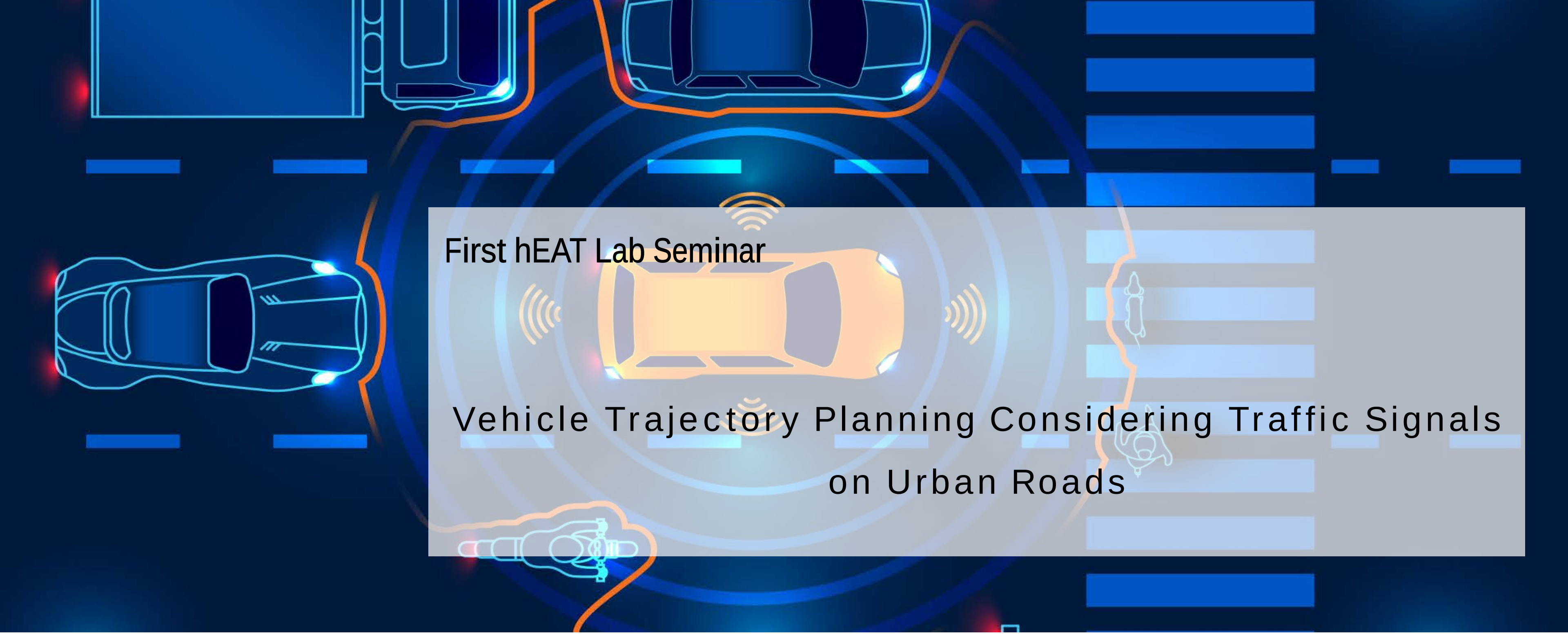


First hEAT Lab Seminar

Vehicle Trajectory Planning Considering Traffic Signals on Urban Roads

Meiqi Liu

Meng Wang, Serge Hoogendoorn

Transport & Planning, TU Delft

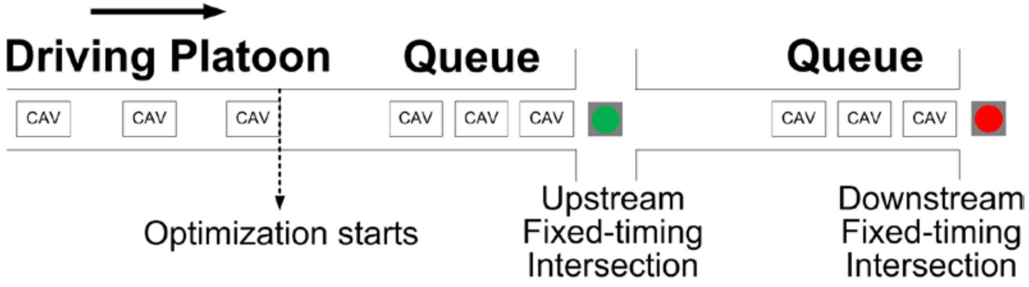
December 6 2019

TUDelft

CONTENTS

I. Platoon trajectory planning under fixed traffic signal

I. Fixed-timing | II. Actuated signal | III. Adaptive (ongoing)



Motivation

1) Scalable to multiple intersections with queues;
2) Capture queue discharging, platoon splitting and merging performances;
3) Multi-criteria in the objective function, jointly optimizing fuel efficiency and travel delay of the whole platoon.

I. Fixed-timing | II. Actuated signal | III. Adaptive (ongoing)

Control objectives

1) driving comfort
2) throughput in green phase
3) travel delay of passing vehicles (speeds)
4) fuel consumption of vehicles that stop

$$\min_{\mathbf{u}} J = \min_{\mathbf{u}} \int_0^T \left(\beta_1 \sum_{i=1}^{N} a_i^2(t) - \beta_2 q - \beta_3 \sum_{i=1}^{Q_2+q} v_i(t) + \beta_4 \sum_{i=Q_2+q+1}^{N} f(v_i(t), a_i(t)) \right) \mathrm{d}t$$

Controller Constraints

1) Admissible acceleration: $a_{\min} \le a_i(t) \le a_{\max}$
2) Limited speed: $0 \le v_i(t) \le v_{\max}$
3) No-collision requirements: $x_i(t) - x_{i+1}(t) \ge v_{i+1}(t) t_{\min} + x_0 + l$
4) Red phase position constraint:

$$x_{q_j}(t = g_j) \ge L_j$$

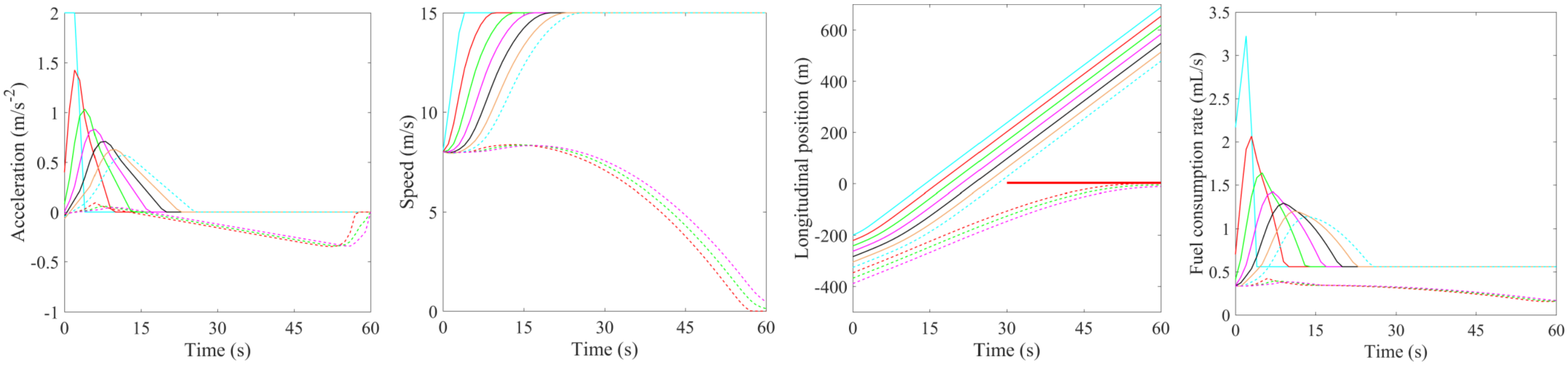
$$x_i(g_j \le t \le g_j + r_j) \le L_j \quad i \in (Q_{j-1}, Q_j)$$

u -- control input variable;
$a_i(t)$ -- accelerations at time step t;
i -- vehicle sequence number;
q -- throughput in green phase;
N -- the number of controlled vehicles;
i=1 to $i=Q_2$ -- queues on downstream intersections;
$i=Q_2+1$ to $i=Q_2+q$ -- q passing vehicles at the most upstream intersection.

TU Delft

I. Fixed-timing | II. Actuated signal | III. Adaptive (ongoing)

Simulation results: Scenario 1

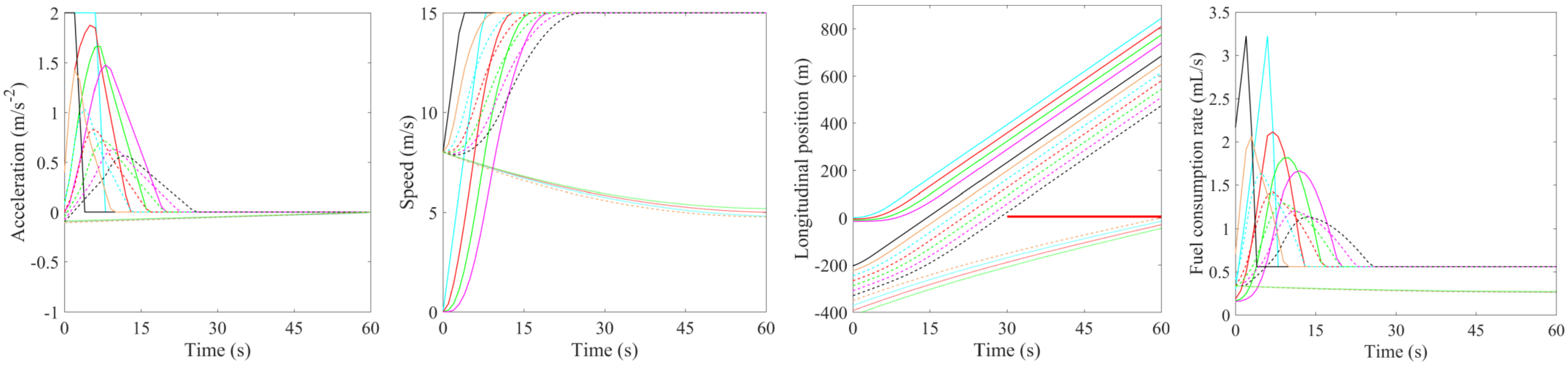


(a) Acceleration **(b) Speed** **(c) Position** **(d) Fuel consumption**

	Scenario design	Settings	Experiment objectives
Scenario 1	An isolated intersection without downstream queue	10 vehicles	To test the validity of position constraint during red phase and the flexibility of the control framework under multiple objectives, and to tune the cost weights under eco-driving objective function

TUDelft

Simulation results: Scenario 2



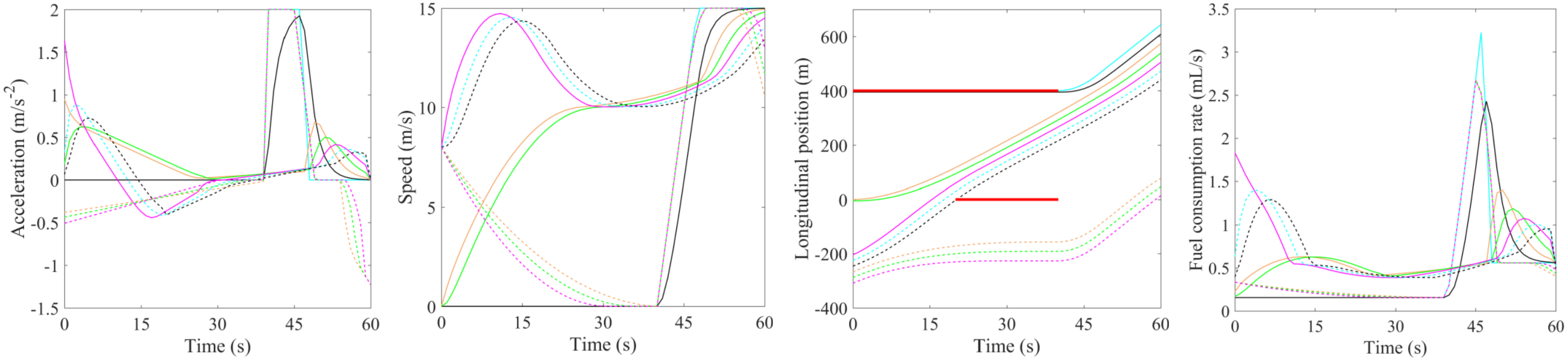
(a) Acceleration **(b) Speed** **(c) Position** **(d) Fuel consumption**

	Scenario design	Settings	Experiment objectives
Scenario 2	An isolated intersection with downstream queue	15 vehicles; 4 queueing vehicles	To evaluate the effectiveness of downstream queue constraints and the scalability of control system

TU Delft

I. Fixed-timing | II. Actuated signal | III. Adaptive (ongoing)

Simulation results: Scenario 3



(a) Acceleration **(b) Speed** **(c) Position** **(d) Fuel consumption**

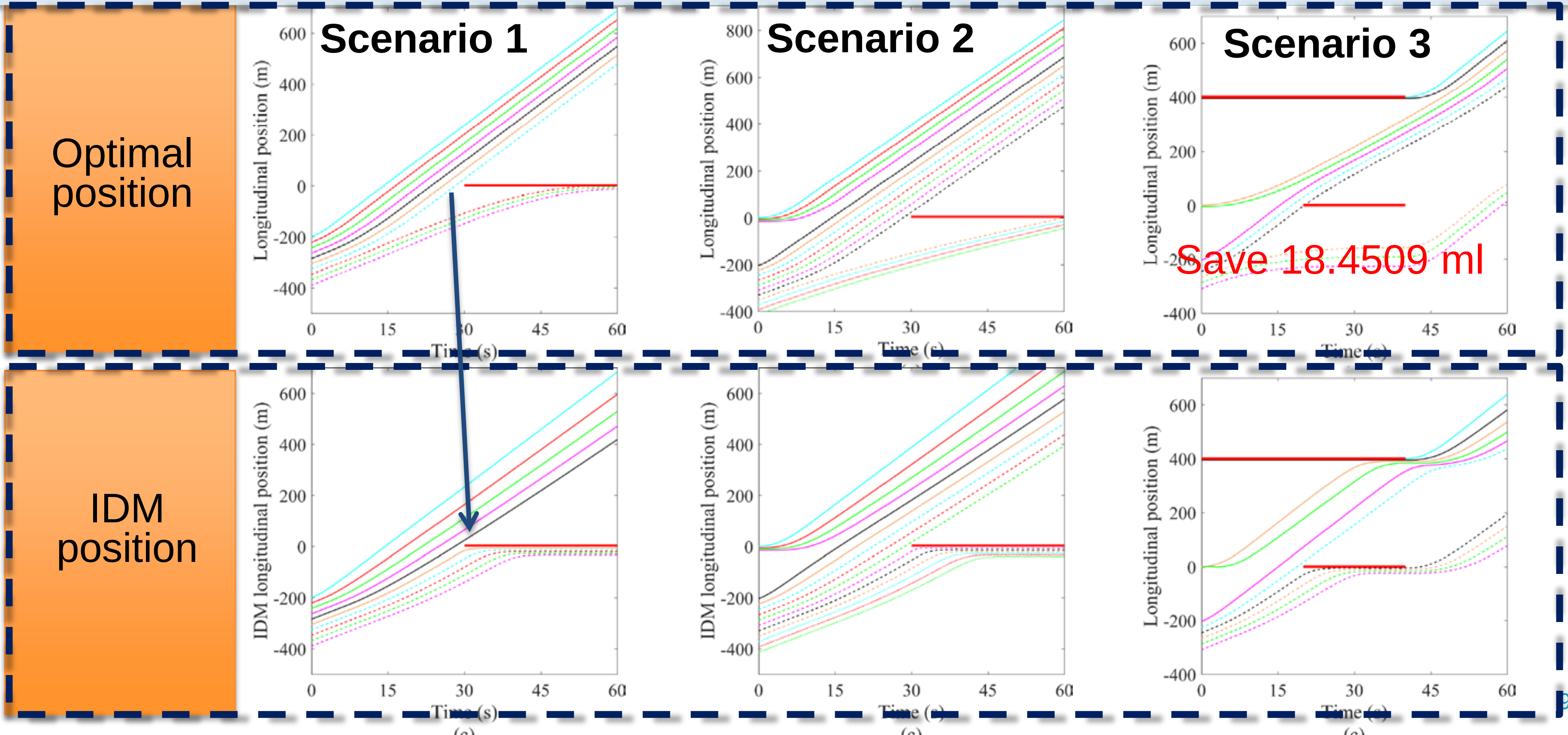
	Scenario design	Settings	Experiment objectives
Scenario 3	An arterial corridors of two signalized intersections with downstream queue	10 vehicles; Queue: 2 and 2 separately; 400 m lane length	To examine the application of the control framework on urban corridors and validate possible deceleration maneuvers

TUDelft

I. Fixed-timing

II. Actuated signal

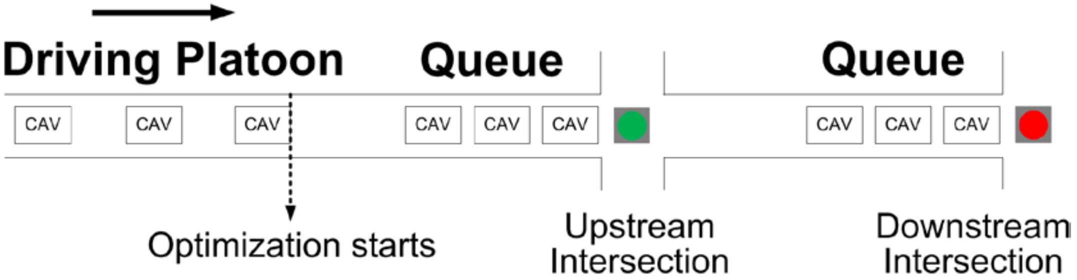
III. Adaptive (ongoing)



II. Platoon trajectory planning under actuated traffic signal

TU Delft

I. Fixed-timing | **II. Actuated signal** | III. Adaptive (ongoing)



- **Red phase**: Position constraint → penalty term
- **Control approach**: Feedforward (open loop) → feedback (closed loop)
- **Signal control approach**: fixed timing → (semi-) actuated signal

Control objectives

- Optimizing multi-criteria of the whole platoon (e.g. driving comfort, travel delay, throughput);
- Guarantee no-collision and safe driving requirements;
- Stop/decelerate before the stop-line during the red phase;
- Computational load.

TU Delft

Controller formulization

- **Control variable**: acceleration u
- **State variables**: longitudinal position x, speed v
- **System dynamics model**: $\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} x(t) \\ v(t) \end{pmatrix} = \mathrm{f}(\mathbf{x},\mathbf{u})$
- **Initial condition**: $\mathbf{x}(0)=\mathbf{x}_0$
- **Constraints**: $\mathbf{x}(t) \in X, \mathbf{u}(t) \in U, t \in [0, t_f]$
- **Cost function**: $\min_{\mathbf{u},q} J(\mathbf{x},\mathbf{u},t,q) = \min_{\mathbf{u},q} \int_0^{t_f} L(\mathbf{x},\mathbf{u},t,q) + G(\mathbf{x}(t_f))dt$

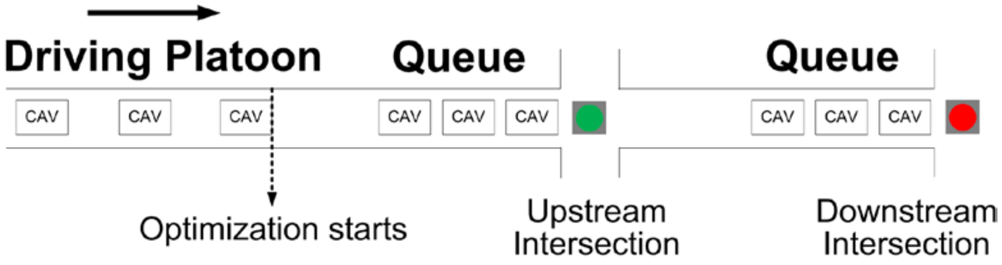
i -- vehicle sequence number

q -- the maximal throughput

L -- running cost

G -- terminal cost

Running cost specification



1) Driving comfort term: $u_i^2(t)$
2) Travel delay term: $-v_i(t)$
3) Safe following term: $\left(v_{i-1}(t)-v_i(t)\right)^2 \big/ \left(x_{i-1}(t)-x_i(t)-l\right)$
4) Desired time gap term: $\left(x_{i-1}(t)-x_i(t)-v_i(t)t_{\min}-s_0-l\right)^2$
5) Fuel consumption term: $f_{eco}=b_0+b_1v(t)+b_2v^2(t)+b_3v^3(t)+a(t)\left(c_0+c_1v(t)+c_2v^2(t)\right)$
6) Virtual vehicle term: $\dfrac{\left(v_{virtual}(t)-v_i(t)\right)^2}{x_{virtual}(t)-x_i(t)}$ and $v_{virtual}(t)=0, x_{virtual}(t)=0$

$t_{\min}$ -- the minimum safe car-following time gap
s_0 -- the minimum space gap at standstill conditions
l – the length of controlled vehicle

TU Delft

Running cost specification

$$L\left(\mathbf{x},\mathbf{u},t,q_j\right)=\sum_{i=1}^{N}L_i(\mathbf{x},\mathbf{u},t,q_j)$$

Leading mode: Leader within the signal cycle $i=1, t\in\left[0,t_f\right]$

1. Driving comfort + 2. Travel delay + 5. Fuel saving

$$L_i=\beta_1 u_i^2(t)-\beta_2 v_i(t)+\beta_5 f_{\text{eco}}\left(u_i,v_i\right)$$

First-stopping mode: First-stopping vehicle during the red phase $i=q+1, t\in\left[g,t_f\right]$

1. Driving + 2. Travel + 5. Fuel + 6. Virtual vehicle

$$L_i=\beta_1 u_i^2(t)-\beta_2 v_i(t)+\beta_5 f_{\text{eco}}\left(u_i,v_i\right)+\beta_6\frac{\left(v_{\text{virtual}}(t)-v_i(t)\right)^2}{x_{\text{virtual}}(t)-x_i(t)}$$

Following mode: Followers within the signal cycle; First-stopping vehicle during the green phase Others

1. Driving + 2. Travel + 3. Safe + 4. Desired + 5. Fuel

$$L_i=\beta_1 u_i^2(t)-\beta_2 v_i(t)+\beta_3\frac{\left(v_{i-1}(t)-v_i(t)\right)^2}{x_{i-1}(t)-x_i(t)-l}+\beta_4\left(x_{i-1}(t)-x_i(t)-v_i(t)t_{\min}-s_0-l\right)^2+\beta_5 f_{\text{eco}}\left(u_i,v_i\right)$$

I. Fixed-timing | **II. Actuated signal** | III. Adaptive (ongoing)

Derivation of the optimal control input

- The control problem is solved based on Pontryagin's principle.

- Define Hamiltonian and introduce co-state λ:

$$H_i(\mathbf{x},\mathbf{u},\boldsymbol{\lambda},t,q_j)=L_i(\mathbf{x},\mathbf{u},t,q_j)+\lambda\mathbf{f}_i(\mathbf{x},\mathbf{u},t)$$

$$=\beta_1 u_i^2-\beta_2 v_i+\beta_3\frac{(v_{i-1}-v_i)^2}{x_{i-1}-x_i-l_i}+\beta_4\left(x_{i-1}-x_i-v_i t_{\min}-s_0-l_i\right)^2+\beta_5 f_{\text{eco}}\left(u_i,v_i\right)+\beta_6\frac{\left(v_{\text{virtual}}^j-v_{q_j+1}\right)^2}{x_{\text{virtual}}^j-x_{q_j+1}}$$

$$+\lambda_1^i v_i+\lambda_2^i u_i$$

- Thus, the optimal control law is: $u_i^*=\begin{cases}-\dfrac{\lambda_2^i}{2\beta_1} & \lambda_2^i+\beta_5\left(c_0+c_1v_i+c_2v_i^2\right)\geq 0\\ -\dfrac{\lambda_2^i+\beta_5\left(c_0+c_1v_i+c_2v_i^2\right)}{2\beta_1} & \lambda_2^i+\beta_5\left(c_0+c_1v_i+c_2v_i^2\right)<0\end{cases}$

TU Delft

Controller Constraints

- Admissible acceleration is bounded:

$$a_{\min} \leq u_i(t) \leq a_{\max}$$

- Speed should be lower than the limit speed but nonnegative:

$$0 \leq v_i(t) \leq v_{\max}$$

I. Fixed-timing

II. Actuated signal

III. Adaptive (ongoing)

Solution approach

- Discretization
- iPMP algorithm
- MPC framework
- Constrain control variables
- Computational time

Model predictive control closed-loop

- **Anticipate signals**: update cost weights ahead of the beginning of the red phase
- **Implement actuated signal**: adjust the signal settings and update cost weights

Optimal control open-loop

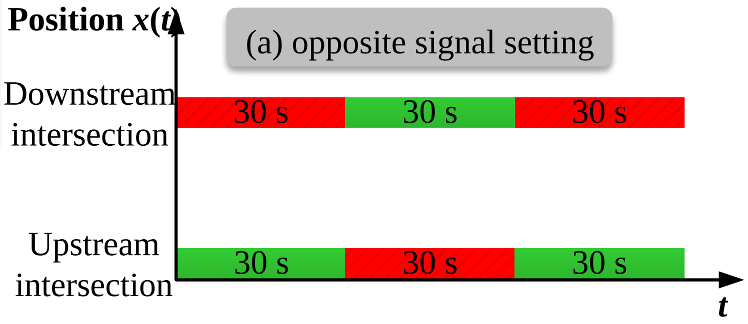
- o Solve the state (co-state) dynamic equation forward (backward) in time
- o Update the co-state

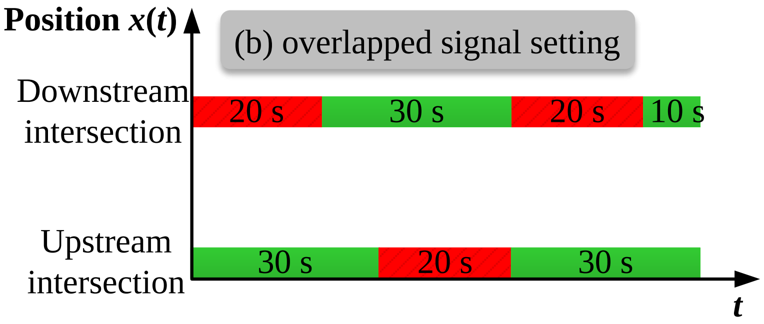
- Implement the solution of the first time step from optimal control
- Update the system state
- Finish the simulation horizon

TU Delft

I. Fixed-timing | **II. Actuated signal** | III. Adaptive (ongoing)

Scenario design





	Signal setting	Anticipation time of the red phase	Objectives
Baseline scenario	Opposite (pre-timed)	No	Test the validity of the red phase (virtual vehicle) term
Scenario 1	Opposite (pre-timed)	10 s	Compare and explore the benefits of anticipation
Scenario 2	Overlapped (pre-timed)	10 s	Prove the workings of the adjustment in signal settings
Scenario 3	Actuated	10 s	Investigate the workings under the actuated signal plan

Simulation results

- green phase: 20 s, 30 s, red phase: 20 s, 30 s
- prediction horizon: 10 s, simulation time step: 1 s
- limit speed: 20 m/s

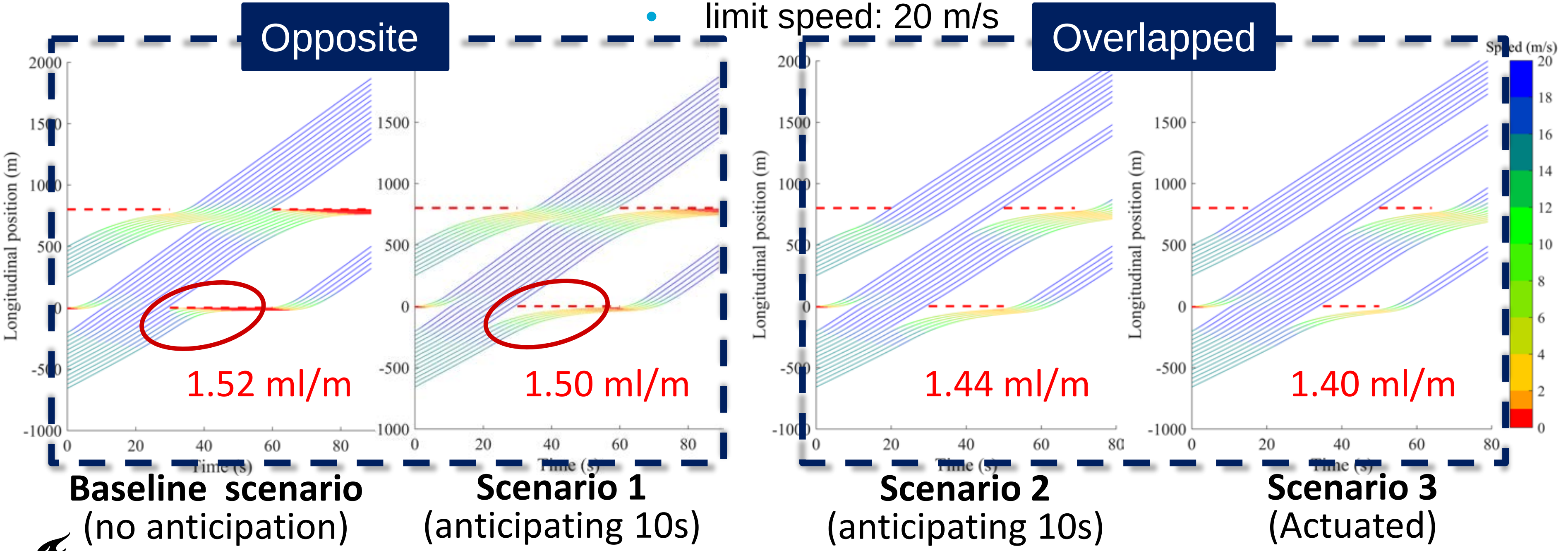


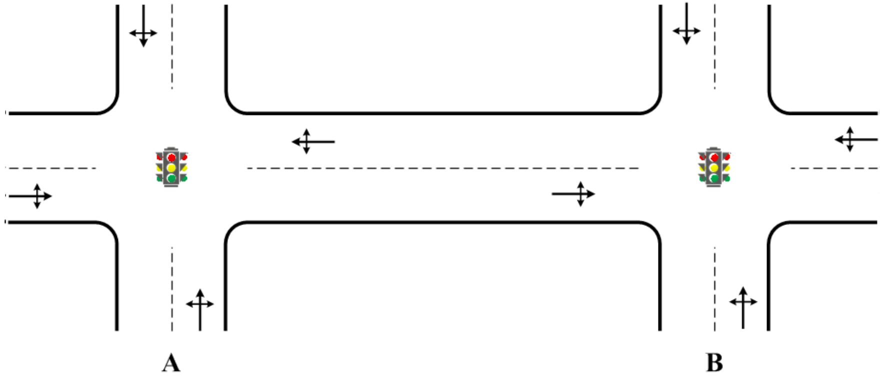
Figure. Optimal trajectories of longitudinal position

Conclusions

- A receding horizon control framework is proposed at signalized intersection, aiming at optimizing throughput, driving comfort, travel delay, fuel consumption and safety.
- The red phase is represented by keeping the safe gap with a virtual vehicle standstill at the stop bar during the red duration with certain anticipation time.
- Simulation under four scenarios verified the performance of the approach.
  - The red phase term with anticipation works better;
  - The flexibility is demonstrated (i.e. changes in signal parameters under pre-timed and actuated signal plan)

III. Platoon trajectory planning under adaptive traffic signal

Control problem



- The integrated optimization of traffic signals and vehicle trajectories at full intersections
- Upper layer: optimize signal
- Lower layer: optimize acceleration → Phase II

TUDelft

I. Fixed-timing | II. Actuated signal | **III. Adaptive (ongoing)**

Simplification

Current/ Initial signal timing plan

↓

Estimated trajectories

First-stopping vehicles

- optimize acceleration in a linear relationship with time

Followers

- apply car-following model

↓

Update signal plan

- based on enumeration
- the length of green and red time
- signal phase sequence

First-stopping vehicles

- optimize acceleration:

$$a_1(k_1, b_1) = k_1 t + b_1$$
$$a_2(k_2, b_2) = k_2 t + b_2$$

- running cost:

$$L(\mathbf{x}, \mathbf{u}, t) = f_{eco}(u(k,b), v(k,b))$$

- terminal cost: (at the end of red phase)

$$G(\mathbf{x}(t_f))\mathrm{d}t$$

to stimulate the first-stopping vehicle to reach the stop-line with the maximal speed; under the collision-free position constraints

- ...

TU Delft

Thank you!

First hEAT Lab Seminar

Vehicle Trajectory Planning Considering Traffic Signals on Urban Roads

Meiqi Liu

Meng Wang, Serge Hoogendoorn

Transport & Planning, TU Delft

December 6 2019

TUDelft