Macroscopic Traffic Control Using Connected Autonomous Vehicle Platoons

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Congestion

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Congestion

- Wasted time
- Air pollution
- Traffic accidents

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Congestion

- Wasted time
- Air pollution
- Traffic accidents

- "Traffic jams and traffic accidents should be a thing of the past. Platooning is a part of the solution"

Prof. Twan Basten, 28.10.2019.

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(Heavy-duty) vehicle platooning

- *A unit of vehicles driving together with short headways*
- Reduced air drag and fuel consumption, less space on the road taken, fewer drivers required
- Control within a platoon *- largely solved*

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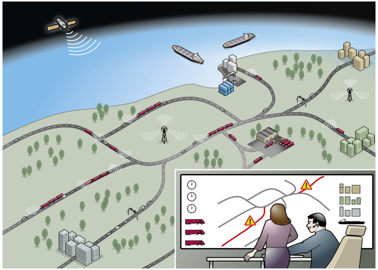
(Heavy-duty) vehicle platooning

- *A unit of vehicles driving together with short headways*
- Reduced air drag and fuel consumption, less space on the road taken, fewer drivers required
- Control within a platoon *- largely solved*
- Fleet management, platooning coordination, and potential for traffic control *- more work is still needed*
- Truck platooning and traffic congestion
- *How does platooning influence the rest of the traffic (and vice versa), and how can we exploit this for traffic control?*



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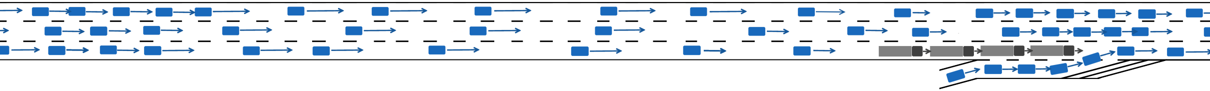
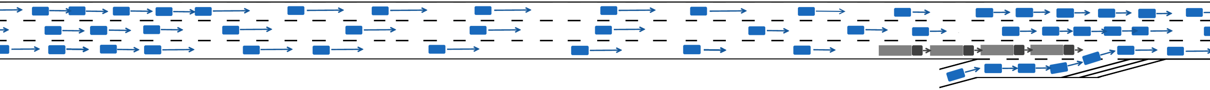
Bottleneck decongestion

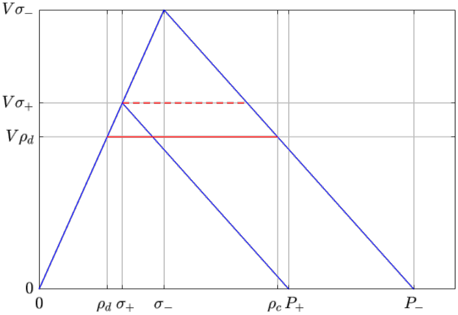


- E.g. lane drop bottleneck, on-ramp

Bottleneck decongestion



- E.g. lane drop bottleneck, on-ramp
- Capacity drop
  - Discharging flow lower than capacity before traffic breakdown



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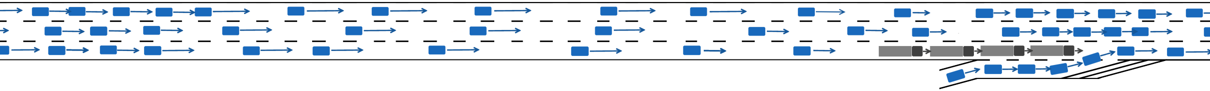
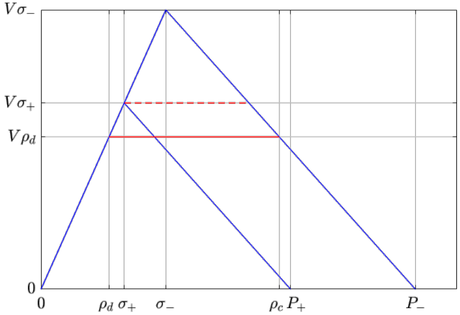
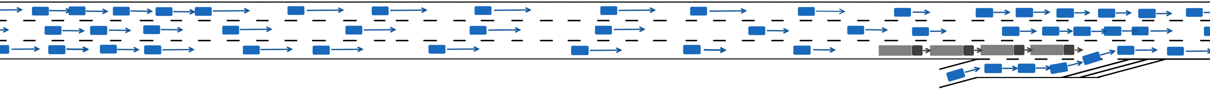


- E.g. lane drop bottleneck, on-ramp
- Capacity drop
  - Discharging flow lower than capacity before traffic breakdown
- Static bottleneck - can be handled by static equipment
  - Ramp metering and variable speed limits



[Papageorgiou et al. 1991], [Carlson et al. 2013]

Bottleneck decongestion



- E.g. lane drop bottleneck, on-ramp
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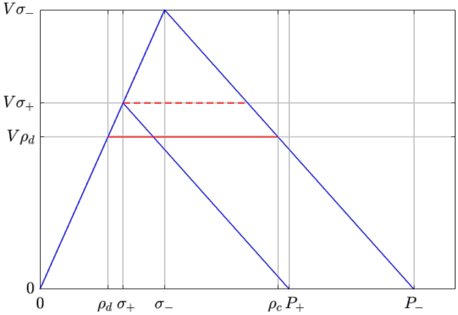
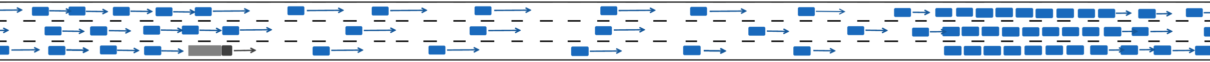
  - Ramp metering and variable speed limits
- *Platoons at bottlenecks?*



[Papageorgiou et al. 1991], [Carlson et al. 2013], **[More research is needed!]**

Stop-and-go wave dissipation



- An upstream-propagating wave of slowed or stationary vehicles without an apparent bottleneck
- Traffic volume close to, but under road capacity
- Caused by *something*, can be resolved by *appropriate* driving behaviour
- *Virtual* upstream-propagating bottleneck due to capacity drop
- Not easy to address using stationary equipment

[Sugiyama et al. 2008], [Stern et al. 2018], [Hegyi et al. 2008]

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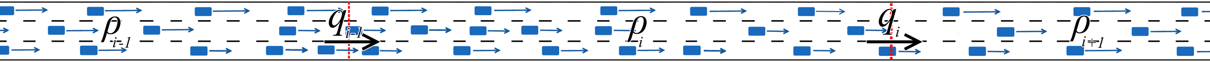
Cell Transmission Model



$$\rho_i(t+1) = \rho_i(t) + \frac{T}{L}\left(q_{i-1}(t) - q_i(t)\right)$$
$$q_i(t) = \min\left(D_i(t), S_{i+1}(t)\right)$$
$$D_i(t) = \min\left(V\rho_i(t), Q_i^{\max}\right)$$
$$S_i(t) = \min\left(W_i(P_i - \rho_i(t)), Q_i^{\max}\right)$$

- $\rho_i(t)$ – traffic density in cell i
- $q_i(t)$ – traffic flow from cell i to cell $i+1$
- $D_i(t)$ – demand of cell i
- $S_i(t)$ – supply of cell i
- V – free flow speed

[Daganzo 1994]

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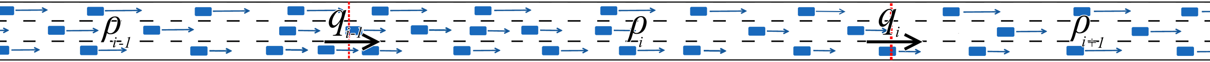
Cell Transmission Model



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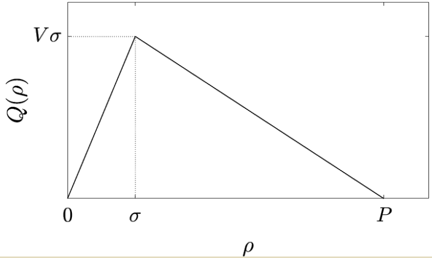
- Corresponds to discretization of the LWR model with Newell-Daganzo (triangular) flux function $Q(\rho)$,

$$\partial_\tau \rho(x,\tau) + \partial_x Q(\rho(x,\tau)) = 0$$

$$Q(\rho) = \begin{cases} V\rho, & \rho \leq \sigma \\ W(P-\rho), & \rho > \sigma \end{cases}$$



[Daganzo 1994] , [Lighthill, Whitham 1955], [Lebacque 1995]

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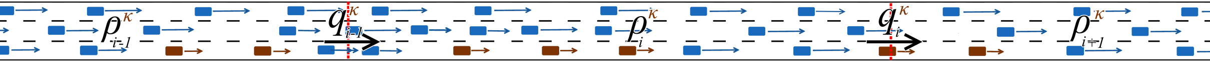
Multi-class Cell Transmission Model



$$\rho_i^\kappa(t+1) = \rho_i^\kappa(t) + \frac{T}{L}\left(q_{i-1}^\kappa(t) - q_i^\kappa(t)\right)$$

$$q_i^\kappa(t) = \min\left(D_i^\kappa(t), S_{i+1}^\kappa(t)\right)$$

$$D_i^\kappa(t) = U_i^\kappa(t)\rho_i^\kappa(t)\min\left(1, \frac{F_i(t)}{\sum_{k\in\mathcal{K}} U_i^k(t)\rho_i^k(t)}\right)$$

$$S_i^\kappa(t) = \frac{\rho_{i-1}^\kappa(t)}{\rho_{i-1}(t)}\min\left(W_i(P_i - \rho_i(t)), Q_i^{\max}\right)$$

$$F_i(t) = \min\left(Q_i^{\max}, W_i\frac{\sigma_{i+1}}{\sigma_i}\left(P_i - (1-\alpha)\sigma_i - \alpha\rho_i(t)\right)\right)$$

- $\rho_i^\kappa(t)$ – class κ traffic density in cell i
- $q_i^\kappa(t)$ – class κ traffic flow from cell i
- $D_i^\kappa(t)$ – class κ demand of cell i
- $S_i^\kappa(t)$ – class κ supply of cell i
- $U_i^\kappa(t)$ – class κ free flow speed in cell i
- $F_i(t)$ – capacity drop

[Daganzo 1994] , [Lighthill, Whitham 1955], [Lebacque 1995]

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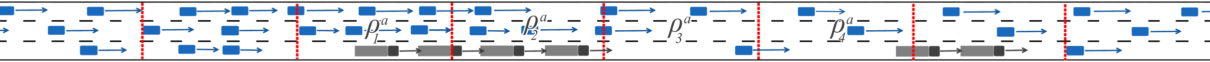
Modelling platoons in multiclass CTM



- Platoon traffic density ρ_p, speed $u_p(t)$, platoon head $x_h^p(t)$ in cell $i_h^p(t)$ and tail $x_t^p(t)$ in $i_t^p(t)$,
  $x_h^p(t+1) = x_h^p(t) + u_p(t)T$

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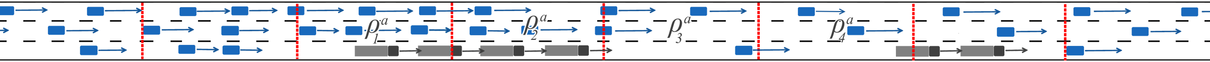

- Platoon traffic density ρ_p, speed $u_p(t)$, platoon head $x_h^p(t)$ in cell $i_h^p(t)$ and tail $x_t^p(t)$ in $i_t^p(t)$, $x_h^p(t+1) = x_h^p(t) + u_p(t)T$
- Correct behaviour of platoons:

$$U_i^a(t) = \begin{cases} V, & i < i_t^p(t) \\ \frac{V}{\rho_i^a(t)}\left(\rho_p - \frac{V-U_{i+1}^a(t)}{V}\rho_{i+1}^a(t)\right), & i_t^p(t) \leq i < i_h^p(t) \\ V - (V-u_p)\,\frac{\rho_p}{\rho_{i_h}^a(t)}, & i = i_h^p(t) \\ 0, & i > i_h^p(t) \end{cases}$$

$$\rho_i^a(t) = \begin{cases} 0, & i < i_t^p(t) \vee i > i_h^p(t) \\ \rho_p \frac{x_t^p(t) - X_{i_t^p(t)+1}}{L}, & i = i_t^p(t) \\ \rho_p, & i_t^p(t) < i < i_h^p(t) \\ \rho_p \frac{x_h^p(t) - X_{i_h^p(t)}}{L}, & i = i_h^p(t) \end{cases}$$

- Traffic densities will converge to $\rho_i^a(t)$!

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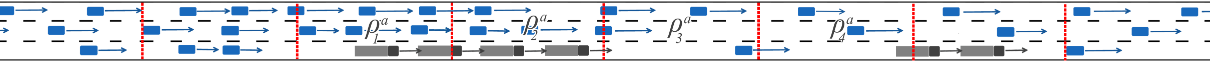

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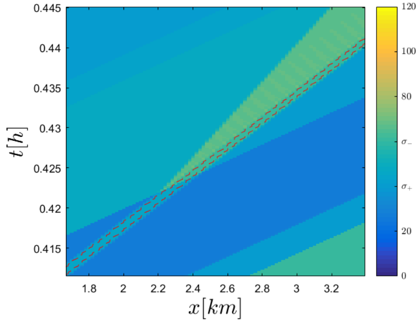
- Moving bottleneck



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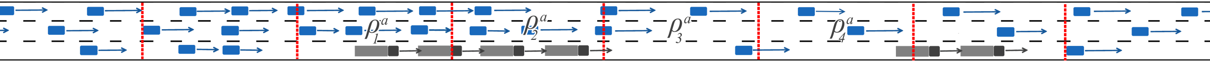

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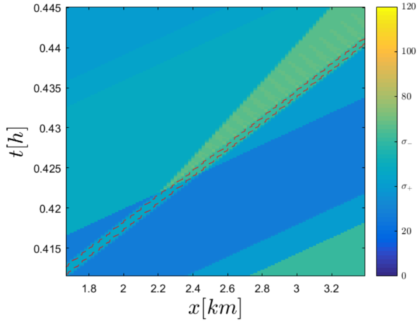
- Moving bottleneck

- Maximum platoon overtaking flow:

$$q_p^{out} = V\left(\sigma - \rho_p\right)$$

- Equivalent to moving bottlenecks in PDE models



[Lebacque et al. 2014], [Delle Monache, Goatin 2014]

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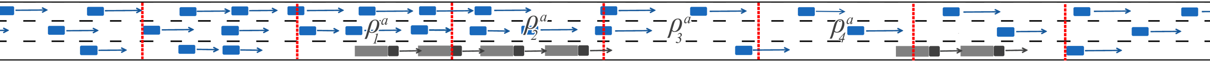
Modelling platoons in multiclass CTM



- Platoon traffic density ρ_p, speed $u_p(t)$, platoon head $x^p_h(t)$ in cell $i^p_h(t)$ and tail $x^p_t(t)$ in $i^p_t(t)$,
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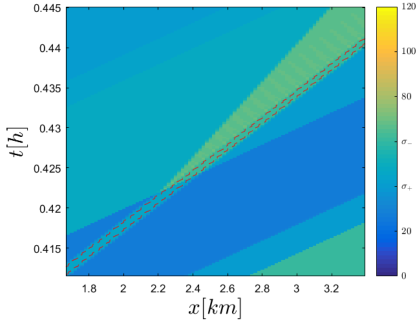
- Moving bottleneck

- Maximum platoon overtaking flow:

$$q_p^{out} = V\left(\sigma - \rho_p\right)$$

- Equivalent to moving bottlenecks in PDE models

- Controlled moving bottlenecks as in-flow actuators!



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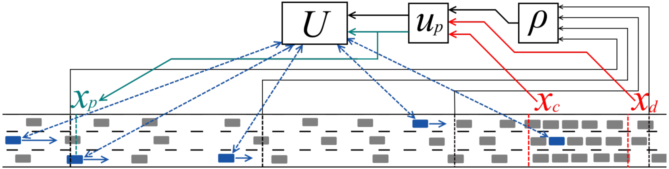
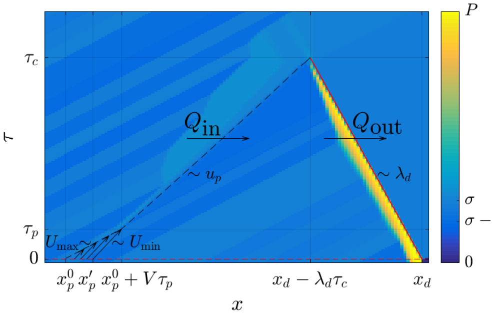
Accumulate-then-actuate



1. Detect a stop-and-go wave



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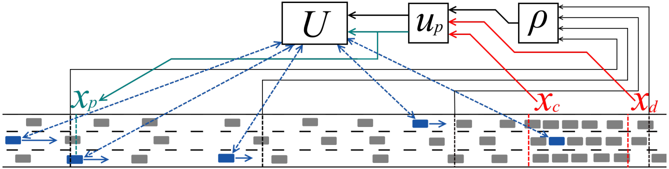
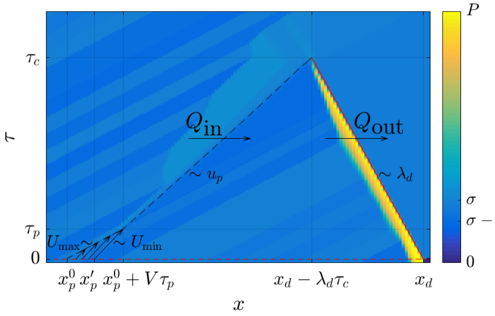


1. Detect a stop-and-go wave
2. Select the initial point where we start accumulating controllable vehicles



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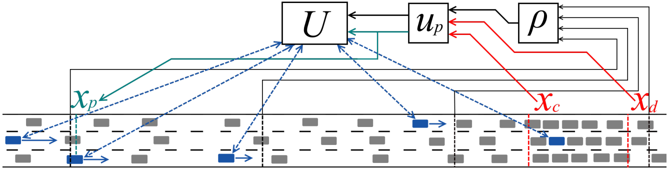
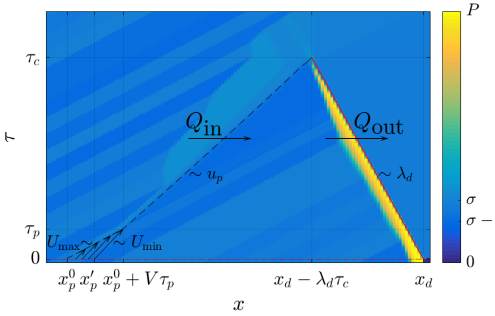
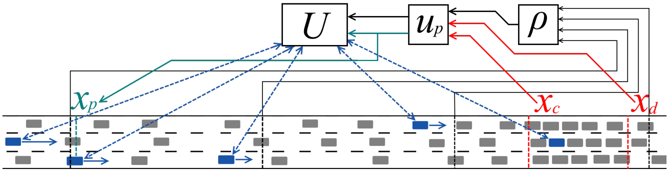


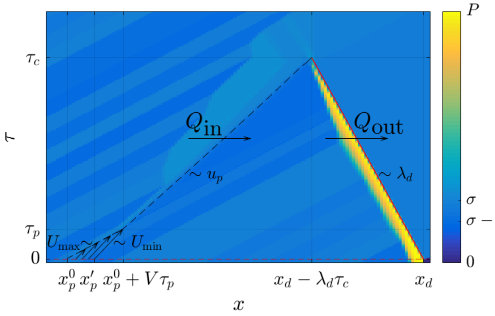
1. Detect a stop-and-go wave
2. Select the initial point where we start accumulating controllable vehicles
3. Collect enough controllable vehicles so that they can affect the rest of traffic



Accumulate-then-actuate



1. Detect a stop-and-go wave
2. Select the initial point where we start accumulating controllable vehicles
3. Collect enough controllable vehicles so that they can affect the rest of traffic
4. Use the collected controllable vehicles as a controlled moving bottleneck



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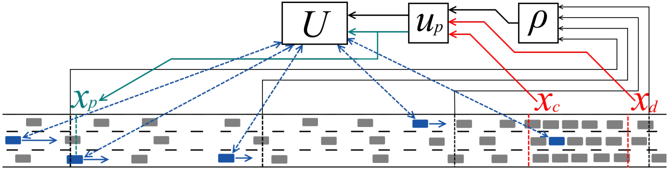

1. Detect a stop-and-go wave
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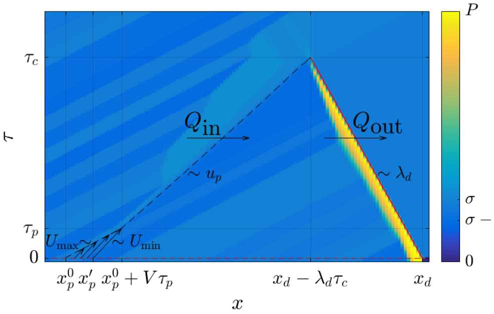
3. Collect enough controllable vehicles so that they can affect the rest of traffic
4. Use the collected controllable vehicles as a controlled moving bottleneck
5. Dissipate the stop-and-go wave with minimum delay



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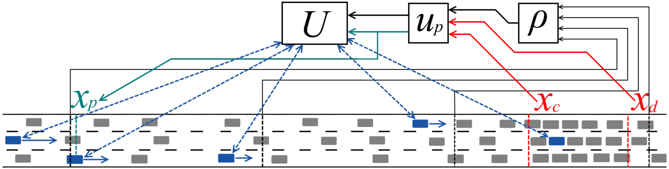


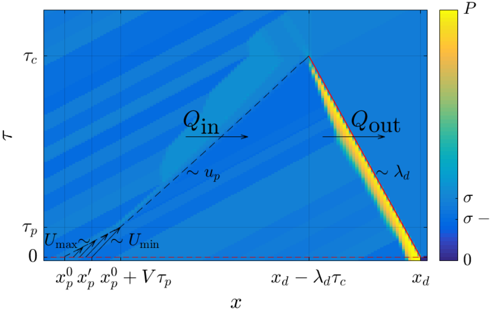
$$u_p(t) = \frac{x_d(t) - x_p(t)}{\tau_c} + \lambda_d$$

$$Q_{out} = (V - \lambda_d)\,\rho_d$$

$$Q_{in} = (V - U_p)\,(\sigma - \rho_p)$$

$$\tau_c = \frac{n_{x_p,x_d}(t) - (x_d(t) - x_p(t))(\sigma - \rho_p)}{(V - \lambda_d)(\rho_d - \sigma + \rho_p)}$$

$$u_p(t) = \frac{V(\rho_d - \sigma + \rho_p) + \lambda_d(\bar{\rho}_{x_p,x_d}(t) - \rho_d)}{\bar{\rho}_{x_p,x_d}(t) - \sigma + \rho_p}$$



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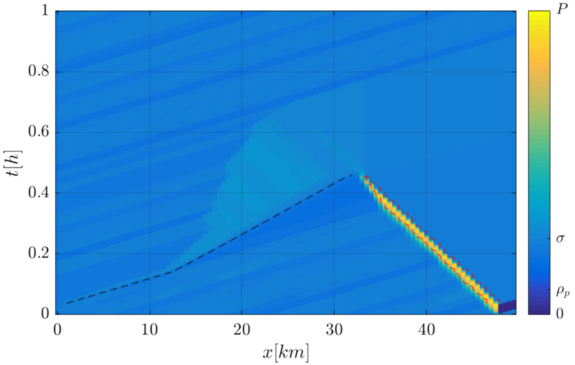
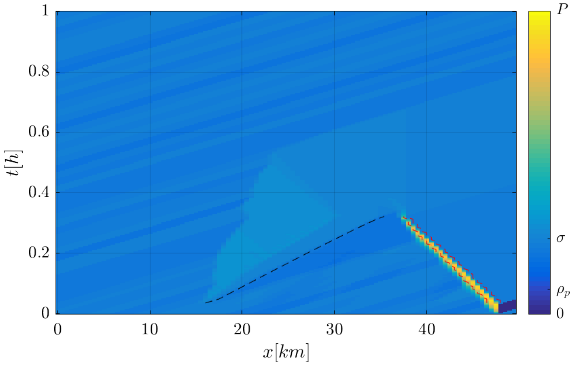
Simulation results



5% penetration rate



10% penetration rate

[Čičić, Johansson 2019]

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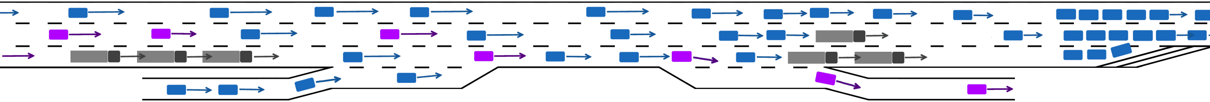
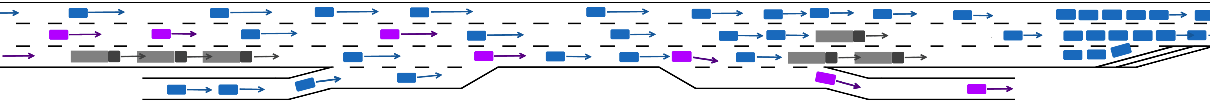
Multiple platoons and queueing representation



- In free flow, the road acts as a simple transport delay

$$\rho_{i+k}(t) = \rho_i(t-k)$$

Multiple platoons and queueing representation



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$$\rho_{i+k}(t) = \rho_i(t-k)$$

- Congestion can only occur at the static and moving bottlenecks!

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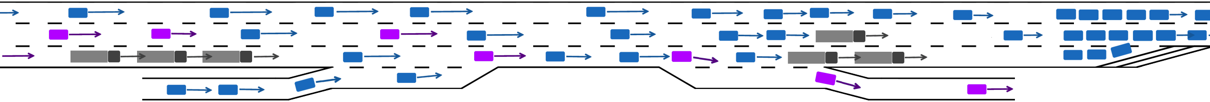
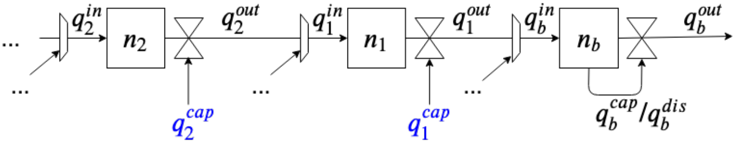


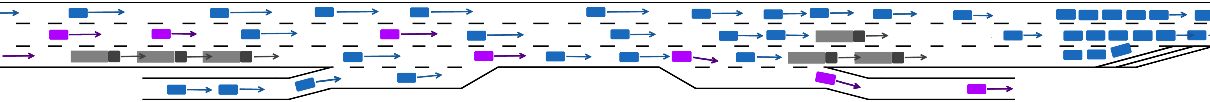
- Queueing representation



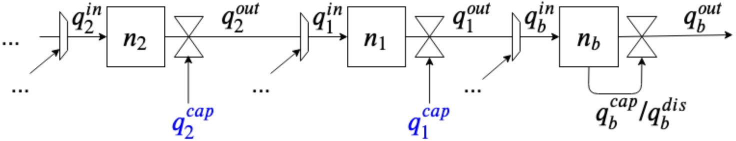
$$\dot{n}_*(t) = q_*^{in}(t) - q_*^{out}(t)$$

$$q_*^{out}(t) = \begin{cases} q_*^{in}(t), & q_*^{in}(t) \leq q_*^{cap} \wedge n_*(t) = 0 \\ q_*^{dis}, & q_*^{in}(t) > q_*^{cap} \vee n_*(t) > 0 \end{cases}$$

Multiple platoons and queueing representation



- Queueing representation



$$\dot{n}_*(t) = q_*^{in}(t) - q_*^{out}(t)$$

$$q_*^{out}(t) = \begin{cases} q_*^{in}(t), & q_*^{in}(t) \leq q_*^{cap} \wedge n_*(t) = 0 \\ q_*^{dis}, & q_*^{in}(t) > q_*^{cap} \vee n_*(t) > 0 \end{cases}$$

- For the static bottleneck, $q_b^{cap} = V\sigma_+$, and due to capacity drop $q_b^{dis} = V\rho_d < q_b^{cap}$.

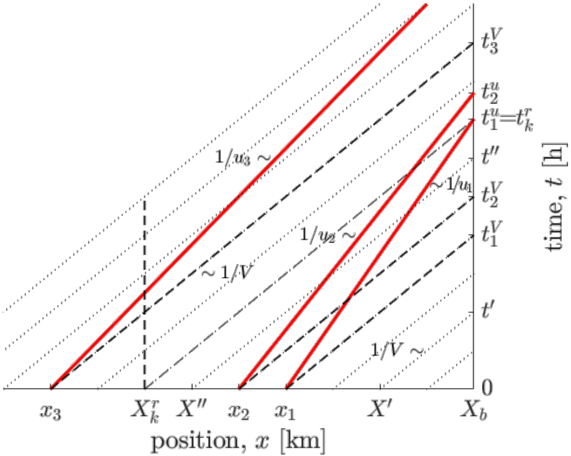
Coordinate transform for simplifying delay

- Inflows to the bottleneck and to the platoons

$$q_b^{in}(t) = q_b^V(t) + q_b^u(t)$$

$$q_b^V(t) = \begin{cases} q_p^{out}\left(\frac{x_p+Vt-X_b}{V-u_p}\right), & \max\left\{t_p^V, t_{p-1}^u\right\} \leq t \leq t_p^u, p = 1,\dots,\Pi \\ V\rho(X_b - Vt), & \text{otherwise}, \end{cases}$$

$$q_p^{in}(t) = \begin{cases} q_{p+1}^{out}\left(\frac{(V-u_p)t - x_p + x_{p+1}}{V-u_{p+1}}\right), & t > \frac{x_p - x_{p+1}}{V-u_p}, \\ V\rho(x_p - (V-u_p)t, 0), & t \leq \frac{x_p - x_{p+1}}{V-u_p}, \end{cases}$$



Coordinate transform for simplifying delay

- Inflows to the bottleneck and to the platoons

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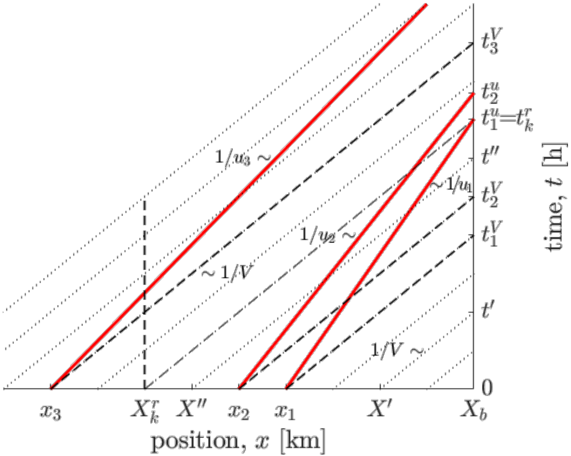
- Coordinate transform for each platoon $\tau_p = \frac{x_p-X_b+Vt}{V-u_p}$:

$$q_b^V(t) = \begin{cases} \tilde{q}_p^{out}(t), & \max\left\{t_p^V, t_{p-1}^u\right\} \leq t \leq t_p^u, p = 1,\dots,\Pi \\ V\rho(X_b - Vt), & \text{otherwise,} \end{cases}$$

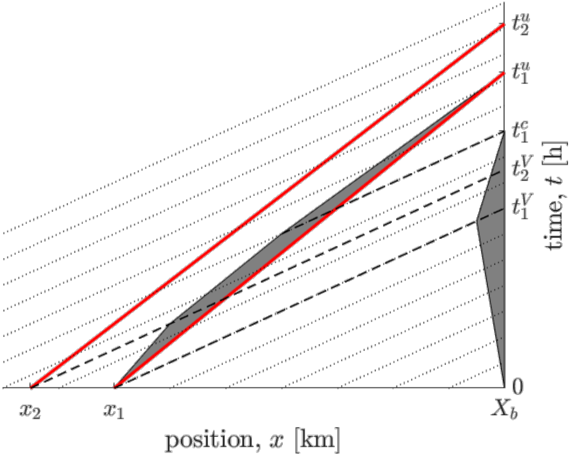
$$\tilde{q}_p^{in}(t) = \begin{cases} \tilde{q}_{p+1}^{out}(t), & t_{p+1}^V < t < t_{p+1}^V, \\ V\rho(X_b - Vt, 0), & t \leq t_{p+1}^V, \end{cases}$$



Bottleneck decongestion control

- Overtaking flow q_p^{cap}

$$\tilde{q}_p^{cap}(t) = \begin{cases} q^{ref}(t), & n_b(t) = 0 \wedge t \geq t_{p-1}^u, \\ \tilde{q}_{p-1}^{cap}(t), & \tilde{n}_{p-1}(t) = 0 \wedge t < t_{p-1}^u, \\ Q^{lo}, & \text{otherwise}, \end{cases}$$



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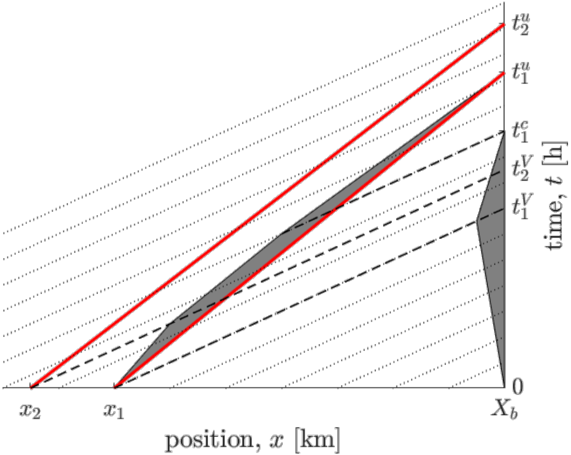
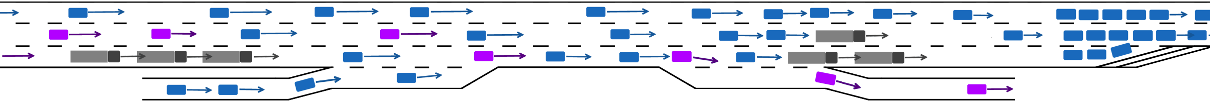
- Platoon speed u_p: drive as fast as possible s.t.:

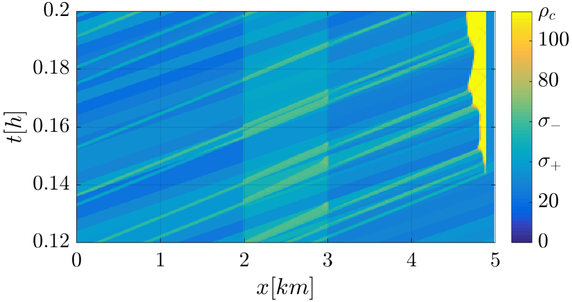
$$\tilde{n}_p(t_p^u) = \tilde{n}_p(t_p^c) + \int_{t_p^c}^{t_1^u} \tilde{q}_1^{in}(t)\mathrm{d}t - Q^{hi}(t_1^u - t_1^c) = 0$$

  - *The queue at the bottleneck is dissipated*
  - *The queue at platoon p is dissipated by t_p^u (when the platoon arrives at the bottleneck)*

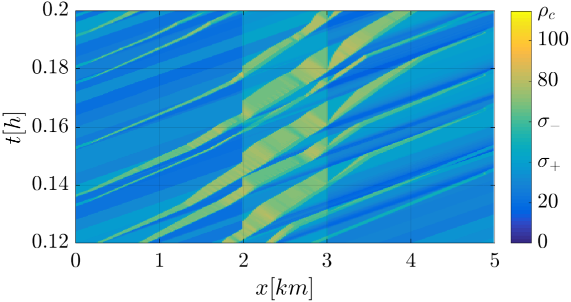


Simulation results with an on- and off-ramp





Without control
$+38.3\%$ TTS

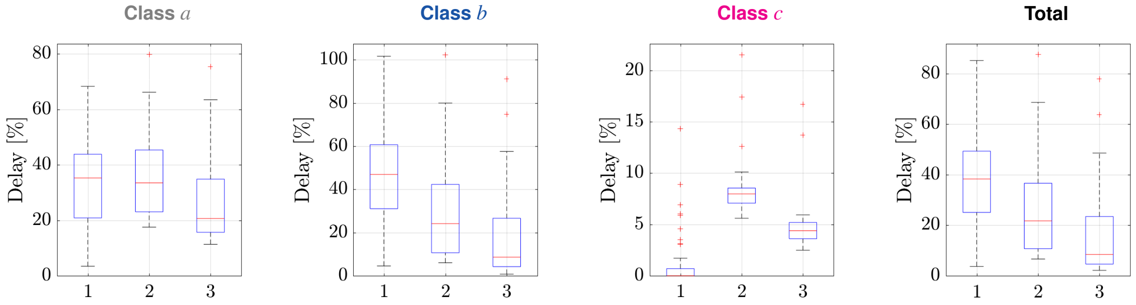


With control
$+8.4\%$ TTS

[Čičić, Jin, Johansson 2019]

Mladen Čičić – cicic@kth.se

Simulation results with an on- and off-ramp



Delay [%]	Class a		Class b		Class c		Total	
	average	median	average	median	average	median	average	median
Case (a)	33.1	35.3	45.0	46.9	1.2	0.0	36.9	38.3
Case (b)	36.8	33.5	29.4	24.1	8.4	8.0	26.2	21.7
Case (c)	28.1	20.7	19.6	8.6	4.8	4.4	17.5	8.4

[Čičić, Jin, Johansson 2019]

Conclusions

- *How can we control the traffic using a small subset of vehicles?*
- Even a few infrastructure-controlled vehicles can have a significant positive impact on the overall traffic
- Prediction-based control using simplified traffic models yields good results!
- We need a better understanding of how platoons interact with the rest of the traffic (especially at the bottlenecks)

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Thank you for your attention!

Questions?