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

Julien Monteil

PhD Dissertation Defense

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Examining committee:

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Introduction



Cooperative vehicles = connected + autonomous vehicles?

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



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Multi-agent modelling framework

Introduction



Cooperative vehicles = connected + autonomous vehicles?

- V2X communication channels (4G, WIFI...)
- 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

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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





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Towards cooperative vehicles



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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)



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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



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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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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.

- 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



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- 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 $\rho(x, t)$

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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) :

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

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Time continuous models

► General form :

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





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Time continuous models

► General form :

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

Examples : OVM (Bando et al., 1995), OVRV model (Jiang) et al., 2001), IDM (Treiber et al., 2000), IOVM (Treiber and Kesting, 2013)

OVRV :

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





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vehicles on highway traffic flow

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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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- Physical behavior
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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





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Modelling choice for future developments

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



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Modelling choice for future developments

Time continuous models





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

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

Favor stability analyses

Why?



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Stability criteria of traffic flow

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Stability criteria of traffic flow

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

Locally unstable





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





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Stability criteria of traffic flow



Instability level

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





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Stability analyses Presentation of the cooperative car-following model



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Linear stability analyses $_{\text{Contributions }1/3}$

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

Dispersion relation : $z^{2} - z (f_{1} + f_{3} (e^{ik} - 1)) - f_{2} (e^{ik} - 1) = 0$



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Linear stability analyses Contributions 1/3

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



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

 $\begin{array}{l} \mbox{Result}: \mbox{without cooperation} \\ (a_0 = 1, \ a_{j \neq 0} = 0), \ k_z = \\ \mbox{arccos} \, \big(\frac{f_1^2 + 2f_3^2 - 3f_1f_3 - f_2}{f_2 + 2f_3^2 - f_3f_1} \big) \end{array}$



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Linear stability analyses Contributions 2/3



Analytical results at long wavelengths

- 1. Bilateral traffic brings stability
- Linear control term c₁ brings stability





-0.6 P1c

-0.4 -0.2 0

-1 -0.8

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Linear stability analyses Contributions 3/3



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



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Linear stability analyses Contributions 3/3

Root locus : graphical tool to evaluate stability at all wavelengths.
► Influence of forward multi-anticipation (*ν* = *z*/*f*₁) : cosine window, *m* = 1, 3, 4, 6







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Linear stability analyses Contributions 3/3

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









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The needed percentage to remove instabilities depends on :

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







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Weakly non-linear stability analyses Contributions 1/2



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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 : C₁∂³_XR + C₂R∂_XR + C₃∂_TR = 0,
- a condition over the sign of the shock wave (same sign as C_2),
- the amplitude of the shock wave.

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



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Weakly non-linear stability analyses Contributions 2/2





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Weakly non-linear stability analyses Contributions 2/2





Stability analyses

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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Weakly non-linear stability analyses

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

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



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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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Filtering trajectories

- Issues : spikes from post processing images
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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)



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Methodology for calibration

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)



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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)
- 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





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Robust calibration Methodology 2/2







Calibration with/without added noise for soft input







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Statistical dependencies Distributions





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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

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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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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.

Realistic traffic simulation $_{\mbox{\scriptsize Settings}}$



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Simulation choices

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- 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 ≠ 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

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25% of equipped vehicles

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

75% of equipped vehicles

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



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Evolution of the PET (s)

 Progressive homogenization with increasing % of cooperative vehicles Investigating the effects of cooperative vehicles on highway traffic flow

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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 !

Evolution of the PET (s)

 Progressive homogenization with increasing % of cooperative vehicles traffic flow Julien Monteil

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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?

Evolution of the PET (s)

 Progressive homogenization with increasing % of cooperative vehicles effects of cooperative vehicles on highway traffic flow Julien Monteil

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Why multi-agent systems?

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



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Why multi-agent systems?

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

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



- ► Physical layer → car-following rules
- ▶ Communication layer → proximity and reliability rules
- Trust layer \rightarrow sensors network



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- 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



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Communication layer

 Cooperative coefficients as a multiplication (proximity×trust) rule

$$a_{ij} = \frac{\mathsf{p}_{ij} \cdot T_{ij}}{\sum_{l} \mathsf{p}_{il} T_{il}}$$

- 2. Required decreasing coefficients with distance
- 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

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1)Multi-agent modelling framework

Multi-agent framework Static trust layer

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



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42 Multi-agent modelling framework

Multi-agent framework Static trust layer

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



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

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2) Multi-agent modelling framework

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





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 \rightarrow Fundamental influence of direct information exchanges

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Performed stability analyses provided

- a complete framework for linear stability analyses of cooperative car-following models at all wavelengths
- new results in the weakly non-linear domain



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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



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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



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Publications



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- 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.*
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- 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.*



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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

- Stability analyses of time discrete models
- Methodology for robust sampling of parameters
- Design of cooperative lane changing strategies, *e.g.* in the case of a necessary lane change
- Extension to optimal/robust control towards a desired stable traffic, e.g. in response to changing weather conditions



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Open questions

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



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Thank you



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Thank you for your attention