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Within-individual variable behavior in traffic flow models

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Once upon a time...

- TNO and TRAIL joined forces in a project aimed at

  better understanding the relationship between driver behavior in congestion and traffic flow dynamics

- 1999-2004: 2 complementary PhD's
  - traffic flow modeling: Chris Tampère
  - driver behavioral modeling: no PhD candidate found...

- PhD Tampère interesting, but limited to modeling, lacking empirical and behavioral underpinning

- Presentation intends to show how PhD Raymond Hoogendoorn is fully complementary!

Human-kinetic traffic flow modeling

- objective
  - to explore traffic flow dynamics of traffic flows for which no macroscopic empirical observations are available yet
  - scaling up individual driver behavioral models to traffic flow

- application domain
  - ADAS: advanced driver assistance systems with drivers in-the-loop
  - theoretical insight micro-macro link (e.g. influence behavior on capacity drop, traffic flow stability,... see ISTTT 2005)

- type of model
  - kinetic: mathematical framework linking (stochastic) micro interactions to macroscopic flow dynamics

human-kinetic model: (gas)kinetic basics

- Kinetic ‘continuity’ equation
  - conservation of probability density ρ of vehicles in state S
  - State S consists of
    - location x
    - vehicle speed v
    - activation level a

$$\frac{\partial \rho}{\partial t} + \nabla_S \left(\rho \frac{dS}{dt} \right) = \left(\frac{d\rho}{dt} \right)_{events}$$

- Apply method of moments to obtain macroscopic equations
  - for the density k
  - for the speed V
  - for the activation level A

$$\frac{\partial k}{\partial t} + \frac{\partial kV}{\partial x} = \left(\frac{dk}{dt} \right)_{inflow}$$

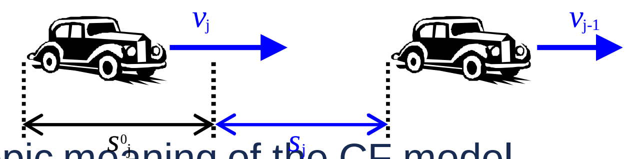
$$\frac{\partial kA}{\partial t} + \frac{\partial kAV}{\partial x} = k \left\langle \frac{da}{dt} \right\rangle_{v,a} + \int_a \int_v a \left(\frac{d\rho}{dt} \right)_{inflow} dv\, da$$

Human-kinetic model: micro – macro link

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = \frac{1}{k}\int v\left(\frac{d\rho}{dt}\right)_{event} dv\,da + \left\langle \frac{dv}{dt} \right\rangle_{v,a} - \frac{1}{k}\frac{\partial (k\Theta)}{\partial x}$$

- Only continuous speed changes, solely from individual behaviour

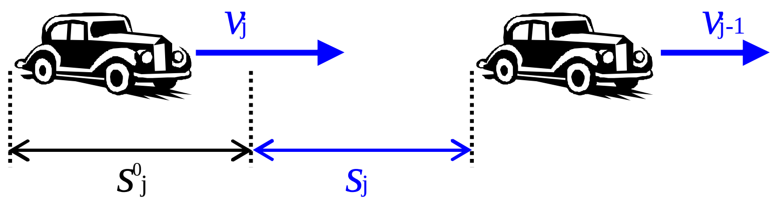
$$\left\langle \frac{dv}{dt} \right\rangle_{v} \equiv \int_{w_j} p_w(w_j) \int_{v_j} p_v(v_j) \int_{s_j} p_s(s_j) \int_{v_{j-1}} p_v(v_{j-1})\, \dot{v}_j(v_j, s_j, v_{j-1})\, dv_{j-1}\, ds_j\, dv_j\, dw_j$$



  - integration of a car-following model
    - direct micro – macro link
    - all parameters of macro model have microscopic meaning of the CF model
  - probabilities *p* all derived from *k*, *V* and Θ and account for
    - anisotropy (only consider forward gap)
    - speed dependent space requirement
    - evaluated non-locally
- note how HKM entails (Eulerian) micro model if all pdf's crisp

Individual driver behavior specification

$$\dot{v}(t+T) \equiv \min\left(\frac{w_j - v_j(t)}{\tau_w} \; ; \; \frac{s_j(t) - s_1^d v_j(t)}{\tau_s} + \frac{v_{j-1}(t) - v_j(t)}{\tau_v} \right)$$



$$acc_{min} \leq \dot{v} \leq acc_{max}$$

- in unconstrained or constrained mode, acc bounded
- response proportional to stimulus
  - unconstrained → deviation from desired speed *w*
  - constrained → deviation from desired distance $s_1^d v_j(t)$
    → speed difference with predecessor $v_{j-1}(t) - v_j(t)$
- any micro specification with similar components could be implemented in HK framework

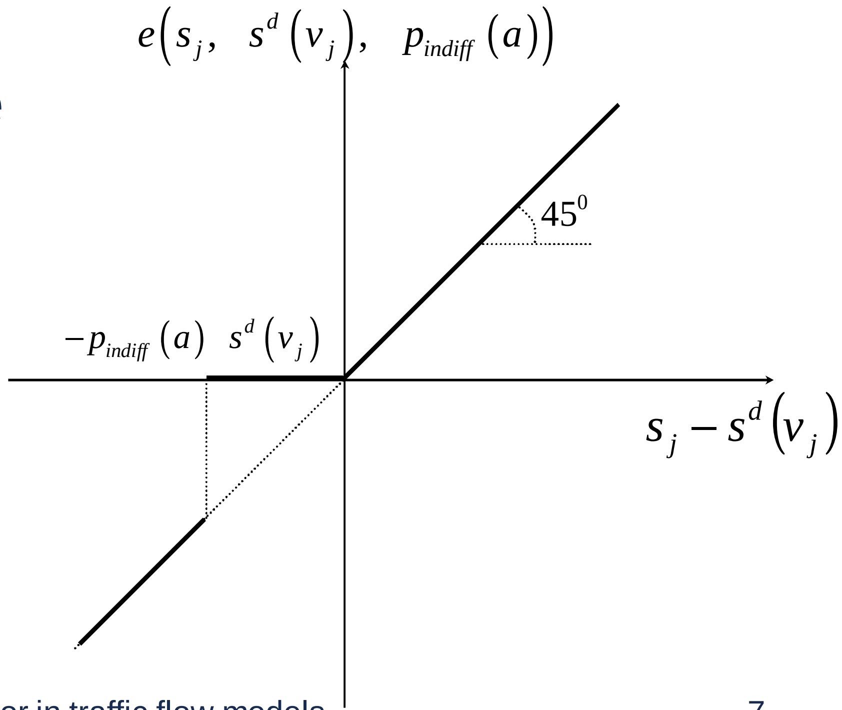
Some relation with psycho-spacing model?

- indifference bands for corrective actions during constrained driving

$$\dot{v}\left(v_j, v_{j-1}, s_j\right) \equiv \min\left(\frac{w_j - v_j}{\tau_w} ; \frac{e\left(s_j, s^d\left(v_j\right), p_{indiff}\left(a\right)\right)}{\tau_s} + \frac{v_{j-1} - v_j}{\tau_v}\right)$$

- could be extended to positive deviations and/or speed term

- note how ‘action point’ depends on activation level!



Some further refined driver behavior: reaction time, anticipation and anisotropy

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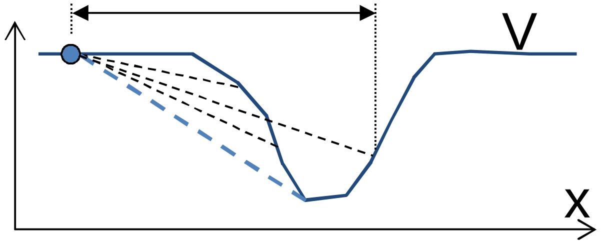
$$\left\langle \frac{dv}{dt}(t,x) \right\rangle_v = \int_{v_j} p(v_j|t,x) \int_{s_j} p_s(s_j|t,x,v_j) \int_{v_{j-1}} p_v(v_{j-1}|t, x+s_j^0+s_j, v_j, s_j)\, \dot{v}_j(v_j, s_j, v_{j-1})\, dv_{j-1} ds_j dv_j$$

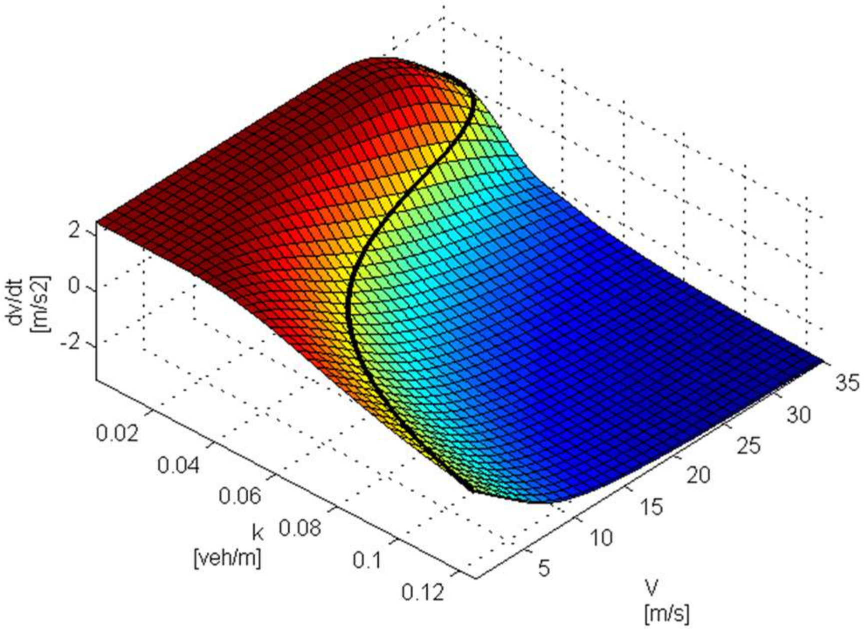
- Reaction time
  - replace $\left\langle \frac{dv}{dt}(x,t) \right\rangle_v$ by $\left\langle \frac{dv}{dt}(x,t+T^r) \right\rangle_v$
- Anticipation
  - Predecessor speed at interaction point = ***subjectively anticipated*** speed v_{j-1}
  - Use steepest speed drop in downstream anticipation range
  - Anticipation strength controlled by factor $f_{anticip}$

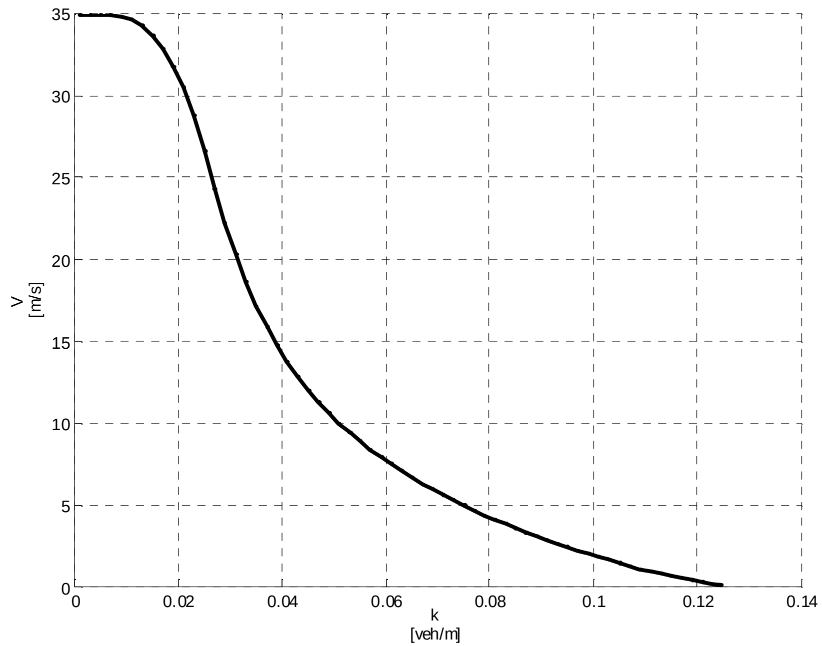


→ Anisotropy and non-locality

Stationary solutions of the HKM: fundamental diagram

- If homogeneous in x, then equilibrium if $\left\langle \frac{dv}{dt}(x,t) \right\rangle_{v,a} = 0$





- depends on pdf’s and activation level (see later)

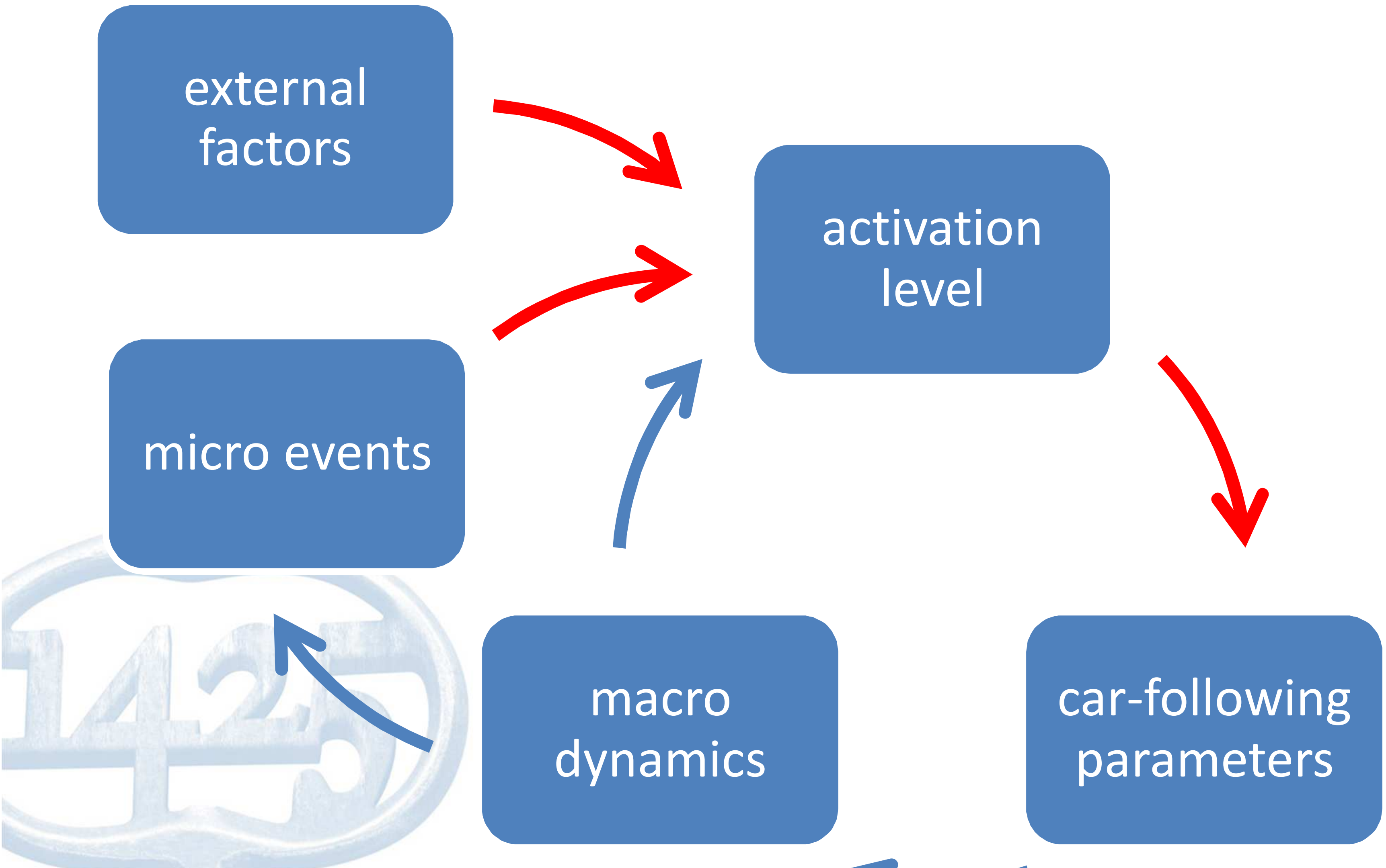
Summary driver behavior in HKM

- Helly-type car-following
- indifference band (action point model) for car-following
- finite reaction time
- anisotropy of car-following stimuli
- spatio-temporal anticipation to speed drops ahead
- bounded acceleration and deceleration

- driver state is characterized by speed, position and activation level (macro: advective property)

- HKM framework offers freedom to specify
  - dynamics of activation level
  - influence activation level on car-following

HKM model summary



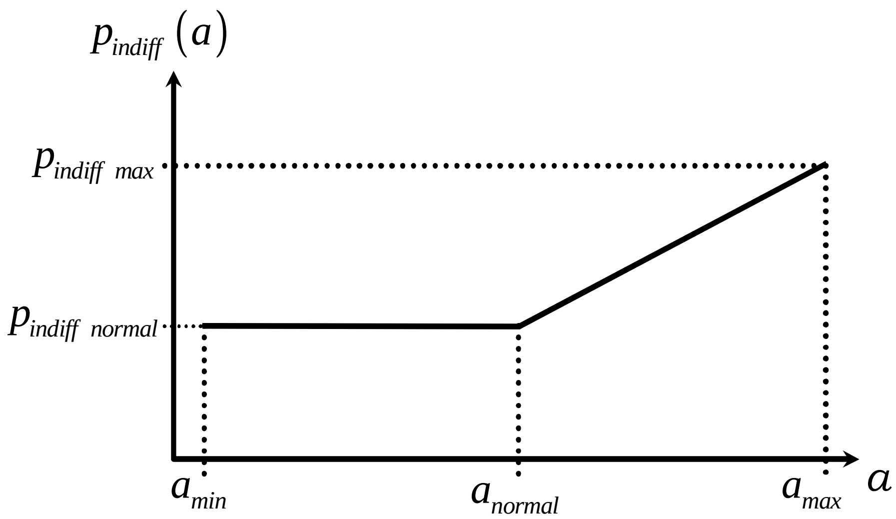
Some example specifications

- capacity funnel / boomerang effect
- capacity drop / hysteresis
- queue-tail warning ADAS

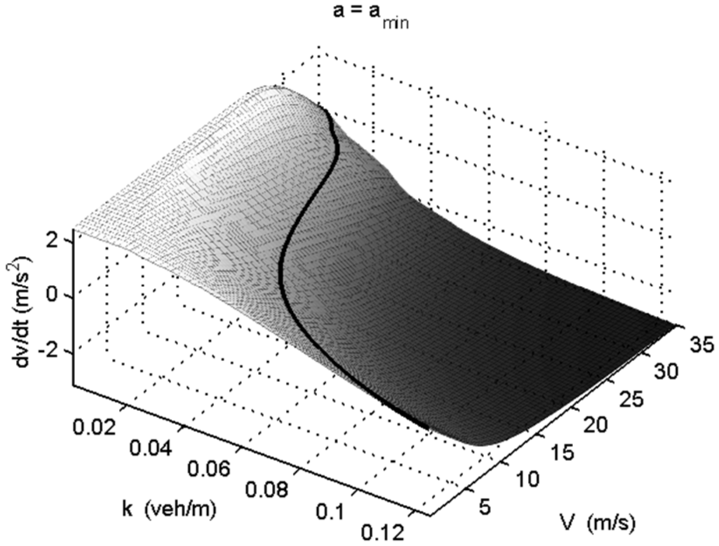
Capacity funnel (delayed onset of congestion near merges)

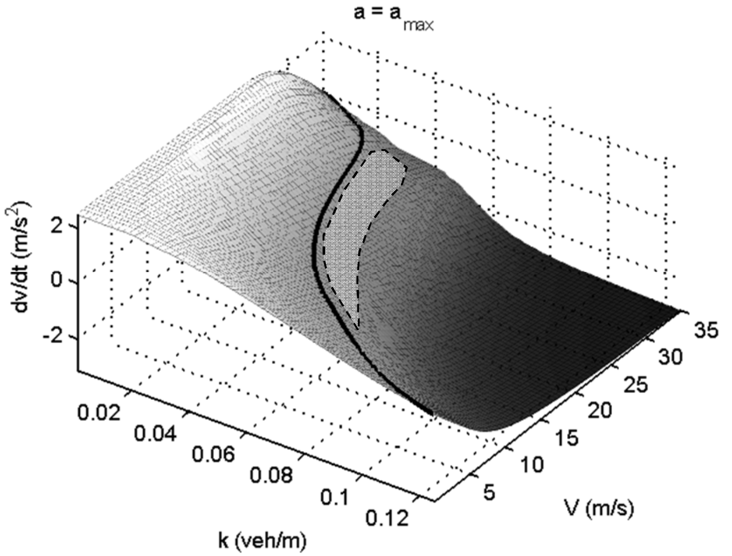
- activation level dynamics
  - cut-in events raise activation (both involved drivers)
  - in absence of other factors: relaxation to comfortable level

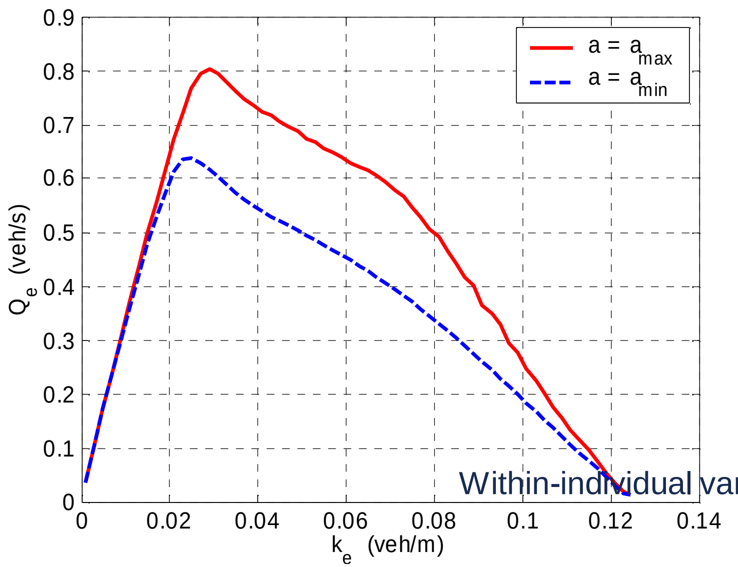
- activation level influence on car-following parameters

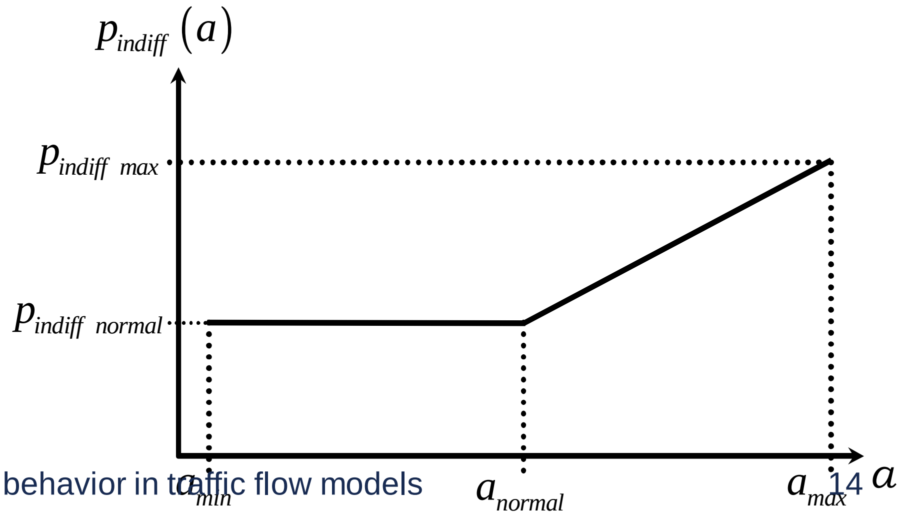


Dependency FD on activation level



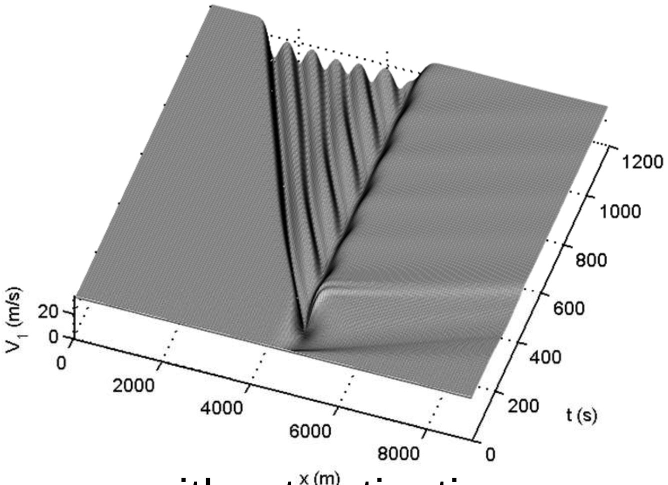




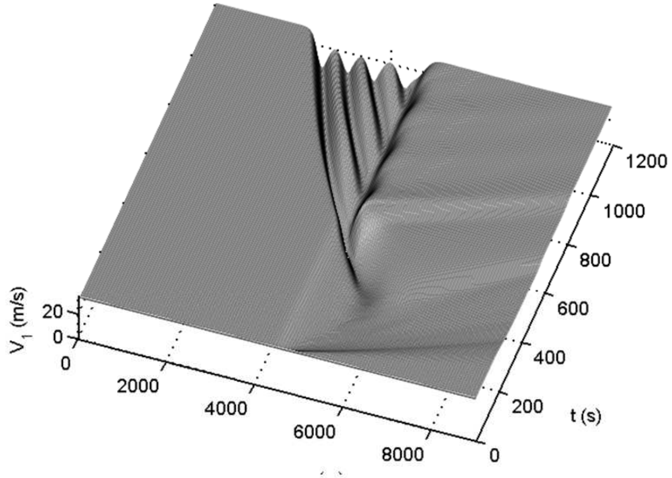


Capacity funnel

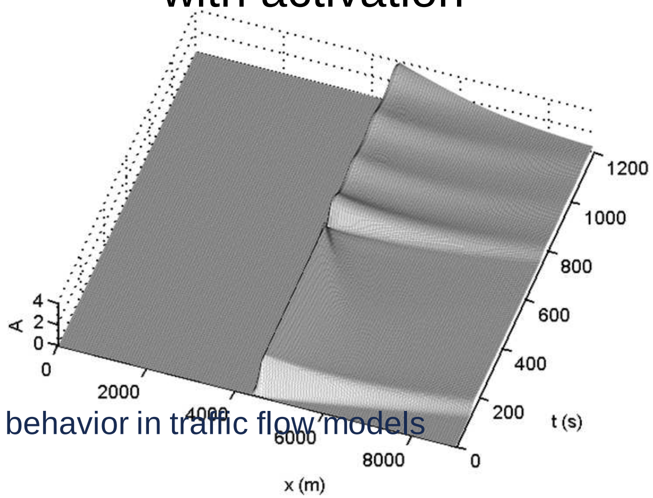
- merging-induced temporal capacity increase postpones congestion formation



without activation



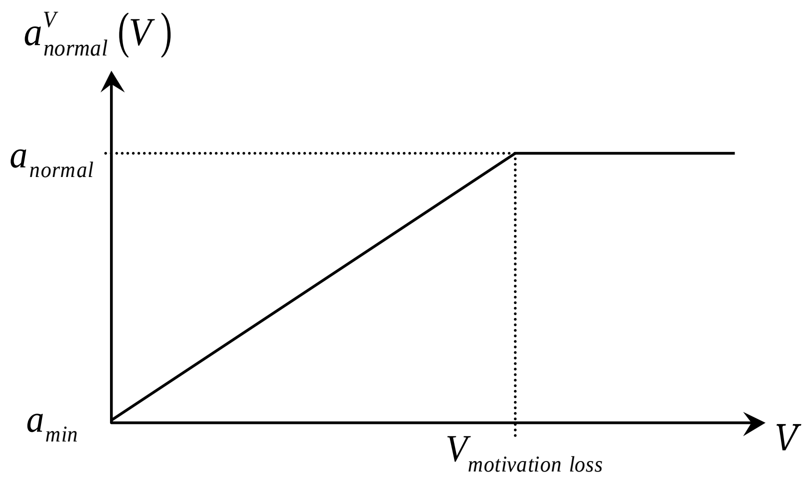
with activation



Capacity drop / hysteresis

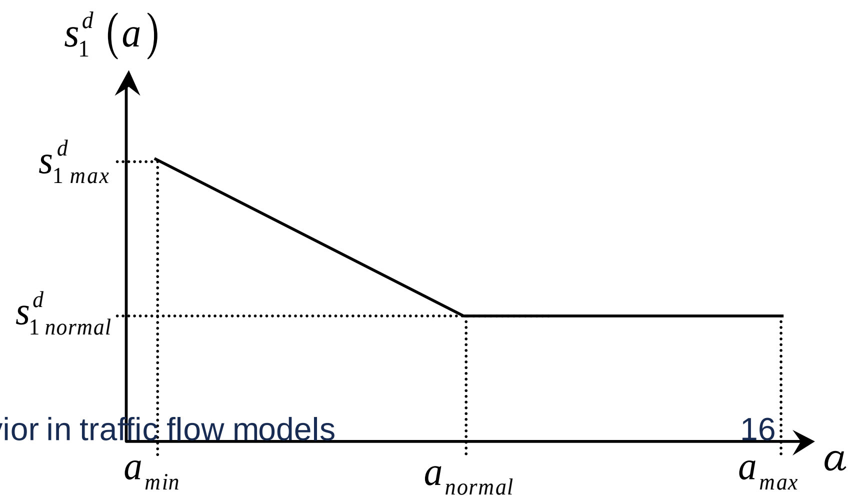
- activation level dynamics
  - low macroscopic speed reduces normal activation

$$\left\langle \frac{da}{dt} \right\rangle_{a,v} \equiv \frac{a^V_{normal}(V) - A}{\tau_a(A,V)}$$

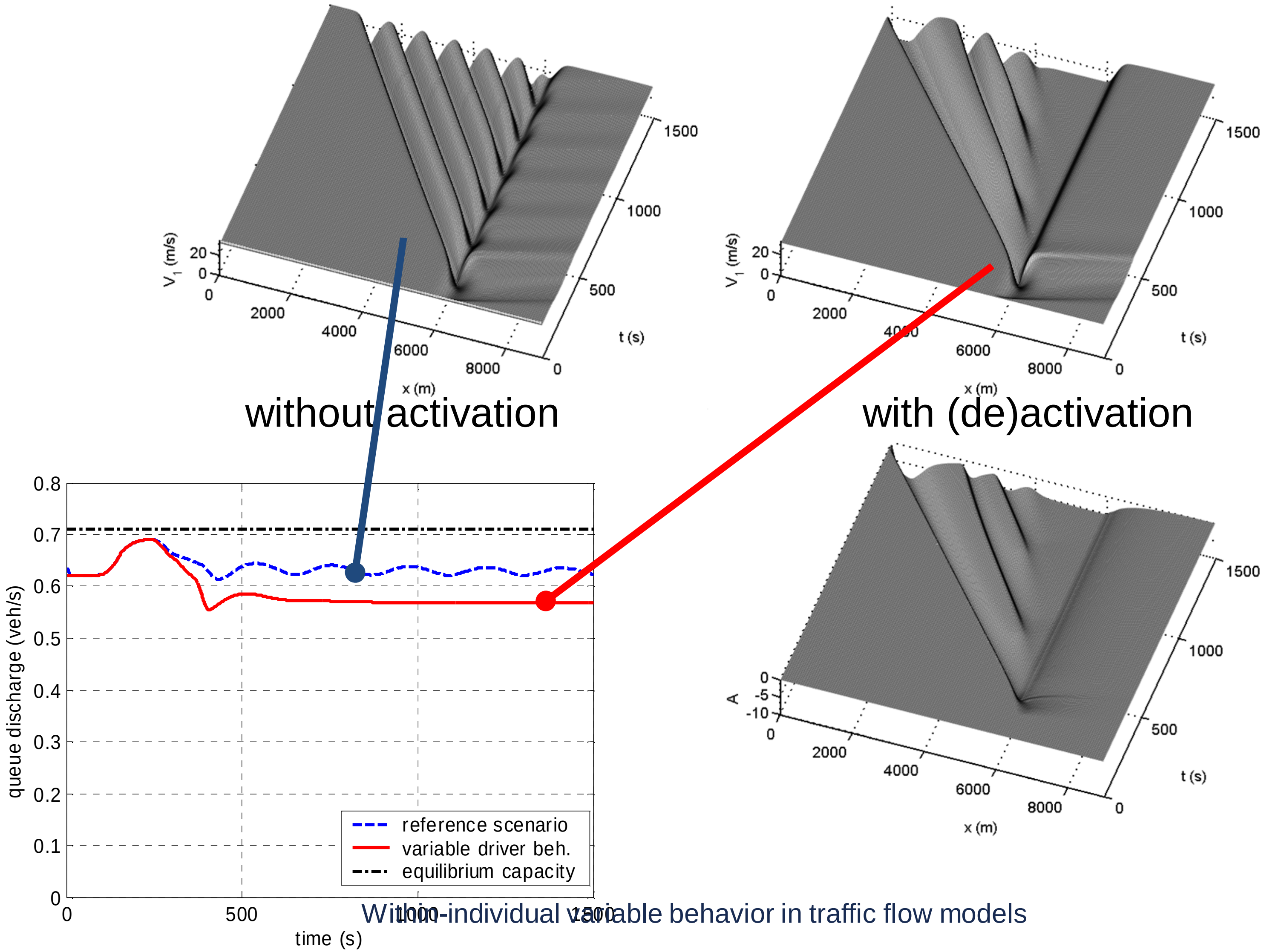


  - relaxation to normal comfortable level
- activation level influence on car-following parameters
  - lower activation compensated by longer time headway in

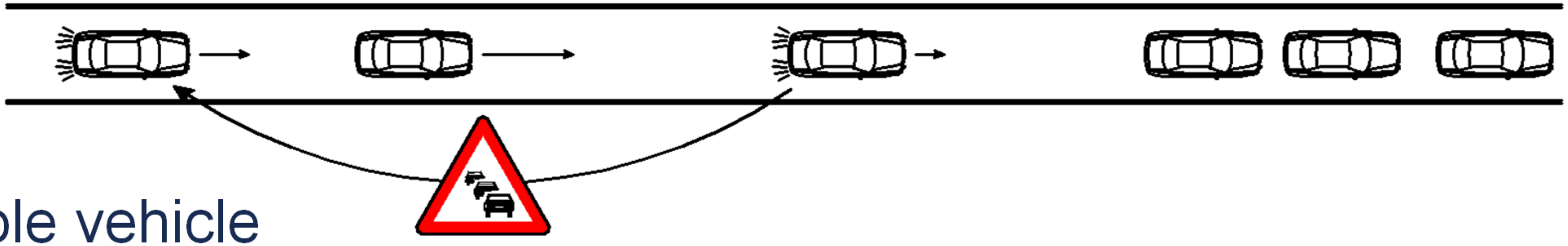
$$\dot{v}(t+T) \equiv \frac{s_j(t) - s^d_1(a)v_j(t)}{\tau_s} + \frac{v_{j-1}(t) - v_j(t)}{\tau_v}$$



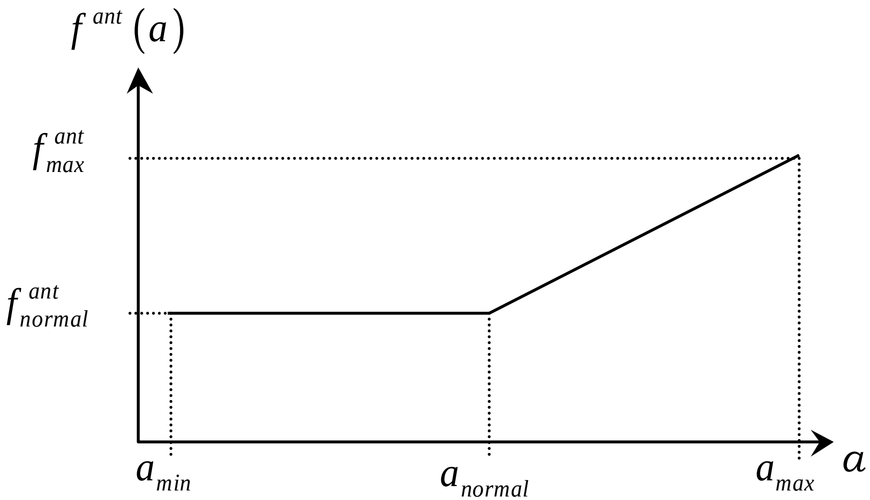
Capacity drop / hysteresis



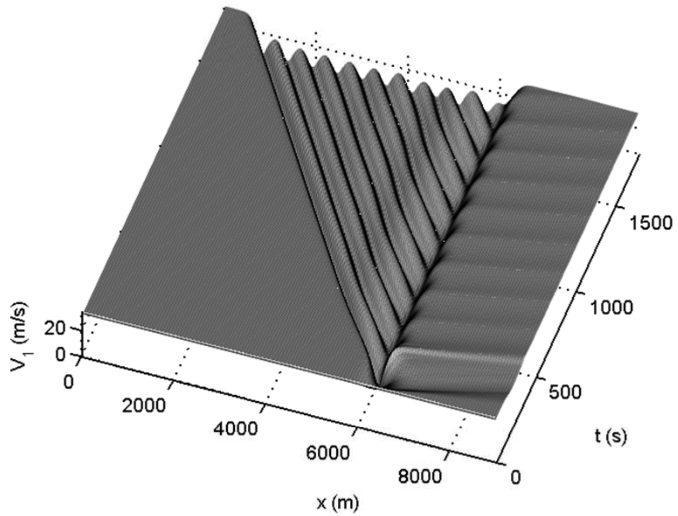
Queue-tail warning ADAS



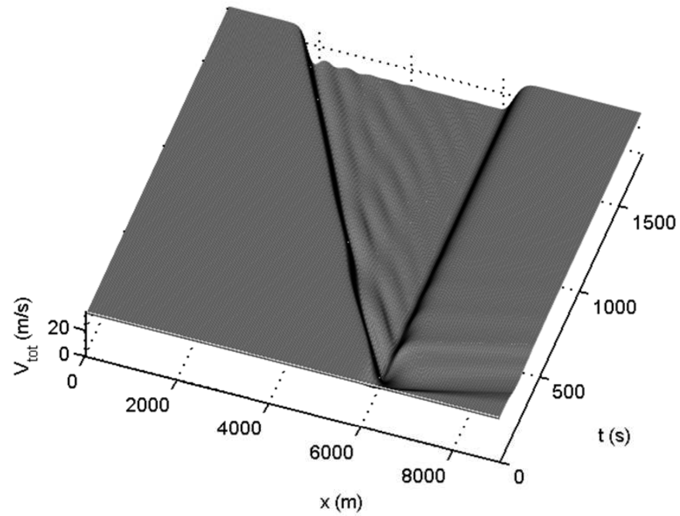
- role vehicle
  - send message upstream when sharp deceleration detected
  - present warning to driver proportional to the danger ahead
- role driver
  - be aware! increase attention level
  - do not act until necessary
  - brake earlier when perceiving speed drop ahead than without warnings



Queue-tail warning ADAS (50% equipped)

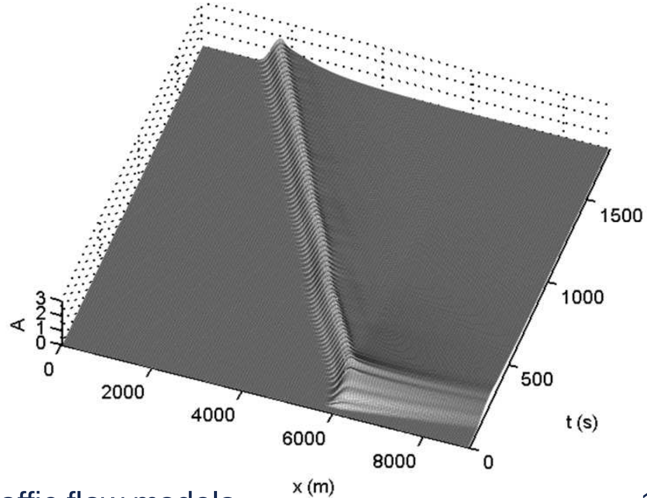


without activation



with activation

Equipment fraction	Free flow speed [m/s]	Speed in queue tail [m/s]	Length of the queue-tail [m] (approx.)	Average deceleration [m/s²]
0%	32	1	200	-2.5
25%	32	3	275	-1.8
50%	32	5	350	-1.4
100%	32	7	500	-1.0



Conclusions

- human-kinetic modeling framework
  - = macroscopic traffic flow model directly (and solely) based on flexible individual driving behavior specification
  - allows defining within-individual variable driving behavior
- specifications tested so far based purely on non-validated behavioral hypotheses
  - only plausibility on micro and macro scales considered
- relates to driving behavior research Hoogendoorn
  - within-individual variability due to external factors
  - variable speed, distance, acceleration, deceleration parameters
  - variable action points
- could/should we link both researches?

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Micro-macro link in dynamic intersection modeling

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Introduction

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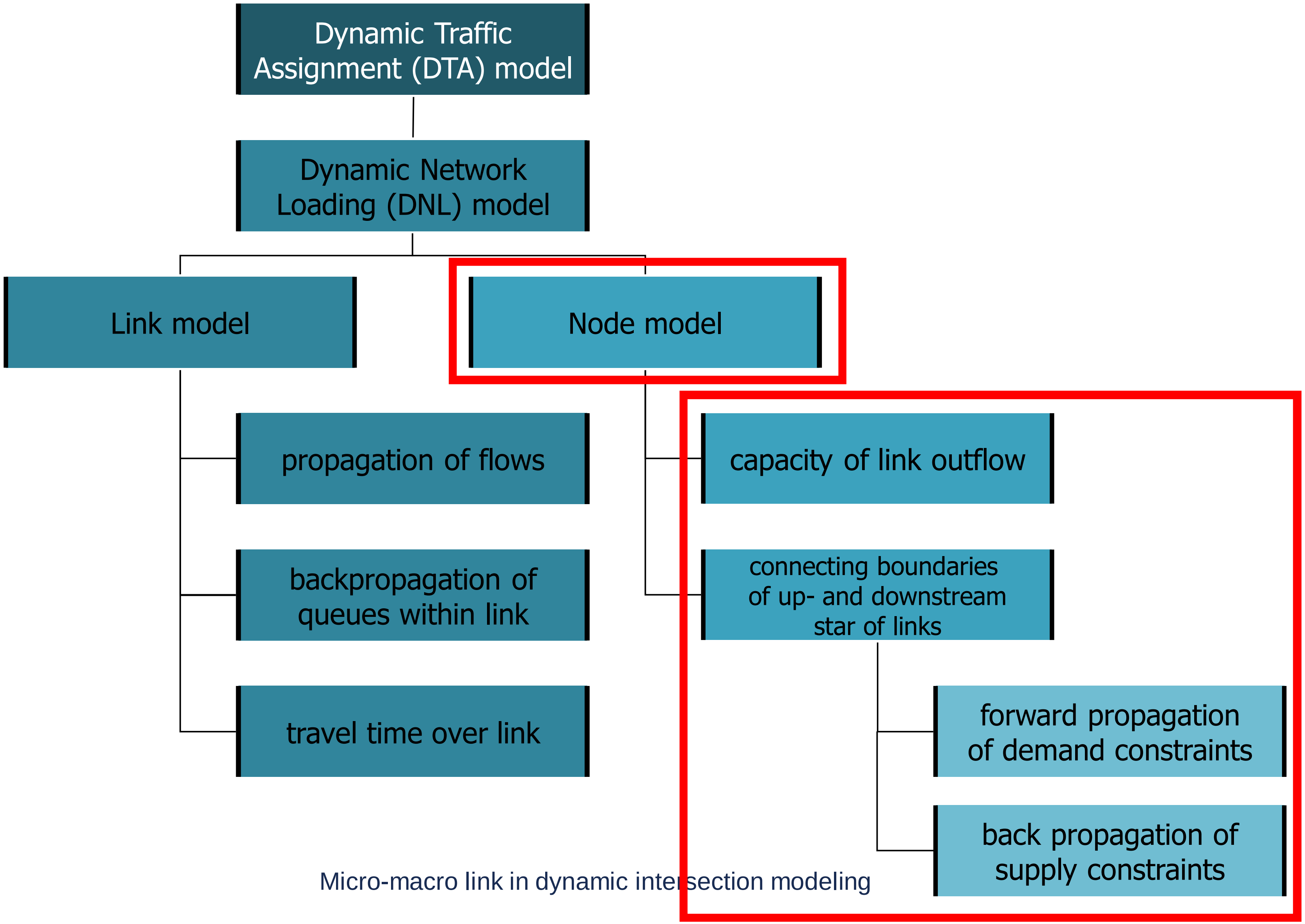
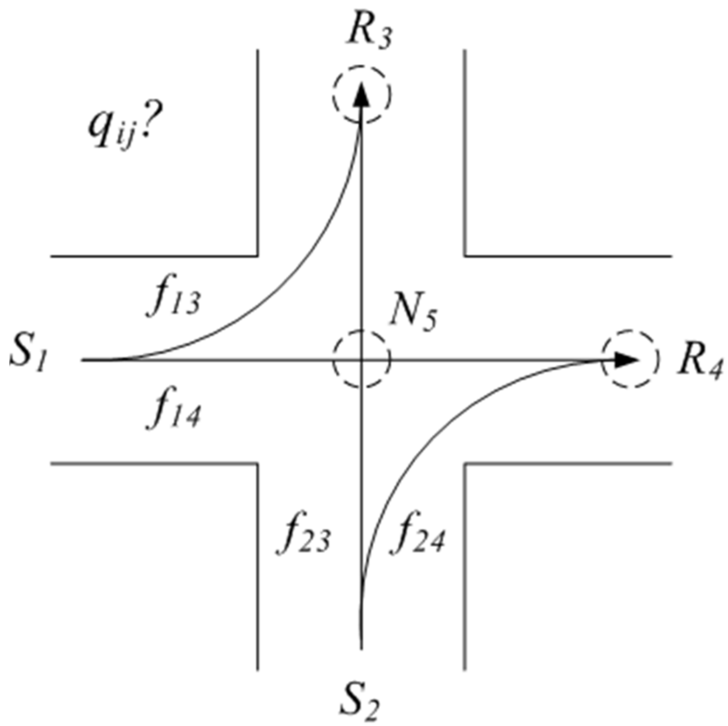
- PhD research by Ruben Corthout (May 2012)
- dynamic node models for 1st order macroscopic dynamic network loading models
- first attempt to include microscopic conflict handling in dynamic macroscopic models

Role of intersection model in DNL



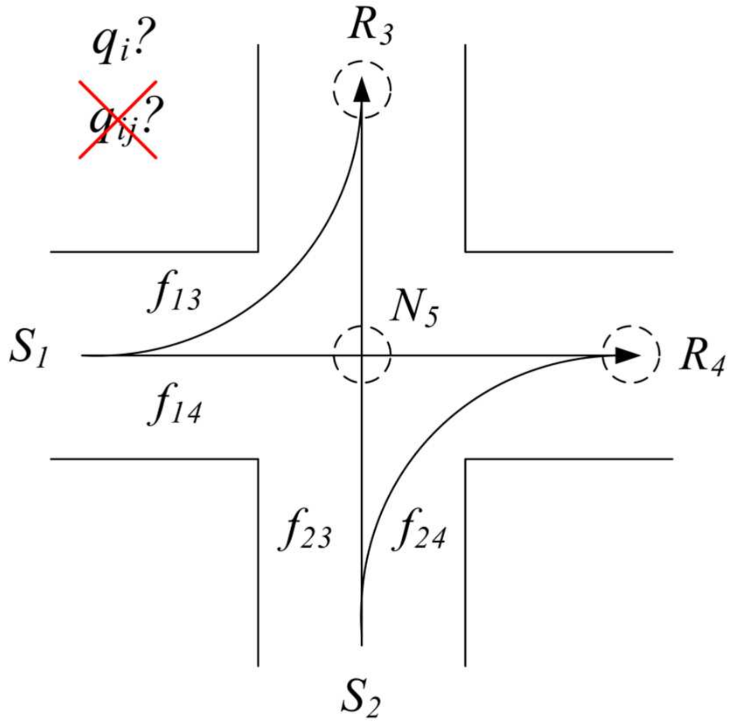
Intersection modelling:
Problem statement

- Incoming links *i* and outgoing links *j*
- Constraints:
  - Demands S_i
  - Supplies R_j
  - Internal supplies N_k
  - Turning fractions f_{ij}
- <u>Problem to be solved:</u>
  Determine flows q_{ij}
- Given flow (restrictions), delays can be determined
  (beyond scope of my research)



Intersection modelling:
Problem statement

- Incoming links *i* and outgoing links *j*
- Constraints:
  - Demands S_i
  - Supplies R_j
  - Internal supplies N_k
  - Turning fractions f_{ij}
- <u>Problem to be solved:</u>
  Determine flows $q_{ij} = f_{ij}q_i$
- Given flow (restrictions), delays can be determined (beyond scope of my research)



Intersection modelling:
Main contributions

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→ Listing seven requirements that guarantee a consistent solution and analysis of violations of existing models
  → Necessity of Supply Constraint Interaction Rules (SCIR) to govern supply distribution while ensuring compliance

→ General intersection model that satisfies these requirements (only external constraints)

- Introduction of internal supply constraints within this modelling framework, based on microscopic behavior
- Intersection models for specific intersection types

Intersection modelling:
Seven requirements

- General applicability
- Non-negativity of flows
- Conservation of vehicles
- Ensuring First-In-First-Out (FIFO) at the intersection level: Conservation of turning fractions (CTF)
- Flow q_i from a congested incoming link i ($q_i < S_i$) must be invariant to increase of demand S_i (Lebacque & Khoshyaran, 2005)
- Compliance with demand and supply constraints

$$q_i \leq S_i \qquad \forall i$$

$$\sum_i f_{ij} q_i \leq R_j \qquad \forall j$$

\+ Supply Constraint Interaction Rules (SCIR)

- Flow maximization from the users' perspective

Intersection modelling:
Supply Constraint Interaction Rules

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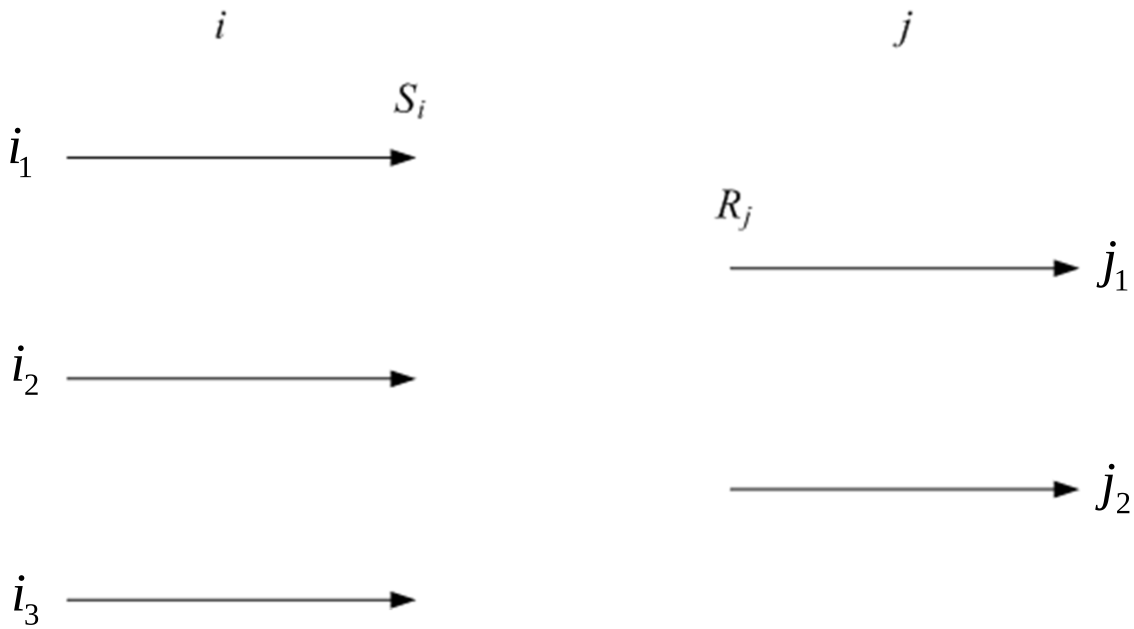
- Various flows q_i want to make use of limited supplies R_j
- SCIR describe distribution of supplies and interaction of various demand and supply constraints in that process
- Difficulty:
  - Which constraint restricts each flow depends on supply distribution
  - Supply distribution depends on which constraint restricts each flow

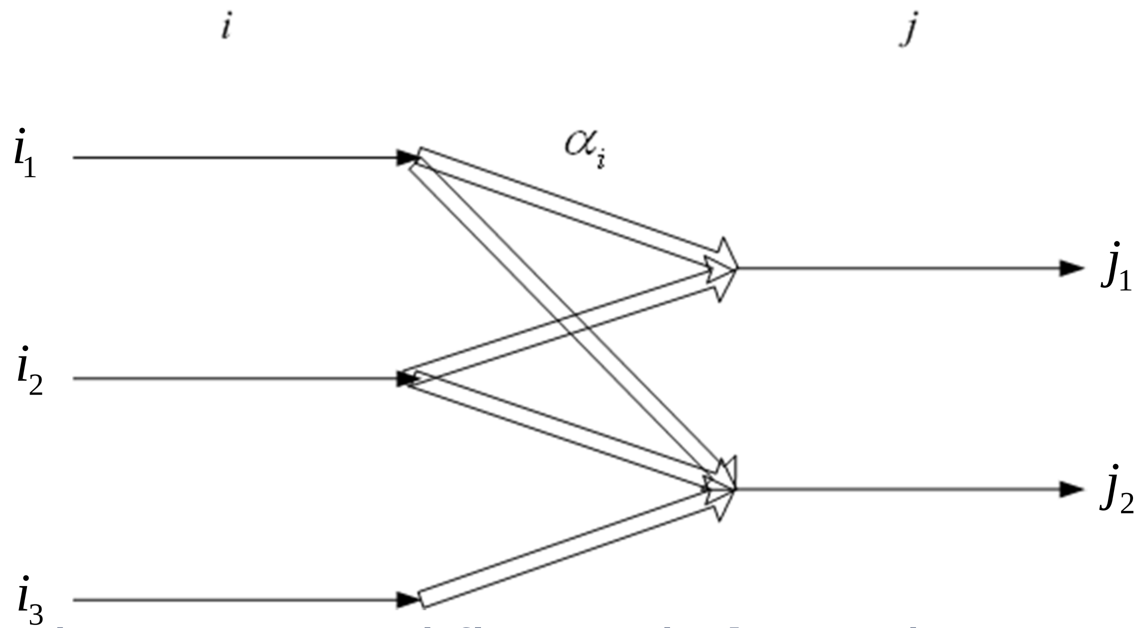
Intersection modelling:
Supply Constraint Interaction Rules

- Three incoming links *i* and two outgoing links *j*



Intersection modelling:
Supply Constraint Interaction Rules

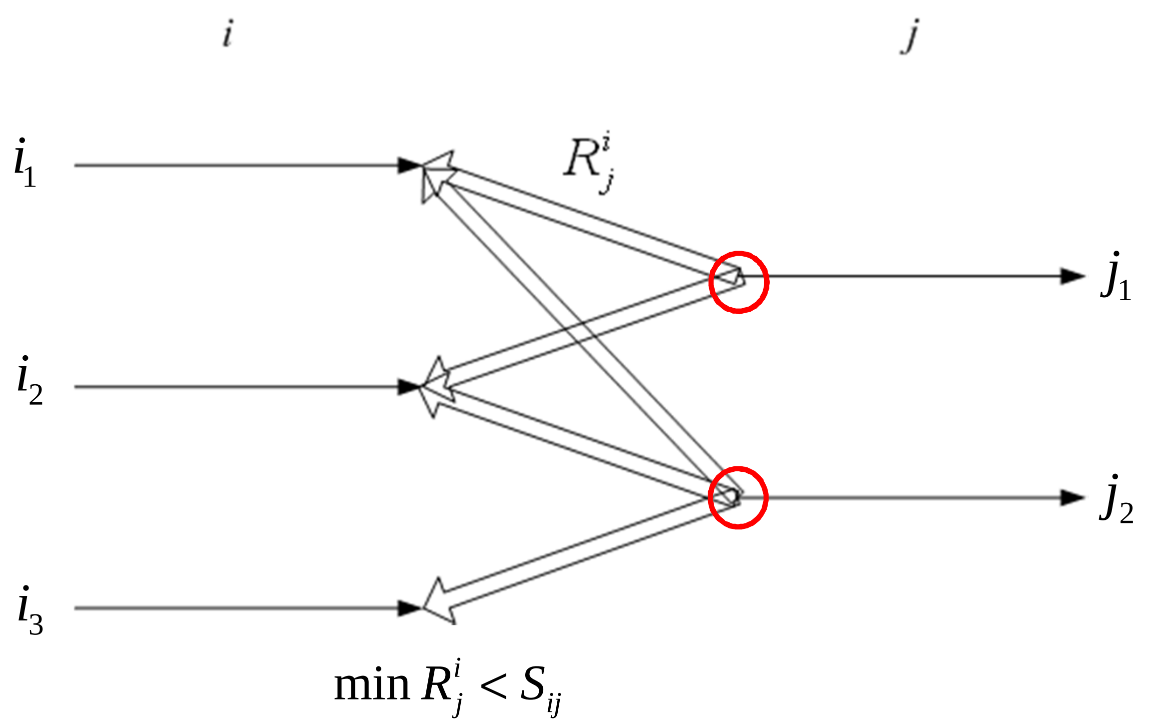
- Priority parameters α_i determine claim R_j^i in supply distribution



- Link i_3 does not send flow to j_1 → no share R_{j1} for i_3 (does not take part in conflict in j_1)

Intersection modelling:
Supply Constraint Interaction Rules

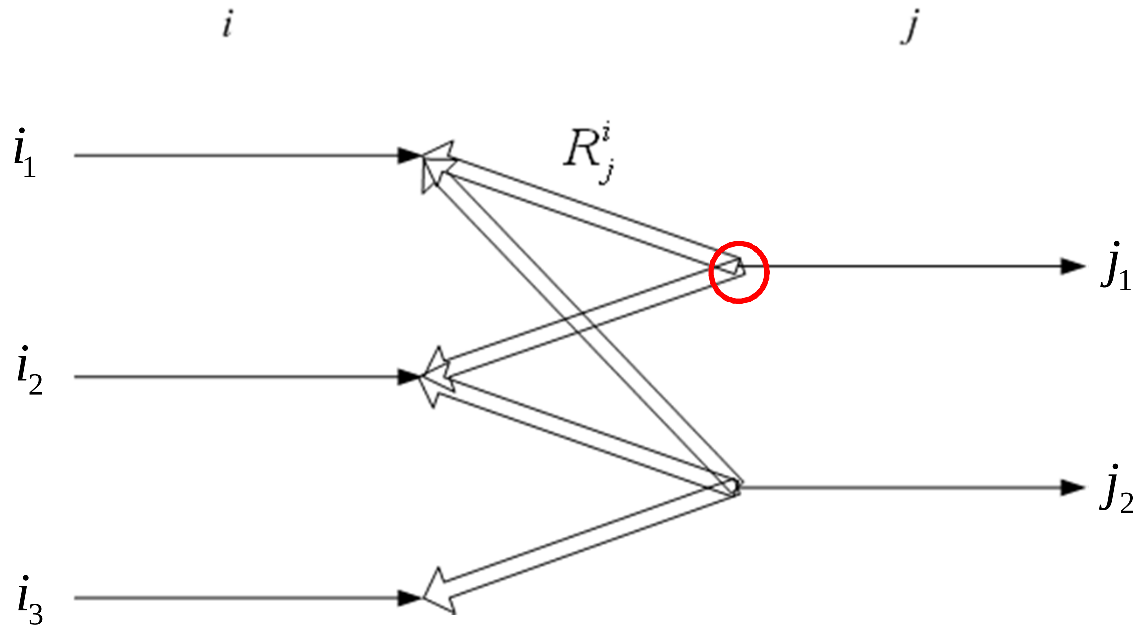
- Shares R_j^i of *j* appointed to competing *i*



- Both supplies are insufficient → Congestion on all three links?

Intersection modelling:
Supply Constraint Interaction Rules

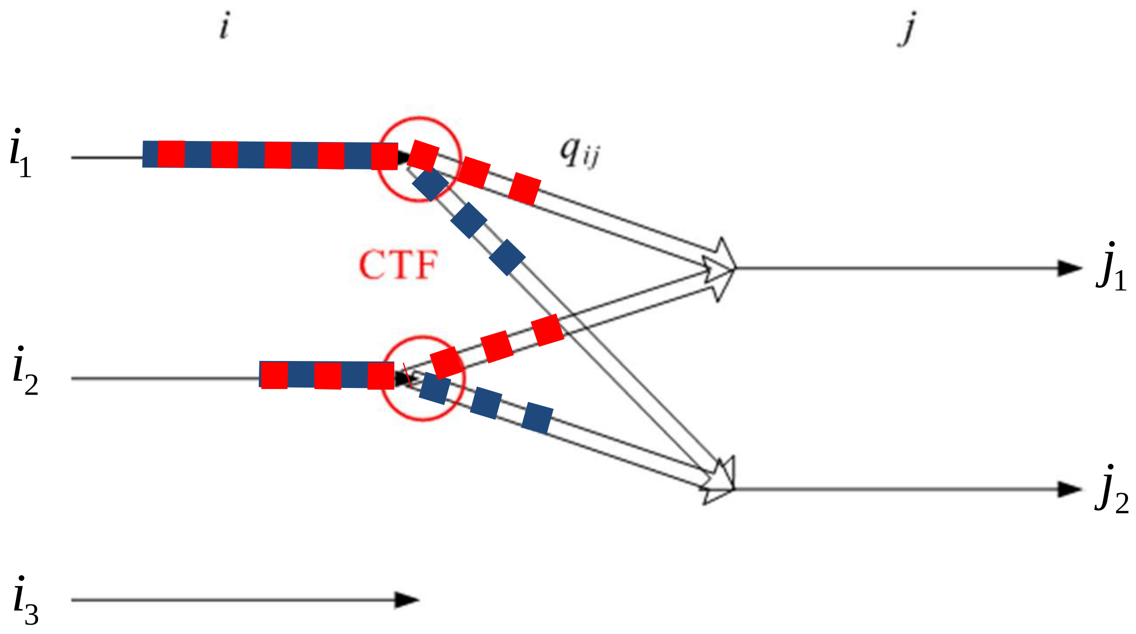
- Shares R_j^i of most restrictive *j* restrict flow from competing *i*



- Supply R_{j1} most restrictive

Kruispuntmodellering:
Distributieregels

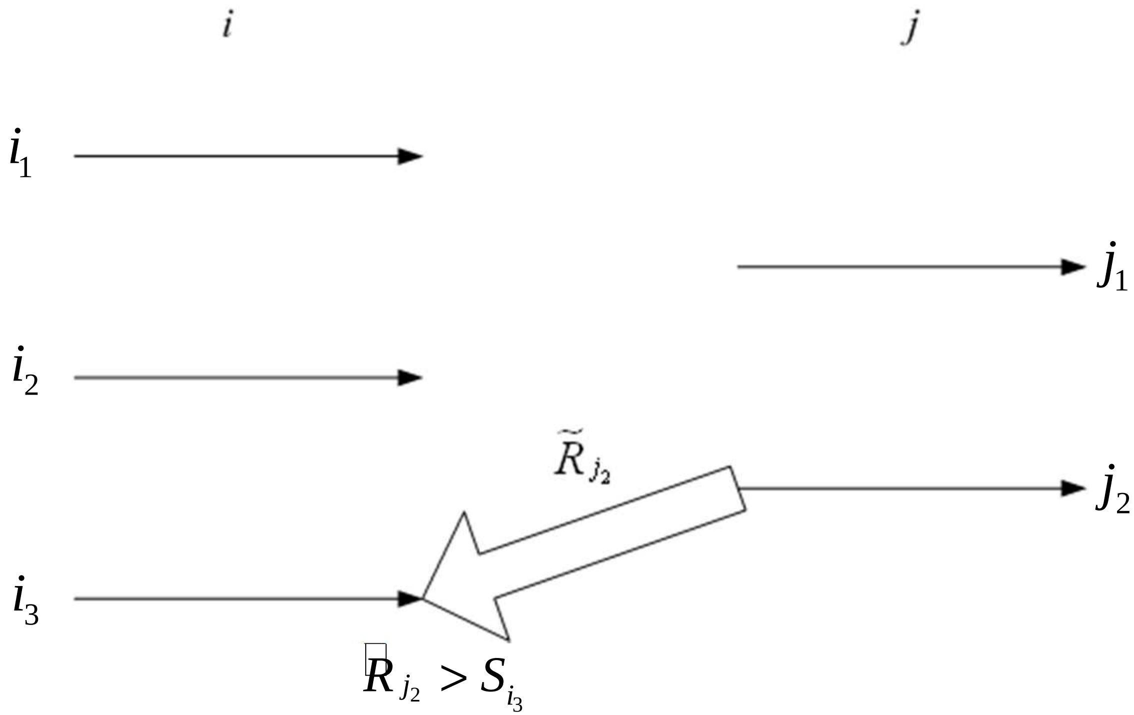
- Due to CTF, outflows are restricted equally in both directions



- Congestion on i_1 and i_2 → $q_{i1} < S_{i1}$ and $q_{i2} < S_{i2}$
- i_1 and i_2 do not fully use their rightful share of R_{j2}

Intersection modelling:
Supply Constraint Interaction Rules

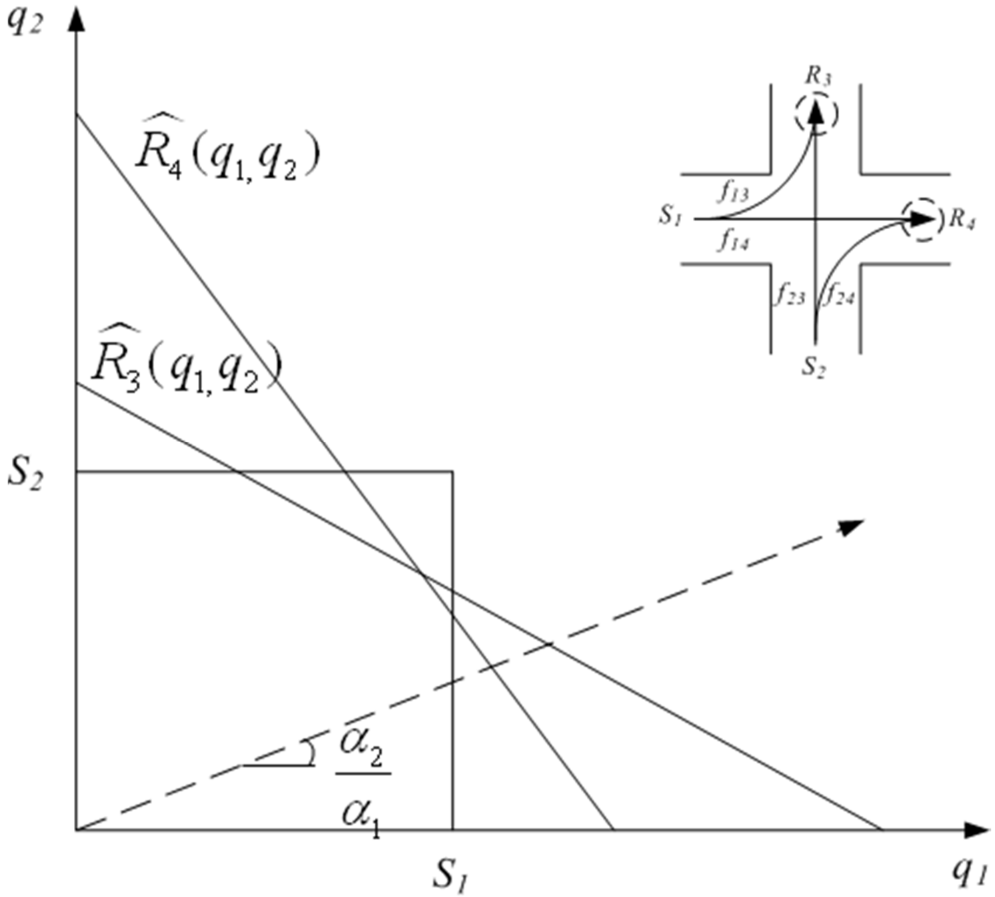
- All remaining supply $\tilde{R}_{j_2} = R_{j_2} - q_{i_1 j_2} - q_{i_2 j_2}$ must be redistributed to i_3



- Flow maximalisation from the user perspective: i_3 can send more flow since i_1 and i_2 do not use their share → $q_{i3} = S_{i3}$ (no congestion on i_3)

Intersection modelling:
General intersection model

- SCIR with distribution based on proportionality of priorities can be visualized as follows:



Intersection modelling:
Main contributions

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- ✓ Seven model requirements + SCIR
- ✓ General intersection model that satisfies these requirements (only external constraints)

“ Without internal constraints, cars could run freely through each other, a little bit as in this movie”

→Introducing internal supply constraints

→Intersection models for different types of intersections

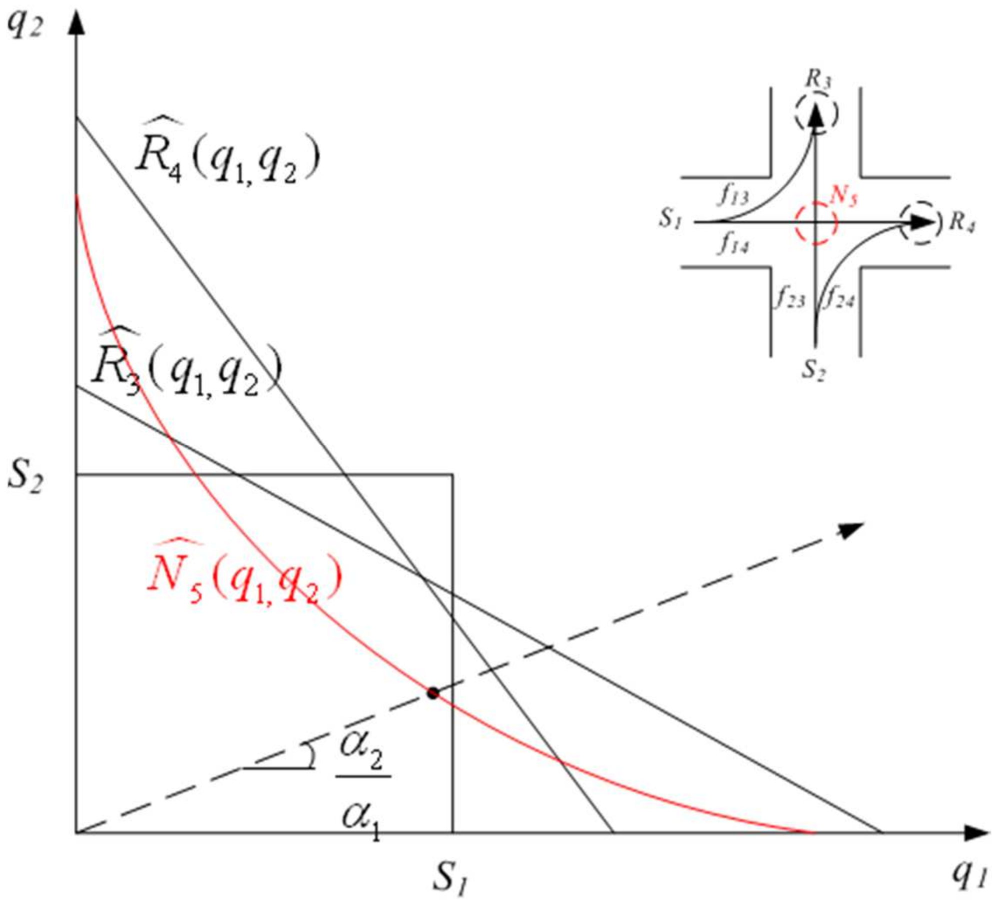
Intersection modelling:
Main contributions

- Introducing internal supply constraints
  - Because of conflicts inherent to the intersection itself (e.g. crossing flows)
  - Not present in most existing models
  - Increase realism; essential in urban networks
  - It turns out that solutions may be non-unique
  - Formulation of uniqueness condition

- Intersection models for different types of intersections
  - With internal constraints
  - Meet seven requirements
  - Guarantee a unique solution

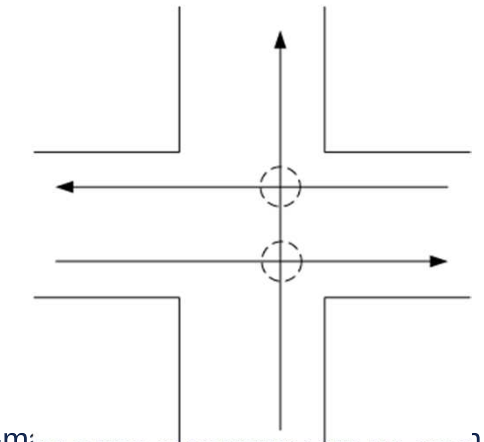
Intersection modelling:
Internal supply constraints

- Introducing additional, internal supply constraints:



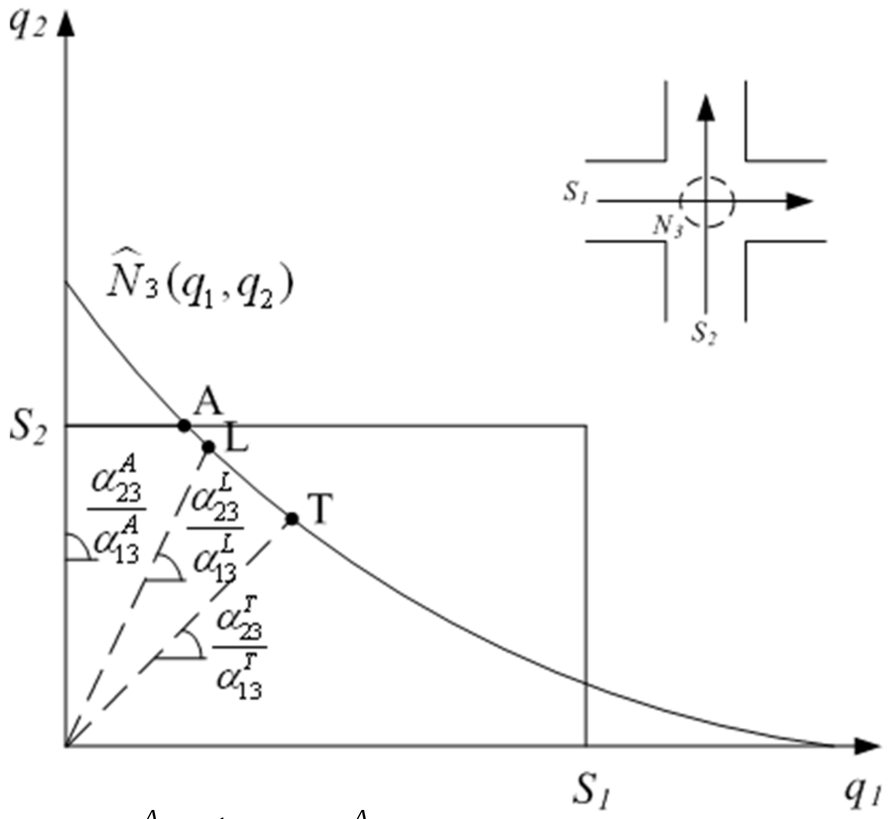
Intersection modelling:
Internal supply constraints

- Additional modelling assumptions are necessary to introduce internal supply constraints in the modelling framework:
  - Internal supply constraint functions have to be further detailed
  - Different priorities for different (internal) supplies are a more natural choice than single-valued priorities
    - e.g. priority-to-the-right



Intersection modelling:
Internal supply constraints

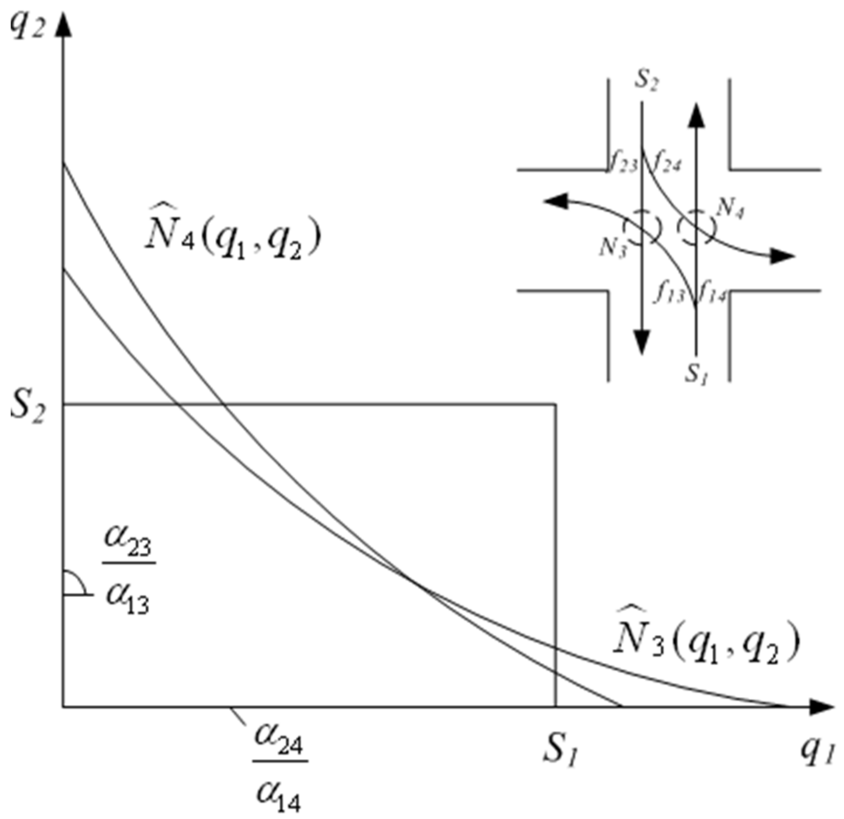
- Priority parameters are used to represent driver behaviour:



- Absolute compliance: $\alpha_{23}^A = 1 - \varepsilon;\ \alpha_{13}^A = \varepsilon$
- Limited compliance: anything in between
- Turn-taking: $\alpha_{23}^C = C_2;\ \alpha_{13}^C = C_1$

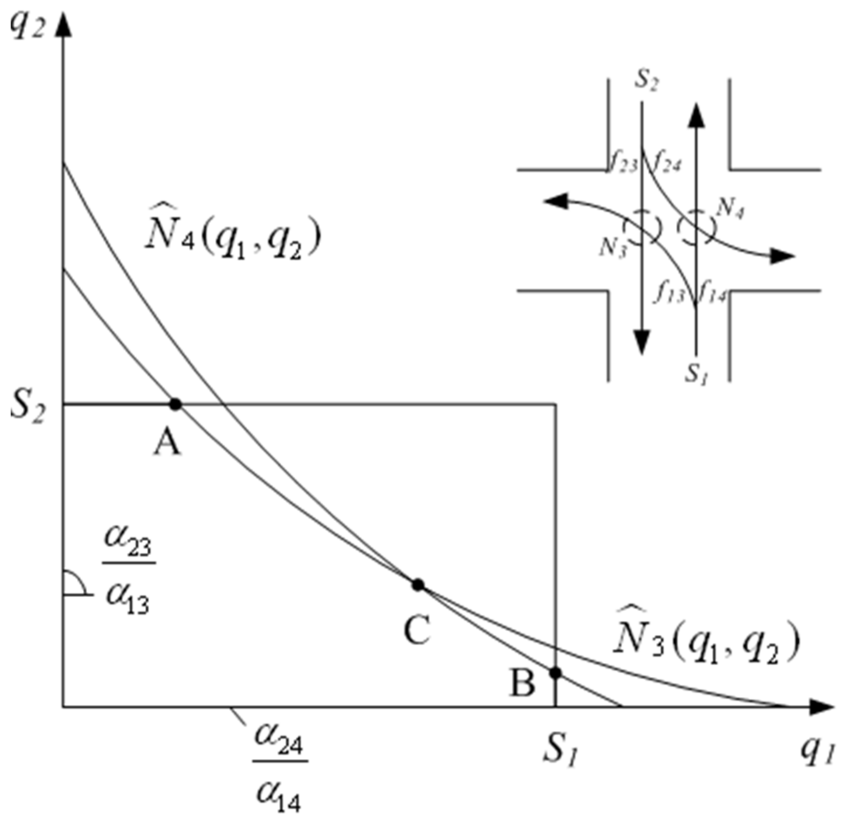
Intersection modelling:
Solution non-uniqueness

- Different priority ratios represent different priorities in the two internal conflicts: (left-turn yield to straight)



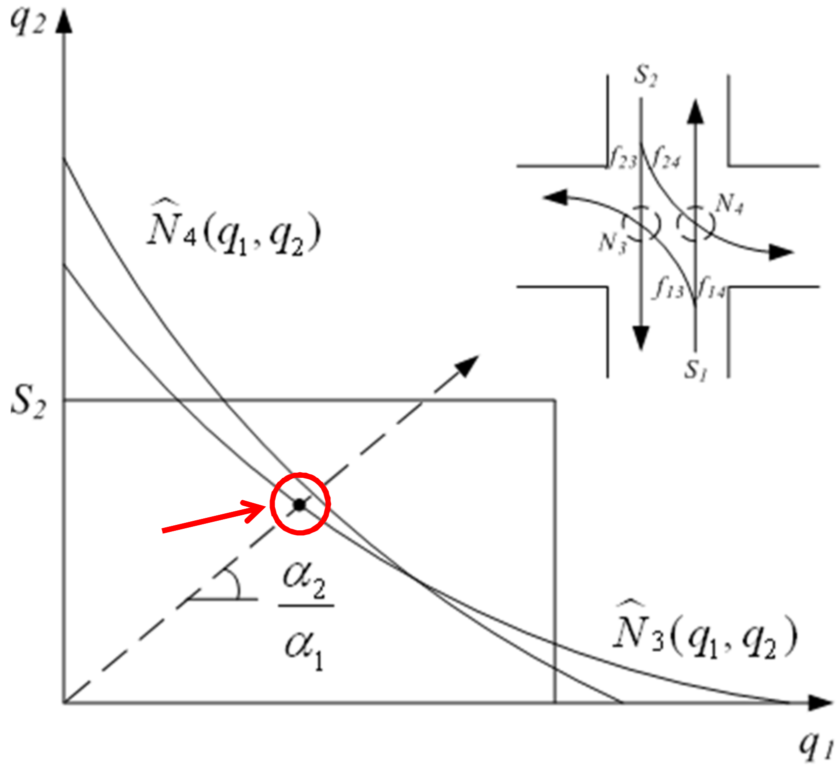
Intersection modelling:
Solution non-uniqueness

- With realistic behavioural assumptions regarding priority sharing, multiple solutions may occur:



Intersection modelling:
Solution non-uniqueness

- Uniqueness requires the same priority ratio between any two incoming links for all supplies:



- Universal uniqueness condition

Intersection modelling:
Solution non-uniqueness

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- Contradiction:
  - Non-unique solutions result from realistic assumptions
- Why do we need a unique solution?
  - → DNL models in which intersection model is embedded cannot deal with non-unique flows
- Pragmatic approach to guarantee unique solution while accounting (to some extent) for different priorities:
  - Different priorities α_{ij} and α_{ik} are defined per conflict
  - Weights w_{ij} and w_{ik} combine α_{ij} and α_{ik} into one representative α_i

$$\alpha_i = \sum_j w_{ij}\alpha_{ij} + \sum_k w_{ik}\alpha_{ik} \quad \forall i$$

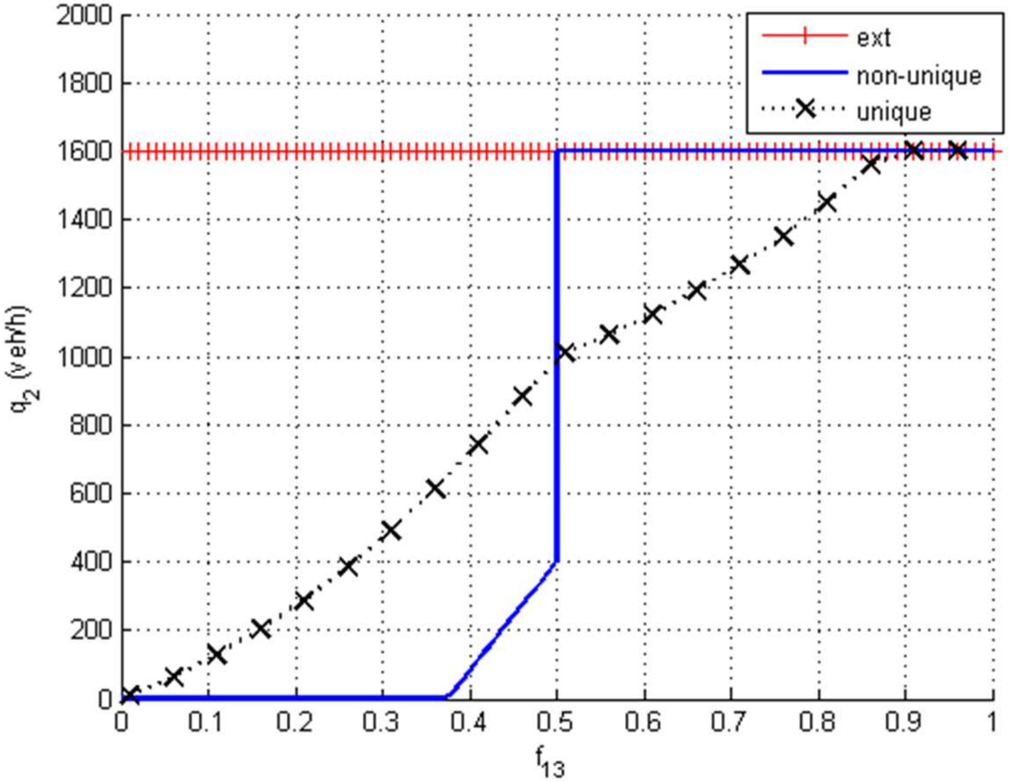
  - $w = f(C, f_{ij})$

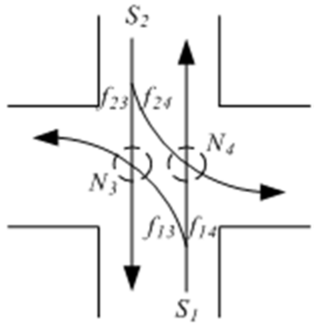
Intersection modelling:
Specific intersection models

- The presented approach is followed to compose intersection models for specific intersection types:
  - All-Way-Stop-Controlled (AWSC), Priority-To-The-Right (PTTR), roundabout, priority-controlled and signalized
  - Internal supply constraint functions based on conflict theory (Brilon & Wu, 2001)
  - Compliant with all seven fundamental modelling requirements
  - Guaranteeing a unique solution

Intersection modelling:
Specific intersection models

- $f_{23} = f_{24} = 0.5$; f_{13}: $0 \rightarrow 1$





Kruispuntmodellering:
Specificieke kruispuntmodellen

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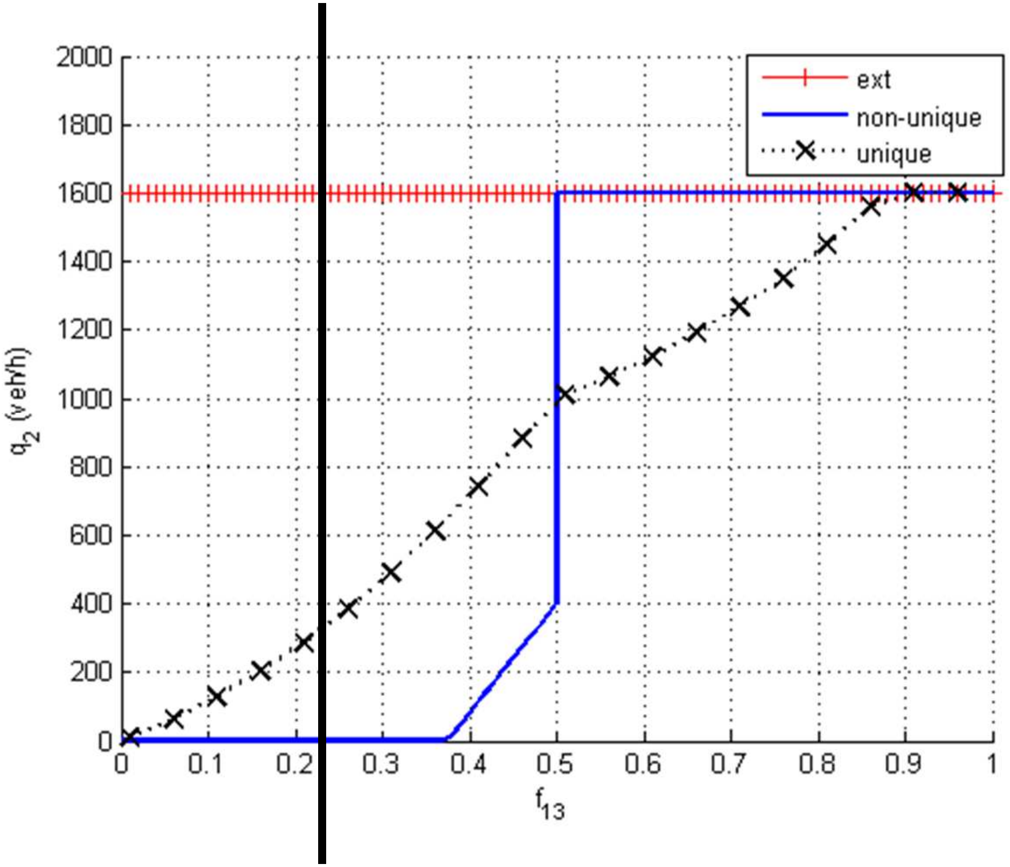

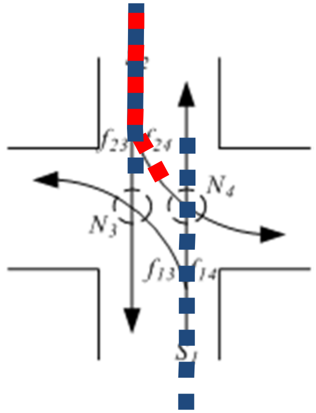

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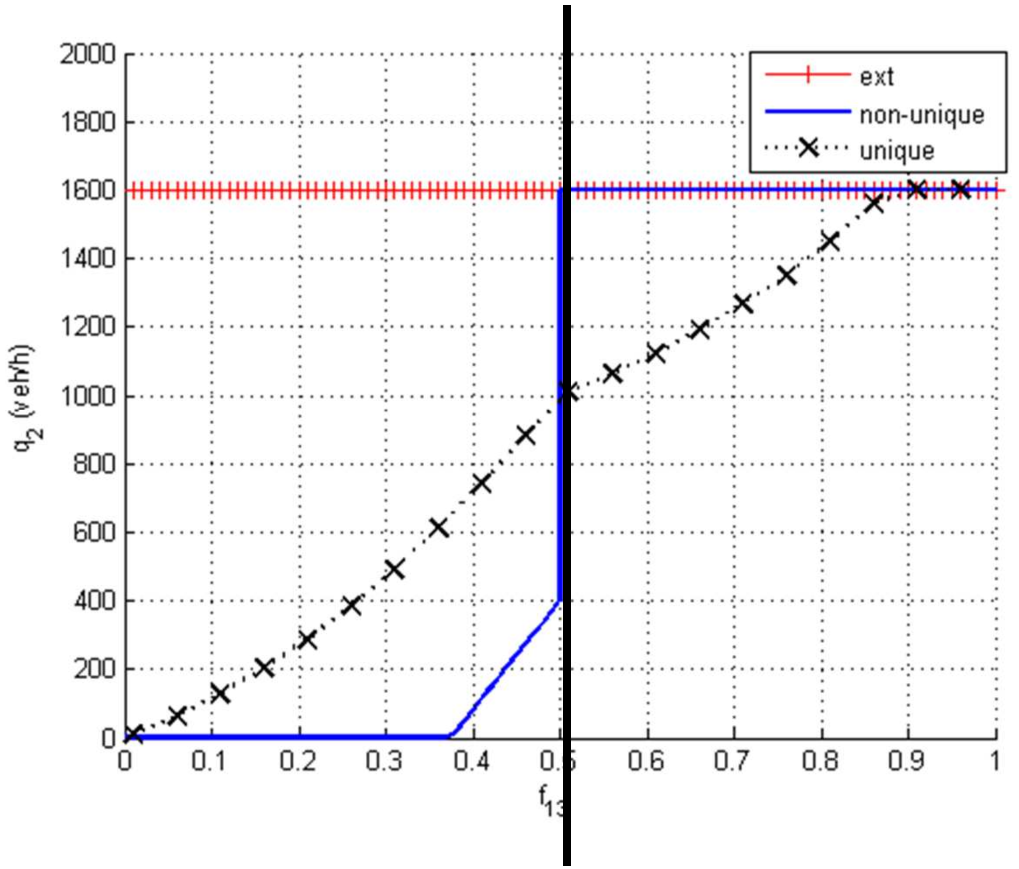

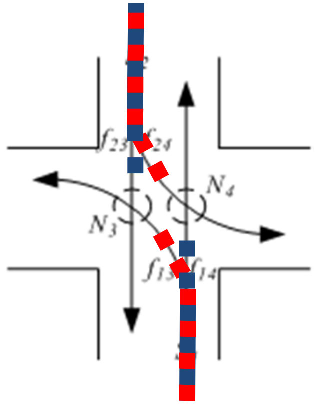

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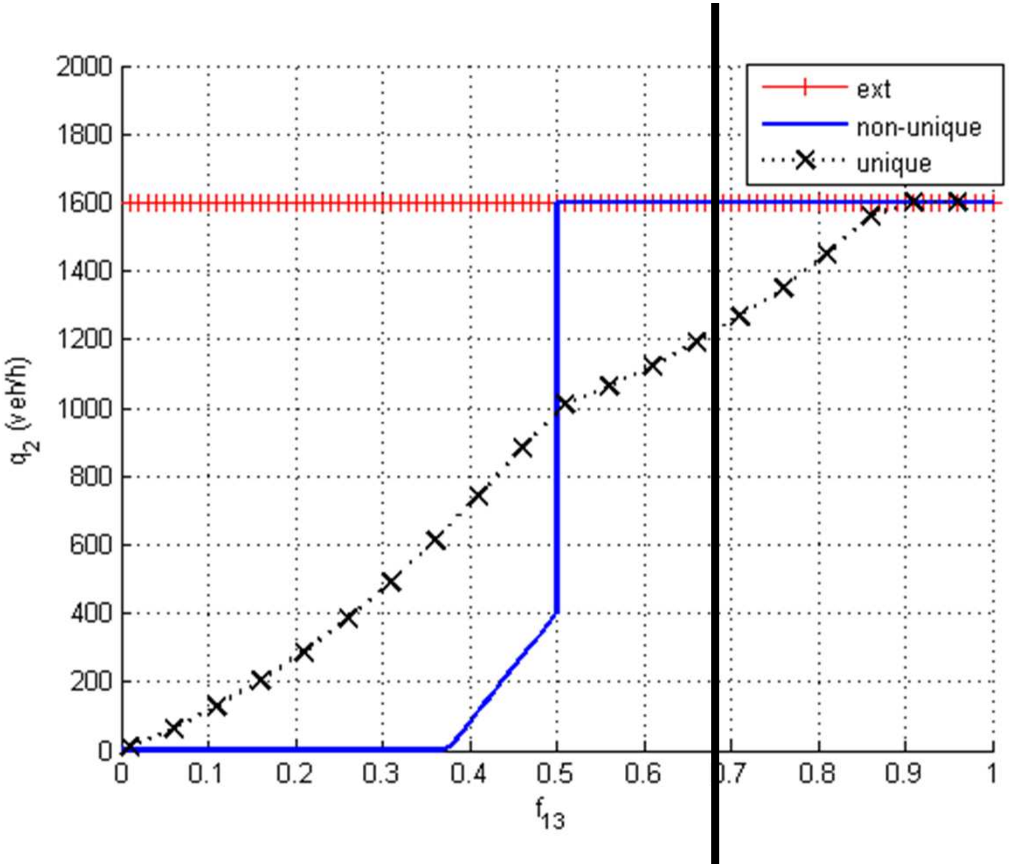

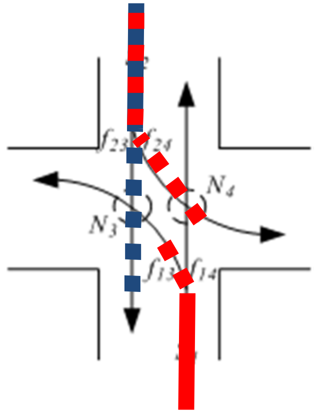

Intersection modelling:
Main conclusions

- Internal supply constraints
  - based on microscopic conflict handling and space requirements
  - Identification solution non-uniqueness
  - A uniqueness condition is found
  - Specific intersection models are developed

→ Important advance for the theoretical knowledge and the practical applicability of the intersection model

- Future research:
  - Validation of proposed models with real data (MsC thesis KUL - Delft
  - Is a paradigm shift in DNL possible to allow for non-unique solutions?