Investigating the effects of cooperative vehicles on highway traffic flow homogenization: analytical and simulation studies

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PhD Dissertation Defense

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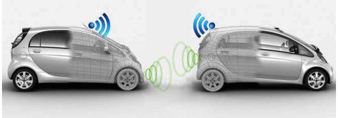
Cooperative vehicles = connected + autonomous vehicles ?

- V2X communication channels (4G, WIFI...)
- In-vehicle sensors (embedded cameras, radars...)



Introduction

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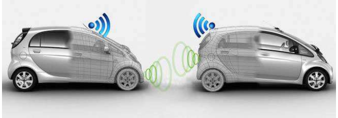
- In-vehicle sensors (embedded cameras, radars...)



Future of traffic flow ?

- Transition of a mixed traffic...
- Cooperative vehicles should relieve the driving task and adapt to **safe** drivers' behavior

Outline of the presentation

Context and motivations

Traffic modelling and cooperation

Stability analyses

Real data-based simulation

Multi-agent modelling framework

Conclusions and perspectives

Outline

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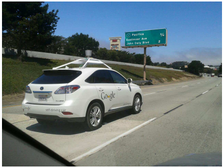
Conclusions and perspectives

Automation and connection for vehicles

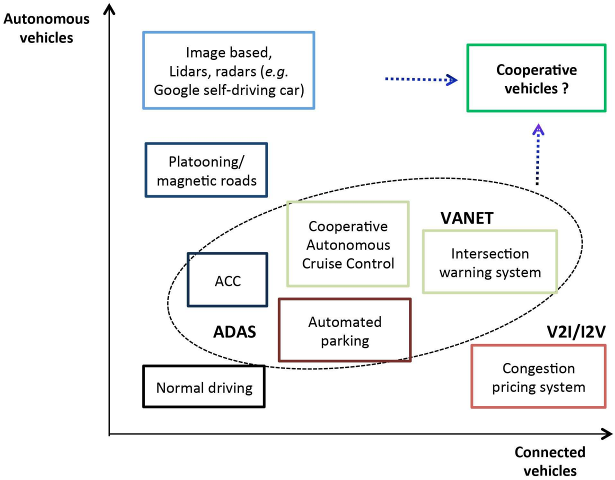
- Adaptive Driver assistance systems (ADAS) : Adaptive Cruise Control (ACC), collision avoidance systems, automated parking



- Autonomous vehicles : PROMETHEUS project, Google driverless car, Oxford car
- Platooning : PATH Automated Highway Systems, SARTRE project, NEDO driverless trucks

- Vehicular Ad hoc NETworks (VANET) for connected vehicles : toll collection, intersection warning, Cooperative ACC

Towards cooperative vehicles



Sites for testing connected applications

- FOT, DRIVEC2X : methodology for implementation and evaluation on 7 European test sites
- Safety applications (traffic jam ahead, weather, obstacle warning), traffic efficiency applications (post crash warning) and selected infotainment (traffic information)

Sites for testing connected applications

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- Safety pilot, VTTI : large testbeds of connected vehicles in a real-life environment
- Focus on safety applications (crash warning, intersection management) and infrastructure assessment (pavement)

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Aim to evaluate the :

- efficiency of the applications, driver acceptance
- interoperability of dedicated wireless communications

Research questions

Future situation : a mixed fleet made of cooperative vehicles and non-cooperative vehicles (normal drivers) on highways, with the goal to increase traffic flow safety.

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1. What physics to explain the formation of stop and go waves ?
2. What information/data is relevant to exchange between cooperative vehicles ?
3. How to use this information, how should cooperative vehicles behave ?
4. How to deal with communication noises ?
5. Is a mixed traffic made of cooperative and « normal »vehicles safer ?

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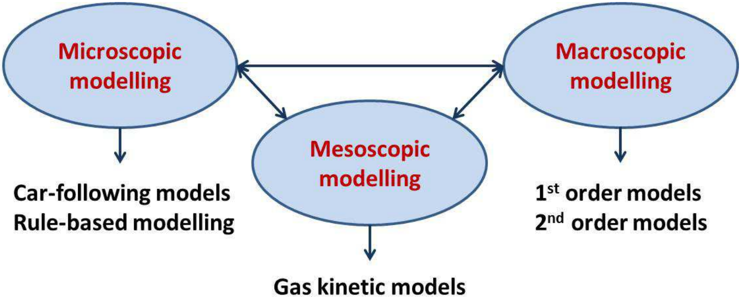
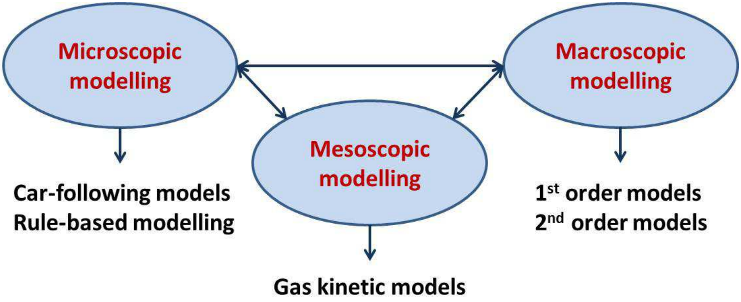
Modelling scales



- Microscopic : particles with specificities $(x_n(t), LN_n(t))$
- Mesoscopic : probability density function $f(x, V, t)$
- Macroscopic : traffic density $k(x, t)$, speed $V(x, t)$, flow $\rho(x, t)$

Modelling scales



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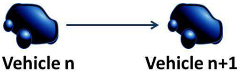
Car-following models

Car-following models

Time discrete models



- Stimulus-response models : Pipes GM-1 (1953), Greenberg GM-3 (1959), Van Aerde (1995), RPA (2009) models

GM-1 :

$$\ddot{x}_n(t+\tau) = \alpha \cdot [\dot{x}_{n+1}(t) - \dot{x}_n(t)]$$

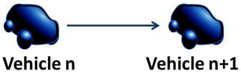
- Other types : Gipps (1976), Newell (1961, 2002)

Simplified Newell (2002) :

$$x_n(t+\tau) = x_{n+1}(t) - d$$

Car-following models

Time continuous models

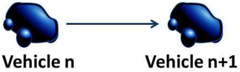


- General form :

$$\dot{x}_n = \frac{dx_n}{dt}$$
$$\ddot{x}_n = f(\dot{x}_n, \Delta x_n, \Delta \dot{x}_n)$$

Car-following models

Time continuous models



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$$\dot{x}_n = \frac{dx_n}{dt}$$
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- Examples : OVM (Bando *et al.*, 1995), OVRV model (Jiang *et al.*, 2001), IDM (Treiber *et al.*, 2000), IOVM (Treiber and Kesting, 2013)

  OVRV :

$$f(\dot{x}_n, \Delta x_n, \Delta \dot{x}_n) = -\frac{1}{\tau}\dot{x}_n + \frac{1}{\tau}V(\Delta x_n) + \eta \Delta \dot{x}_n$$

Cooperation in traffic models

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ACC model : Kesting *et al.* (2010)

- IDM+CAH model for lane changing maneuvers
- Implemented on motorways

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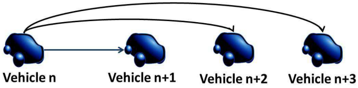
Multi-anticipation framework : Ge *et al.* (2006), Hoogendoorn *et al.* (2006), Treiber *et al.* (2006)

- Physical behavior
- CACC framework



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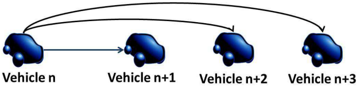
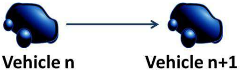


Flocking framework : Reynolds (1987), Olfati-Saber (2006)

- Behaviors of groups of particles in 3D
- Algorithms for speed homogenization and collision avoidance

Modelling choice for future developments

Time continuous models



$$\ddot{x}_n = f(\dot{x}_n, \Delta x_n, \Delta \dot{x}_n)$$

Modelling choice for future developments

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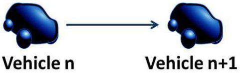


$$\ddot{x}_n = f(\dot{x}_n, \Delta x_n, \Delta \dot{x}_n)$$

Why ?

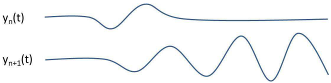
- Empirical models close to ground truth traffic
- Continuous formulation close to communication issues
- Favor stability analyses

Outline

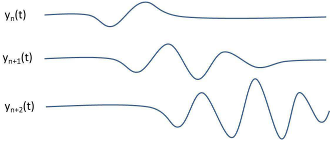
Stability criteria of traffic flow

Local *vs* string unstable : Wilson and Ward (2011) $y_n = x_n - x_{eq}$

- Locally unstable



- String unstable



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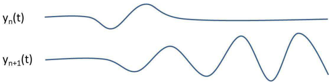

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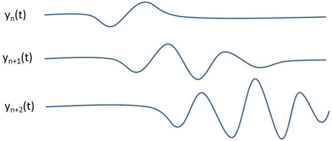
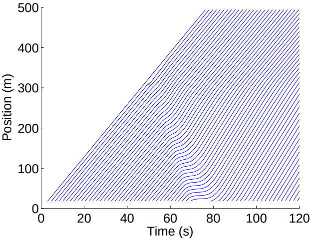
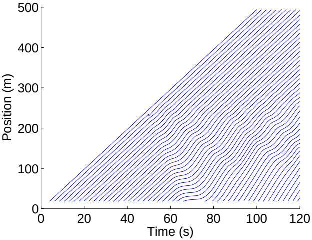


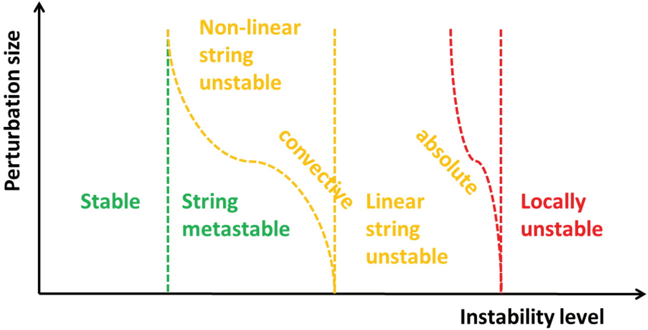
String convective *vs* string absolute : Treiber and Kesting (2012)





Stability criteria of traffic flow

Linear *vs* non-linear stability : Treiber and Kesting (2013)

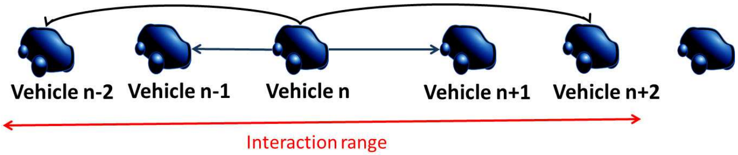


Usual approach : $\Delta y_n(t) = Y_0 e^{i(kn+zt)},\ z = -i\omega,\ k \in [0, \pi]$

- Derivation of analytical conditions for linear string (small perturbations) and local stability
- In traffic, only convective instabilities are observed
- Forward multi-anticipation increases stability

Stability analyses

Presentation of the cooperative car-following model



$$\ddot{x}_n = f_c(\dot{x}_n, \sum_{j=-m_b}^{m_f} a_j \Delta x_{n+j}, \sum_{j=-m_b}^{m_f} a_j \Delta \dot{x}_{n+j})$$

Continuous relation : $\sum_{j=-m_b}^{m_f} a_j = \sum_j a_j = 1$

$$f_c = f_{\mathrm{IDM/OVRM/IOVM}} - c_1(\dot{x}_n - \dot{x}_d) + c_2\Big(\sum_j a_j \Delta x_{n+j} - \Delta x_d\Big)$$

Linear stability analyses
Contributions 1/3

First order development : $\Delta \ddot{y}_n = f_1 \Delta \dot{y}_n + f_2 \sum_j a_j \left(\Delta y_{n+j+1} - \Delta y_{n+j}\right) + f_3 \sum_j a_j \left(\Delta \dot{y}_{n+j+1} - \Delta \dot{y}_{n+j}\right)$,
with $f_1 = \partial f / \partial \dot{x}(\dot{x}_{eq}, \Delta x_{eq}, 0)$,...

Dispersion relation : $z^2 - z\left(f_1 + f_3\left(e^{ik} - 1\right)\right) - f_2\left(e^{ik} - 1\right) = 0$

Linear stability analyses
Contributions 1/3

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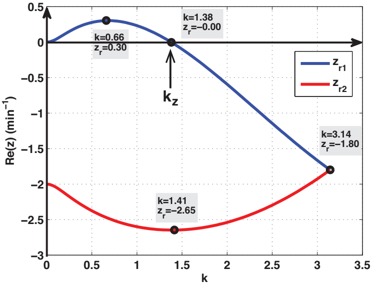


Let us remind $\Delta y_n(t) = Y_0 e^{i(kn+zt)}$. Growing perturbations are of the long wavelength type.

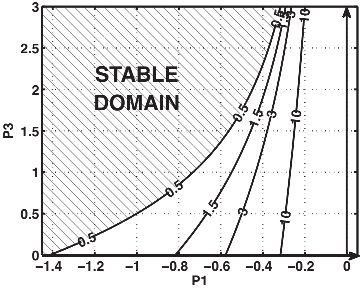
Result : without cooperation ($a_0 = 1,\ a_{j\neq 0} = 0$), $k_z = \arccos\left(\frac{f_1^2 + 2f_3^2 - 3f_1 f_3 - f_2}{f_2 + 2f_3^2 - f_3 f_1}\right)$

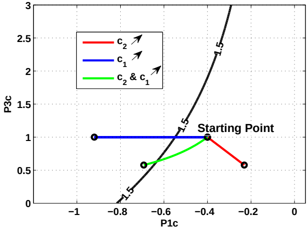
Linear stability analyses

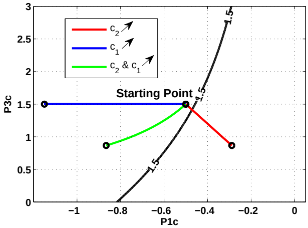
Contributions 2/3

Analytical results at long wavelengths

1. Bilateral traffic brings stability
2. Linear control term c_1 brings stability







Linear stability analyses
Contributions 3/3

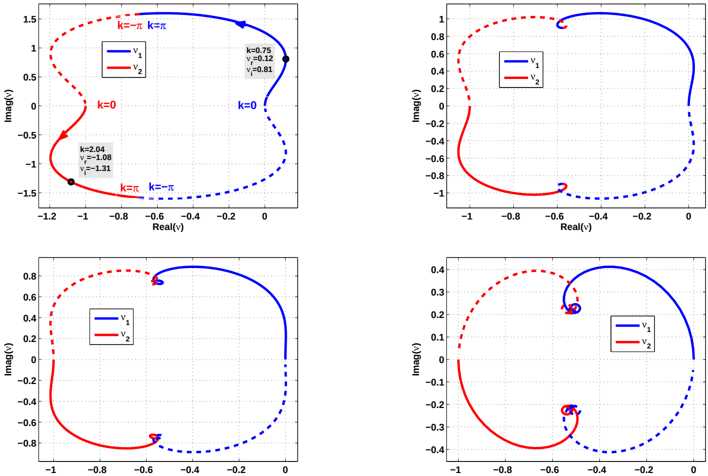
Root locus : graphical tool to evaluate stability at all wavelengths.

Linear stability analyses

Contributions 3/3

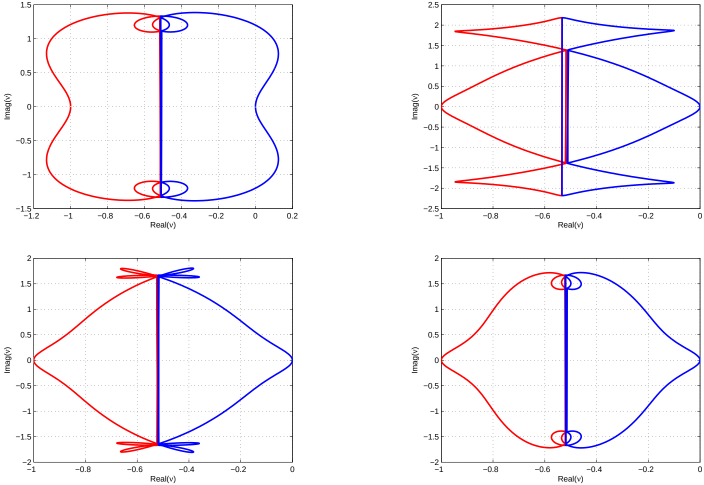
Root locus : graphical tool to evaluate stability at all wavelengths.

- Influence of forward multi-anticipation ($\nu = z/f_1$) : cosine window, $m = 1, 3, 4, 6$



Linear stability analyses
Contributions 3/3

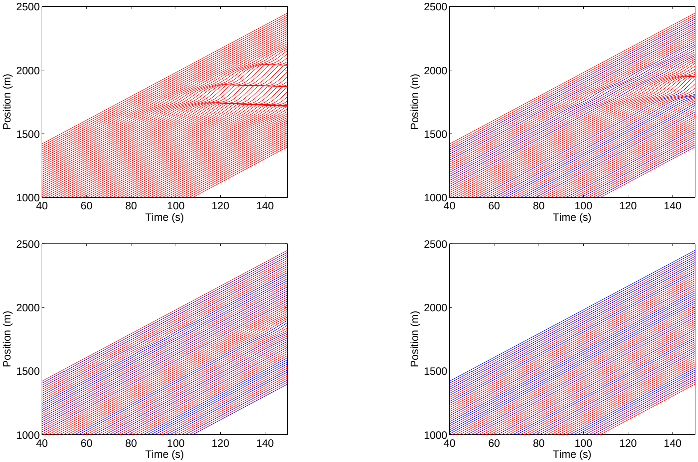
- Influence of backward multi-anticipation : linear window, $m = 3, \; m' = 0, 1, 2, 3$



Linear stability analyses
Case of a mixed traffic

The needed percentage to remove instabilities depends on :

- the traffic state,
- the location of the perturbation.



Weakly non-linear stability analyses
Contributions 1/2

Weakly non-linear stability analyses

Contributions 1/2

Time continuous CF (cooperative or not) have a Korteweg de Vries (Korteweg and de Vries, 1895 ; Nagatani, 2001) development for the perturbation growth.

Series of mathematical developments to get :

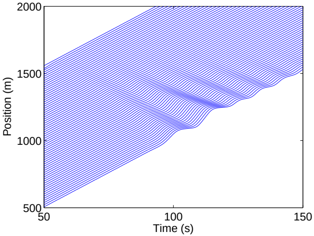
- the general expression of the KdV equation near the string stability surface for cooperative and non-cooperative traffic : $C_1 \partial_X^3 R + C_2 R \partial_X R + C_3 \partial_T R = 0$,
- a condition over the sign of the shock wave (same sign as C_2),
- the amplitude of the shock wave.

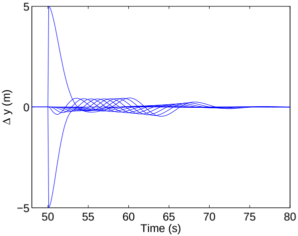
$$\Delta y_n(t) = \operatorname{sgn}(C_2) \mathbf{A} \operatorname{sech}^2 \left[\sqrt{\frac{|C_2| \mathbf{A}}{12 C_1}} (n - \alpha_s t) \right]$$

Weakly non-linear stability analyses

Contributions 2/2

OVRV model : $C_2 = f_{22}$, sign of C_2= sign of $(h_c - \Delta x_{eq})$





Weakly non-linear stability analyses

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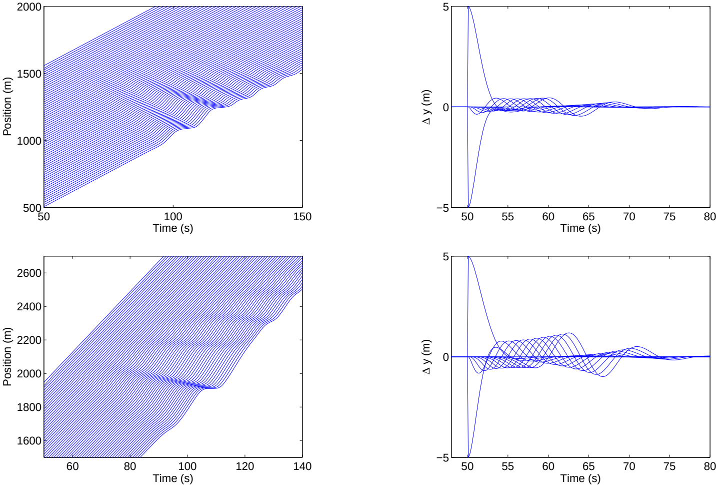

Stability analyses
Conclusions

Linear stability analyses

- Extension to bilateral multi-anticipation with linear control terms
- Use of the root locus graphical tool to design cooperative strategies

Weakly non-linear stability analyses

- KdV development
- Validation of : sign of the perturbation leading edge, amplitude value

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Needs of further investigation

- Insights from a deterministic approach
- Variability of drivers behavior ?

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Trajectory-based data calibration

Significant research in recent years

- Trajectory-based datasets (*e.g.* NDS, NGSIM, MOCoPo)
- Calibration methodology (MULTITUDE COST action)

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Selected dataset

- NGSIM dataset, US 101, Los Angeles
- Morning peak time, 3 left lanes

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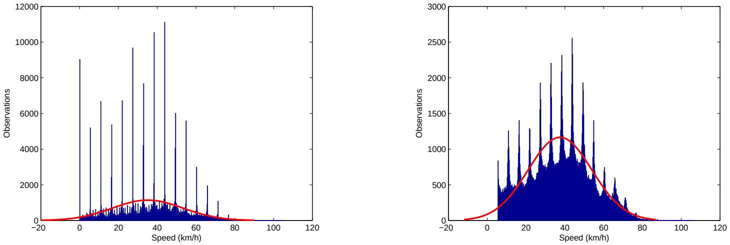
Methodology from filtering to sampling

- Filtering trajectories
- Robust calibration for each leader-follower pair
- Statistical analyses of dependencies
- Discussion of sampling methods

Filtering trajectories

- Issues : spikes from post processing images
- Flat magnitude filter in its passband : Butterworth (order 4) (Punzo and Montanino, 2013).



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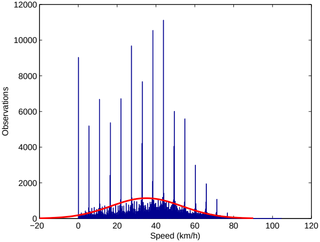

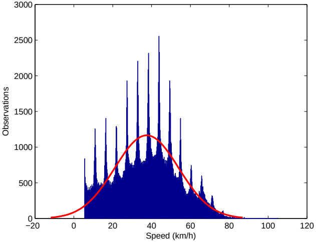

Consequences on calibration

- Calibration objective : for each leader, match observed speed trajectory with the modelled trajectory
- Focus on speed trajectories as Measure of Performance (MoP)

Robust calibration
Methodology 1/2

- Statistical meaning of the Goodness of Fit (GoF) test (James, 2006)

$$\chi^2 = \sum_{i,j} (x_{i,\text{obs}} - y_i(a)) \Gamma_{ij}^{-1} (x_{j,\text{obs}} - y_j(a))$$

- Optimization procedure : genetics algorithms with penalty function (Kesting and Treiber, 2008)

Robust calibration

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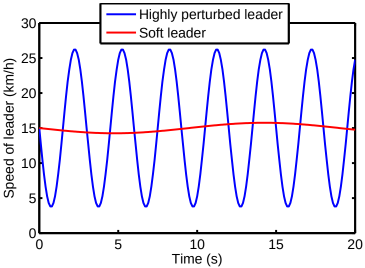
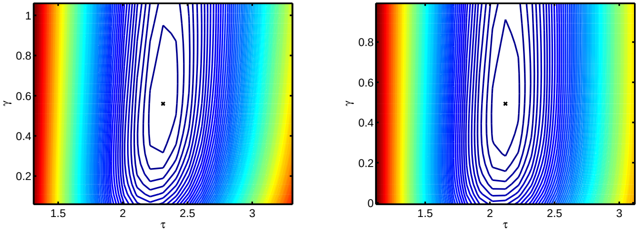
$$\chi^2 = \sum_{i,j}(x_{i,\mathrm{obs}} - y_i(a))\Gamma_{ij}^{-1}(x_{j,\mathrm{obs}} - y_j(a))$$

- Optimization procedure : genetics algorithms with penalty function (Kesting and Treiber, 2008)
- Selection of appropriate trajectories to be calibrated (filter the standard deviation of leaders speeds) to stimulate all parameters of the systems (except for $V_{\max}$)

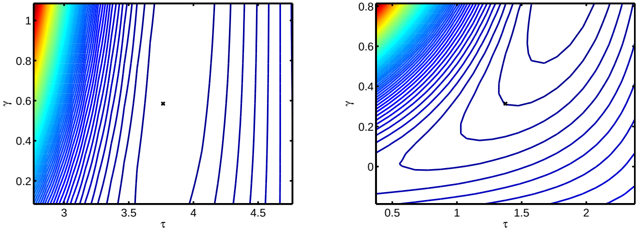
An example on the importance of inputs



IOVM : calibration with/without added noise for perturbed input

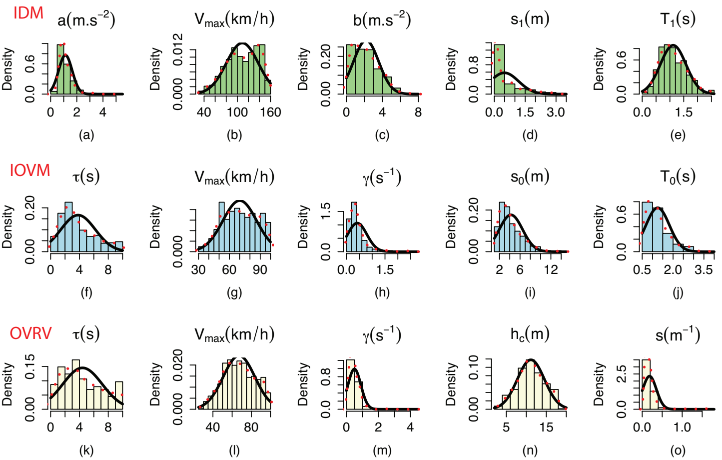


Calibration with/without added noise for soft input



Statistical dependencies

Distributions



Statistical dependencies

Analyses and correlation

Methods for correlation analyses

- The normality hypothesis does not stand for all parameters marginal distributions (based on the Shapiro-Wilk test)
- The Pearson test should be completed by the Kendall and Spearman methods, which account for the discordance and concordance values
- Principal Component analysis for linear correlation between parameters
- Observed correlations oppose reactive to passive driving styles

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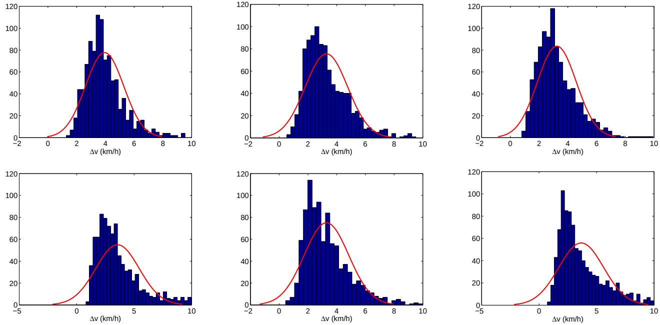
Objectives to understand the correlation between parameters in order to

- Estimate joint distributions while preserving the correlation structure
- Sample a realistic traffic from the estimated joint distributions

Discussion of sampling methods

Indicator : relative speeds standard deviation distribution



Comparison of **5 sampling strategies** of the OVRV parameters to the (a) ground truth : (b) random, (c) random with correlation, (d) from multivariate normal distribution, (e) from multi-variate normal distribution of only correlated parameters, (f) from Kernel density estimation.

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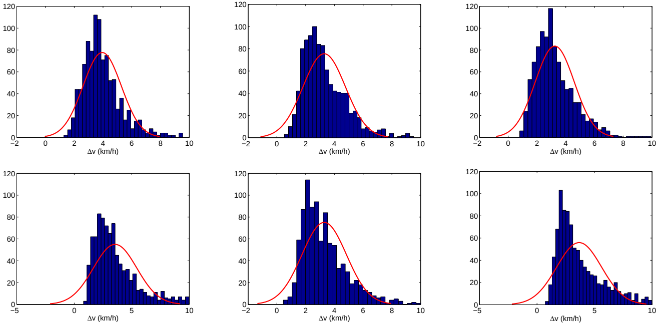

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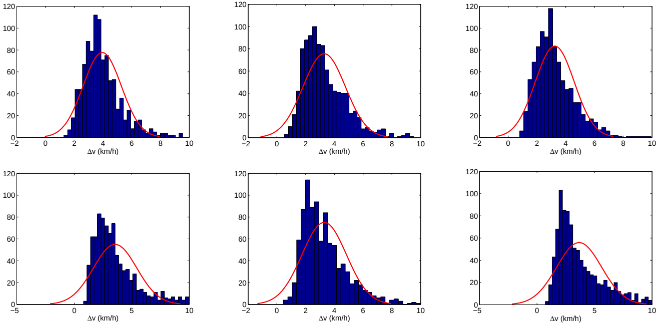

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Realistic traffic simulation
Settings

Simulation choices

- IDM parameters sampled from random sampling with correlation (« mean »traffic linearly unstable)
- Lane-changing model : MOBIL model (Treiber and Kesting, 2009)
- Numerical scheme : mixed first order second order Euler scheme
- Cooperative law : cosine window, bilateral law with tuned linear control terms

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' Scenario

- 6 minutes simulation, 200 vehicles per lane, 3 lanes, open boundaries
- Perturbations from : initial conditions (global steady-state $\neq$ individual steady-state), regular « manual »perturbations, aggressive lane changes (set to 25%).
- Graphical interface : GUIDE

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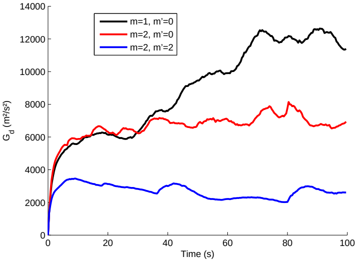
Realistic traffic simulation

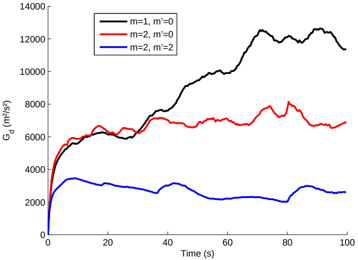
Evolution of the group disagreement value



75% of equipped vehicles

- Positive impact of bilateral multi-anticipation
- Negative impact of a too high number of leaders/followers

Realistic traffic simulation
Evolution of the group disagreement value



75% of equipped vehicles

- Positive impact of bilateral multi-anticipation
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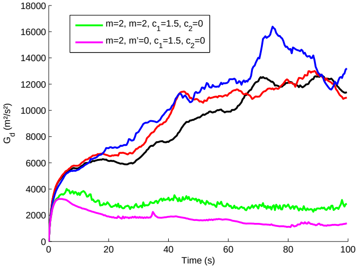
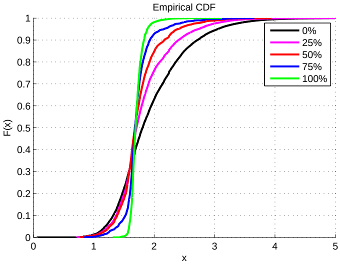
25% of equipped vehicles

- Positive impact of added linear control
- Bilateral multi-anticipation ≈ forward multi-anticipation



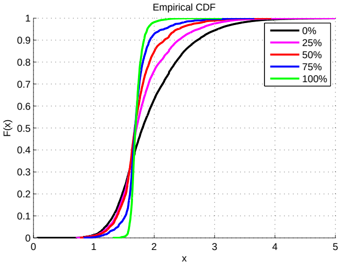
Realistic traffic simulation
Conclusions



Evolution of the PET (s)

- Progressive homogenization with increasing % of cooperative vehicles

Realistic traffic simulation
Conclusions



Evolution of the PET (s)

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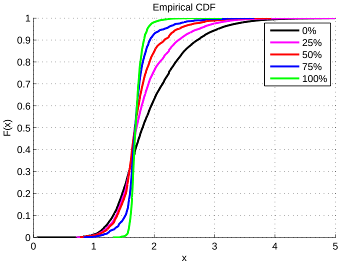
Conclusions

- For this traffic configuration, for a well tuned cooperative car-following model, assuming a prior knowledge of the drivers behavior variability, 20% of cooperative vehicles remove instabilities !

Realistic traffic simulation
Conclusions



Evolution of the PET (s)

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Conclusions

- For this traffic configuration, for a well tuned cooperative car-following model, assuming a prior knowledge of the drivers behavior variability, 20% of cooperative vehicles remove instabilities !
- No more than 2 leaders/followers are required !
- How to deal with communication noises, to detect unreliable sensors ?

Outline

Context and motivations

Traffic modelling and cooperation

Stability analyses

Real data-based simulation

Multi-agent modelling framework

Conclusions and perspectives

Multi-agent framework
Introduction

Why multi-agent systems ?

- Partial and noisy perception of the environment
- Flexibility of interactions
- Idea of **self-organization**

Multi-agent framework
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Why multi-agent systems ?

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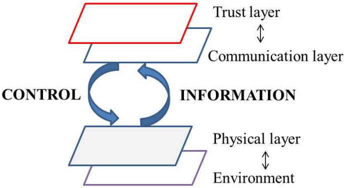
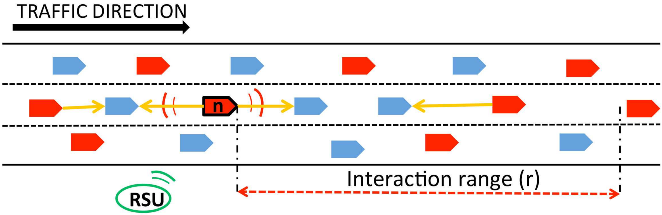
Multi-agent structure with trust layer (Nguyen Vu *et al.*, 2012)



- Physical layer → car-following rules
- Communication layer → proximity and reliability rules
- Trust layer → sensors network

Multi-agent framework
Definition

Physical layer



- Cooperative IDM model
- Limited interaction range ($r = 4 \cdot \Delta x_{eq}$) : avoid scaling effects for low coverage
- Limited number of information data points ($m = 2 \; m' = 2$) : avoid loss of reactivity to the leader trajectory

Multi-agent framework
Definition

Communication layer

1. Cooperative coefficients as a multiplication (proximity$\times$trust) rule

$$a_{ij} = \frac{\mathrm{p}_{ij} \cdot T_{ij}}{\sum_l \mathrm{p}_{il} T_{il}}$$

2. Required decreasing coefficients with distance
3. Required minimum trust in the relative information to the leader
4. Multiplication of control gains by self-trust

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Trust layer

1. Relation between error measurements and direct trust

$$DT_{ij} = \max(1 - m_{ij}\sigma, 0)$$

2. Computation of an indirect trust
3. Update rule for the trust

$$T_{ij} = \frac{T_{ii} DT_{ij} + IT_{ij}}{T_{ii} + 1}$$

4. Update rule for the self-trust

Multi-agent framework
Static trust layer

- Hypothesis : each vehicle has a prior knowledge of the quality of its sensors
- Scenario : $\nearrow$ error measurement for 25% and 100% of cooperative vehicles

Multi-agent framework

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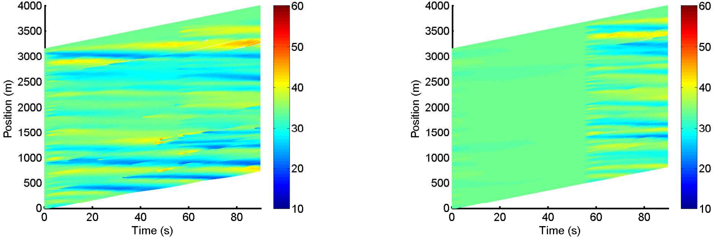
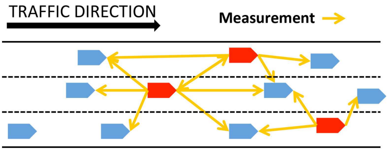


- High robustness of the cooperative strategy to error measurements
- Threshold corresponding to the required minimum trust in the relative information to the leader

Multi-agent framework
Dynamic trust layer

- Hypothesis : each vehicle senses its nearest neighbors
- Scenario : detection of unreliable sensors ?



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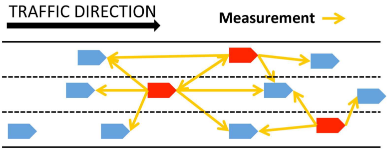

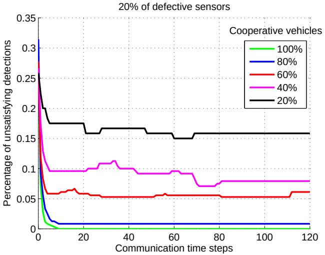

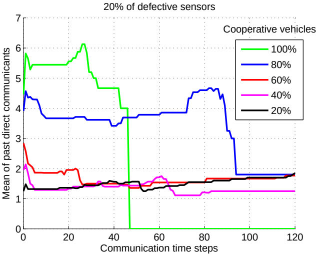

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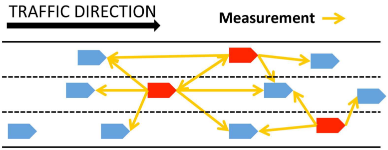

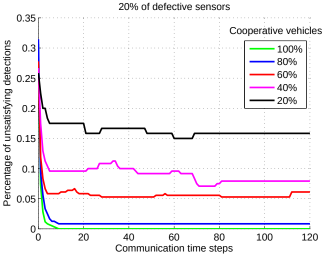

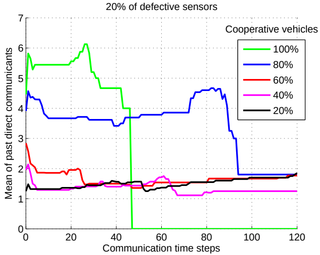

→ **Fundamental influence of direct information exchanges**

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Parameters identification of car-following models

- was done through a robust calibration process
- lead to a dicussion on statistical dependencies and sampling of parameters

Simulations were conducted and a multi-agent modelling framework was designed, enabling

- to demonstrate the high potential of cooperation in traffic flow, even with low coverage of cooperative vehicles
- sensitivity analyses on control and communication strategies
- the real time detection of unreliable sensors

Publications
Journal publications

- Monteil, J., Billot, R., Sau, J., Buisson, C., El Faouzi, N.-E., Calibration, estimation and sampling issues of car-following parameters. *Transportation Research Records, journal of the Transportation Research Board, 2014.* Submitted.
- Sau, J., Monteil, J., Billot, R., El Faouzi, N.-E., Design of cooperative car following models using root locus analysis. *Tranportmetrica B : Tranport Dynamics.* Submitted.
- Monteil, J., Billot, R., Sau, J., El Faouzi, N.-E., Linear and Weakly Non-linear Stability Analyses of Cooperative Car Following Models. *IEEE Transactions on Intelligent Transportation Systems, 2013.*
- Monteil, J., Nantes, A., Billot, R., El Faouzi, N.-E., Microscopic Cooperative Traffic Flow : calibration and simulation based on a NGSIM dataset. *IET Intelligent Transport Systems, 2013.*
- Monteil, J., Billot, R., Sau, J., Armetta, F., Hassas, S., El Faouzi, N.-E., Cooperative highway traffic : multi-agent modelling and robustness assessment to local perturbations. *Transportation Research Records, journal of the Transportation Research Board, 2013.*
- Monteil, J., Billot, R., El Faouzi, N.-E., Des véhicules coopératifs pour une gestion dynamique du trafic : approche théorique et simulation. *Revue Recherche Sécurité Transports, 2012.*

Publications
Conference publications

- Monteil, J., Billot, R., Gueriau, M., Armetta, F., Hassas, S., El Faouzi, N.-E., A three-layer multi-agent framework for sensor reliability issues : application to cooperative highway traffic. *AAAI 2014*.
- Monteil, J., Billot, R., Sau, J., Buisson, C., El Faouzi, N.-E., Calibration, estimation and sampling issues of car-following parameters. *93^rd^ Annual Meeting of Transportation Research Board (TRB) 2014*, Washington D.C., USA.
- Monteil, J., Billot, R., Sau, J., Armetta, F., Hassas, S., El Faouzi, N.-E., Cooperative highway traffic : multi-agent modelling and robustness assessment to local perturbations. *92nd Annual Meeting of Transportation Research Board (TRB) 2013*, Washington D.C., USA.
- Monteil, J., Nantes, A., Billot, R., El Faouzi, N.-E., Microscopic Cooperative traffic based on NGSIM data. *Proceedings of the 19th ITS World Congress 2012*, Vienna, Austria.
- Monteil, J., Billot, R., Rey, D., El Faouzi, N.-E., Distributed and Centralized Approaches for Cooperative Road Traffic Dynamics. *Procedia of Social and Behavioral Sciences, Volume 48, pp. 3198 - 3208*, *4th Transportation Research Arena, TRA 2012*, Athens, Greece.
- Monteil, J., Billot, R., El Faouzi, N.-E., Towards cooperative traffic management : methodological issues and perspectives. *Australasian Transport Research Forum 2011 Proceedings*, Adelaide, Australia.

Perspectives of future work

Towards experimentation

- Online estimation of car-following parameters
- Incorporation of smoother acceleration patterns, *e.g.* in reaction to lane changes

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Developments of the presented work include

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- Methodology for robust sampling of parameters
- Design of cooperative lane changing strategies, *e.g.* in the case of a necessary lane change
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Open questions

- Participation of in-vehicle sensors to the network knowledge ?
- Importance of Road Side Units ?

Thank you

Thank you for your attention