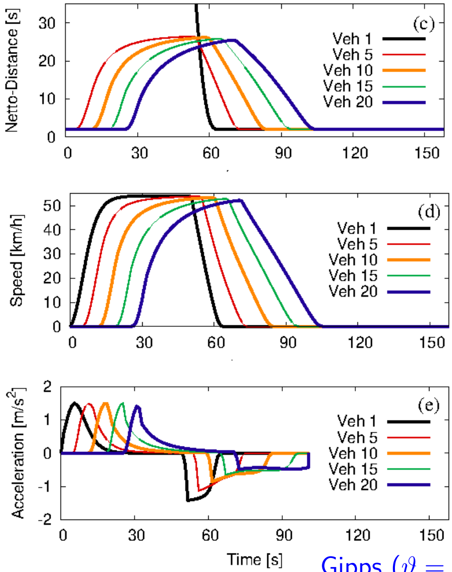
Factsheet of the original Gipps model ($\vartheta = 0.5$)

freeway with on-ramp





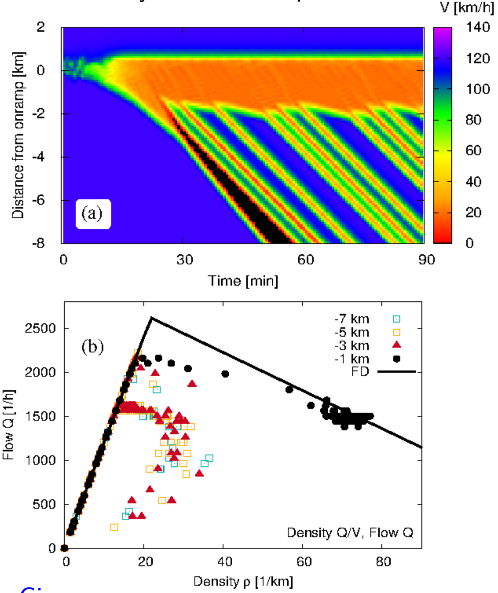
city with traffic lights



Gipps ($\vartheta = 0.06$) $\Rightarrow$

Factsheet of the original Gipps model with $\vartheta = 0.06$

freeway with on-ramp



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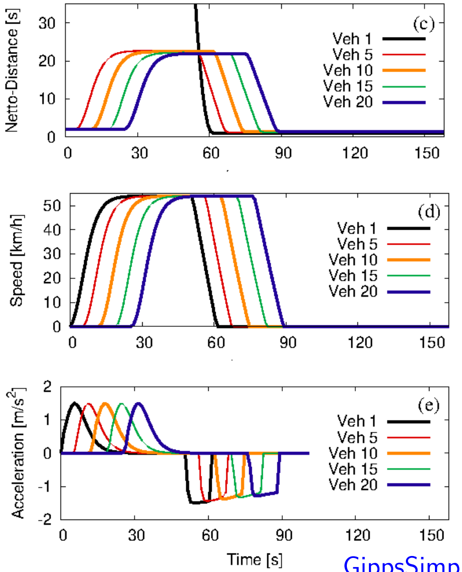

⇐ Gipps

GippsSimple ⇒

Factsheet of the simplified Gipps model

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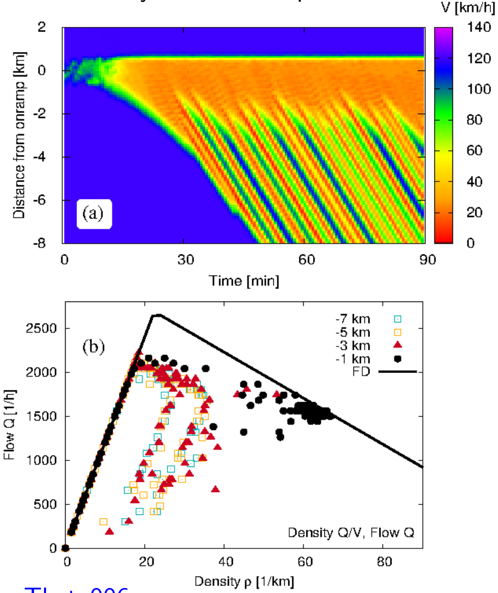

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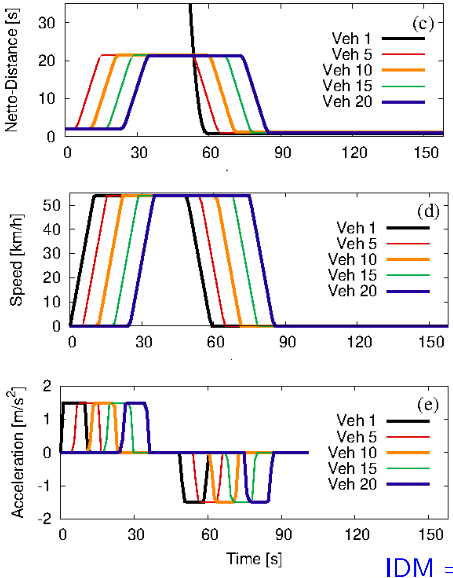

⇐ GippsTheta006

IDM ⇒

9.3 Intelligent Driver Model (IDM)

Probably the most parsimonious car-following model satisfying following conditions:

- All *plausibility conditions* satisfied
- *smooth driving regime transitions* (i.e., a smooth or even differentiable acceleration function), unlike the Gipps model
- *collision free* if physically possible
- *unique feature:* Continuous and stable transition from an emergency to a regular braking maneuver by an *intelligent* driving strategy
- all model parameters are *intuitive* describing distinct aspects of the driving behavior: aggressive/timid, anticipative/short-sighted, responsive/sleepy, and of course slow/fast

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IDM equations

$$\frac{\mathrm{d}v}{\mathrm{d}t} = a\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*(v, v_l)}{s}\right)^2\right]$$ IDM acceleration

free acceleration: $a[1-(v/v_0)^4]$, repulsive force: $-a(s^*/s)^2$

$$s^*(v, v_l) = s_0 + \max\left(0, vT + \frac{v(v-v_l)}{2\sqrt{ab}}\right)$$ desired gap

Parameter	Cars Highway	Cars City	Trucks Hwy	Bicycles
Desired speed v_0	$120\,\mathrm{km/h}$	$50\,\mathrm{km/h}$	$80\,\mathrm{km/h}$	$20\,\mathrm{km/h}$
Time gap T	$1.0\,\mathrm{s}$	$1.0\,\mathrm{s}$	$1.8\,\mathrm{s}$	$0.6\,\mathrm{s}$
Minimum gap s_0	$2\,\mathrm{m}$	$2\,\mathrm{m}$	$3\,\mathrm{m}$	$0.4\,\mathrm{m}$
Acceleration a	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$0.5\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$
Comf. deceleration b	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$	$1.5\,\mathrm{m/s^2}$

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Parameter	**Cars Highway**	**Cars City**	**Trucks Hwy**	**Bicycles**
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Acceleration a	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$0.5\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$
Comf. deceleration b	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$	$1.5\,\mathrm{m/s^2}$

IDM equations

$$\frac{\mathrm{d}v}{\mathrm{d}t} = a\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*(v, v_l)}{s}\right)^2\right]$$ IDM acceleration

free acceleration: $a[1-(v/v_0)^4]$, repulsive force: $-a(s^*/s)^2$

$$s^*(v, v_l) = s_0 + \max\left(0, vT + \frac{v(v-v_l)}{2\sqrt{ab}}\right)$$ desired gap

Parameter	Cars Highway	Cars City	Trucks Hwy	Bicycles
Desired speed v_0	$120\,\mathrm{km/h}$	$50\,\mathrm{km/h}$	$80\,\mathrm{km/h}$	$20\,\mathrm{km/h}$
Time gap T	$1.0\,\mathrm{s}$	$1.0\,\mathrm{s}$	$1.8\,\mathrm{s}$	$0.6\,\mathrm{s}$
Minimum gap s_0	$2\,\mathrm{m}$	$2\,\mathrm{m}$	$3\,\mathrm{m}$	$0.4\,\mathrm{m}$
Acceleration a	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$0.5\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$
Comf. deceleration b	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$	$1.5\,\mathrm{m/s^2}$

IDM equations

$$\frac{dv}{dt} = a\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*(v, v_l)}{s}\right)^2\right] \qquad \text{IDM acceleration}$$

free acceleration: $a[1-(v/v_0)^4]$, repulsive force: $-a(s^*/s)^2$

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Parameter	**Cars Highway**	**Cars City**	**Trucks Hwy**	**Bicycles**
Desired speed v_0	$120\,\mathrm{km/h}$	$50\,\mathrm{km/h}$	$80\,\mathrm{km/h}$	$20\,\mathrm{km/h}$
Time gap T	$1.0\,\mathrm{s}$	$1.0\,\mathrm{s}$	$1.8\,\mathrm{s}$	$0.6\,\mathrm{s}$
Minimum gap s_0	$2\,\mathrm{m}$	$2\,\mathrm{m}$	$3\,\mathrm{m}$	$0.4\,\mathrm{m}$
Acceleration a	$1.5\,\mathrm{m/s^2}$	$2.0\,\mathrm{m/s^2}$	$0.5\,\mathrm{m/s^2}$	$1.0\,\mathrm{m/s^2}$
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Minimum gap s_0	2 m	2 m	3 m	0.4 m
Acceleration a	1.5 m/s^2	2.0 m/s^2	0.5 m/s^2	1.0 m/s^2
Comf. deceleration b	1.5 m/s^2	2.0 m/s^2	1.0 m/s^2	1.5 m/s^2

IDM equations

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Acceleration a	1.5 m/s^2	2.0 m/s^2	0.5 m/s^2	1.0 m/s^2
Comf. deceleration b	1.5 m/s^2	2.0 m/s^2	1.0 m/s^2	1.5 m/s^2

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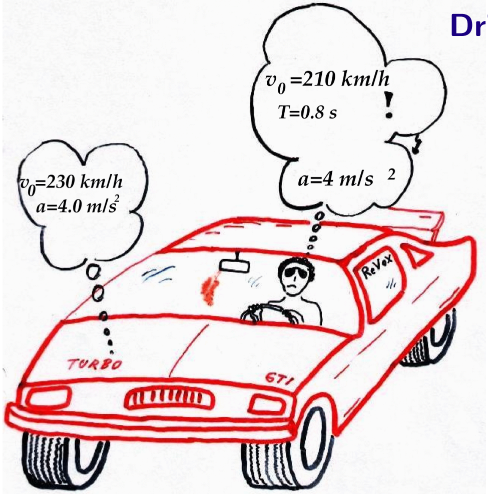
Driving styles



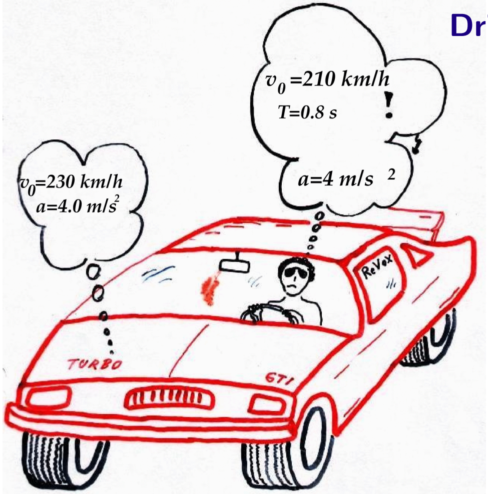
Aggressive driver:
v_0, a and b high, T and s_0 low

Relaxed driver:
v_0, a low, b normal, T and s_0 high

Experienced responsive driver:
a high, b low, rest normal

Experienced defensive driver:
v_0, a normal, b low, T and s_0 high

Driving styles



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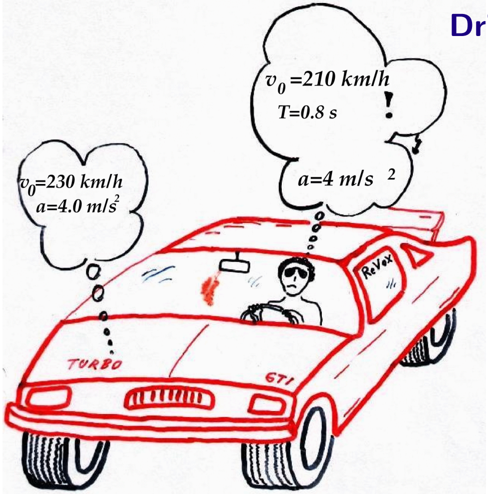
Driving styles



Aggressive driver:
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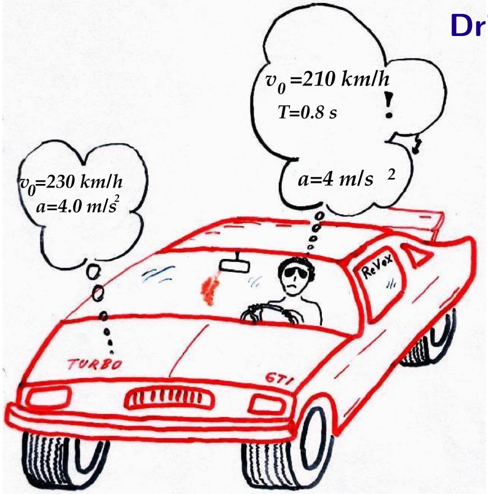

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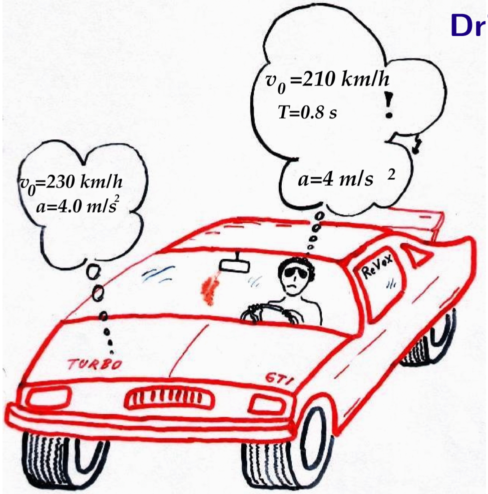

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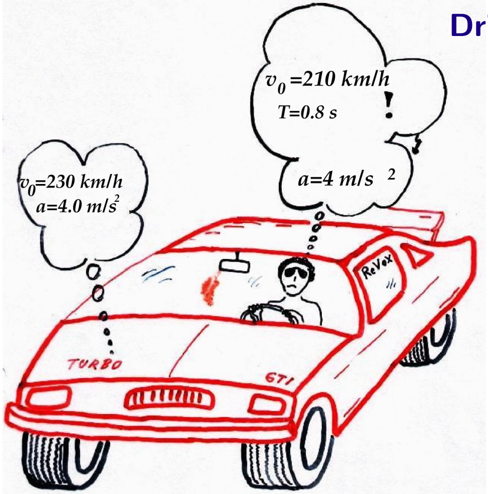

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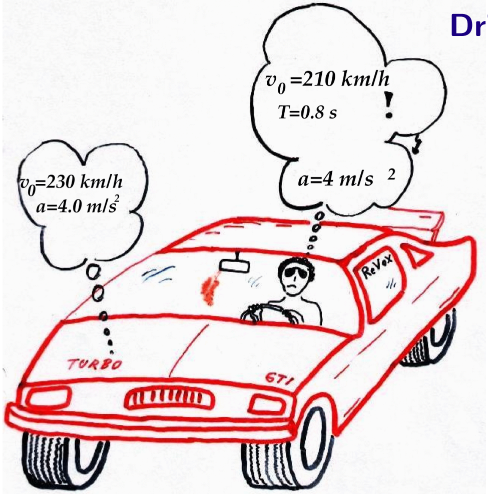

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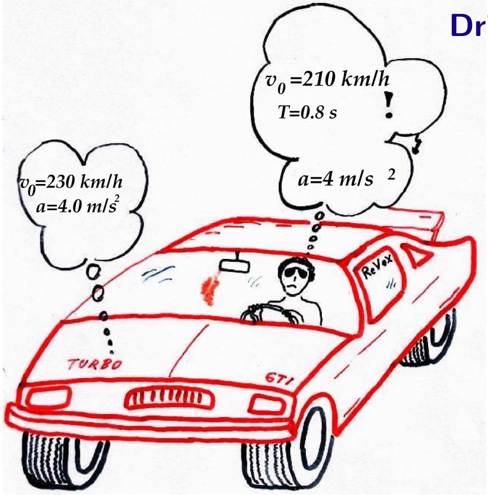

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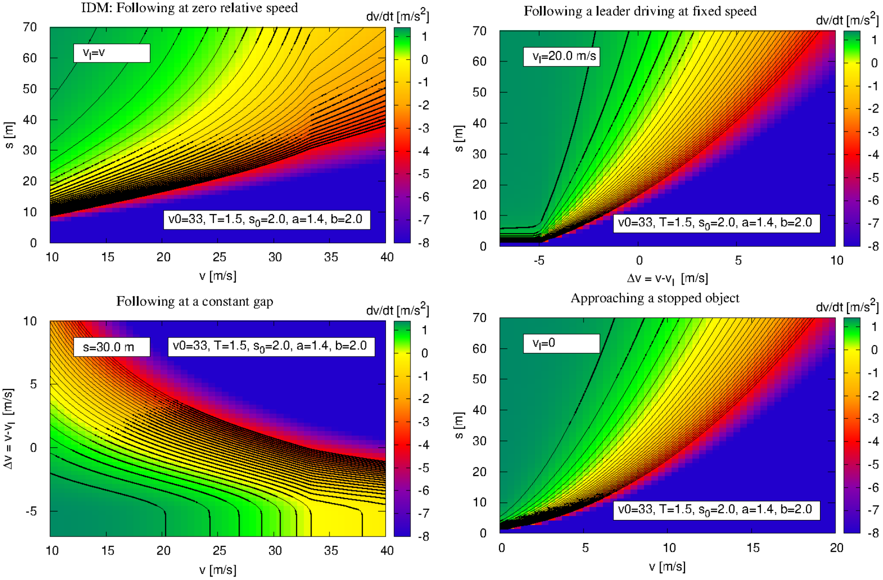
IDM acceleration function



⇐ accGippsSimple
⇒ accIDM+

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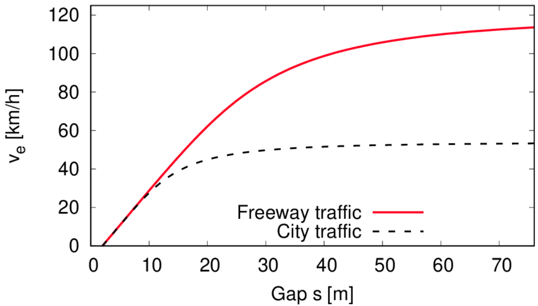

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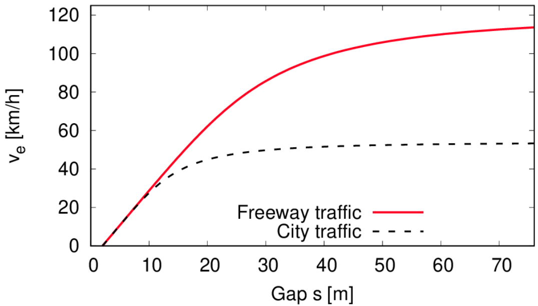

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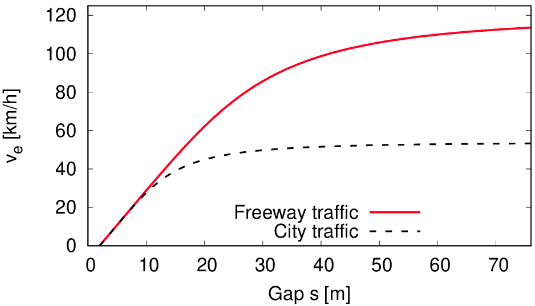

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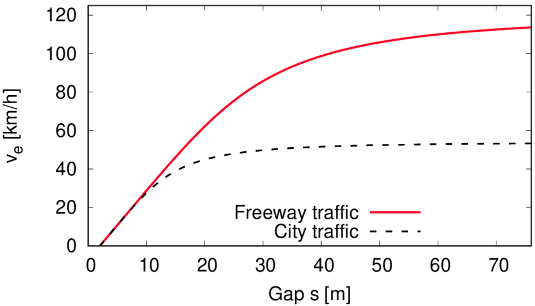

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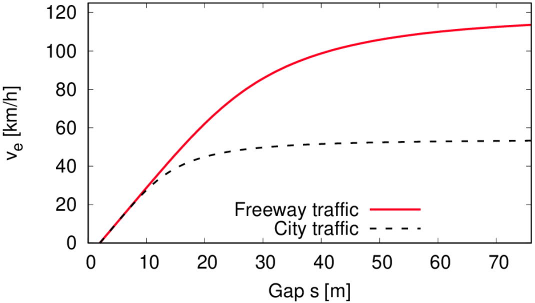

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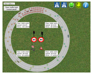
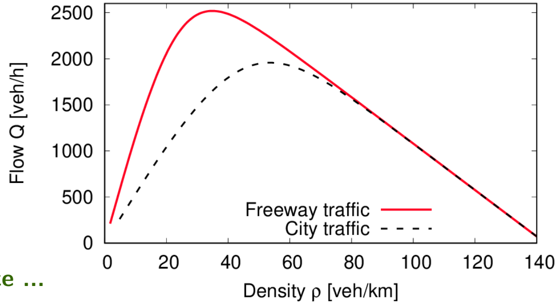


simulate ...



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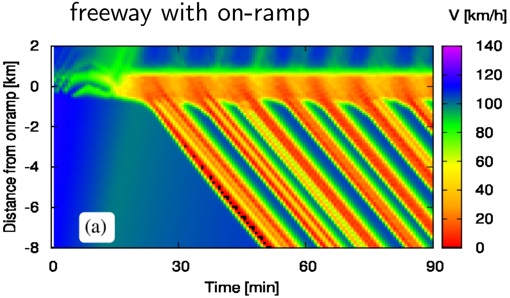
- How manages the IDM to not brake too early but bring a critical situation under control? Rewriting $\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{b_{\text{kin}}^2}{b}$ reveals the trick:
  - Situation safe or $b_{\text{kin}} < b \Rightarrow |\frac{\mathrm{d}v}{\mathrm{d}t}| < b_{\text{kin}}$ $\Rightarrow$ brake *less* than b_{kin}: too early is bad!
  - Situation critical or $b_{\text{kin}} > b \Rightarrow |\frac{\mathrm{d}v}{\mathrm{d}t}| > b_{\text{kin}}$ $\Rightarrow$ brake *more* than b_{kin}: get situation under control!

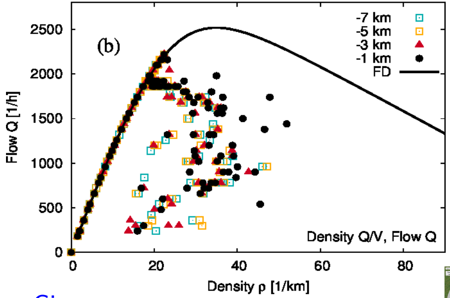
In both cases, the comfortable deceleration b is *dynamically* reached!

simulate ...

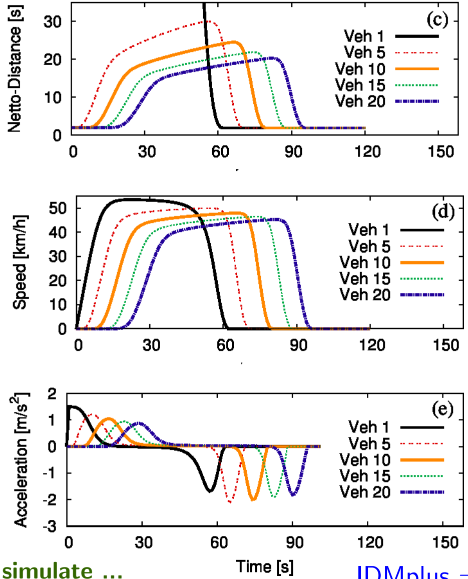
Factsheet of the Intelligent-Driver Model (IDM)

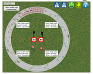
freeway with on-ramp





city with traffic lights



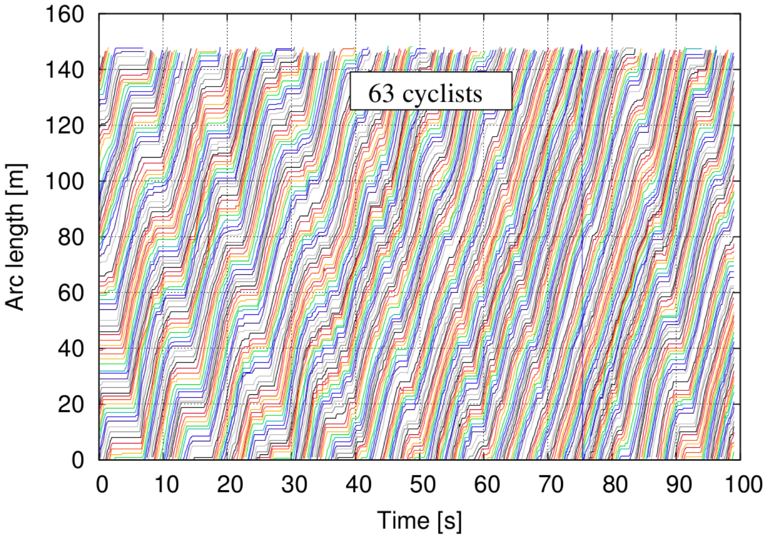


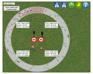
⇐ Gipps

simulate ...

IDMplus ⇒

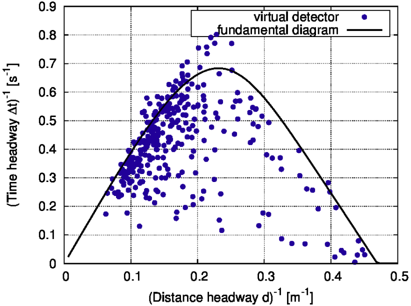
IDM for bicycle traffic? Single-file bicycle traffic experiment

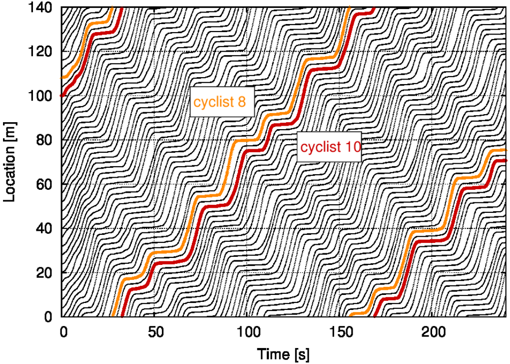


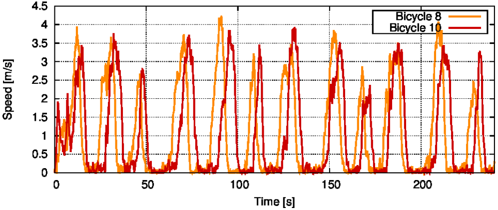


simulate ...

Simulating single-file bicycle traffic with the IDM







$l_{\text{bike}} = 1.7\,\text{m},\ v_0 = 4\,\text{m/s},\ T = 0.6\,\text{s},$
$s_0 = 0.4\,\text{m},\ a = 0.8\,\text{m/s}^2,\ b = 1.5\,\text{m/s}^2$

9.4 Derivatives of the Intelligent Driver Model

For a realistic driving feeling or for use as the core of an ACC controller, the IDM still has several deficiencies:

- When reaching the desired speed, the steady-state time gap

$$T = \frac{s_e(v) - s_0}{v} = \frac{T}{\sqrt{1-(v/v_0)^4}}$$

  becomes significantly larger than T leading to a somewhat unrealistic platoon behaviour in the *city with traffic lights* situation.

- The IDM reacts too sensitively if the gap is too low, even if there is no real danger. This happens regularly if the leader changes (active and passive lane changes)

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IDM with triangular fundamental diagram: IDM+

The time-gap deficiency can be solved by following modification:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \min\left[a\left(1-(v/v_0)^4\right), a\left(1-(s^*/s)^2\right)\right] \qquad \textbf{IDM+}$$

- The acceleration function is no longer smooth but still continuous
- Instead of the continuous transition of the IDM, the IDM+ has two distinct regimes: free acceleration (the first expression of the min function is relevant), and interacting (the second expression matters)
- Steady-state time gap: $\frac{\mathrm{d}v}{\mathrm{d}t}=0 \Rightarrow$ if $v<v_0$, the second expression in the min-condition matters
  $\Rightarrow s = s^*(v,v) = s_0 + vT \Rightarrow$ constant time gap and triangular FD
- The *intelligent* braking strategy is not affected (see the following plots)

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IDM with triangular fundamental diagram: IDM+

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$$\frac{\mathrm{d}v}{\mathrm{d}t} = \min\left[a\left(1 - (v/v_0)^4\right), a\left(1 - (s^*/s)^2\right)\right] \qquad \textbf{IDM+}$$

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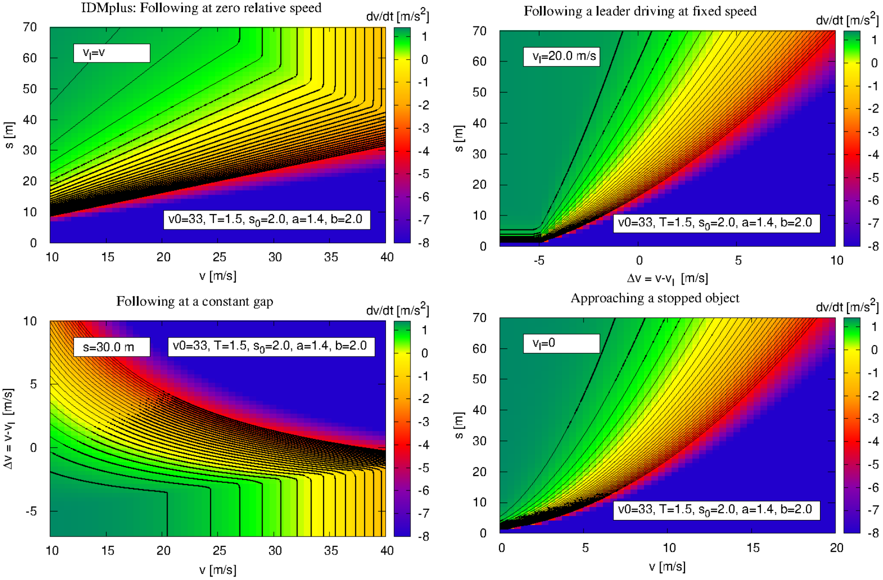
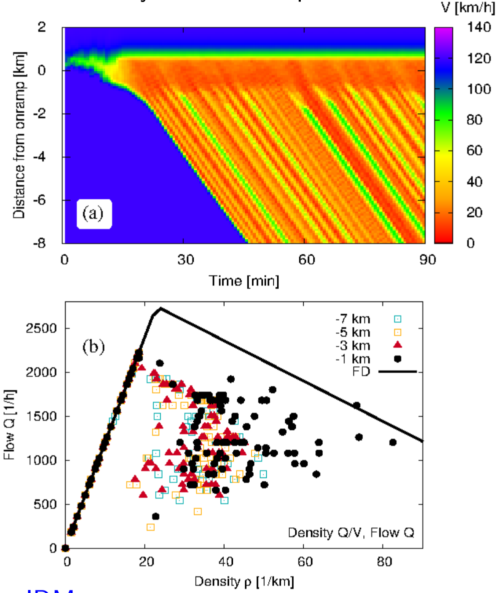
IDM+ acceleration function



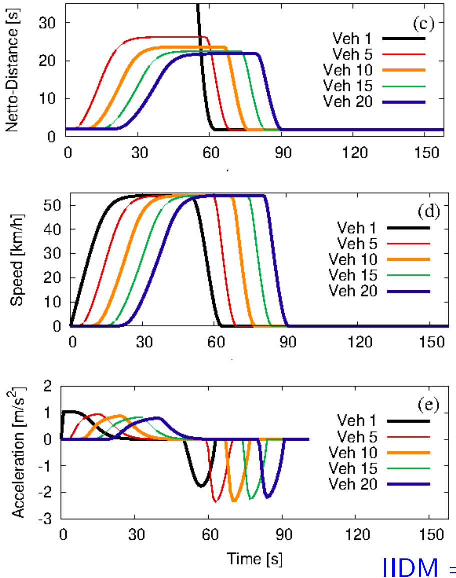
⇐ accIDM ⇒ accACC

Factsheet of the Improved IDM (IDM+)

freeway with on-ramp



city with traffic lights



⇐ IDM

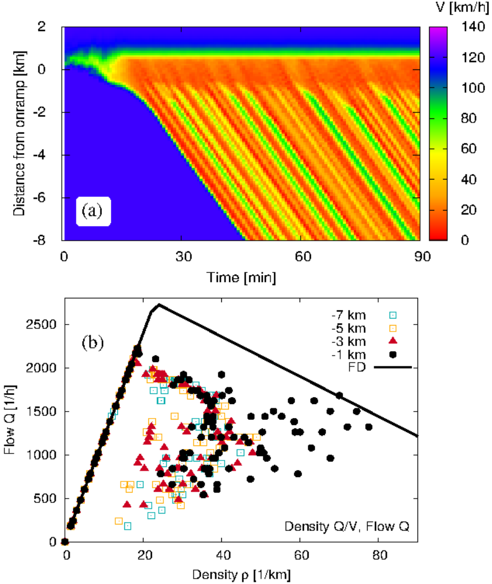
IIDM ⇒

Another IDM with triangular fundamental diagram: IIDM

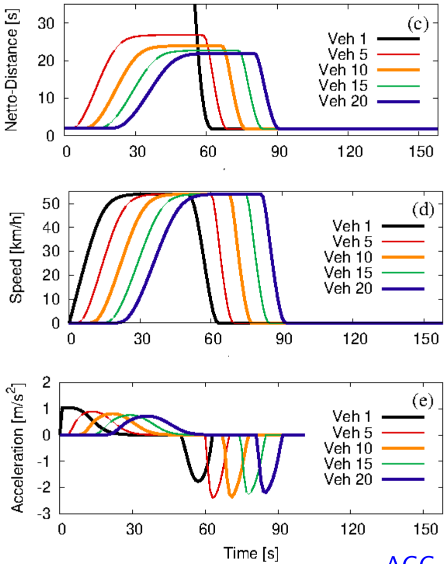
- Another possibility to obtain an IDM-like model with a triangular FD and the intelligent brakingstrategy unaffected
- In contrast to the IIDM, the acceleration function is smooth
- However, this implies a more complicated formulation (not shown)

Factsheet of the Improved IDM (IIDM)

freeway with on-ramp



city with traffic lights



⇐ IDMplus

ACC ⇒

9.5 Models for Adaptive Cruise Control

- Besides a triangular FD (i.e., constant time gaps in the following regime), an ACC model needs to be robust against changing leading objects caused, e.g., by active or passive lane changes
- This is realized by replacing the worst-case heuristics of the IDM by a more realistic "constant acceleration heuristics": Human drivers also do not expect a full braking maneuver to the stop *out of the blue* (and would not be able to handle it)
- In contrast, because the ACC model does only have insignificant reaction delays (all IDM variants presented in this lecture have zero reaction time!), the ACC controller could even handle this
- The actual model is not shown, just the results

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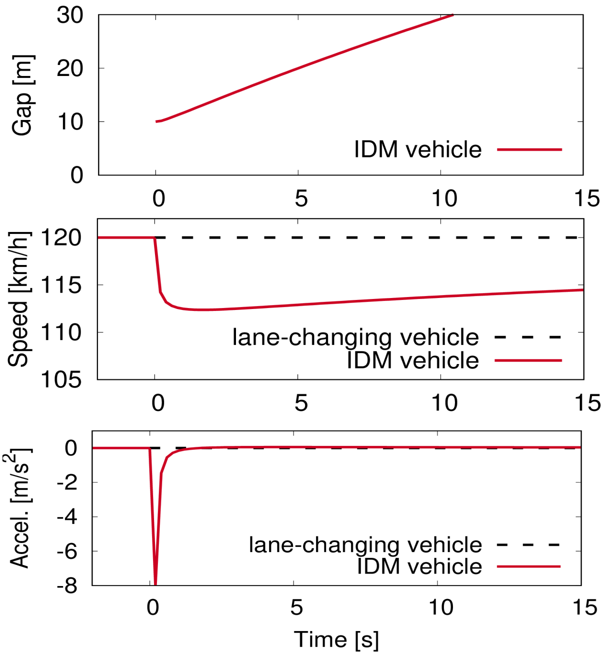
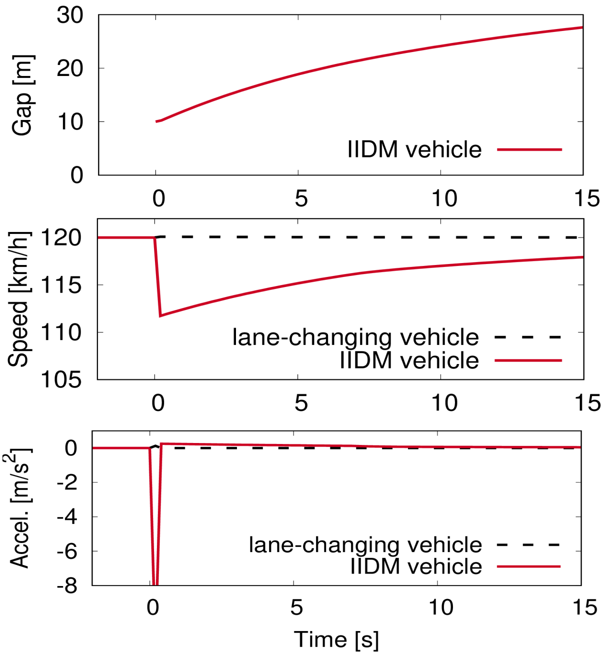
Response to a close cut-in maneuver at same speed: IDM



Lane-changing vehicle: same speed 120 km/h as the follower, cuts in leaving a gap of 10 m

IDM responds too panically

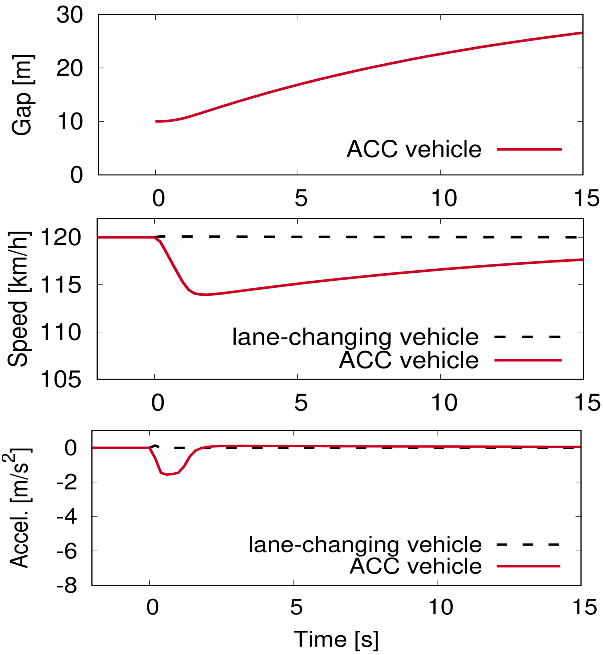
Response to a close cut-in maneuver at same speed: IIDM



Lane-changing vehicle: same speed 120 km/h as the follower, cuts in leaving a gap of 10 m

IIDM response similarly panically but has a better following behaviour afterwards

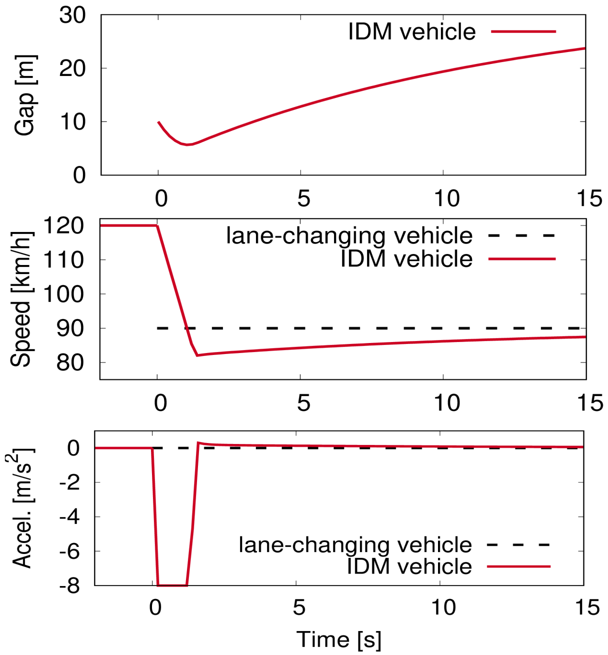
Response to a close cut-in maneuver at same speed: ACC



Lane-changing vehicle: same speed 120 km/h as the follower, cuts in leaving a gap of 10 m

The (IDM+-based) ACC model has a *cool* immediate response and a plausible following behaviour afterwards

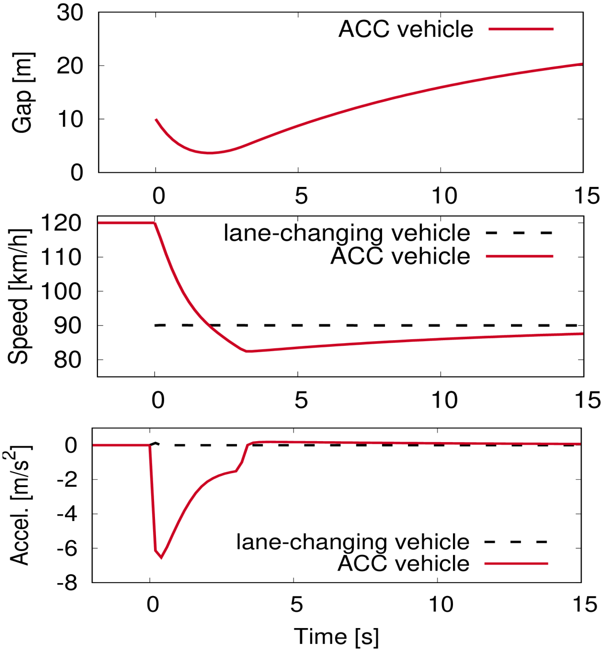
Response to a critical cut-in maneuver: IDM



Lane-changing vehicle: 30 km/h slower than the follower, cuts in leaving a gap of just 10 m

IDM switches to emergency mode which is right in this situation

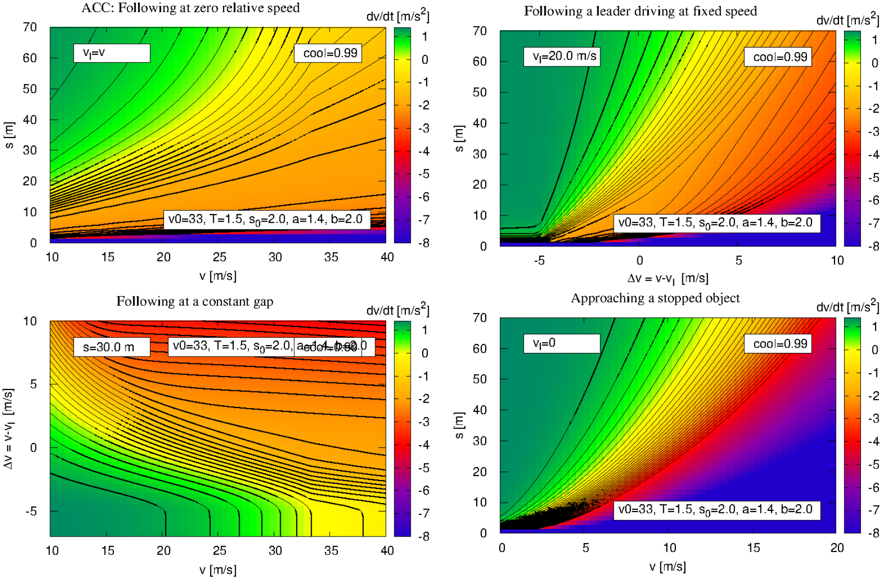
Response to a critical cut-in maneuver: ACC model



Lane-changing vehicle: 30 km/h slower than the follower, cuts in leaving a gap of just 10 m

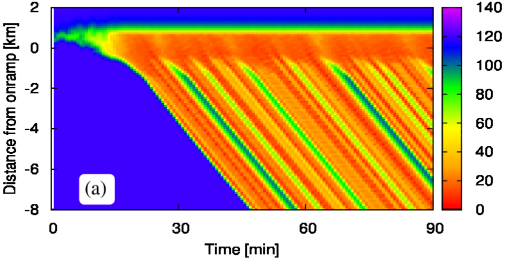
Also the ACC model looses its *coolness* which is completely justified in this situation

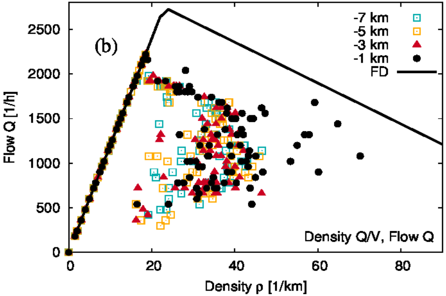
ACC model acceleration function



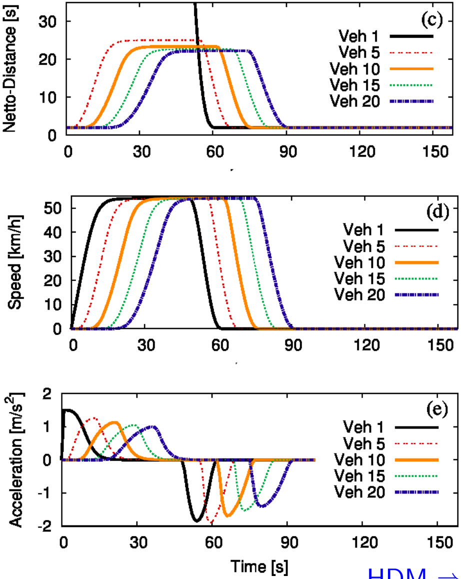
Factsheet of the ACC model

freeway with on-ramp



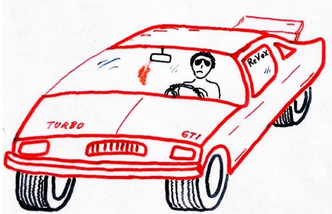


city with traffic lights

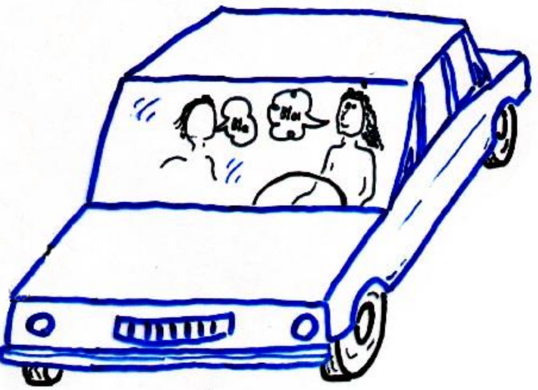


⇐ IDM+
HDM ⇒

9.6 Human-Driver Car-Following Models



In contrast to ACC controllers, humans have ...



- Significant **reaction times** $\Rightarrow$ state $s(t-T_r)$, $v_l(t-T_r)$
- Response **thresholds** ($\Rightarrow$ Wiedemann)
- Risk **attitude** ($\Rightarrow$ **Prospect Theory**)
- Correlated **estimation errors** in s, v, and v_l and general acceleration noise
- Temporal **anticipation**: $s(t+T_a) = s(t) + T_a\,(v_l(t) - v(t))$
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- Response to braking lights, winkers, ...

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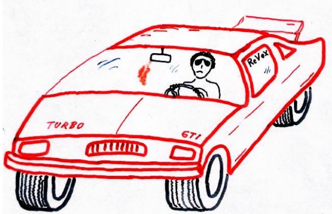

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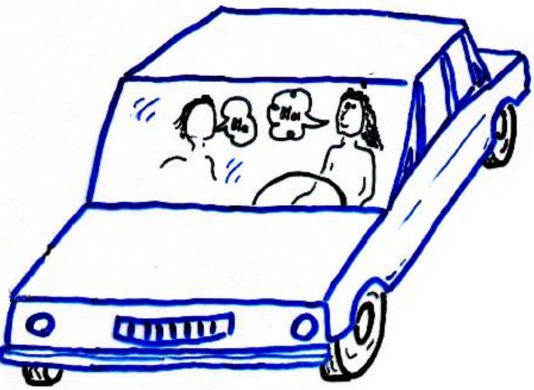

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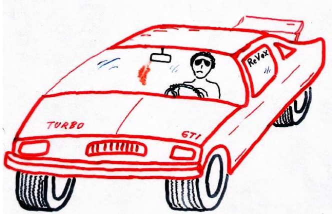

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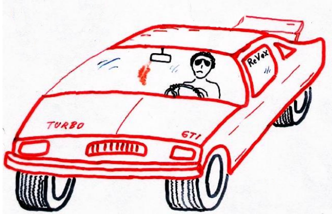

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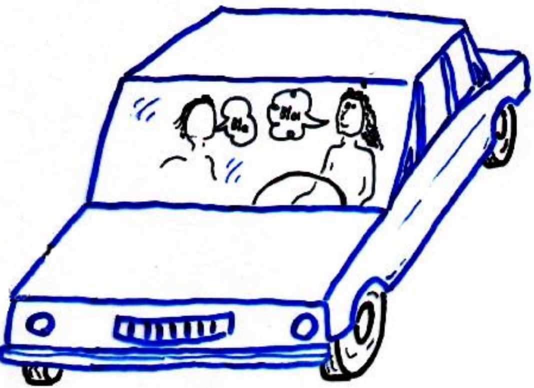

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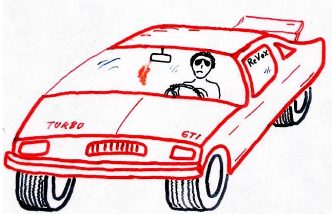

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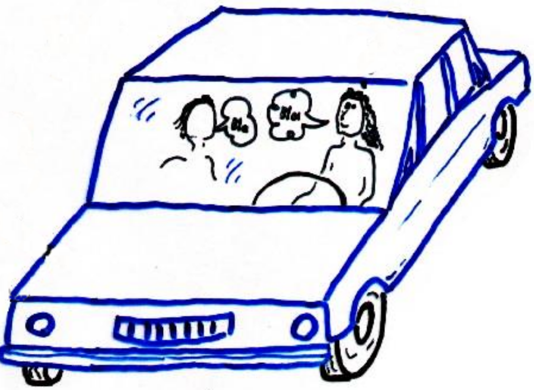

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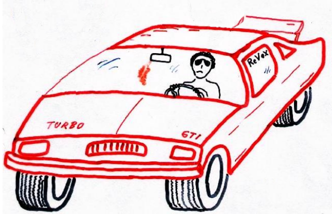

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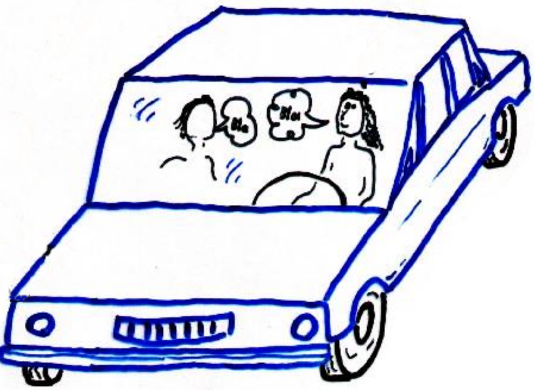

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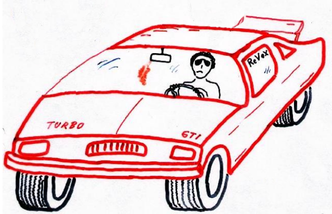

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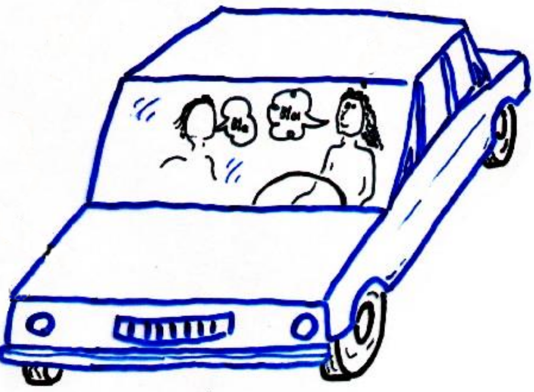
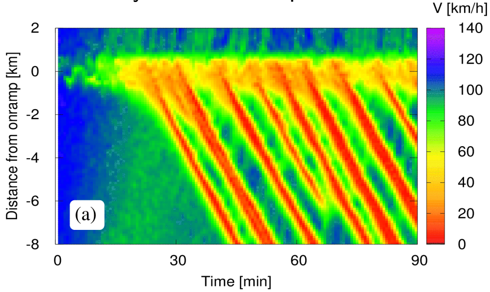
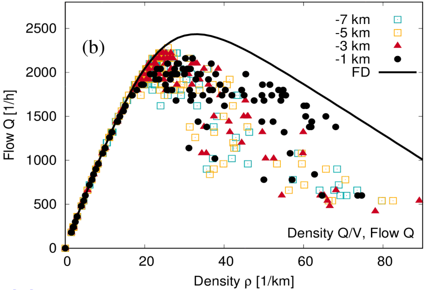


- Significant **reaction times** $\Rightarrow$ state $s(t-T_r)$, $v_l(t-T_r)$
- Response **thresholds** ($\Rightarrow$ Wiedemann)
- Risk **attitude** ($\Rightarrow$ **Prospect Theory**)
- Correlated **estimation errors** in s, v, and v_l and general acceleration noise
- Temporal **anticipation**: $s(t+T_a) = s(t) + T_a\,(v_l(t) - v(t))$
- Spatial anticipation: **multi-anticipation** to next-nearest leaders
- Response to braking lights, winkers, ...

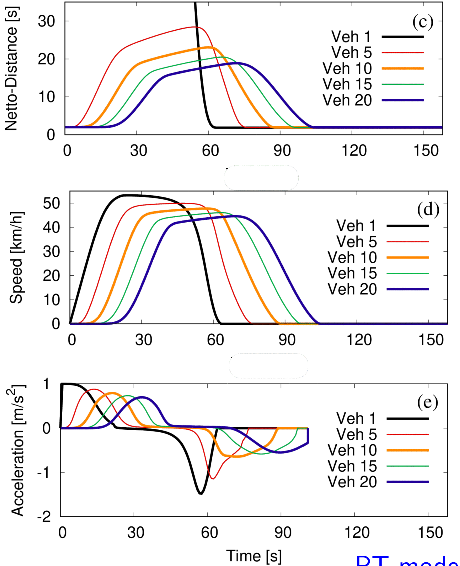
Factsheet of the IDM-based Human Driver Model

freeway with on-ramp





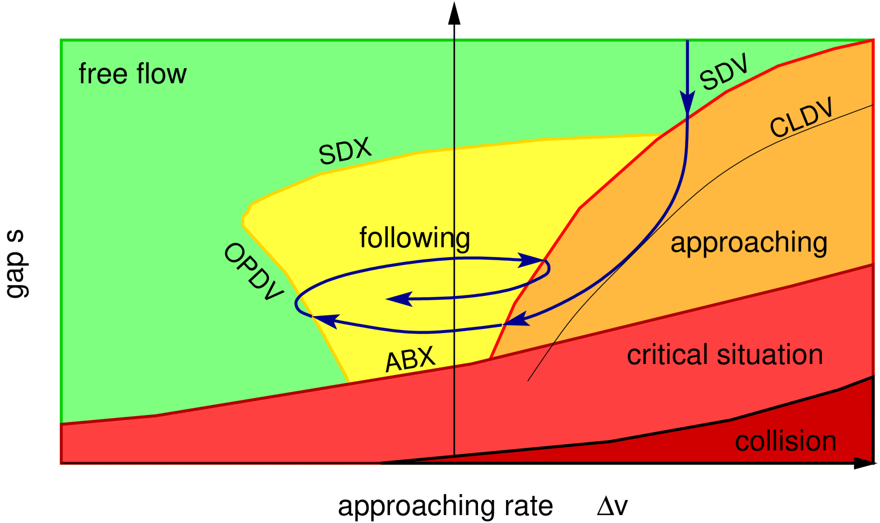
city with traffic lights



⇐ ACC model

PT model ⇒

Response thresholds:
Wiedemann trajectories in space-relative speed space



Base model in VISSIM

CF models based on risk perception: Prospect Theory of Kahneman and Twersky

Prospect theory is a variant of **Expected Utility Theory (EUT)**:

- Given is a decision situation where, depending on the action a, a discrete set of outcomes $k \in \mathcal{K}(a)$ with utilities $U_k(a)$ can happen with probabilities $P_k(a)$
- The *Homo Oeconomicus'* action a tries to maximize the **expected utility**

$$E(U) = \sum_{k \in \mathcal{K}(a)} P_k(a) U_k(a) \stackrel{!}{=} \max_a$$

- The actions a can be discrete such as accepting an offer or not, or continuous such as deciding on an acceleration
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  - Small probabilities are overestimated (for probabilities > 0.5, the complement probability is considered)
  - At a certain **framing reference**, the sensitivity to utility changes is at its maximum
  - Losses with respect to the reference are weighted more than wins: **loss aversion**

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Formulation of a CF model based on Prospect Theory

General observations:

- The probability P_1 of the outcome $k=1$: "crash" increases with the acceleration a (because of the future speed increasing and the future gaps decreasing with a)
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Assumptions of the presented PT model:

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Formulation of a CF model based on Prospect Theory

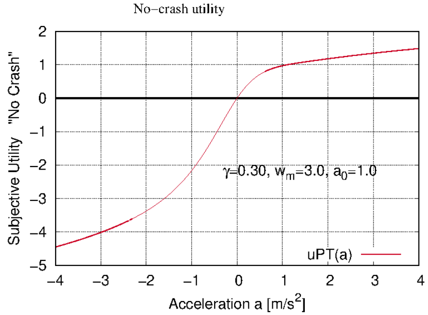
General observations:

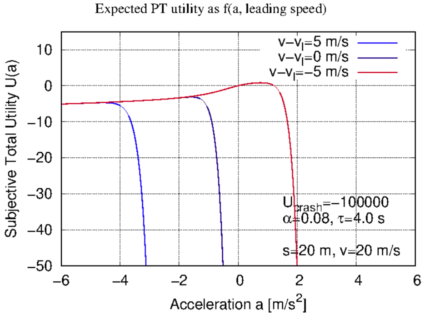
- The probability P_1 of the outcome $k = 1$: "crash" increases with the acceleration a (because of the future speed increasing and the future gaps decreasing with a)
- The probability $P_2 = 1 - P_1$ of the outcome "no crash" decreases accordingly but its utility U_2 increases: "due to my higher future speed, I will need less time"

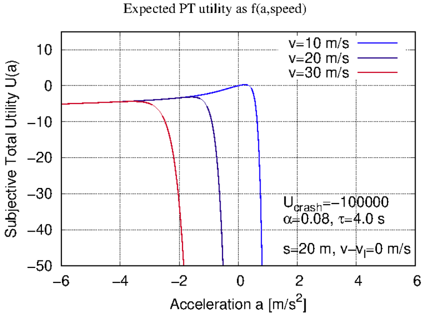
Assumptions of the presented PT model:

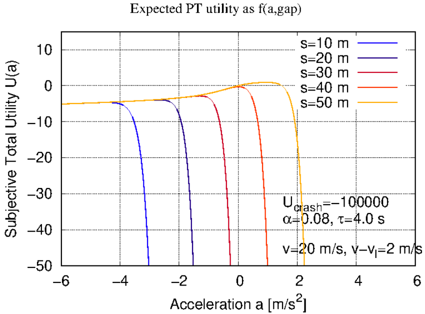
- Anticipation time horizon τ_a (e.g., $\tau_a = 5\,\mathrm{s}$) for assessing the crash risk $P_1 \ll 1$
- The leader's speed is unchanged and the uncertainty of assessing the relative speed Δv increases with the speed: $\Delta\hat{v} \sim N(\Delta v, \sigma)$ with $\sigma = \alpha v$ (e.g., $\alpha = 0.2$).
- The utility $U_2(a)$ with the slope $U_2'(a)$ of the order of 1 (scaling of U) reflects the reference at $a = 0$ and loss aversion
- The subjective crash utility U_1 is a very negative constant (e.g., $U_1 = -10^5$)
- Minimum of free and PT acceleration is taken

Prospect-theoretic utilities

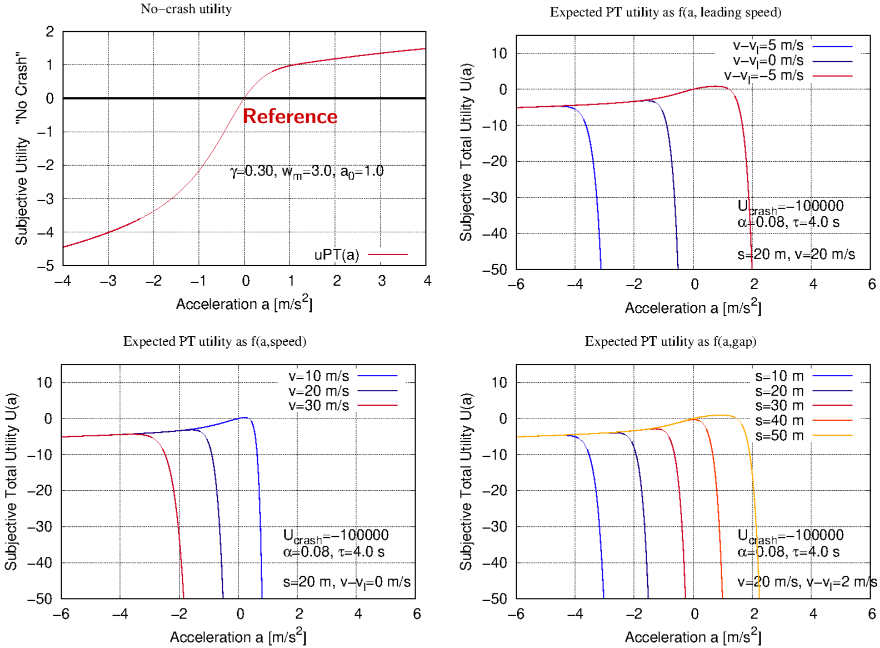




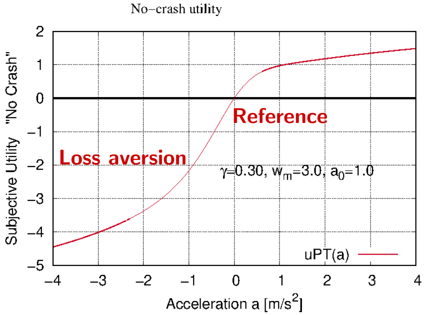


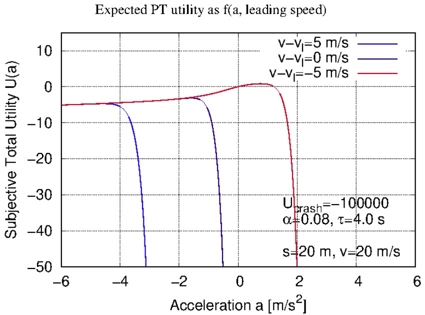


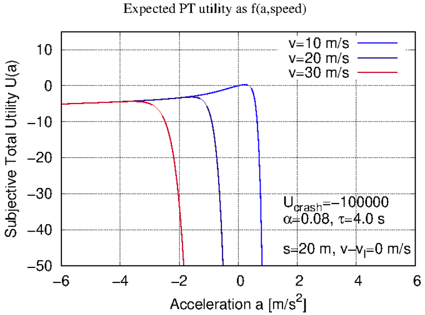
Prospect-theoretic utilities

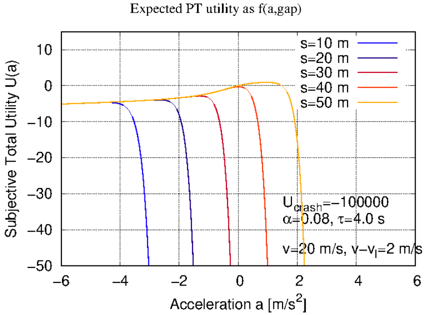


Prospect-theoretic utilities



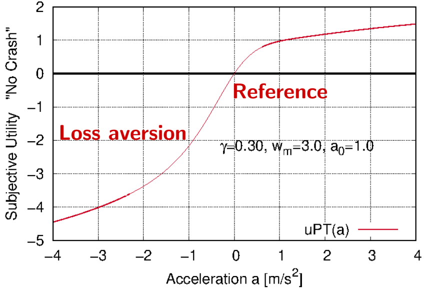




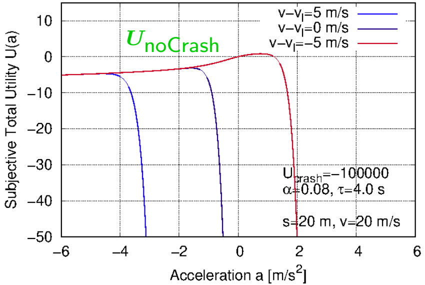


Prospect-theoretic utilities

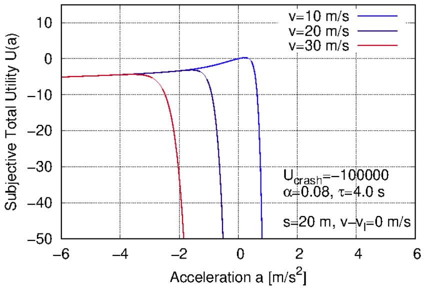
No−crash utility



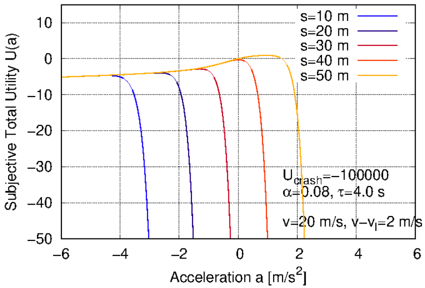
Expected PT utility as f(a, leading speed)



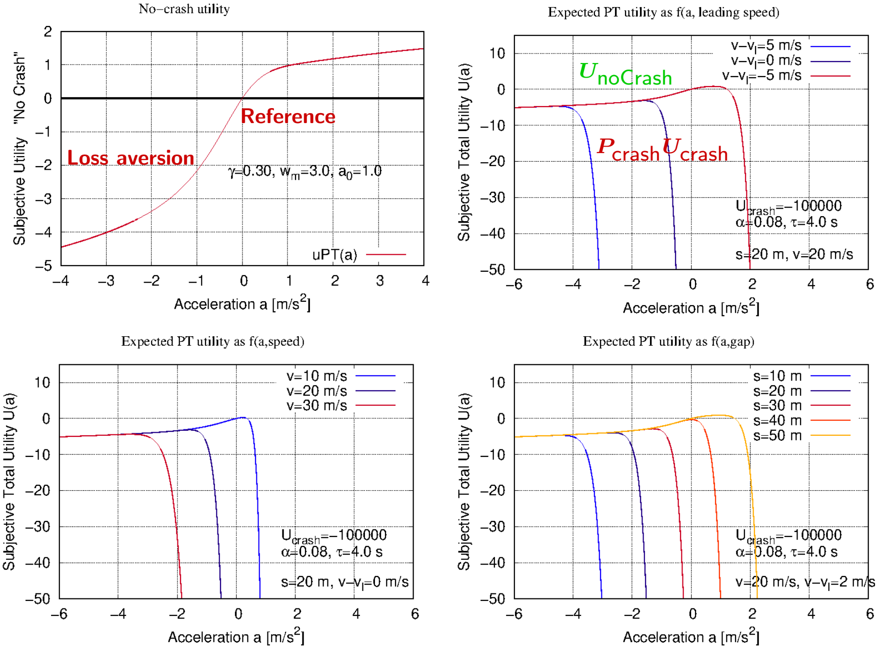
Expected PT utility as f(a,speed)



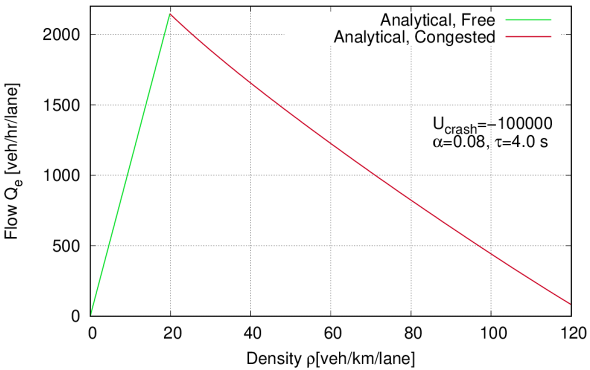
Expected PT utility as f(a,gap)

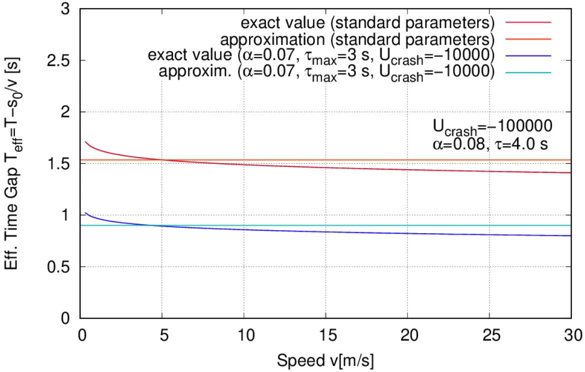


Prospect-theoretic utilities



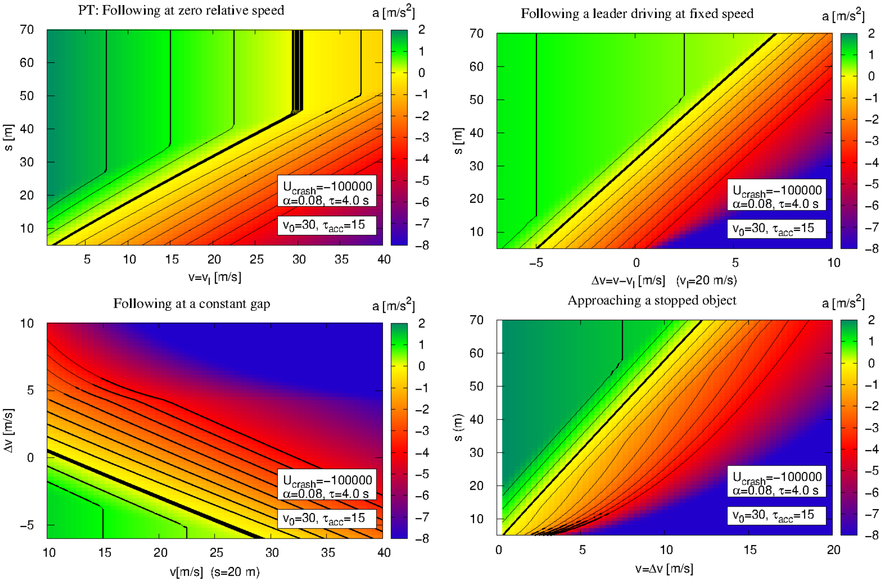
Fundamental diagram and steady-state gap





$$T_{\text{eff}} \approx \alpha \tau_a \sqrt{2 \ln(-P_{\text{crash}})}$$

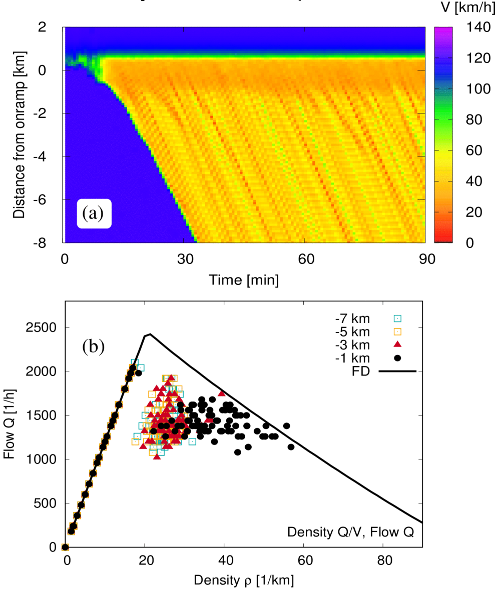
PT model acceleration function



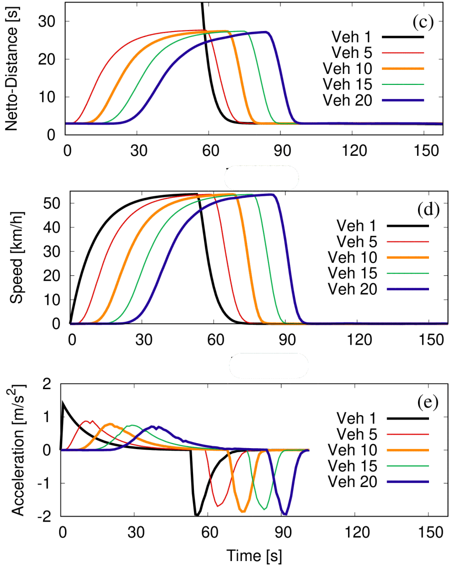
⇐ accACC

Factsheet of the PT model based on Kahneman and Twersky

freeway with on-ramp



city with traffic lights



⇐ HDM