Towards Fair and Efficient Traffic Flow Coordination Mechanisms for 2+1 Roadways

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Motivation – 2+1 Roadways

- Alternating lane segments with one or two lanes per direction
  - Increase safety of overtaking manoeuvres
  - Compromise: +40% capacity with one additional lane
- *2+1 systems* mandatory in Germany for newly constructed urban roadways
- Existing roadways to be extended during normal maintenance phases

  [Arbeitsgruppe Straßenentwurf, 2013, BASt, 2013]

B 54 near Steinfurt
(picture: public domain)

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Motivation – Managed Lanes

Example: Managed HOT lane on Interstate 15 with variable pricing
(picture: Chevy111, CC BY-SA 4.0, cropped)

High-occupancy vehicle (HOV)/high-occupancy toll (HOT) lanes

- Access based on dynamic rules, e.g. fixed or dynamic congestion pricing [de Palma and Lindsey, 2011, Rouhani, 2016]

Assumptions – Autonomous Vehicles and Smart Infrastructure

We envision a (near) future scenario comprising

- Autonomous vehicles
  - Automated Driving Systems (ADS) commonly available
  - Classified as level 3 and above [SAE International, 2016] ($\Rightarrow$ autonomous overtaking and lane changing manoeuvres)
  - Drivers provide individual preferences, e.g.
    - desired speed
    - acceptable time loss
- Communication infrastructure on HOV/HOT lanes
  - 4G and upcoming 5G/G5 networking technology
  - Real-time traffic observation

System vs. User Level Optimisation

System Level: Traffic Management

- Goals: Optimise efficiency on 2+1 roadways and HOT/HOV lanes
  - minimise travel time losses, maximise traffic flow, reduce congestions
- Mechanisms: Change rules dependent on situations
  - e.g. denying access to overtaking lane for slow vehicles.
- But: Consider fairness!

User Level: Drivers

- Minimise dissatisfaction, quantifiable by travel time loss
  - but individual preferences (time pressure / relaxed driving) also relevant
- Acceptable time loss depending on time pressure

Research Goals

- Identify potentials of optimising the *2+1 system* by means of coordination
  - Minimisation of *unfairness*, *inefficiency* and *dissatisfaction*

- Considered input-orderings of vehicles by *desired speeds* of drivers

  1. best-case: already optimal ordering of vehicles
  2. random-case: arbitrary ordering of vehicles
  3. worst-case: ascending ordering of vehicles

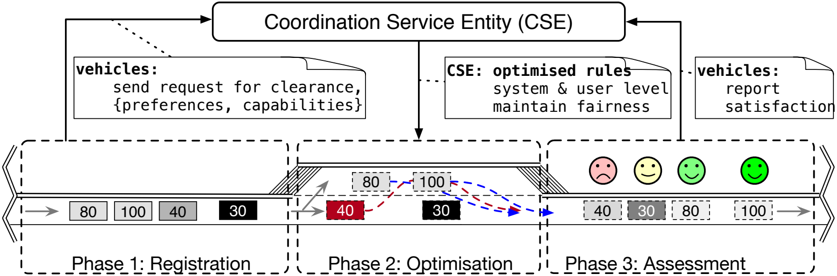
State of the Art and Related Work

- 2+1 Roadways
  - [Irzik, 2010a, Irzik, 2010b]
- Coordination and management of vehicles on a microscopic level
  - Autonomous Intersection Management (AIM) platform [Dresner and Stone, 2004, Dresner and Stone, 2005, Dresner and Stone, 2008]
    - Policies for linked intersections [Hausknecht et al., 2011a]
    - Extension Semi-AIM: More efficient *intersection management* [Au et al., 2015]
  - High level of compliance to policies on managed lanes (MLs) with only painted barriers, i.e. obeying the rules implemented by a coordination service entity (CSE) [Halvorson and Buckeye, 2006]
  - Coordination mechanism for handling varying demand (e.g. commuter traffic) by employing a *dynamic lane reversal* for maximising throughput [Hausknecht et al., 2011b]
- Driver preferences
  - [Ringhand and Vollrath, 2017] investigated driver preferences for route choices and analysed acceptance threshold regarding travel time loss

Design Decisions – Coordination Service Entity (CSE)

Vision: CSEs, governing 2+1 roadway segments, for

- receiving access requests
- granting access to the overtaking lane based on rules
- observing traffic flow, driver satisfaction, coordination efficiency and fairness



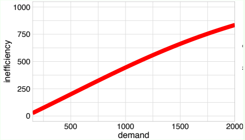
Model – Basic Definitions

1. Inefficiency
2. Dissatisfaction
3. Unfairness

Model – Inefficiency

Inefficiency derived from relative time loss and scenario parameters

$$\left.\begin{array}{r}\text{relative time loss}\\ \text{scenario parameters}\end{array}\right\} \Rightarrow \sum_{Vehicles} \Rightarrow$$



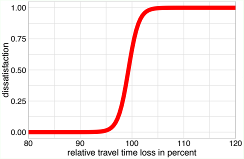
- *Relative time loss*: normalised by optimal travel time $\Rightarrow$ comparability

Model – Dissatisfaction I

- We designed our dissatisfaction model related to [Ringhand and Vollrath, 2017]
  - sigmoid function and threshold when satisfaction turns into dissatisfaction

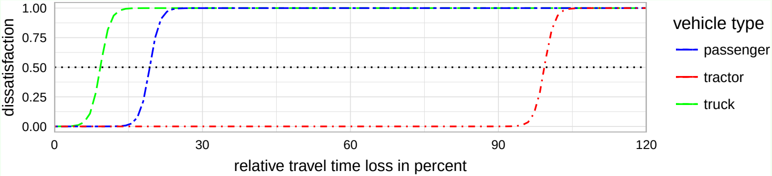
Dissatisfaction derived from relative time loss and time loss threshold

$$\left.\begin{array}{r} \text{relative time loss } \triangle \\ \text{time loss threshold } \clubsuit \\ \text{optimal travel time } \spadesuit \\ \text{smoothing factor } \rho \end{array}\right\} \Rightarrow \text{sigmoid function: } \frac{1}{1+e^{(-\triangle+\clubsuit\cdot\spadesuit)\cdot\rho}} \Rightarrow$$



Model – Dissatisfaction II

Dissatisfaction parametrisation



- Time loss thresholds
  - passenger vehicles: 0.2 [Ringhand and Vollrath, 2017]
  - trucks: 0.1
  - tractors: 1.0
- Optimal travel time: $\frac{length(r)}{v^{max}(a)}$
- Relative time loss: $\frac{TT^{act}(a,r)-TT^{opt}(a,r)}{TT^{opt}(a,r)}$
- Smoothing: $\rho = 0.5$

Model – Unfairness

Interquartile range (IQR)[1] as a general indicator of *unfairness* in the system

Unfairness derived from inter-quartile distance of relative time losses

relative time-losses of vehicles $\Rightarrow$ *IQR* (H-Spread[1]) $\Rightarrow$

$$\begin{array}{ccccccc} 26 & & & 40 & & & 54 \\ & 34 & 36 & & 41 & 46 & \\ & & \underbrace{36 \quad\quad\quad\quad 42}_{} & & & & \end{array}$$

$$\text{unfairness} = |36 - 42| = 6$$

- Domain independent
- Can be applied independently from the underlying system/scenario
  - $\Rightarrow$ Robustness against unfair configurations
- IQR ≈ 0: Fair system, i.e. no particularly (dis)advantaged drivers
- IQR > 0: Certain drivers are (dis)advantaged

[1] H-Spread see [Weisstein, 2017]

Research Questions I

Hypotheses

H.1 *Best-case* ordering yields close to optimal results.

H.2 *Random-* and *worst-case* ordering negatively affects optimisation dimensions with rising demand.

Research Questions II

Research Questions

RQ.1 Can optimisation potentials from traffic management and drivers' perspectives be identified, i.e. at what traffic service levels it is sensible to apply optimisations?

RQ.2 Can an estimation be given on how much improvement could theoretically be achieved?

RQ.3 Does the *ordering of vehicles* by their maximum driving speed play an important role regarding room for optimisation?

Evaluation – Experimental Study Setup

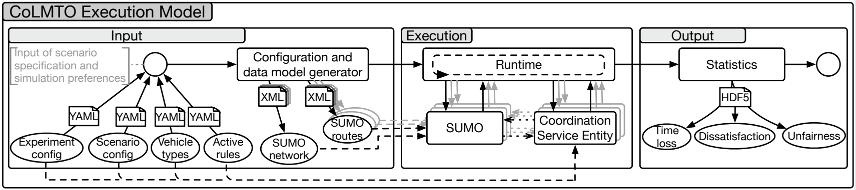
- *B 210*: 2+1 roadway with parameters as in [Irzik, 2010b, p. 167]

length	switches	speed limit	vehicles/lane/hour
6800 m	4	100 km/h	$514.\overline{6}$

- Consistent driver model: sigmoid with 20% threshold for passengers [Ringhand and Vollrath, 2017]
- Vehicle type distribution:
  - 80% passenger vehicles
  - 15% trucks
  - 5% tractors
- Tested demand of 200 to 2000 vehicles/lane/hour in steps of 150
  - covering service level classification A to E [TDM Encyclopedia, 2017]

Evaluation – Simulation of 2+1 Roadways with SUMO

1. Modelled scenario with Simulation of Urban MObility (SUMO)
2. Implemented our models and a runtime with Python to
   - Receive vehicle information
   - Compute current *dissatisfaction*, *fairness* and *efficiency*
   - Write/update vehicle information
3. Connected our runtime with SUMO via Traffic Control Interface (TraCI)



Cooperative Lane Management and Traffic flow Optimisation (CoLMTO)

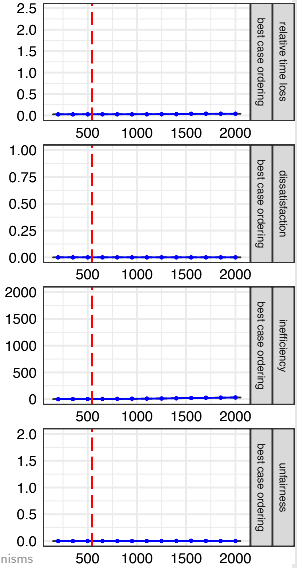
Discussion of Results – Hypothesis H.1

Passenger vehicles are the main beneficiary in our scenarios and comprise the major share (80%) ⇒ focus of discussion

Hypothesis (H.1)

Best-case ordering yields close to optimal results.

⇒ Potentials are slim and not worthy of further consideration, **supported by results** for the best case ordering of vehicles.



Discussion of Results – Hypothesis H.2

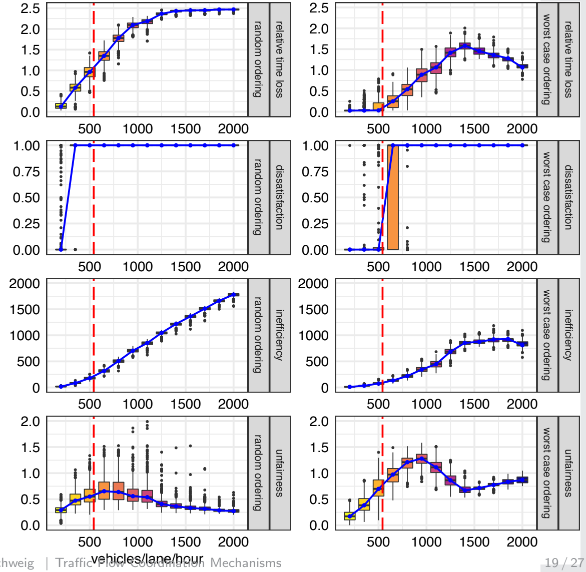
Hypothesis (H.2)

Random- and *worst-case* ordering of vehicles negatively affects optimisation dimensions with rising demand.

⇒ supported by results.

Observations

- Peaks with declining slopes
- Decline *after peak* (*peak*•):
  - – attributed to vehicles avoiding overtaking lane
  - ⇒ less friction induced by lane changes
- Local minimum after peak: *min*(*peak*•)

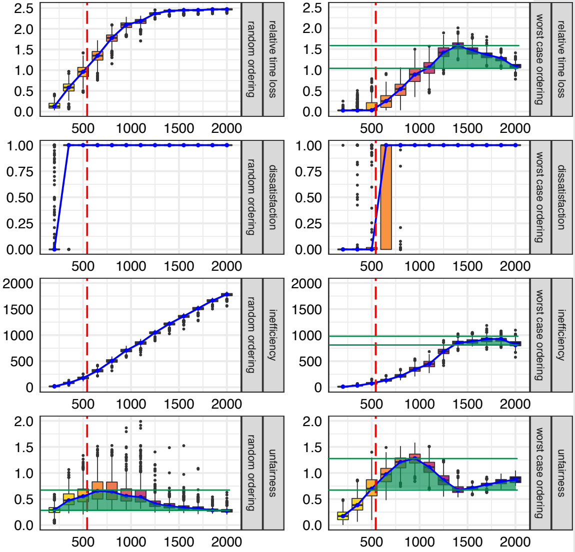


Discussion of Results – Research Question RQ.1

Research Question RQ.1

Can optimisation potentials from traffic management and drivers' perspectives be identified, i.e. at what traffic service levels it is sensible to apply optimisations?

- Potentials to reduce *relative time loss* and *unfairness*
  - $\Rightarrow$ indirectly *dissatisfaction* and *inefficiency*
- Optimise where $X(demand) \geq \min(peak\bullet)$

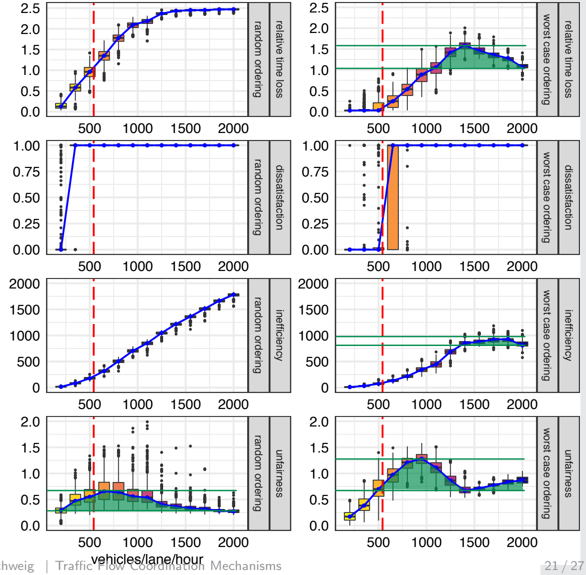


Discussion of Results – Research Question RQ.2

Research Question RQ.2

Can an estimation be given on how much improvement could theoretically be achieved?

- Estimated improvement $\approx |peak - \min(peak\bullet)|$

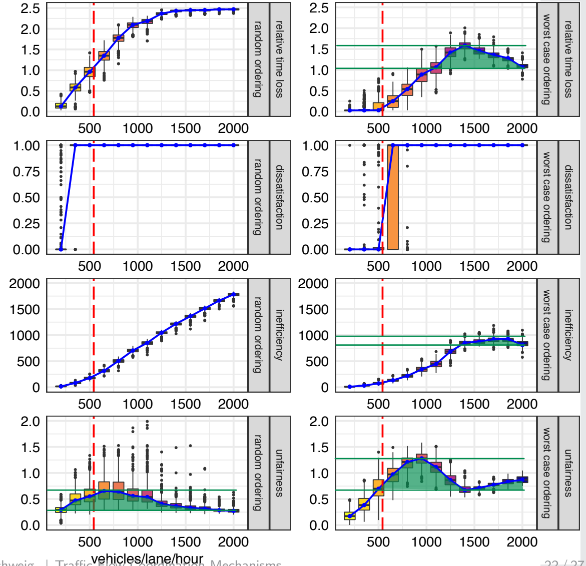


Discussion of Results – Research Question RQ.3

Research Question RQ.3

Does the *ordering of vehicles* by their maximum driving speed play an important role regarding room for optimisation?

- Worst case ordering more sensitive to losses due to lane-change friction
  - shows distinct min(*peak*•) compared to random case



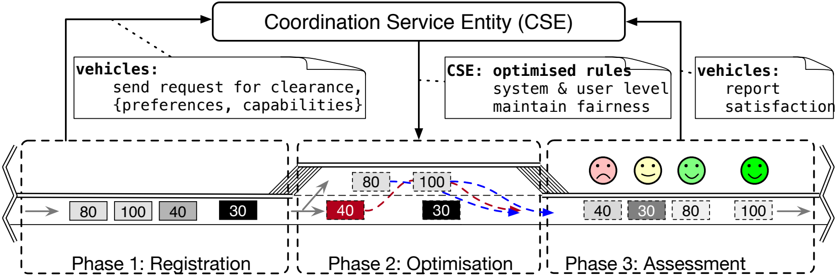
Conclusion and Outlook

- We modelled the combination of driver preferences and optimisation goals of managed lanes
- We conducted a pre-study on simulated 2+1 manoeuvres by using our own framework with SUMO to estimate optimisation potentials of coordination
- We identified potentials to reduce driver dissatisfaction while maintaining fairness
  - policy-based fine-tuning is necessary to avoid imbalances between optimisation goals

Future Work

- Baseline for further studies to enhance the effectiveness of chosen rules
- Integrate a fine-grained control for accessing managed lanes based on policies attractive to drivers and effective coordination mechanisms for a cooperative traffic management

Thank You For Your Attention



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