FROM CONNECTED AND AUTONOMOUS VEHICLES CONTROL TO VEHICULAR TRAFFIC CONTROL, A MULTI-SCALE PERSPECTIVE

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### CREDITS

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| **Annual Reviews in Control** | Traffic control for freeway networks with sustainability-related objectives: Review and future challenges | Volume 48, 2019

C. Pasquale, S. Siri, S. Sacone, A. Ferrara

| **Transportation Research Part C: Emerging Technologies** | A variable-length Cell Transmission Model for road traffic systems | Volume 97, 2018

C. Canudas-de-Wit, A. Ferrara

| **SIAM Journal on Applied Mathematics** | A macroscopic model for platooning in highway traffic | Volume 80, 2020

G. Piacentini, P. Goatin, A. Ferrara


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**Other recent works with:**

Kalle Johansson, Giulia Piacentini, Mladen Čičić
Efficient management of road traffic networks: crucial in all the developed countries

Growth in the number of vehicles:

- increase of congestion phenomena
- increase of pollution and huge waste of time

Photo Credit: Camilla Bastianon, my daughter
MOTIVATION

- Direct road fatalities are strictly related to intense and not well regulated vehicular traffic

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European Commission - Fact Sheet

2018 Road safety statistics: what is behind the figures?

Brussels, 4 April 2019

The European Union has some of the safest roads in the world […]

Road fatalities in the EU by transport mode in 2017
(Credits: Antonella Ferrara; Source of data: EC)
Indirect Fatalities

Number of deaths which can be attributed to air pollution

Source: 2018 World Health Organization (WHO) #UnitedNations’ health agency
WHAT CAN CONTROL EXPERTS DO?
THE ROLE OF CONTROL

- New sensors, new actuators, new communication technologies
- Efficient resource-aware control strategies

Controlled Road Traffic Systems

⇒ more coordinated
⇒ more sustainable
⇒ safer

smart traffic systems
TRAFFIC CONTROL IN A NUTSHELL
WHAT DOES IT MEAN TO CONTROL ROAD TRAFFIC?

- A road traffic system is a dynamical system (complex, large-scale, etc.)
- The traffic state evolution can be influenced by designed system inputs
- Specific desired equilibria are attained
Traffic Control in a Nutshell
Which Are the Control Objectives?

### Control Objectives

- Minimization of the **Total Time Spent [veh h] (TTS)** by vehicles in the road traffic network
- Maximization of the **Total Traveled Distance [veh km] (TTD)** by vehicles in the road traffic network
- **Set-point Tracking** to maximize capacity exploitation, to penalize situations when the traffic density or the queue lengths at the on-ramps exceed given thresholds, etc.
- **Other objectives**: safety, emissions and noise reduction, energy efficiency, environmental risk mitigation, eco-driving, etc.
THE RESEARCH ON ROAD TRAFFIC CONTROL

**SCOPUS Analytics**

- **KEY (road AND traffic AND control)**
- **Selecting year range to analyze: 1980 to 2019** → 15,765 documents

Credits: Antonella Ferrara, Qualitative Plot and Pie Chart based on Scopus data
OUTLINE

- Traffic Modelling and control: classic methods
- Traffic Modelling and control: new methods
- Traffic models incorporating CAVs and their use for traffic control

Photo Credit: Antonella Ferrara
TRAFFIC MODELLING AND CONTROL: CLASSIC METHODS
- Designing controllers

it is necessary to formulate a mathematical model of the process to control
DIFFERENT MODELS FOR DIFFERENT SCALES

- Designing controllers

It is necessary to formulate a mathematical model of the process to control.

Traffic flow models

- Microscopic
- Mesoscopic
- Macroscopic

- Continuous
- Discrete

- First-order
  - Single-class
  - Multi-class
- Second-order
  - Single-class
  - Multi-class

Majorly used for traffic control design

C. Pasquale, S. Siri, S. Sacone, A. Ferrara, Traffic Control for Freeway Networks with Sustainability-Related Objectives: Review and Future Challenges, Annual Reviews in Control, 2019
THE LIGHTHILL, WHITHAM AND RICHARDS MODEL (LWR MODEL)

Macroscopic variables:
- \( \rho \) is the **density** of vehicles.
- \( v \) is the average **speed** of the flow.
- \( f = \rho v \) is the **flow**.

- Macroscopic model based on the equation of vehicles conservation
- Traffic Fundamental Diagram: the theoretical relation between flow and density in steady-state conditions

In the LWR Model \( f(\rho(x,t)) \) is a strictly concave \( C^2 \) function, \( f(0) = 0 \) and \( f(\rho_{\text{max}}) = 0 \)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial f(\rho)}{\partial x} = 0
\]


\[ \rho_i(k + 1) = \rho_i(k) + \frac{T}{L} [f_i(k) - f_{i+1}(k)] \]

**THE CELL TRANSMISSION MODEL (CTM MODEL)**

- Discretized version of the LWR model
- \( v \) is the free-flow speed
- \( \omega \) is the congestion wave speed


**Demand:**

\[
D_i(k) = \begin{cases} 
    f(\rho_i(k)) & \text{if } \rho_i(k) < \rho_{cr}, \\
    f_{\max} & \text{if } \rho_i(k) \geq \rho_{cr},
\end{cases}
\]

**Supply:**

\[
S_i(k) = \begin{cases} 
    f_{\max} & \text{if } \rho_i(k) < \rho_{cr}, \\
    f(\rho_i(k)) & \text{if } \rho_i(k) \geq \rho_{cr},
\end{cases}
\]

\[
f_i(k) = \min \{D_{i-1}(k), S_i(k)\}
\]
MERGE AND DIVERGE

In the presence of a bottleneck the discharge flow is lower than the capacity of the bottleneck.

The flow reduction is around the 5-20 %.

The CTM is not able to capture such a phenomena. An extension to model the capacity drop:
THE VARIABLE LENGTH CELL TRANSMISSION MODEL (VLM)

Macroscopic variables:
- Continuous-time lumped variables model based on three state variables only.
- Simpler than classical continuous macroscopic models.
- It captures relevant phenomena of traffic dynamics such as shock waves and rarefaction waves propagation.

\[
\begin{align*}
\dot{\rho}_f &= \frac{1}{L - l} [\varphi_{in} - \Phi(\rho_f)] \\
\dot{\rho}_c &= \frac{1}{l} [\Phi(\rho_c) - \varphi_{out}] \\
i &= \frac{\Phi(\rho_f) - \Phi(\rho_c)}{\rho_c - \rho_f}
\end{align*}
\]
OTHER MACROSCOPIC MODELS

**Asymmetric Cell Transmission Model (ACTM), different “merge” description**


**Multi-Class Versions of the CTM, different classes of vehicles (car/trucks)**


**METANET, discrete, second order**

A. Messmer, M. Papageorgiou, METANET: A Macroscopic Simulation Program for Motorway Networks, Traffic Engineering & Control 31 (1990)
CLASSICAL TRAFFIC CONTROL

TRAFFIC MODELLING AND CONTROL: NEW METHODS
A PARADIGM SHIFT: CONNECTED AND AUTOMATED VEHICLES (CAVS) WHICH ROLE IN ROAD TRAFFIC CONTROL?

Given a traffic system with mixed traffic, different possibilities to control it by controlling CAVs:

- Controlled as a macroscopic vehicular class*

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Given a traffic system with mixed traffic, different possibilities to control it by controlling CAVs:

- **Controlled as a macroscopic vehicular class**

  $$\rho_{i-1}^a(k), \rho_{i-1}^b(k) \xrightarrow{\phi_{i}^a(k)} \rho_i^a(k), \rho_i^b(k)$$

  - **Class a:** CAVs, headway $h_a$
  - **Class b:** human-driven/conventional vehicles, headway $h_b$

---

CONNECTED AND AUTOMATED VEHICLES (CAVS): WHICH ROLE IN ROAD TRAFFIC CONTROL?

Given a traffic system with mixed traffic, different possibilities to control it by controlling CAVs:

- **Controlled as a macroscopic vehicular class**

  \[ \begin{align*}
  \phi_i^a(k) & : \rho_{i-1}^a(k), \rho_{i-1}^b(k) \\
  \phi_i^b(k) & : \rho_i^a(k), \rho_i^b(k)
  \end{align*} \]

  - **Class a:** CAVs, headway \( h_a \)
  - **Class b:** human-driven/conventional vehicles, headway \( h_b \)

---

SIMULATION RESULTS

- Trend of the density with different penetration rate of CAVs.

- The effectiveness of the control increases if the penetration rate increases.

Different possibilities to control the traffic system by controlling CAVs:

- Controlled as a macroscopic vehicular class
- Controlled individually
Different possibilities to control the traffic system by controlling CAVs:

- **Controlled as a macroscopic vehicular class**

- **Controlled individually**

Balance between selfish behaviours and social optimum
Different possibilities to control the traffic system by controlling CAVs:

- Controlled as a macroscopic vehicular class
- Controlled individually
- Controlled to create formations (e.g. platoons)
CONNECTED AND AUTOMATED VEHICLES (CAVS): WHICH ROLE IN ROAD TRAFFIC CONTROL?

Different possibilities to control the traffic system by controlling CAVs:

- Controlled as a macroscopic vehicular class
- Controlled individually
- Controlled to create formations (e.g. platoons)
Platooning/vehicle formation generation to create artificial moving bottlenecks to be used as a kind of special actuators to control road traffic.
CONNECTED AND AUTOMATED VEHICLES (CAVS): WHICH MODELS FOR CONTROL DESIGN?

The different possibilities to control traffic systems by controlling CAVs require different types of models:

- **Single-scale modelling**
  - CAVs controlled as a macroscopic vehicular class

- **Multi-scale modelling**
  - CAVs controlled individually

- **Multi-scale modelling**
  - CAVs controlled to create formations (e.g. platoons)
In case of multi-scale models:

- Single CAV
- Platoons of CAVs
- Road traffic
MULTI-SCALE TRAFFIC MODELS INCORPORATING CAVs AND THEIR USE FOR TRAFFIC CONTROL
CTM FOR TRAFFIC WITH PLATOONS OF CAVS
EXTENSION OF THE CTM MODEL TO INCLUDE PLATOONS OF CAVS (I.E. MOVING BOTTLENECKS)

The dynamic state equation of $\rho$ is extended in order to consider the presence of moving bottlenecks

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{L} \left[ f_i(k) - f_{i+1}(k) \right] + \sum_{j=1}^{J} \left[ \delta^j_i(k) \frac{O^j}{L} - \delta^j_{i+1}(k) \frac{O^j}{L} \right]$$

where $O^j$ is the occupancy of the moving bottleneck $j=1,\ldots, J$,
$
\delta$ is a binary variable adopted to indicate the entrance of the moving bottlenecks in a cell.

The presence of the platoon in cell modifies the free flow speed $v$:

$$v_i(k) = \begin{cases} 
  f(\bar{v}^j(k)) & \text{if the moving bottleneck } j \text{ is in cell } i \text{ at time } k \\
  v_i^\text{free} & \text{otherwise}
\end{cases}$$
EXTENSION OF THE CTM MODEL TO INCLUDE PLATOONS OF CAVS

The dynamic state equation of $\rho$ is extended in order to consider the presence of moving bottlenecks

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where $\delta^j$ is the occupancy of the moving bottleneck $j=1,\ldots,J$, $\delta$ is a binary variable adopted to indicate the entrance of the moving bottlenecks in a cell.

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$$

where $o_j^i$ is the occupancy of the moving bottleneck $j=1,\ldots, J$,

$\delta$ is a binary variable adopted to indicate the entrance of the moving bottlenecks in a cell.

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EXTENSION OF THE CTM MODEL TO INCLUDE PLATOONS OF CAVS

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where $\delta_j^i$ is the occupancy of the moving bottleneck $j=1,\ldots, J$, $\delta$ is a binary variable adopted to indicate the entrance of the moving bottlenecks in a cell.

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$$v_i(k) = \begin{cases} \bar{v}_i^j(k) & \text{if the moving bottleneck } j \text{ is in cell } i \text{ at time } k \\ v_i^\text{free} & \text{otherwise} \end{cases}$$
MPC CONTROL

Control variable: the speed of the platoons of CAVs traveling in the traffic system

Control Problem: find the optimal control sequence $u(h), h = k...k + K_p$ that minimizes the cost function:

$$C = \beta_1 T \sum_{i=1}^{N} L_i \rho_i(k) - \beta_2 \sum_{h=k}^{k+K_p} \phi_i(k) - \beta_3 \sum_{h=k}^{k+K_p} |\rho_i(k) - \rho^{cr}|$$

- Total Travel Time
- Max the discharge flow from the bottleneck
- Density error to keep the density below its critical value
To create congestion, a temporary physical bottleneck is simulated in cell $i = 13$. It reduces the capacity to $c_{13} = 5400$ [veh/h] for $k < 540$, then it is restored to 6000 [veh/h].

For the MPC, the prediction horizon $K_p$ is 20 time steps.

During the 2 hours of simulation several CAVs enter the stretch and are controlled creating 13 platoons of 2 vehicles.
SIMULATION RESULTS

CTM no capacity drop, no control
CTM with capacity drop, no control
CTM with capacity drop, control
Even with a small number of CAVs the capacity drop effect has been strongly reduced (a higher discharge flow from the temporary physical bottleneck has been observed) → Congestion is mitigated and travel times reduced

Piacentini G., Ferrara A., Papamichail I., Papageorgiou M., 58th Conference on Decision and Control (CDC 2019), Nice, France, 2019
COUPLED PDE-ODE MODELS FOR TRAFFIC WITH CAVS (MOVING BOTTLENECKS)
The first equation of the system is the classical equation of conservation of vehicles of the LWR model. The MB is expressed as a constraint on the flow at the MB position in the third equation. $\alpha$ is MB occupancy ratio, i.e. the number lanes occupied by the MB. The last two equation describes the trajectory of the MB.

\[\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial f(\rho)}{\partial x} &= 0 \\
(\rho, x) &= \rho_0(x), \\
\frac{\partial}{\partial t} f(\rho(t, y(t)) - \dot{y}(t)\rho(t, y(t)) &\leq \frac{\alpha \rho_{\text{max}}}{4V} (V - \dot{y}(t))^2 \\
\dot{y}(t) &= \omega(\rho(t, y(t))), \\
y(0) &= y_0
\end{align*}\]

- $\rho$ is the density of vehicles.
- $v$ is the average speed of the flow.
- $f = \rho v$ is the flow.
- $\omega$ is the speed law of the MB.
- $y$ is the position of the MB.


A FIRST COUPLED PDE-ODE MODEL TO TAKE INTO ACCOUNT CAVS AS MOVING BOTTLENECKS IN A MACROSCOPIC TRAFFIC FLOW

\[
\begin{aligned}
\frac{\partial \rho}{\partial t} + \frac{\partial f(\rho)}{\partial x} &= 0, \quad (t, x) \in \mathbb{R}^+ \times \mathbb{R} \\
\rho(0, x) &= \rho_0(x), \quad x \in \mathbb{R} \\
f(\rho(t, y(t))) - \dot{y}(t)\rho(t, y(t)) &\leq \frac{\alpha \rho_{\text{max}}}{4V} (V - \dot{y}(t))^2, \quad t \in \mathbb{R}^+ \\
\dot{y}(t) &= \omega(\rho(t, y(t))), \quad t \in \mathbb{R}^+ \\
y(0) &= y_0
\end{aligned}
\]

- $\rho$ is the density of vehicles.
- $v$ is the average speed of the flow.
- $f = \rho v$ is the flow.
- $\omega$ is the speed law of the MB.
- $y$ is the position of the MB.

The MBs speeds: controlled by means of a Model Predictive Control (MPC) to reduce the overall travel time.


A second coupled PDE-ODE model has been proposed as an extension of the previous coupled PDE-ODE model for moving bottlenecks with the aim of capturing the presence of platoons of CAVs (their length can vary in time).

A SECOND COUPLED PDE-ODE MODEL

\[ \partial_t \rho + \partial_x F(t, x, \rho) = 0, \]
\[ \rho(0, x) = \rho_0(x), \]
\[ \dot{z}_u(t) = v_u(t, \rho(t, z_u(t)+)), \]
\[ z_u(0) = z_u^0, \]
\[ \dot{z}_d(t) = v_d(t, \rho(t, z_d(t)+)), \]
\[ z_d(0) = z_d^0, \]

The macroscopic traffic flow is described by means of the LWR model.

The flow \( F \) is discontinuous due to the presence of the platoon.

ODEs describing the trajectories of the initial and final points (front-end and back-end).

The length of the platoon is allowed to vary depending on the number of vehicles joining the platoon and their spacing.

\[ \dot{L}(t) = \dot{z}_d(t) - \dot{z}_u(t) = v_d(\rho(t, z_d(t)+)) - v_u(\rho(t, z_u(t)+)). \]

The platoon occupies a portion of the road, acting as a flux constraint in the interval \([z_u(t), z_d(t)]\).

The flux function can be defined as:

\[
F(t, x, \rho) := \begin{cases} 
  f(\rho) & \text{if } x \not\in [z_u(t), z_d(t)], \\
  f_\alpha(\rho) := \alpha f(\rho/\alpha) & \text{if } x \in [z_u(t), z_d(t)]. 
\end{cases}
\]

The flux is reduced in correspondence of the platoon.

\[
f(\rho) = V\rho \left(1 - \frac{\rho}{R}\right),
\]

\[
f_\alpha(\rho) = V\rho \left(1 - \frac{\rho}{\alpha R}\right).
\]

HOW TO SOLVE THE CONSERVATION LAW WITH DISCONTINUOUS FLOWS?

- The literature on conservation laws having discontinuous flux functions is vast.
- Most of the works focus only on discontinuities at fixed points in space (e.g., Andreianov, Hvistendahl Karlsen, Risebro).
- Only a few face the issue of time dependent discontinuities (our case).

Modified demand and supply

- For each cell demand and supply are defined.
- Interfaces with discontinuous flow need a special treatment.
RECONSTRUCTION STRATEGY (E.G. THE FRONT END CASE)

1. Consider the cell $i_d$ in which the front-end point of the platoon lies.

2. At each time step $k$ the density in the platoon cell $i_d$ is approximated by considering the value $\rho_l = \rho_{i_d-1}(k)$ upstream, and $\rho_r = \rho_{i_d+1}(k)$ downstream the platoon position $z_d(k)$. 
SOLUTION OF THE RIEemann problems

3. The following Riemann problem is then solved

\[
\begin{align*}
\partial_t \rho + \partial_x F(t, x, \rho) &= 0, \\
\rho(0, x) &= \rho_0(x) = \begin{cases} 
\rho_l & \text{if } x < z_d^0, \\
\rho_r & \text{if } x \geq z_d^0;
\end{cases}
\end{align*}
\]

To get the solutions \( \hat{\rho}^\alpha, \hat{\rho} \)

4. The flux at the interface is then reconstructed via a numerical method able to numerically capture non-classical shocks for the coupled PDE-ODE problems with moving constraints*

---

EVOLUTION IN TIME OF THE DENSITY
FROM THE NEW MODEL A NEW CONTROL APPROACH

**Idea:** control the speeds of the platoon downstream and upstream end-points

This results in controlling both the **SPEED** and the **LENGTH** of the platoon

\[
\dot{L}(t) = \dot{z}_d(t) - \dot{z}_u(t) = v_d(\rho(t, z_d(t)+)) - v_u(\rho(t, z_u(t)+)).
\]

CONTROL PROBLEM: MINIMIZE THE TOTAL FUEL CONSUMPTION

- MPC control approach.
- At each iteration $k$, the input $u(k) = [V_d(k)\ V_u(k)]$ is solution to:

$$\min_{u} \sum_{h=k}^{k+K_p} \sum_{i=1}^{N} TFC(\rho_i(h))\Delta x \Delta t,$$

$$L_{min} \leq L(h) \leq L_{max},$$

$$V_{d}^{min} \leq V_d(h) \leq V_{d}^{max} \quad \text{for } h = k, \ldots, k+K_p$$

$$|V_d(h) - V_u(h)| \leq c.$$
Fuel–speed curves of different vehicles are weighted and approximated via a $6^\circ$ order polynomial:

$$K(v) = 5.7 \cdot 10^{-12} \cdot v^6 - 3.6 \cdot 10^{-9} \cdot v^5 + 7.6 \cdot 10^{-7} \cdot v^4 - 6.1 \cdot 10^{-5} \cdot v^3 + 1.9 \cdot 10^{-3} \cdot v^2 + 1.6 \cdot 10^{-2} \cdot v + 0.99.$$  

$K(v)$ is re-parametrized in terms of density and multiplied by the density to get the Total Fuel Consumption (TFC): $F(\rho) = \rho K(\rho)$.

Control Problem: 

$$\min_u \sum_{h=k}^{k+K_p} \sum_{i=1}^{N} F(\rho_i(h)) \Delta x \Delta t.$$
### SIMULATION SCENARIO

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<th>Value</th>
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<tr>
<td>Length of each cell</td>
<td>250 m</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>140 km/h</td>
</tr>
<tr>
<td>Maximum density</td>
<td>400 veh/km</td>
</tr>
<tr>
<td>Capacity</td>
<td>14000 veh/h</td>
</tr>
<tr>
<td>Sampling time</td>
<td>5.76 s</td>
</tr>
<tr>
<td>Occupancy rate</td>
<td>0.6</td>
</tr>
<tr>
<td>Simulation time</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

The arriving demand, the in-flow, is equal to the capacity for the first half of the simulation, while it is zero in the second half:

\[
\begin{aligned}
    f_{in} &= \begin{cases} 
        f_{max} & \text{if } t < 0.5 \cdot T_f \\ 
        0 & \text{if } t > 0.5 \cdot T_f 
    \end{cases} \\
    f_{out} &= 0.5 \cdot f_{max} \quad \forall t \in [0, T_f]
\end{aligned}
\]
SIMULATION RESULTS: DENSITY VS TIME AND SPACE

TFC reduction (vs. no control case): 2.6%

Fuel consumption of the overall traffic flow from 27629 liters to 26903 liters, that represents a saving of 726 liters of fuel (in this small scale example).
COMPARISON WITH THE SIMPLE MB CONTROL (FIRST PDE-ODE MODEL)

CONCLUSIONS

- Traffic Modelling and control: from classic methods to new methods taking into account CAVs
- Multi-scale traffic models incorporating CAVs are needed (in this talk CTM with CAVs, and coupled PDE-ODEs)
- Their use for traffic control seems promising and worth of further investigation
THANKS TO MY CO-AUTHORS AND COLLABORATORS

THANK YOU FOR YOUR ATTENTION!