Control for transportation vehicle & urban traffic networks

Course: Intelligent Transportation Systems (ITS)
ITS for Smart Mobility

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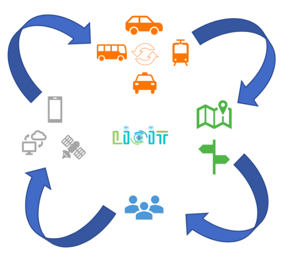
Université Gustave Eiffel (UGE)

Team & Expertise



- Modeling & Characterization
  - Multi network traffic approach
    mode, physical, scale, criteria
  - Cooperation and autonomous vehicles
    CAV - platooning
  - Realtime operations
    Short-term traffic forecast
- Optimal & decision making
  - Model optimization via
    Dynamic control, route choice
  - Integrated & hierarchical control
    Tactical, operational
  - Demand management
    Dynamic traffic assignment

Opportunities & Partnerships

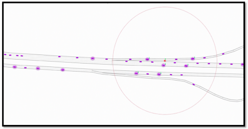
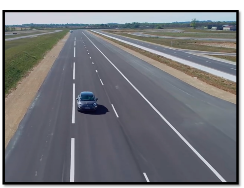


Figure 1: Traffic simulation in Symuvia

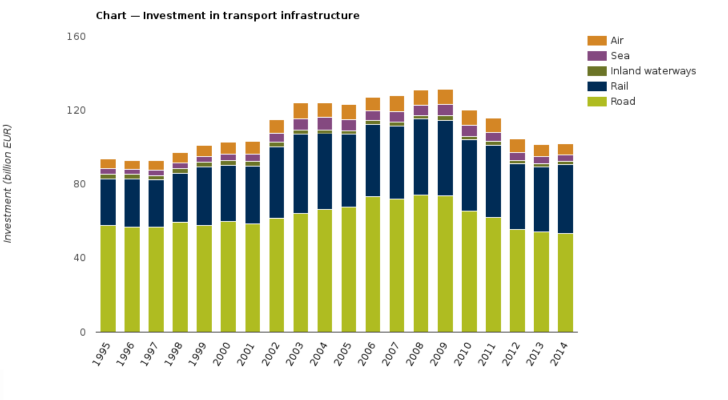
Example

- **SymuVia:** Inhouse simulator →Open Source
- **Transpolis:** Field Operational Tests
  - Autonomous vehicles
  - Controlled tests
  - C-ITS services



Motivation

Top-companies investing in R&D on road traffic management



Some traffic statistics ...

Are we improving the conditions? [1]

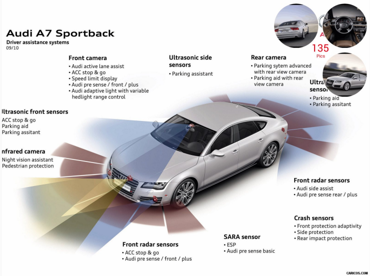
Inrix

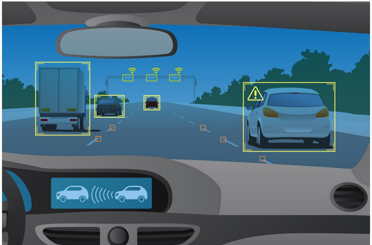
URBAN AREA	IMPACT RANK (2018 RANK)	HOURS LOST IN CONGESTION (2019 RANK)	YEAR-OVER-YEAR CHANGE	LAST MILE SPEED (MPH)	INCIDENT IMPACT	BIKE	TRANSIT
Bogota	1 (2)	191 (1)	3%	9			
Rio de Janeiro	2 (1)	190 (2)	-5%	11			
Mexico City	3 (5)	158 (6)	2%	12			
Istanbul	4 (9)	153 (8)	6%	11			
Sao Paulo	5 (10)	152 (9)	5%	13			
Rome	6 (7)	166 (3)	1%	11			
Paris	7 (4)	165 (4)	-4%	10			

URBAN AREA	IMPACT RANK (2018 RANK)	HOURS LOST IN CONGESTION (2019 RANK)	YEAR-OVER-YEAR CHANGE	LAST MILE SPEED (MPH)	INCIDENT IMPACT	BIKE	TRANSIT
Lyon	39 (40)	105 (35)	1%	10			

[1] https://inrix.com/scorecard/

Evolution of new technologies





Current trends

1. Development of *Small Network Sensors*
2. From *Infrastructure* towards *Vehicle services*
3. Introduction of automation

Current needs

1. *Standardization*: Technologies & services
2. *Certification*: Testing and regulation
3. *Modality*: Efficient network exploitation

Big challenge...

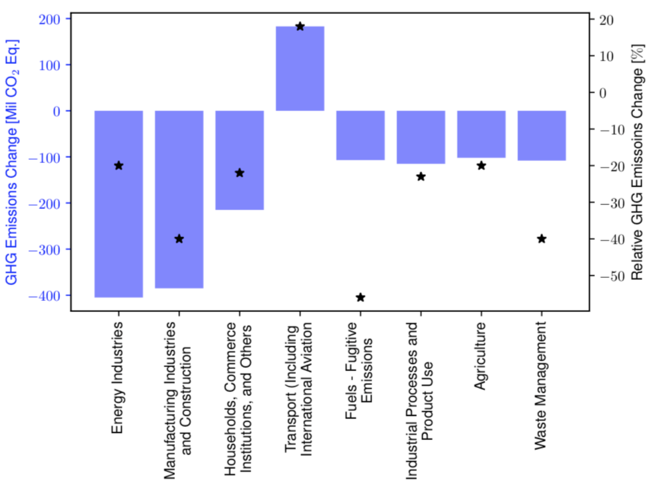


Figure 3: Green house emissions change due to transportation from 1990-2005

Big challenge...

GHG Emissions up to the date

1. From 1990-2005 the relative increase in *GHG* is still important
2. Policies have been adopted EURO1-EURO6

On the other hand

1. *Standardization*: Technologies are reaching efficiency limtits for fosil fuel
2. *Certification*: New alternative energies on the market
3. *Modality*: We understand mobility in a different way

Potential on new technologies

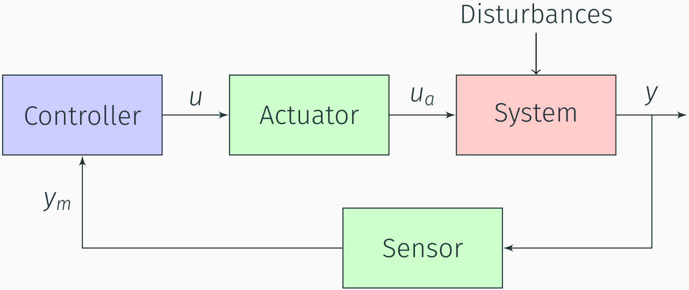
There is potential on new *ITS systems* that may provide new capabilities and improve efficiency leveraged by new technologies such as *data, models and automation*.

General outline

Topics for today

1. Introduction to: Automation in transportation systems.
    - Models in transportation and current technologies
2. Traffic control from infrastructure point of view.
    - Control of traffic lights
    - Scalable control laws for traffic networks
3. Vehicle control to improve traffic network performance.
    - Connected vehicles and connected infrastructures
    - Vehicle platooning and vehicle automation.

Basic concepts of control

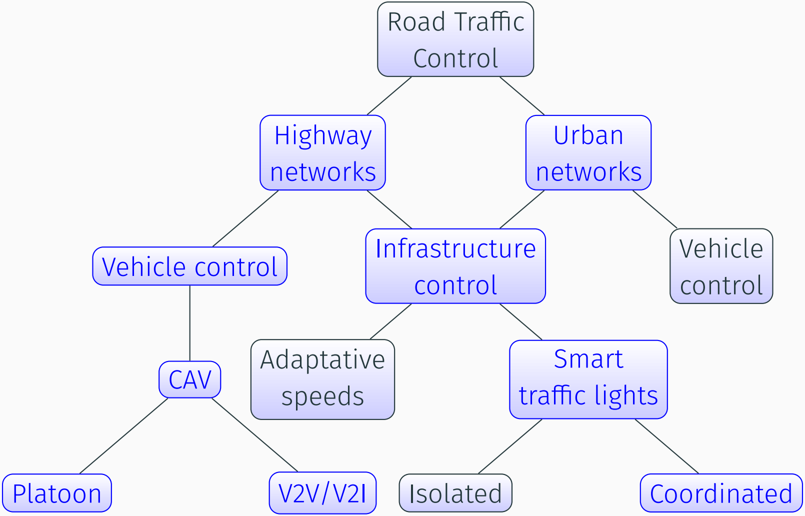


- u - Control input
- u_a - Actuation input
- y - Output system

Objective

- Track a particular value in the output of the system.
- Regularize a value in the output (Stabilize).

Control approach to traffic systems ...



Disclaimer about today's talk

Good solutions for mobility:

Figure 4: Bikesharing

Figure 5: Carsharing

Figure 6: Ridesharing

Alternative Intelligent Transportation Systems

- Leveraged by data and incentives.
- Complex but interesting algorithms for *Dynamic traffic assignment*
- Sorry ☹ not the topic for today, but these are efficient systems from *user's* point of view.
- Focus of today is *single* mode transport optimization

Traffic light control

Motivation

Scope for traffic light control:

- Focus: Urban area networks.
- Objective: Improve urban traffic conditions via control of traffic light (Macroscopic approach)[2].
- How: Efficient and distributed optimization methods for the aforementioned problems[3].

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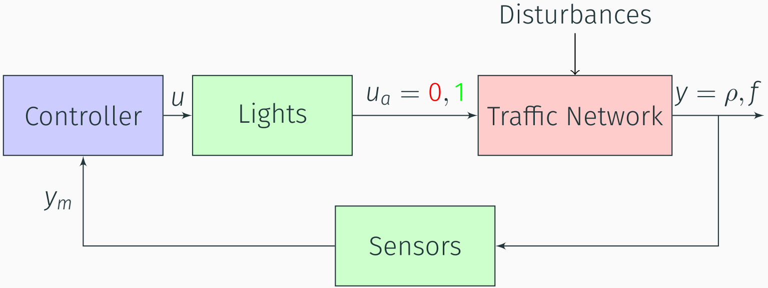
[2] Pietro Grandinetti, Carlos Canudas de Wit, and Federica Garin. "An efficient one-step-ahead optimal control for urban signalized traffic networks based on an averaged Cell-Transmission-Model". In: *2015 European Control Conference (ECC)*. July 2015, pp. 3478–3483.

[3] Pietro Grandinetti, Federica Garin, and Carlos Canudas de Wit. "Towards scalable optimal traffic control". In: *2015 54th IEEE Conference on Decision and Control (CDC)*. Oct. 2015, pp. 2175–2180.

Light control in traffic networks

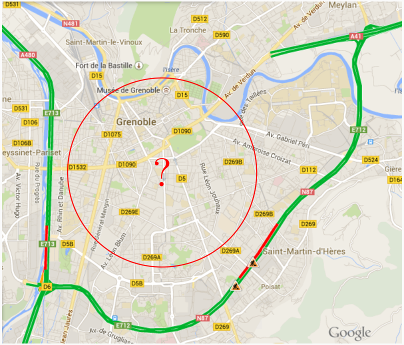


- u - Green times / Red times
- u_a - Actuation input (Green/Red)
- y - Output system (Densities, Flows)

Objective

- Alleviate congestions over the network.
- Adapt green times based on measurements.

Urban vs Highway model



Topology gap

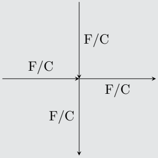
- Control strategies from *highways* can be *adapted* to urban cases?
- Is it possible to design control for the full network?

Traffic light modeling

Two level of complexity

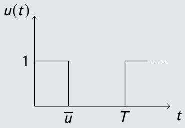
- Size of the network's model
- Traffic light almost each intersection

Piece–wise system representation



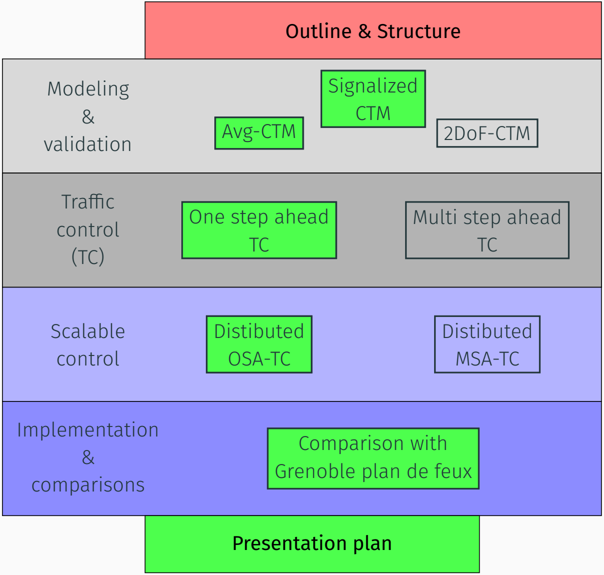
CTM still possible (each road is a cell) but the choice Free/Congested can give dimensional problem ($\sim 2^{\#\text{roads}}$)

Discontinuities in traffic signal



A traffic light is a T−periodic, discontinuous signal $u(t) \in \{0, 1\}$, with duty cycle $\frac{1}{T}\int_0^T u(t) = \frac{\overline{u}}{T}$

Traffic light control

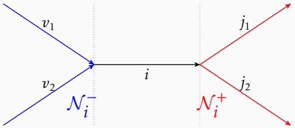


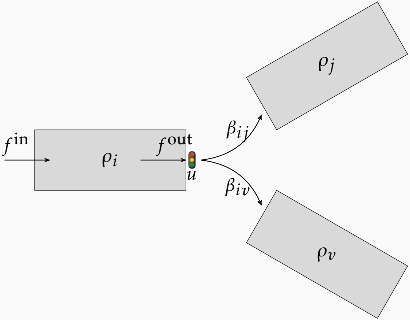
The signalized cell transmission model (S-CTM)

CTM properties:

- Macroscopic model
- Network partitioned into cells

Notation	Value
$\rho_i^{\max}$	Cell i jam density
v_i	Free-flow speed
w_i	Congestion wave speed
$f_i^{\max}$	Capacity flow
L_i	Cell i length



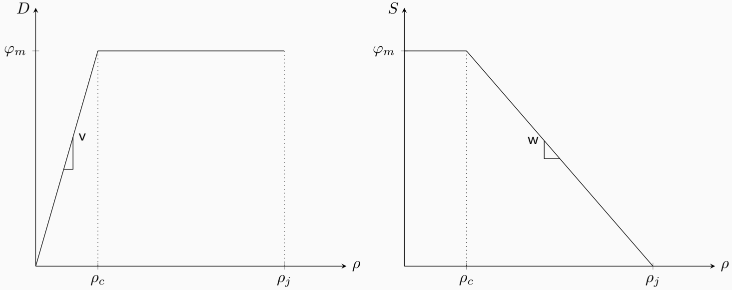


Model for urban traffic network

Demand & Supply paradigm

For a road *r* we define

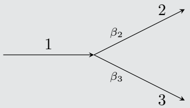
- Demand of *r* the flow of vehicles that can go out from *r*
- Supply of *r* the flow of vehicles that *r* can receive



$$D_r = \min\{v\rho_r, \varphi_m\} \qquad S_r = \min\{w(\rho_j - \rho), \varphi_m\}$$

Model for urban traffic network

Diverge network (Daganzo, 1994)



$$
\begin{aligned}
f_1^{out} = & \max\ \phi \\
\text{s.t.}\quad & \phi \le D_1 \\
& \beta_2\phi \le S_2 \\
& \beta_3\phi \le S_3
\end{aligned}
$$

$$f_1^{out} = \min\left\{D_1, \frac{S_2}{\beta_2}, \frac{S_3}{\beta_3}\right\}$$

Split ratio

Several different choices for the βs are possible, e.g. defining β_{ij} which express the percentage of drivers in road i that want to go in road j

The signalized cell transmission model (S-CTM)

$$\rho_i(t+T_s) = \rho_i(t) + \frac{T_s}{L_i}\Big(f_i^{\text{in}}(t) - u_i(t) f_i^{\text{out}}(t)\Big)$$

$D_i(t), S_i(t)$: demand (supply) of cell i

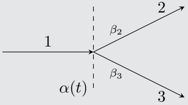
f^{in} weighted sum of f^{out} $\longrightarrow$ $f_i^{\text{in}}(t) = \sum_{j \in \mathcal{N}_i^-} \beta_{ji} f_j^{\text{out}}(t) u_j(t)$

f^{out} with FIFO policy $\longrightarrow$ $f_i^{\text{out}}(t) = \min\left(D_i(t), \left\{\frac{S_j(t)}{\beta_{ij}}\right\}_{j \in \mathcal{N}_i^+}\right)$

$$\boxed{\begin{aligned} f_i^{\text{out}}(t) &= \max \phi \\ \text{subj. to: } & \phi \le D_i(t) \\ & \beta_{ij}\phi \le S_j(t)\ \forall j \in \mathcal{N}_i^+ \end{aligned}}$$

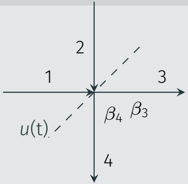
S-CTM - Example

Diverge network



$$\dot{\rho}_1 = \frac{f_1^{in} - f_1^{out} u_1(t)}{L_1}$$

4–roads intersection



$$\dot{\rho}_3 = \frac{1}{L_3}\left(f_3^{in} - f_3^{out}\right) =$$

$$\frac{\left(\left(u_1(t) f_1^{out} \beta_{13} + \left(1 - u_1(t)\right) f_2^{out} \beta_{23}\right) - f_3^{out}\right)}{L_3}$$

Model simplification

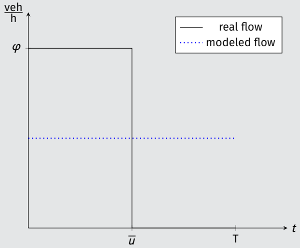
Why simplification/approximation ?

- To have a more scalable model (thanks to continuous instead of binary function)
- To include duty cycle as a new variable (towards control application)

Store & forward method (Aboudolas et al., 2008)

Provided that spills are avoided (Demand &Supply paradigm) a flow f becomes

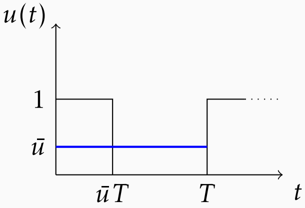
$$f = \begin{cases} 0 \text{ if } u(t) = 0 \\ \varphi \text{ otherwise} \end{cases}$$



The average cell transmission model (Avg-CTM)

Model reduction

Can the binary behavior of the S-CTM be simplified?



Compute the average value

$$\bar{u}_i(t) = \frac{1}{T/T_s} \sum_{k=1}^{T/T_s} u_i(t + kT_s)$$

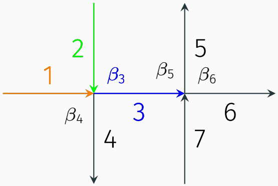
$$\bar{\rho}_i(t + T_s) = \bar{\rho}_i(t) + \frac{T_s}{L_i}\left(f_i^{\text{in}}(t) - \bar{u}_i(t) f_i^{\text{out}}(t)\right)$$

subj. to constraints from the S-CTM

$$\forall\, i \in \mathcal{R} \setminus \mathcal{R}^{\text{in}}, \forall\, t \in \mathbb{N}_+ \quad \sum_{j \in \mathcal{N}_i^-} \bar{u}_j(t) \leq 1.$$

Note: $\mathcal{R} \setminus \mathcal{R}^{\text{in}}$ denote the set of *internal roads* in the network.

Avg-CTM: Example



$$\frac{L_3}{T_s}\left(\overline{\rho_3^+} - \bar{\rho}_3\right) = f_3^{in} - \bar{u}_3 f_3^{out} = \bar{u}_1 \beta_{13} f_1^{out} + (1 - \bar{u}_1)\beta_{23} f_2^{out} - \bar{u}_3 f_3^{out} =$$

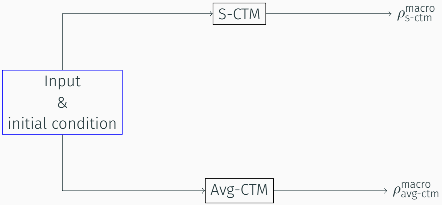
$$= \bar{u}_1 \beta_{13} \min\left\{D_1, \frac{S_3}{\beta_{13}}, \frac{S_4}{\beta_{14}}\right\} + (1 - \bar{u}_1)\beta_3 \min\left\{D_2, \frac{S_3}{\beta_{23}}, \frac{S_4}{\beta_{24}}\right\}$$

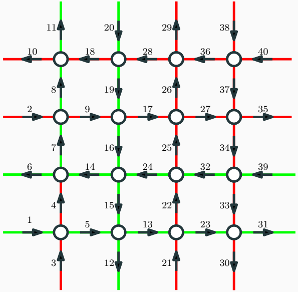
$$- \bar{u}_2 \min\left\{D_3, \frac{S_5}{\beta_5}, \frac{S_6}{\beta_6}\right\}$$

Consistency of the model

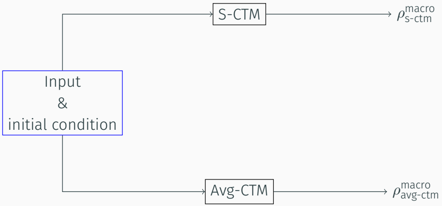
- Total outflow never bigger than inflow
- Inflow/outflow respect the Demand & Supply paradigm

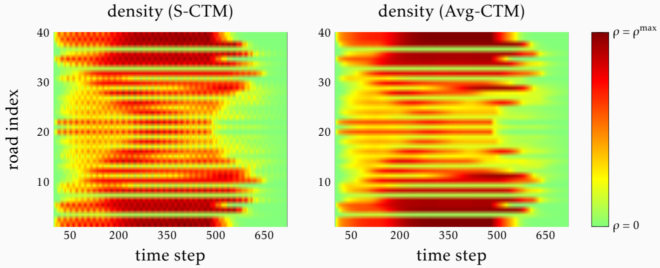
Avg-CTM — Macroscopic validation





Results — Macroscopic validation

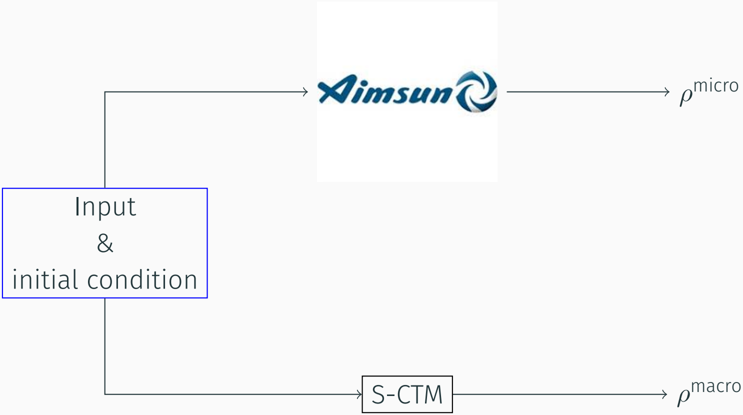




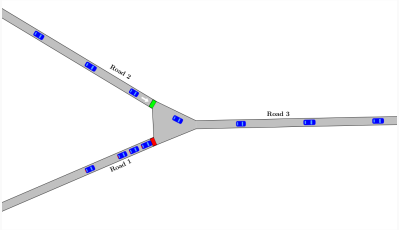
S-CTM — Microscopic validation

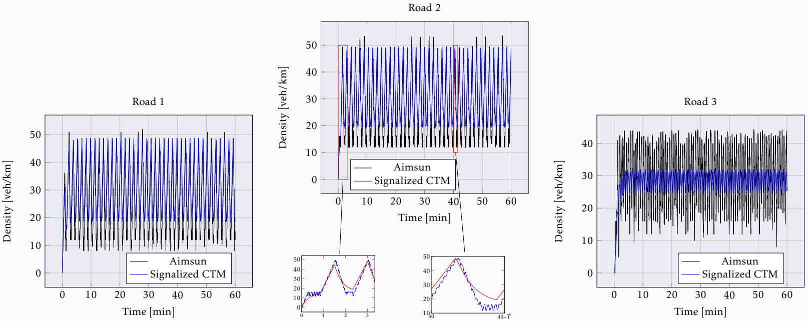
Validation objective

How close is the signalized CTM to a realistic behavior (e.g., microscopic models)?



S-CTM — Microscopic validation





Comments

- The intrinsic complexity of the most descriptive traffic models (microscopic) makes them unsuitable for control synthesis
- We rely on macroscopic representations, starting off with the CTM and extending it to account for signalized intersections (S-CTM)
- The binary dynamics of traffic lights can be approximated with an average trajectory (Avg-CTM) that proves in practice to be a good approximation of the former
- The Avg-CTM is a smoother model, suitable for control design with duty cycle as control variables

Remaining question

How to design a control for such a model?

Control history

- **1772** - Manual of traffic flow control
- **1866** - Heritage from railway systems
- **1960** - Driver Aided Information and Routing (DAIR)
- **1990** - Loop detectors + Message signs
- **1991** - ALINEA
- **2000** - Hierarchical control
- **2010+** - Vehicle focus/ MAAS


GMR DAIR SYSTEM

Driver Aid, Information & Routing

Highway Communications for Safety

TODAY'S COMPLEX ROADWAYS, increased vehicle speeds, and heavy traffic intensify the driver's need for frequent directions and information. DAIR meets this need for increased safety and driving enjoyment with a simple, low-cost communications system. Features include two-way radio communication, a display panel with warnings to supplement upcoming traffic signs, messages about the road ahead, and an in-car route direction indicator.

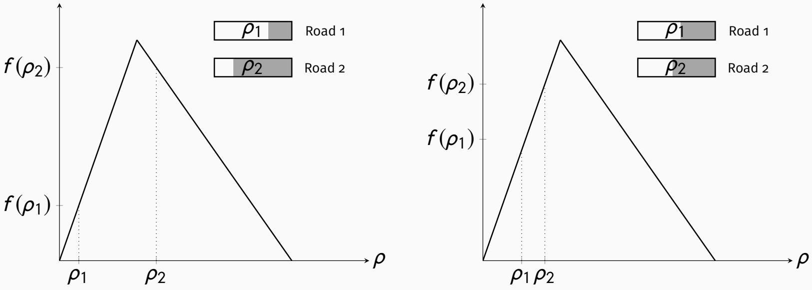
Picture yourself on a long, lonely segment of highway. It's a rainy night, and you're trying to stretch your gasoline to the next service station.

Sure enough, the engine begins to sputter. You coast to the shoulder and stop. Your wife, who suggested a stop at the last town, gives you the special look she saves for such occasions.

It's a bad situation at best. But if the car is equipped with GMR DAIR, you simply dial a series of numbers on a small instrument panel. The message is received

The Visual Sign Minder alerts Clark Quinn with a "beep" as it repeats an upcoming Stop sign on the display panel inside the car. The inset shows the panel with all features lighted for a better view. The DAIR console fits between the seat and the dashboard next to the driver.

Control objective



Objectives of u

- Maximize the throughput of the network.
- Homogenize the use of the network (when possible)

Traffic performance metrics

Total travel distance:

Full amount of distance travelled by all vehicles in the network

$$\mathrm{TTD}(t) = \sum_{k=0}^{\lfloor t/T_s \rfloor} \sum_{i \in \mathcal{R}} f_i(kT_s)$$

Density balancing

Notion on how uniformly vehicles spread in the network. Ideally *uniform* vehicle distribution.

$$\mathrm{Bal}(t) = \sum_{k=0}^{\lfloor t/T_s \rfloor} \sum_{i \in \mathcal{R}} \sum_{j \in \mathcal{N}_i^+} (\rho_i(kT_s) - \rho_j(kT_s))^2 = \sum_{k=0}^{\lfloor t/T_s \rfloor} \rho'(kT_s)\mathcal{L}\rho(kT_s)$$

where

$$\mathcal{L}_{ii} = |\mathcal{N}_i|, \mathcal{L}_{ij} = \begin{cases} -1 & \text{if } j \in \mathcal{N}_i \\ 0 & \text{elsewhere.} \end{cases}$$

Traffic performance metrics

Traffic signal regularization

This intends to reduce strong changes in the control cycle of the traffic signal.

$$R(\bar{u}(t, T)) = \|\bar{u}(t) - \bar{u}(t - T)\|_2^2$$

Note: T represents the full signal cycle period.

Other traffic indicators:

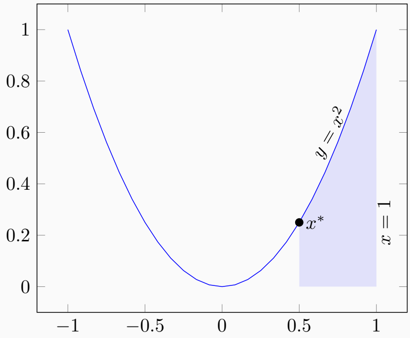
- Service of demand
- Total travel time
- Queues length
- Stop time

Tools to improve traffic indicators

Optimization

In order to optimize the *cost* $f(x)$, the value of x should be found, while respecting the constraints

$$x^* = \begin{array}{ll} \min\limits_{x} & f(x) \\ \text{s.t} & x \geq 0.5 \end{array}$$



Design & Constraints

- Duty cycle $\bar{u}$ as control variable
- Maximize network throughput + minimize the balance
- Model-based predictions computed by using the Avg-CTM

Optimal criteria

$$\min_{\bar{u}} Bal\left(\bar{u}(t)\right) - TTD\left(\bar{u}(t)\right) + R\left(\bar{u}(t, T)\right)$$

Control problem formulation

The traffic signal control problem then consists in finding a solution to the following optimization problem:

$$\min_{\bar{u}} \quad \sum_{k=1}^{K} \left(k_{\text{bal}} \bar{\rho}'(t + kT_s) \mathcal{L} \bar{\rho}(t + kT_s) - k_{\text{ttd}} \sum_{i \in \mathcal{R}} f_i(t + kT_s) \right) + \| \bar{u} - \bar{u}(t - T) \|_2^2$$

$$\text{subj. to: } \forall i,\ \forall t \quad 0 \leq \bar{u}_i(t) \leq 1$$

$$\sum_{j \in \mathcal{N}_i^-} \bar{u}_j(t) \leq 1.$$

Control problem characteristics

- Minimize density balancing
- Maximize total travel distance
- A convex formulation is achievable when $K = 1$

Convexity of the formulation — ideas

- One step ahead density:

$$\bar{\rho}_i(t+T_s) = \bar{\rho}_i(t) + \frac{T_s}{L_i}\left(\sum_{j\in\mathcal{N}_i^-} \beta_{ji} f_j^{\text{out}}(t)\bar{u}_j - \bar{u}_i f_i^{\text{out}}(t)\right) \tag{1}$$

$$\bar{\rho}(t+T_s) = H(t)\bar{u} + c(t) \tag{2}$$

- Bal + regularization:

$$\bar{u}^T Q \bar{u} + p^T \bar{u} \tag{3}$$

where

$$Q = k_{\text{bal}} H'(t)\mathcal{L}H(t) + I, \tag{4}$$

$$p = \left(2k_{\text{bal}} c^T(t)\mathcal{L}H(t) - \bar{u}'(t-T)\right)^T. \tag{5}$$

Convexity of the formulation — ideas

- Problem formulation (equivalent):

$$\begin{aligned} \min_{\bar{u}} \quad & \bar{u}' Q \bar{u} + p' \bar{u} - k_{\text{ttd}} \mathbf{1}' f(\bar{u}) \\ \text{subj. to, } \forall i: \; & l_i \leq \bar{u}_i \leq 1 \\ & \sum_{j \in \mathcal{N}_i^-} \bar{u}_j \leq 1 \end{aligned}$$

- The total travel distance can be expressed as a function of $\bar{u}(t)$:

$$\begin{aligned} f_i(\bar{u}) = \min \Bigg(& v_i \Big(\bar{\rho}_i(t) + \frac{T_s}{L_i} \Big(\sum_{j \in \mathcal{N}_i^-} \bar{u}_j \beta_{ji} f_j^{\text{out}}(t) - \bar{u}_i f_i^{\text{out}}(t) \Big) \Big), \\ & w_i \Big(\rho_i^{\max} - \bar{\rho}_i(t) - \frac{T_s}{L_i} \Big(\sum_{j \in \mathcal{N}_i^-} \bar{u}_j \beta_{ji} f_j^{\text{out}}(t) + \bar{u}_i f_i^{\text{out}}(t) \Big) \Big) \Bigg). \end{aligned}$$

Convexity of the formulation — ideas

- Problem formulation (relaxed):

$$\min_{\bar{u},y\geq 0} \quad \bar{u}'Q\bar{u} + p'\bar{u} - k_{\text{ttd}}\mathbf{1}'y$$

$$\begin{aligned}
\text{subj. to, } \forall i:\ & l_i \leq \bar{u}_i \leq 1 \\
& \sum_{j\in\mathcal{N}_i^-} \bar{u}_j \leq 1 \\
& y_i \leq v_i\Bigg(\bar{\rho}_i(t) + \frac{T_s}{L_i}\Big(\sum_{j\in\mathcal{N}_i^-} \bar{u}_j f_j^{\text{out}}(t) - \bar{u}_i f_i^{\text{out}}(t)\Big)\Bigg) \\
& y_i \leq w_i\Bigg(\rho_i^{\max} - \bar{\rho}_i(t) - \frac{T_s}{L_i}\Big(\sum_{j\in\mathcal{N}_i^-} \bar{u}_j f_j^{\text{out}}(t) + \bar{u}_i f_i^{\text{out}}(t)\Big)\Bigg).
\end{aligned}$$

Comments

Observations

- Pros:
  - The relaxed formulation is provably *equivalent* to the original problem
  - Convex problems are generally considered ”easy” to solve
- Cons:
  - Although efficient, the solution does not scale well with the size of the network

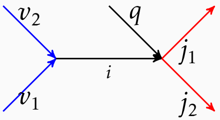
Remaining question
How to design scale the control to large traffic networks?

Scalability requirements

- Decomposition in subproblems
- Communication of efficient information
- Iterative and distributed algorithm
- Optimality of the distributed algorithm

Scalability - Communication graph

Minimum information required to determine the solution of a single traffic light $\bar{u}_i$



Set of roads that can "talk" to i:

$$\mathcal{S}_i = \mathcal{N}_i^- \cup \mathcal{N}_i^+ \cup \mathcal{I}_i,$$

where

$$\mathcal{I}_i = \{q : \mathcal{N}_q^+ \equiv \mathcal{N}_i^+\}.$$

Why?

$\mathcal{N}_i^-$ and $\mathcal{N}_i^+$ are needed for density prediction. $\mathcal{I}_i$ is needed for constraints over traffic lights.

Scalability - Problem decomposition

Problem set-up (e.g., problem i):

$$
\begin{aligned}
\min_{\bar{u}} \quad & \sum_{i \in \mathcal{R}} g_i\big(\bar{u}^{(i)}_{[p \in \mathcal{S}_i]}\big) \\
\text{s.t.} \quad & \bar{u}^{(i)}_{[p \in \mathcal{S}_i]} \in \mathcal{X}_i, \; \forall\, i \in \mathcal{R}, \\
& \bar{u}^{(i)}_i = \bar{u}^{(p)}_i, \quad \forall\, i \in \mathcal{R}, \forall\, p \in \mathcal{S}_i \setminus i \\
& \bar{u}^{(i)}_p = \bar{u}^{(p)}_p, \quad \forall\, i \in \mathcal{R}, \forall p \in \mathcal{S}_i \setminus i.
\end{aligned}
$$

where $\bar{u}^{(i)}_p$ is the copy of the global variable $\bar{u}_p$ kept in memory locally by subproblem i.

Why?

Each subproblem needs to be self–contained: variables will be requested from others according to the communication graph

Distributed algorithm

Partial (separable) Lagrangian:

$$L = \sum_{i \in \mathcal{R}} L_i = \sum_{i \in \mathcal{R}} g_i\big(\bar{u}_{[p \in \mathcal{S}_i]}\big) + \bar{u}_i^{(i)} \sum_{p \in \mathcal{S}_i \setminus i} \big(\lambda_i^{(i,p)} - \lambda_i^{(p,i)}\big) + \sum_{p \in \mathcal{S}_i \setminus i} \bar{u}_p^{(i)} \big(\lambda_p^{(i,p)} - \lambda_p^{(p,i)}\big).$$

Initialization. Set $k = 0$. Create local variables for each subproblem

Primal update. Update primal variables $\bar{u}_p(k+1)$ by minimizing the i-th term of the partial Lagrangian

Transmission. Send primal local variables to requiring neighbors $p \in \mathcal{S}_i$, and collect the most recent values of $\bar{u}_i^{(p)}$, $\bar{u}_p^{(p)}$ from them

Dual update. Update the Lagrangian multipliers with a gradient update of step α

Stop condition. If the solution has numerically stabilized then stop, otherwise increment k and go to 1

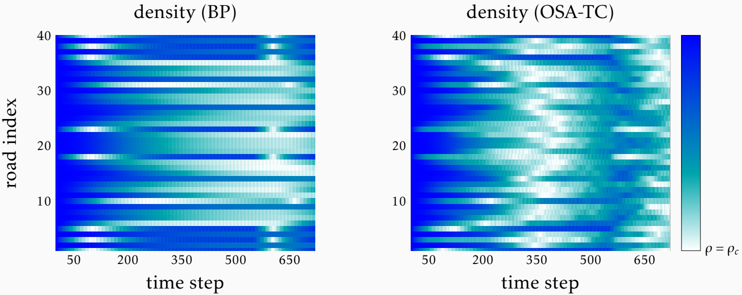
Numerical simulations

Two-fold evaluation

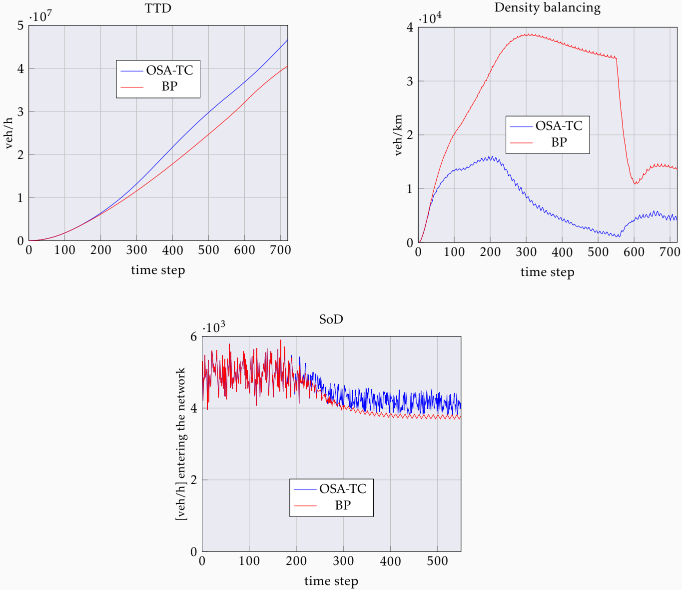
- Time to convergence of the distributed algorithm
  - Number of iteration before the iterative procedure stabilizes, measured in different numerical scenarios
- Traffic performance
  - Measure of traffic metrics, both macroscopic and microscopic
- Simulation setup
  - Several network dimensions (from 4 to 180 roads)
  - Initial state randomly selected (in 300 simulations)

Traffic performance

- Comparisons with a best practice (BP) schedule, chosen to optimize the statistical traffic behavior



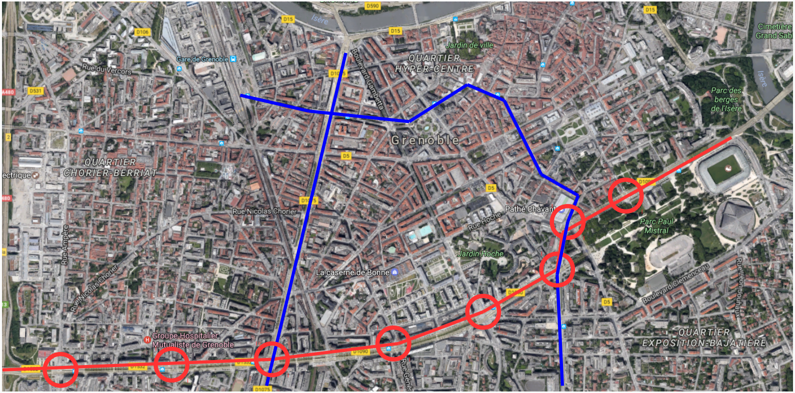
Traffic performance



Miscroscopic simulation

Index	Scenario 1		Scenario 2	
	BP	OSA-TC	BP	OSA-TC
Travelled distance [km]	23396	26471	19772	17003
Travel time [h]	1775	1462	1955	1583
Mean queue [veh]	496	441	627	564
Stop time [sec/km]	123	97	172	139

Scenario description - Case study Grenoble

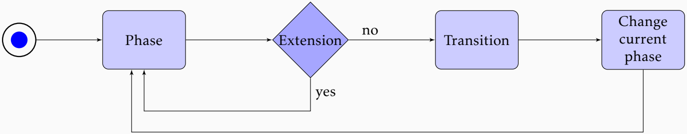


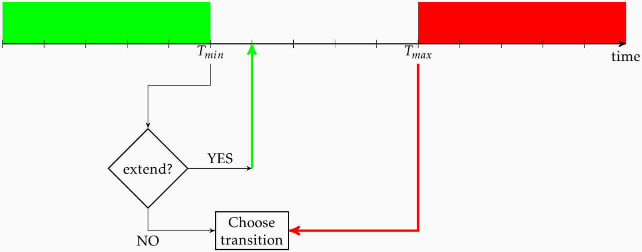
Scenario description

General characteristics

- Intersection are equipped with several on–off detectors
- Every intersection is controlled by a single–intersection controller
- A fusion of data from GPS and magnetic detectors is used in order to say to the controller how far the trams are
- Several constant parameters (min/max green time, amber time) are decided as function of the speed limit, the number and size of lanes, the size of the intersections

Grenoble traffic lights plan (plan de feux)





Numerical comparisons

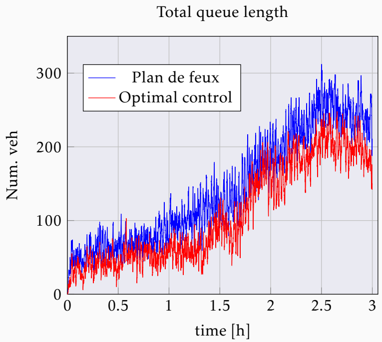
General characteristics - Light traffic plan

Set up:

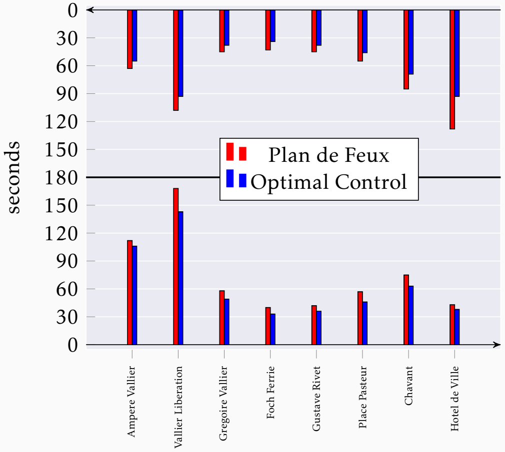
- Traffic lights plan virtually replicated into Aimsun
- Input flow and supply estimated by real data extracted by loop detectors...
- ...as well as split ratios at intersections...
- ...from 7am to 10am
- Adaptation of the OSA-TC to fit this scenario's technological requirements
- A posteriori analysis of on–line measured data (within Aimsun)

Numerical results

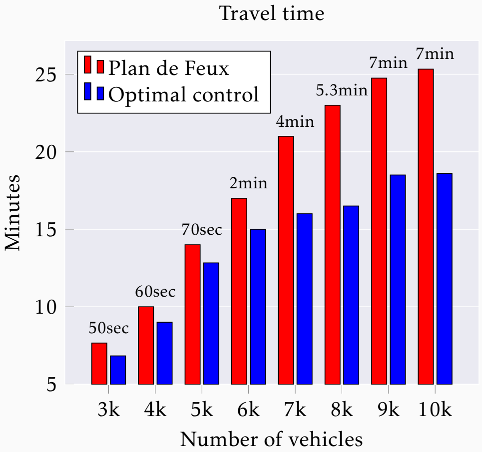
Index	Plan de feux	Optimal control
Input flow [veh/h]	6097	6151
Mean queue [veh]	152	113
Stop time [sec/km]	110	83
TTD [km]	16307	16411
TTT [h]	794	680
Veh. waiting [veh]	333	240



Numerical results



Numerical results

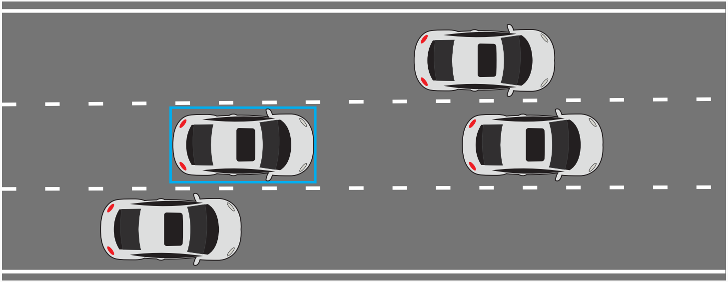


Final comments

- We have designed an optimization–based algorithm to control green split of traffic lights
- The control algorithm is applicable to large cities thanks to its scalability property
- Numerical simulations show the improvements w.r.t. standard fixed–time policies
- The algorithm can be adapted to real scenarios and in simulations it performs better than ”real world” traffic lights scheduling algorithms

Connected vehicles

Classical Vehicles

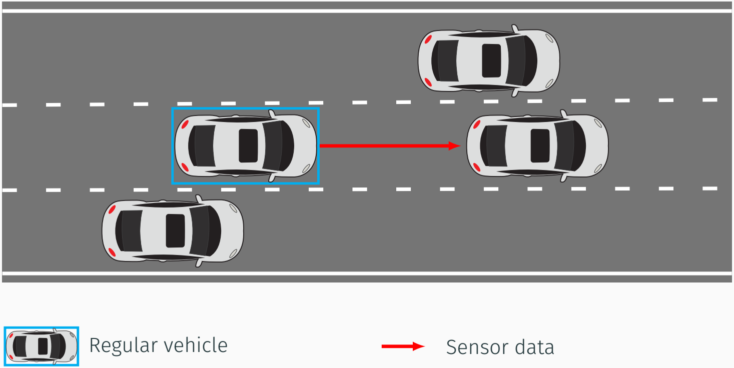



Regular vehicle

Features

- Perception only from the driver's perspective
- Local information only available
- Poor accuracy on observed data

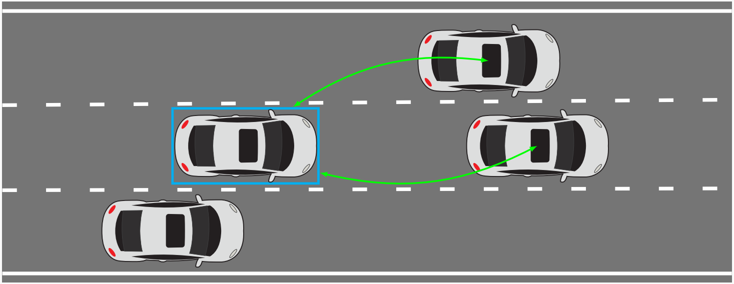
Equipped Vehicles



Features

- Improved perception via radar sensors
- Speed regulation via Adaptive Cruise Control (ACC)
- Only longitudinal information

Connected Vehicles - V2I



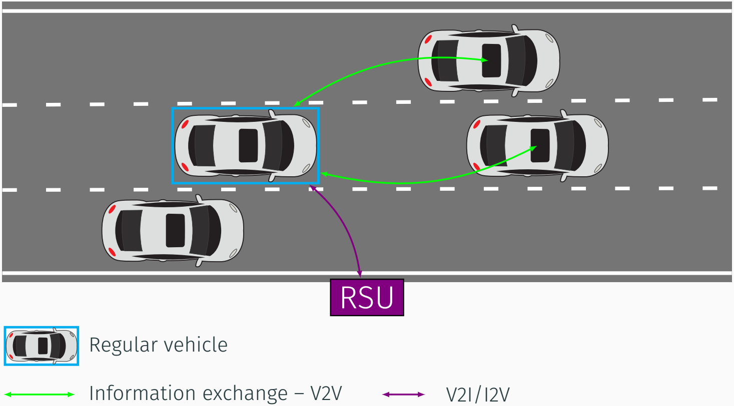

Regular vehicle


Information exchange – V2V

Features

- Improved perception via communication with other vehicles
- Accuracy on information depend on external sensors
- Longitudinal + lateral information

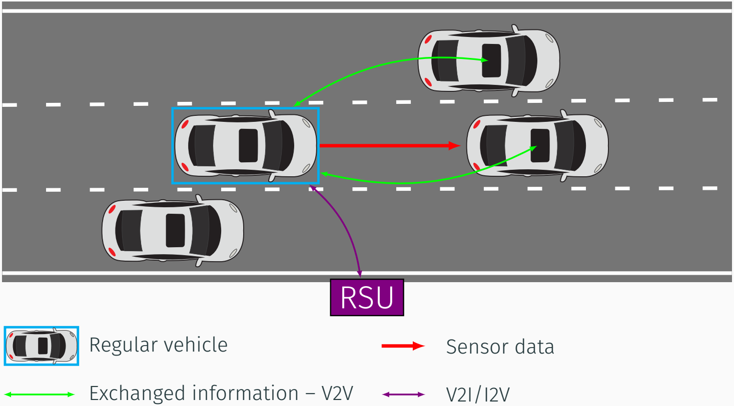
Connected Vehicles - V2I



Features

- Non local information from infrastructure
- Local information (longitudinal + lateral)
- Accuracy limited by data provided via V2V/V2I

Smart Vehicles



Features

- Local and non local information leveraged by V2X communications
- Improved possibility for better automation (ACC/CACC)

Smart Vehicles

What could be the potential impact of those connected vehicles?

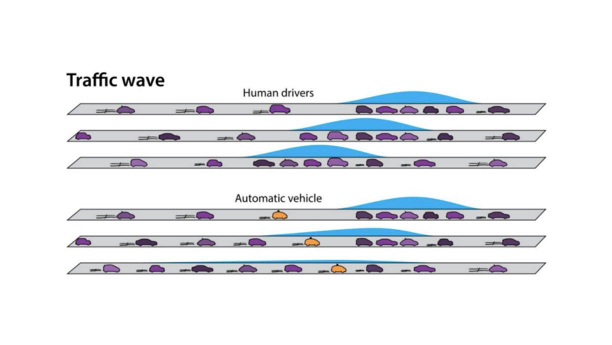
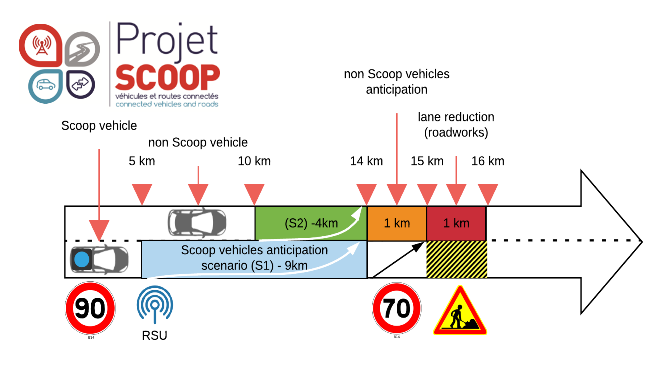


Figure 7: Impact of connected vehicles on traffic

Features

- They contribute as *sensors* for current traffic condition
- They can adapt to traffic conditions known in advance

SCOOP Scenario



Sensitivity analysis

- Emission distance of broadcasted messages
- Speed drop message
- Demand
- Market penetration rate

Results in terms of Market Penetration Rate

Spatial distribution of congestion is better achieved at higher *penetration rates*, effects of works are better avoided. Nevertheless, increasing the *penetration rate* may also have an impact on the *network throughput*.

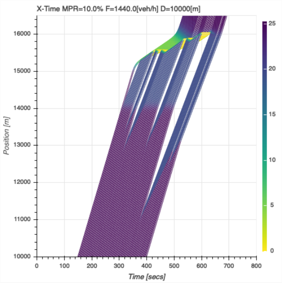


Figure 8: MPR = 10%

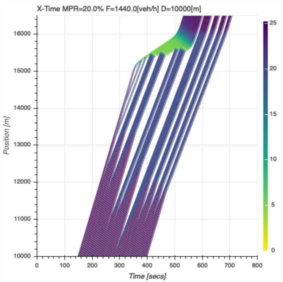


Figure 9: MPR = 20%

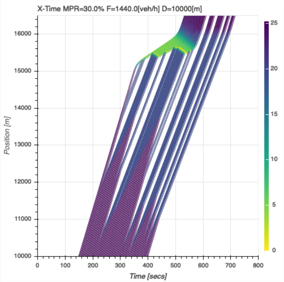


Figure 10: MPR = 30%

Potential impact of Connected vehicles

Earlier messages may potentially increase the impact of CO_2 emissions. The *market penetration rate* is an important factor that may also reduce the impact on CO_2 emissions.

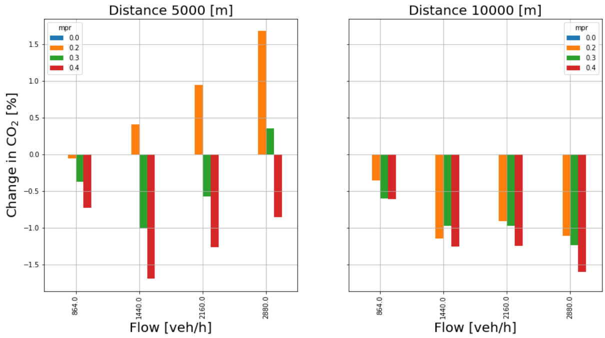


Figure 11: Relative change in CO_2 emissions with SCOOP technolgies

Conclusions & Observations

To takeaway

- Introduction of V2V/V2I may have a potential impact on traffic safety, road operation efficiency and emissions.
- Speed drop policies may conduct to optimal absorption of traffic effects
- Market penetration rate itself constitute an important factor for potential environmental impacts.

Current research directions

- Analyzing the impact of delayed acceptation on policies and the effect of anarchy.
- Non-uniform market penetration rates.

Vehicle platooning

Dynamic traffic assingment - Problem

Questions
How to assign the flow at time t?

Some key principles[a]:

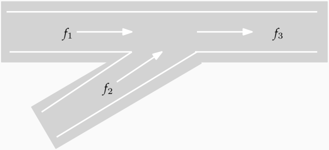
1. Flow conservation
2. Flow maximization
3. Infrastructure limitations
4. Set/calibrate drivers' preferences

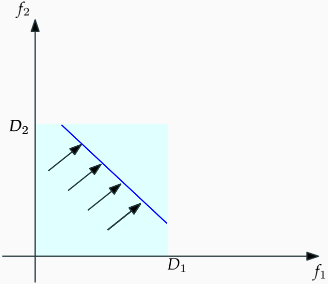
[a] Giuseppe Maria Coclite and Benedetto Piccoli. "Traffic Flo
Society for Industrial and Applied Mathematics 36.6 (Feb. 20
0036-1410. arXiv: 0202146 [math].

Unless the drivers preferences are well known the solution to the DTA problem is undetermined.

Let consider the case:

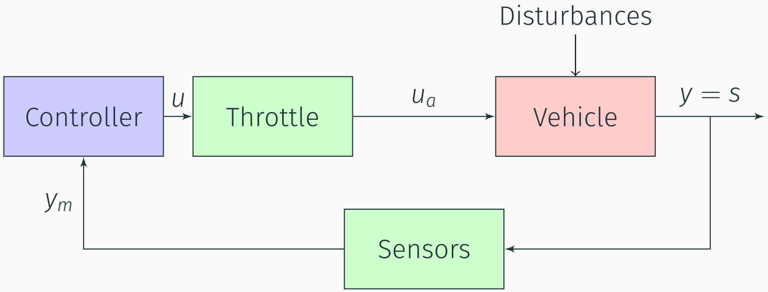
$$\max_{f_i} \quad \sum f_i$$
$$\text{s.t} \quad f_1 \le D_1$$
$$f_2 \le D_2$$
$$f_1 + f_2 \le S_3$$





Solution
In general the dynamic traffic assingment problem has multiple values f_1, f_2 that may satisfy the problem constraints.

Control of vehicle distance in vehicles (ADAS)



- u - Required acceleration
- u_a - Gas pedal
- y - Inter vehicle distance

Objective

- Regulate the headway space between two vehicles.
- Adapt to dynamic condition of the leader.

Context on vehicle platooning

Truck platooning has some ideas in mind:

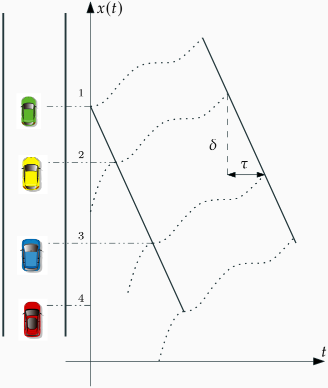
- **Objective**: Improve fuel consumption in trucks
- **Traffic issues**:
  - String stability $\rightarrow$ flow stability.
  - Interactions at network discontinuities $\rightarrow$ Capacity drop.

There however still some concerns regarding interaction between them and the reality

Objective

The main objective today is to propose a strategies for promoting Connected & Automated Vehicles maneuvers at network discontinuities.

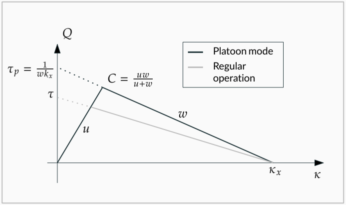
Human Driven - Car following model



$$x_i(t) = \min(x_i^F(t), x_i^C(t))$$

$$\begin{cases} x_i^F(t) = x_i(t-\tau) + u\tau \\ x_i^C(t) = x_{i-1}(t-\tau) - \delta \end{cases}$$

- Truck properties
  - L Vehicle's length
  - u Free flow speed
  - κ_x Maximum density
- Platoon properties
  - N Number of trucks
  - g_t Time gap policy
- Time headway: $h^p = g^t + L/u$



Low speed insertion Problems[4]

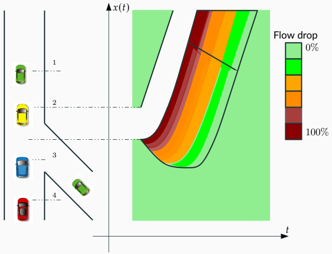


Figure 12: Low speed wave propagation

- Low safety
- Shockwave initiation
- Transition period until equilibirum
- This may create capacity drop

Proposal
It is necessary to anticipate for truck platoons to anticipate these maneuvers.

[4] Aurélien Duret, Jacques Bouffier, and Christine Buisson. “Onset of Congestion from Low-Speed Merging Maneuvers Within Free-Flow Traffic Stream”. In: *Transportation Research Record: Journal of the Transportation Research Board* 2188 (2011), pp. 96–107. ISSN: 0361-1981.

Truck platoon models near a merge

Assumption — V2V/V2I full connectivity

Objective — Safety at the merge condition, + smoothed traffic in main lane/ carrigeway

Anticipated maneuver

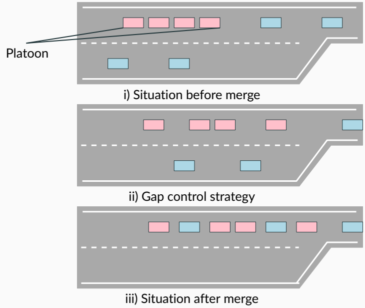
Detection	Measurement / detection of vehicles far upstream
Yielding	Coordinated deccelearation between all trucks.
Insertion	Smooth insertion

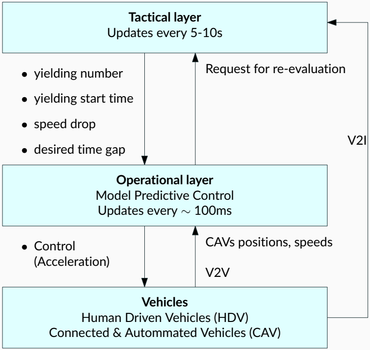
Maneuver execution

The maneuver is executed via a bi-level control strategy[5]:

Tactical layer Takes decision at the traffic level.

Operational layer Operates vehicles and control its acceleration.





[5] A Duret, A Ladino, and M Wang. "Hierarchical multi-injection strategy and platoon manoeuvres at network junctions". In: *2nd Symposium on Management of Future Motorway and Urban Traffic Systems*. Ed. by EU. Vol. 2. Ispra, 2018, pp. 11–13.

Important aspects in maneuver executions

This maneuver can be executed in multiple ways,

- Designed focused on trajectory planning problem.
- Mixed traffic. It is a key important factor for the controllability of the system.

Inputs

T_m merging time

X_m merging position

u merging speed

Parameters

ε maximum speed drop

$a^{-/+}$ maximum acceleration.

Decision variables

i Truck index

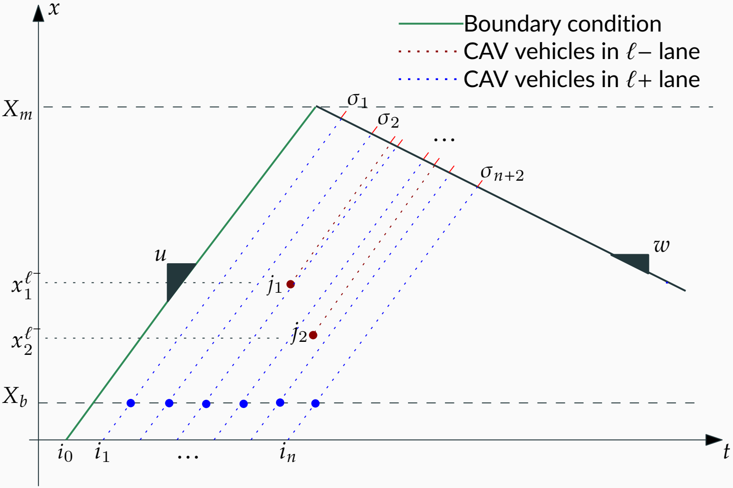
T_a anticipation time

Mixed traffic assumption

Regarding the mixed traffic $w = \underbrace{\delta_p/\tau_p}_{\text{CAV}} = \underbrace{\delta/\tau}_{\text{HDV}}$

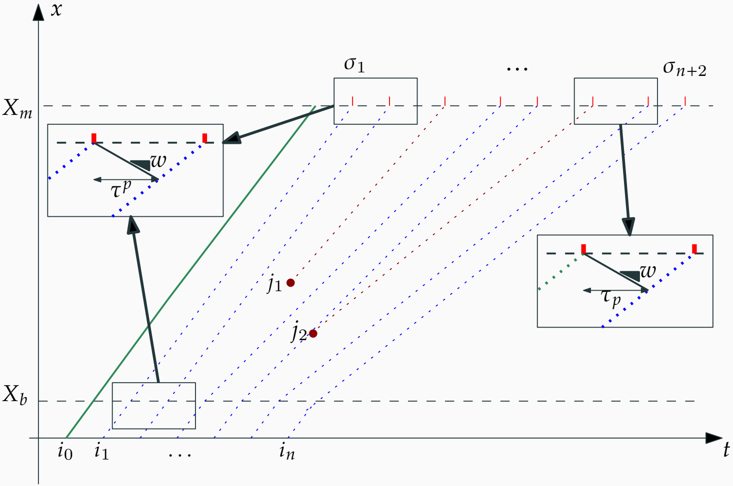
Vehicle merging case I: CAV environment

Before

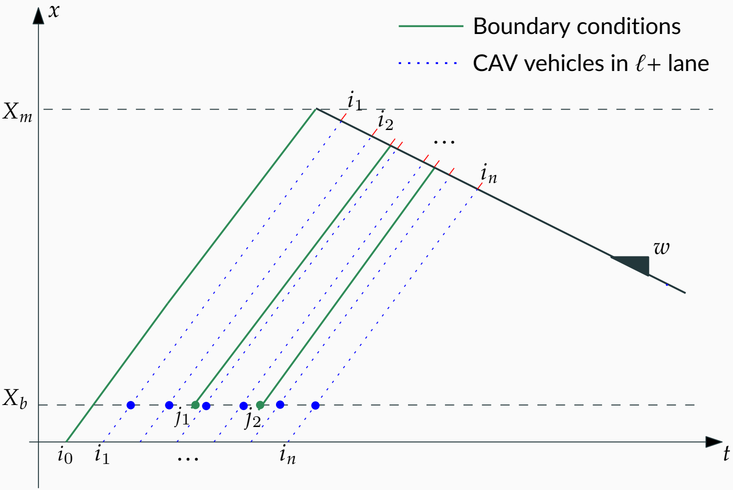


Vehicle merging case I: CAV environment

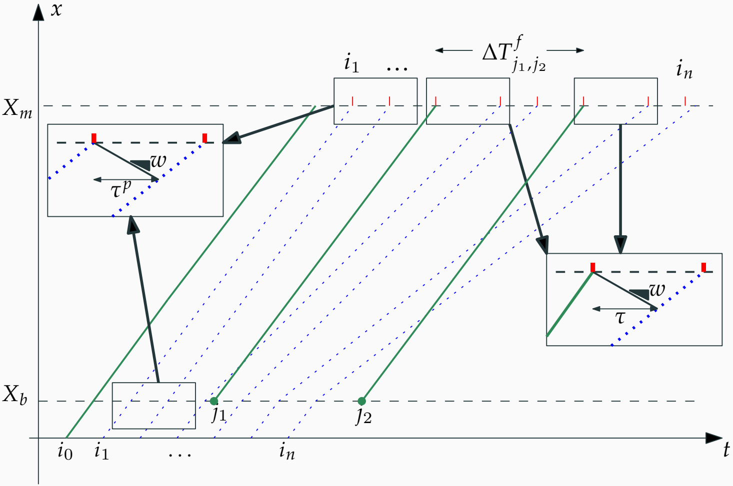
After



Before


x
Boundary conditions
CAV vehicles in $\ell+$ lane
X_m
i_1
i_2
$\dots$
i_n
w
X_b
j_1
j_2
i_0
i_1
$\dots$
i_n
t

After



Vehicle merging - summary

Finding intersections with congestion wave

Let $g_k^\ell = \begin{pmatrix} x_k^\ell & t_k^\ell \end{pmatrix}^T$ if $p(g_k^\ell)$: projection to the shockwave w

$$\begin{pmatrix} p_x(g_k^\ell) \\ p_t(g_k^\ell) \end{pmatrix} = \frac{1}{u+w} \begin{bmatrix} 1 & u \\ -1 & w \end{bmatrix} \left(\begin{pmatrix} X_m \\ x_\ell^k \end{pmatrix} + \begin{bmatrix} w & 0 \\ 0 & -u \end{bmatrix} \begin{pmatrix} T_m^0 \\ t_k^\ell \end{pmatrix} \right)$$

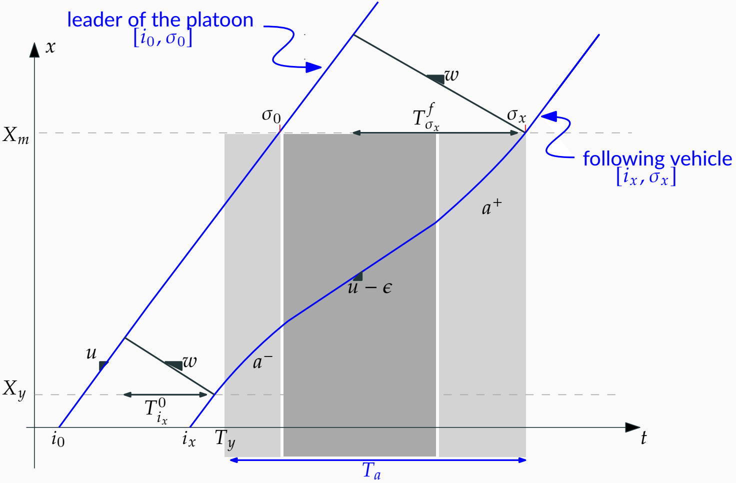
CAV

The *a-priori* order is obtained by organizing the full set of projections $\mathcal{P} = \{p(g_1^{\ell^+}), \ldots, p(g_{n+m}^{\ell^+})\}$

Mixed case

The problem in this case can be as a resource allocation problem. Vehicles can be allocated between two internal boundary conditions j_k, j_{k+1} as:

$$\eta \leq \left\lfloor \left(\Delta\tau^f_{j_k, j_{k+1}} - 2\tau \right) / \tau_p \right\rfloor + 1$$



leader of the platoon
$[i_0, \sigma_0]$
x
w
σ_0
$T^f_{\sigma_x}$
σ_x
X_m
following vehicle
$[i_x, \sigma_x]$
a^+
$u - \epsilon$
u
w
a^-
X_y
$T^0_{i_x}$
i_0
i_x
T_y
t
T_a

Transient period: Anticipation time

$$T_a = \frac{\epsilon}{2}\left(\frac{1}{a^+} - \frac{1}{a^-}\right) + \frac{u+w}{\epsilon}(T^f_{\sigma_x} - T^0_{\sigma_x})$$

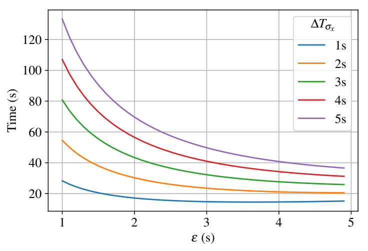
Parameter detail

Parameter Name	Description
$T^f_{\sigma_x}, T^0_{\sigma_x}$	Time shifts leader/follower
ϵ	Speed drop
u, w	Free flow/ shockwave speeds
a^+, a^-	Bounding accelerations

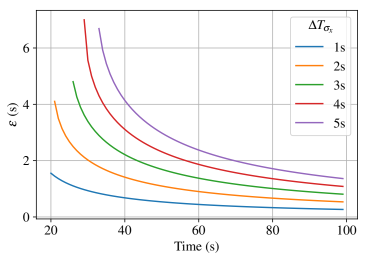
Table 1: Parameter dependence

$$T_a = \frac{\epsilon}{2}\left(\frac{1}{a^+} - \frac{1}{a^-}\right) + \frac{u+w}{\epsilon}\left(T^f_{\sigma_x} - T^0_{\sigma_x}\right)$$

Anticipation Time



Speed drop



Operational layer

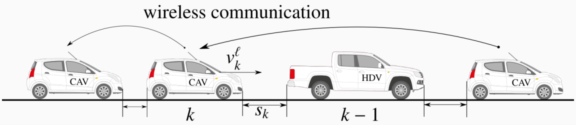


Figure 13: Mixed traffic scenario

- Available measurements for a vehicle:

  s_k Headway space

  v_k Vehicle's speed

  v_{k-1} Leader's speed

- Consideration of 3rd order linear dynamics.

$$x_i(s) = \left(\frac{1}{s}\right)\left(\frac{1}{s+b}\right)\left(\frac{1/T_e}{s+1/T_e}\right)$$

Model Predictive Control

- Integration of optimality safety, comfort + model constraints.
- Predictive feauture for CAVs until the merging position.

Vehicle's dynamics

$$\dot{\mathbf{x}}(t) = \frac{d}{dt}\begin{pmatrix}\mathbf{e}_s & \mathbf{e}_v\end{pmatrix} \rightarrow \text{LTI system} + \mathbf{a} \in \; [a^-, a^+]$$

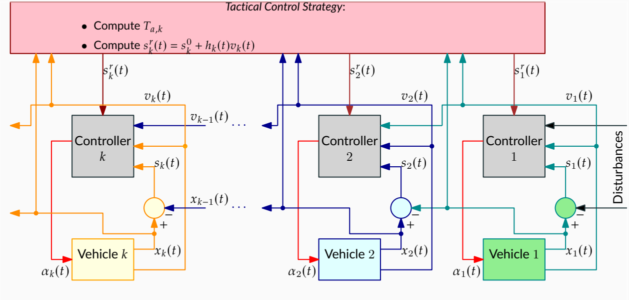
Cost function

$$\mathcal{L}(\mathbf{e}_s, \mathbf{e}_v, \mathbf{a}) = \sum_{k=1}^{n} \underbrace{c_1\left(s_k - s_k^r\right)^2}_{\text{Safety}} + \underbrace{c_2\left(v_{k-1} - v_k\right)^2}_{\text{Homogeneity}} + \underbrace{c_3 a_k^2}_{\text{Comfort}}$$

Note: For this case the control can eventually be distributed.

Full control strategy deployment

Decisions require T_a, amount of time and the desired time gap (headway space) that should be opened. Constant time gap policy $s = s_0 + hv$



Note: Gap policy at equilibrium will depend on the leader after merge.

Experimental setup

Example
Scenario

- Single merge
- 8 CAV vehicles on the main lane: Platoon in equilibrium conditions
- 2 HDV vehicles on the onramp: HDV in free flow condition

Operational layer performance

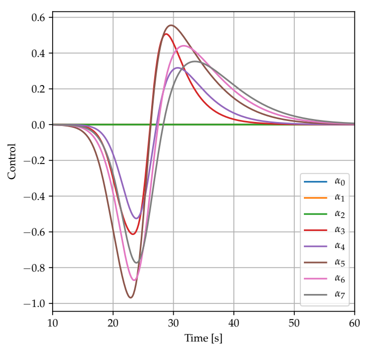


Figure 14: Control signal

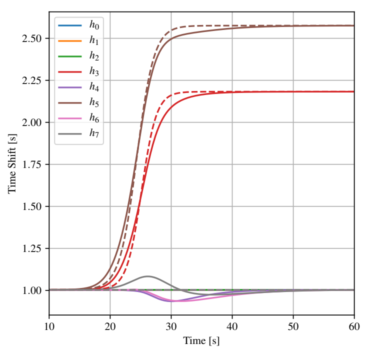


Figure 15: Time gap reference

Operational layer performance - model mismatch

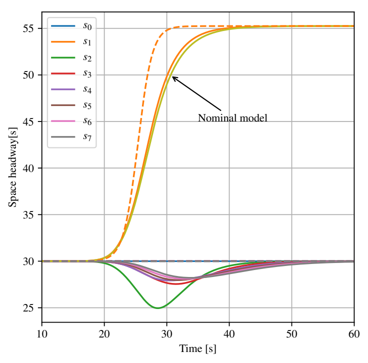


Figure 16: Vehicle's reference

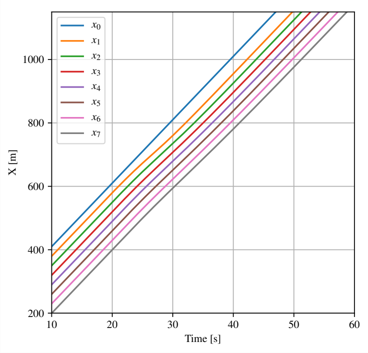


Figure 17: Space-time plane

Operational layer performance - Delay effects

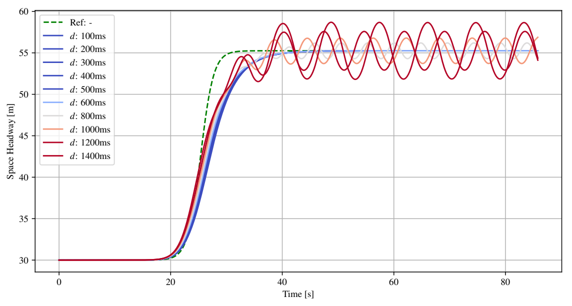


Figure 18: Vehicle's reference

Lag compensation in the actuator, via the cost function[6].

[6] M. Wang et al. "Delay-compensating strategy to enhance string stability of adaptive cruise controlled vehicles". In: *Transportmetrica B* 6.3 (July 2018), pp. 211–229. ISSN: 21680582.

Case I - CAV scenario

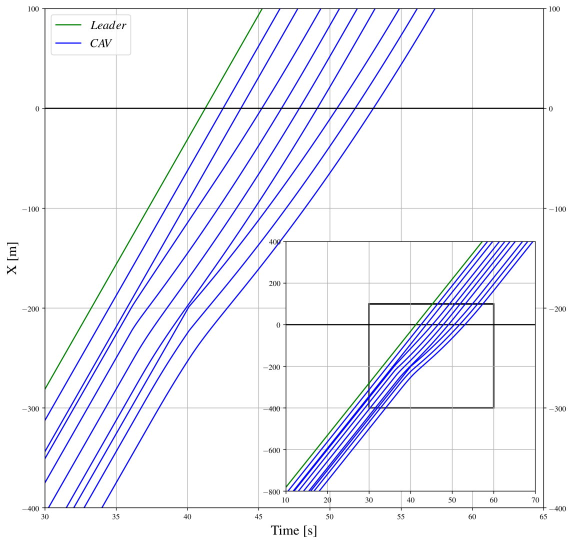


Figure 19: Mixed traffic scenario

Case II - Mixed traffic scenario

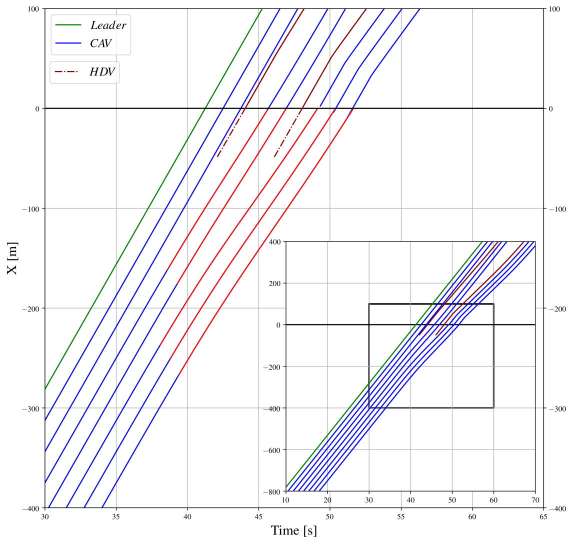


Figure 20: Mixed traffic scenario

Results

Yielding T_y and anticipation time T_a in seconds

	Full CAV			Mixed scenario		
Vehicle index i_k	T_y	T_a	$T^f_{\sigma x} - T^0_{\sigma x}$	T_y	T_a	$T^f_{\sigma x} - T^0_{\sigma x}$
i_3	37.1	9.16	1.0	37.3	8.83	0.91
i_5	39.6	9.18	0.0	36.4	13.77	1.18
j_1 (merging)	34.4	8.60	0.86	N/A	N/A	N/A
i_7	37.9	13.33	1.0	N/A	N/A	N/A
j_2 (merging)	38.0	11.99	0.81	N/A	N/A	N/A

Table 2: Vehicle index to be relaxed - Anticipation times

Conclusions & Observations

To takeaway

- Bi-level controllers: Flexible, suitable for integration.
- A method to safely split vehicle/truck platoons.
    - Safe + comfortable gap
    - Smooth trajectories
- A solution for low speed insertions empowered by anticipation.
- Formulation within an optimal framework.

Open problems

- Large flow considerations, in particular the combination.
- Merging point $\rightarrow$ Merging zones.
- Uncertainty within the tactical layer.

Questions?

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