Traffic control for sustainable freeway networks

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◆ A large part of the freeway networks is not able to meet the current mobility needs → recurrent and non-recurrent congestion phenomena often occur

◆ In a sustainable vision, the transport system should enhance the social equity and ensure a safer mobility by increasing the access to services and to the most disadvantaged areas, without damaging the environment and people’s health

◆ Efficient control methodologies must aim at fully utilizing the freeway capacity with a balanced satisfaction of the occurring traffic demand in a sustainable way

◆ It is necessary to adopt suitable models and to define performance indicators (objective functions) related to safe and sustainable mobility (e.g. reduction of pollutant emissions, reduction of noise, increase of safety)
Objective of this talk is to present the state of the art and future challenges of freeway traffic control schemes explicitly dealing with sustainable issues.

A control scheme for sustainable freeway networks is characterised by prediction models and control objectives explicitly addressing:

- congestion reduction
- environmental impact reduction
- safety improvement

SURVEY PAPER:
Review and classification


TU Delft, the Netherlands

TU Crete, Greece & Univ. of Genova, Italy

Univ. of Genova, Italy & Univ. of Pavia, Italy

TU Delft, the Netherlands

Univ. of Genova, Italy & TU Delft, the Netherlands
Review and classification


Virginia Tech, USA

University of Central Florida, USA

University of Waterloo, Canada

Hungarian Academy of Science, Hungary

Shanghai Maritime University, China & Rensselaer Polytechnic Institute, Troy, USA

Southeast University, Nanjing, China
We have classified the literature according to 3 main factors:

- type of sustainable control strategy
- modelling framework
- control methodology

It is hard to make a quantitative comparison of the results provided in these papers, since they adopt different models, they consider different objectives (in terms of pollutant emission and safety indices) and they test their results on different traffic scenarios.

This suggests the need of a benchmark scenario which could be used to test and compare sustainability-oriented traffic control strategies for freeway systems.
Control strategy:
- ramp metering (one-class and multi-class)
- variable speed limits (one-class and multi-class)
- route guidance (one-class and multi-class)

Sustainable issue:
- traffic emissions
- fuel consumption
- dispersion of pollutants in the air
- safety (expected number of accidents)
Ramp metering (alone or combined with other measures): often used for sustainable goals; it may lead to long queues at the on-ramps, with a high concentration of emissions and an increase of the crash likelihood.

Pollutant emissions, their dispersion in the environment and the crash risk at the on-ramps must be explicitly considered in the definition of the ramp metering control schemes.

Variable speed limits: used in combination with ramp metering to mitigate traffic emissions and pollutant dispersion; applied alone to improve safety (by homogenising traffic conditions and limiting risky interactions among vehicles).

The effectiveness of variable speed limits in reducing crash risk depends on the level of acceptance of the recommended speed.

Route guidance strategies have been applied in freeway networks, only for environmental objectives.
The use of **multi-class control** schemes can entail higher benefits in terms of sustainability (specific control actions for each vehicle category taking into account their impact and possible priorities).

**Example** (Pasquale, Papamichail, Roncoli, Sacone, Siri, Papageorgiou, TRC 2015)

Multi-class ramp metering to reduce congestion and emissions in freeway links via nonlinear optimal control.

Simulation results: if the traffic emissions are explicitly minimised, the controller allows trucks enter the freeway without waiting at the on-ramps (trucks emissions are very high for low speeds).
The use of **multi-class control** schemes can entail higher benefits in terms of sustainability (specific control actions for each vehicle category taking into account their *impact* and possible *priorities*)

**Example** (Pasquale, Sacone, Siri, De Schutter, TRC 2017)

Multi-class combined ramp metering and route guidance to reduce congestion and emissions in freeway networks via feedback predictive controllers

The control law allows to give *priorities* (to encourage/discourage) related to the presence of a specific class of vehicle in a given link
There is a small number of papers which explicitly consider safety as control objective.

**Example** (Pasquale, Sacone, Siri, Papageorgiou, T-ITS 2018)

Based on the safety-density relation developed by Potts et al (2015), a new risk indicator is defined, specifically devised for control purposes. This indicator represents the expected number of crashes in a freeway system and in a given time horizon, obtained as a sum of two terms, related to the mainstream and the on-ramps (this latter particularly relevant when applying ramp metering control).

\[
\begin{align*}
MENC &= \sum_{k=1}^{K} \sum_{i=1}^{N} L_i \cdot \frac{s_{\text{tot}}(\rho_i(k))}{10^6} \rho_i(k)v_i(k)T \\
RENC &= \sum_{k=1}^{K} \sum_{i=1}^{N} \lambda_i^d(k) \frac{s_{\text{tot}}(\hat{\rho}_i^d(k))}{10^6} d_i(k)T + \lambda_i^r(k) \frac{s_{\text{tot}}(\hat{\rho}_i^r(k))}{10^6} r_i(k)T
\end{align*}
\]
Some works consider the optimization of multiple objectives, normally the reduction of the total time spent in combination with others.

The aim is find the trade-off among different objectives and to assess whether these objectives are in conflict or not.

Some works highlight conflicting behaviours between congestion reduction and emissions/dispersions phenomena or safety, while in other works this conflict seems negligible.

It is hard to make general statements on the conflicting or non-conflicting behaviour of sustainability versus travel times, again some benchmark scenarios could help in clarifying these aspects.
Review and classification: modelling framework

Traffic models:
- macroscopic models, of first and second order (one-class or multi-class)
- microscopic simulation

Emission/consumption/dispersion models:
- macroscopic models
- microscopic models

Safety models:
- different indicators of safety, often evaluated on the basis of real crash data

<table>
<thead>
<tr>
<th>Traffic model</th>
<th>CTM</th>
<th>METANET</th>
<th>Linearised METANET</th>
<th>Multi-class METANET</th>
<th>Fastlane</th>
<th>Microscopic simulation</th>
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<td>Fuel consumption model</td>
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<td>Safety model</td>
<td>Crash likelihood</td>
<td>Crash prediction</td>
<td>Crash risk evaluation</td>
<td>Rear-end crash risk prediction</td>
<td>Total expected number of crashes</td>
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</table>
The adopted sustainability-related model often depends on the level of detail of the adopted traffic model (or the available traffic measurements).

Traffic safety models correlate the occurrence of traffic accidents with flows or densities and neglect the impact of speed: both first-order and second-order traffic flow models are used to estimate crash risk indices.

The estimation of the pollutant emissions or the fuel consumptions depends on speeds: second-order traffic flow models seem more adequate than first-order ones when accounting for traffic emissions or fuel consumptions.

Other emission/consumption models are based on accelerations, which should be estimated from macroscopic traffic models.

Example (Pasquale, Sacone, Siri, De Schutter, TRC 2017)

Besides segmental and cross-segmental accelerations for the mainstream defined in Zegeye et al (2013), four types of accelerations are defined for the on-ramps, for:
- arriving vehicles
- waiting vehicles
- leaving vehicles with stop
- leaving vehicles without stop
Multi-class traffic flow models are adopted to estimate more accurately phenomena related with sustainability and to be included in multi-class control schemes.

Microscopic simulators allow a very accurate evaluation of traffic emissions and safety and are normally used for validation purposes (microscopic models are hardly used in predictive controllers).

The choice should of sustainability-related models should take into account not only the level of detail of the traffic model adopted but also the availability of other data required by these models.

E.g., microscopic emission models: type of vehicles, road geometry, temperature, humidity; dispersion models: wind direction, air temperature, presence of obstacles; safety models: road geometry, weather conditions, driver behavior.
**Control method:**

- feedback strategies
- optimization-based strategies (optimal control, MPC schemes)
- distributed/decentralized/event-triggered/supervisory control strategies
- other schemes

| Control method                             | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|-------------------------------------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Feedback control                          |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Feedback predictive control               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Supervisory event-triggered control       |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Decentralized event-triggered control     |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Optimal control                           |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Genetic algorithm                         |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Game theory                               |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Impact analysis                           |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Receding-horizon parametrized control     |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                                             |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
|                                             |   |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |
Review and classification: control methodology

- **Feedback control strategies**, often based on local measurements, have shown to be effective in many cases both in reducing emissions and improving road safety.

- **Optimization-based strategies** can be more effective because of their coordinated nature and because they optimize suitable objectives.

- The main drawback of optimisation-based approaches regards the **computational effort** required for real-time applications (nonlinear, non-convex, large-scale optimization problems must be solved).

**Example** (Pasquale, Anghinolfi, Sacone, S. Siri, Papageorgiou, ITSC 2016)

Comparative analysis of solution algorithms (gradient-based and derivative-free) for freeway traffic control problems.
Different control approaches have been developed to overcome the local nature of feedback controllers while guaranteeing predictive capabilities and/or optimality with acceptable computational efforts.

**Example** (Pasquale, Sacone, Siri, De Schutter, TRC 2017)

Ramp metering and route guidance controllers to reduce total travel times and emissions.

They are feedback predictive controllers, i.e. they compute the control actions on the basis of the measured state and on the prediction of the system evolution, which is run periodically.

- **Prediction models**
  - Multi-class macroscopic traffic model
  - Multi-class macroscopic emission model

- **Feedback routing controller**
  - Predicted travel time difference
  - Predicted total weighted emission difference

- **Feedback ramp metering controller**
  - Estimated demand, O/D rates
  - State measurements

- **Freeway system**
  - Demand, O/D rates
  - TOTAL TRAVEL TIME
  - TOTAL EMISSIONS

- **Controller gains selector**
  - Estimated demand, O/D rates
  - Design parameters
  - Controller gains

- **State measurements**
  - Origin link flow
  - Splitting rates

Silvia Siri  e3CAV Workshop, IFPEN, 2019
Different control approaches have been developed to overcome the local nature of feedback controllers while guaranteeing predictive capabilities and/or optimality with acceptable computational efforts.

Example (Pasquale, Sacone, Siri, Ferrara, T-CST, submitted 2019)

Hierarchical event-triggered control schemes for multi-class traffic networks to reduce travel times and emissions.

They are characterized by a low computation and communication effort of the controllers, while overcoming the limits of local controllers: the higher level includes an event-triggered logic and some prediction capabilities, at the lower level extended multi-class ALINEA controllers are applied.
New challenges in the era of CAVs

With the introduction of CAVs and of platoons in freeways, the scientific community working on freeway traffic control is focusing on

◆ evaluating the impacts on the system performance of vehicles with a high level of automation (with specific attention to the mixed-traffic case)


◆ defining new control schemes to exploit the presence of CAVs (as sensors and actuators) passing from road-based control to vehicle-based control

Thanks

Thanks for your attention!!!

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