

Towards cooperative traffic management: methodological issues and perspectives

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Abstract

Advances in sensing and emerging communication technologies allow the transportation community to foresee relevant improvements for the incoming years in terms of a more effective, environmental and safety concerned traffic management. In that context, new ITS paradigm like cooperative systems brings new capabilities enabling an efficient traffic state estimation and control. Cooperative systems refer to three levels of cooperation between vehicles and infrastructure: vehicles (i) equipped with Advanced Driver Assistance Systems (ADAS) adjusting their traffic features to surrounding vehicles; (ii) able to exchange information with the infrastructure; (iii) able to communicate between each other. Therefore, cooperative systems have become a huge topic of interest as they make it possible to go a step further in providing real time information and tailored control strategies to specific drivers. As a response to an expected increasing penetration rate of these communication systems, traffic managers have to come up with new methodologies that override the classical methods of traffic modelling and traffic control. After an overview of the existing approaches in the literature, we focus on the methodological issues following the expansion of such systems. The methods for introducing a cooperative modelling framework within existing traffic models are discussed. As an example, we then propose an application based on a cooperative microscopic model which allows the targeting of particular fleets of vehicles. Finally, the perspectives and potential applications of such a modelling framework are presented from a technical as well as an operational standpoint.

1. Introduction

Advances in sensing technology and communication capabilities stimulate a renewal in the field of traffic engineering. Since the very beginning of transportation engineering around the 60's and the Lightwill Whitham (Lightwill & Whitham 1955) Richards theory (Richards 1956), the main preoccupation of engineers has been to accurately model the physics of traffic. To perform the estimation and prediction work, loop detectors were massively put and maintained on highways. Cameras and infrared beacons were also used for traffic estimation purposes, especially on urban networks. Later, at the beginning of the 21th century, the advent of GPS technology allowed to dynamically follow equipped fleet of vehicles. Taxi fleet were used a lot because of their link to traffic operators. Car manufacturers and researchers experimented and launched Adaptive Driver Assistance Systems (ADAS), supposed to improve traffic safety and traffic efficiency to some extent. The most famous and deployed ADAS systems are the adaptive cruise control (ACC) and the intelligent speed adaptation (ISA), among others such as collision avoidance systems and adaptive light control. Nowadays, the C2X framework, which defines the interaction between cars and infrastructures, infrastructures and cars and among cars, provides more tailored ways of controlling traffic. Many methodological challenges arise from these different levels of interaction and from the difficulties to model and simulate the impacts of these cooperative systems. Besides, privacy issues are and have always been constraints to their expansion.

Cooperative systems gather three different levels of interaction. Each level enables the deployment of better management strategies regarding traffic efficiency, traffic safety and environmentally oriented traffic, but introduces new methodological issues, such as the

difficulty to really evaluate those impacts via simulation. At a first level, which is not within the scope of our study, the Adaptive Driver Assistance Systems (ADAS) consist in in-vehicle sensors that aim at helping drivers to adopt a more comfortable and safer driving. They have a clear impact on microscopic parameters of the traffic flow (Tapani 2007) and can be well studied under simulation (Tapani 2006). A driving simulator is of great help to identify and characterize the impacted parameters of a traffic simulator (Schermers and Malone). Simulations studies of ADAS have provided good results in reducing bottlenecks (Hoogendoorn & Minderhoud 2001) as well as in improving traffic safety (Carsten & Nilsson 2001). As ADAS systems have already been widely investigated, this paper will rather focus on the two next levels of interaction of cooperative systems, i.e. the C2X framework, which offers more powerful possibilities.

Indeed, preoccupations are rising around a traffic management which benefits from the C2X framework. If the penetration rate of equipped vehicles is expected to increase slowly, the traffic community has to be aware that electric vehicles, cheap sensors, and the operability of communication layers will contribute to accelerate the renewal of the vehicle fleet. In such a framework, information could be sent to specific drivers, and a feedback could be received from them, so that new control applications have to be defined and designed. In Europe, a few ongoing projects such as SAFESPOT, CVIS and Pre-Drive C2X help and aim to demonstrate the potentials of such communication systems. The new bandwidth reserved for vehicular networks gives evidence about the willingness of the European Union to move forward in that direction.

This paper presents the models and methodological issues arising from the cooperative framework, with a great focus on what has been done regarding the traffic engineering side, and what could be the modelling choices to be made in a near future. An application based on traffic micro-simulation aims to demonstrate the potential of communication technologies. In section 2, the global architecture of cooperative systems is presented with the expected benefits of cooperative systems through a wide range of applications. In section 3 we present some modelling approaches enabling the simulation of cooperative traffic. In section 4 we present a simple application of cooperative traffic, where a percentage of the vehicles are assigned as communicant vehicles. We end with our conclusions and prospects in section 5.

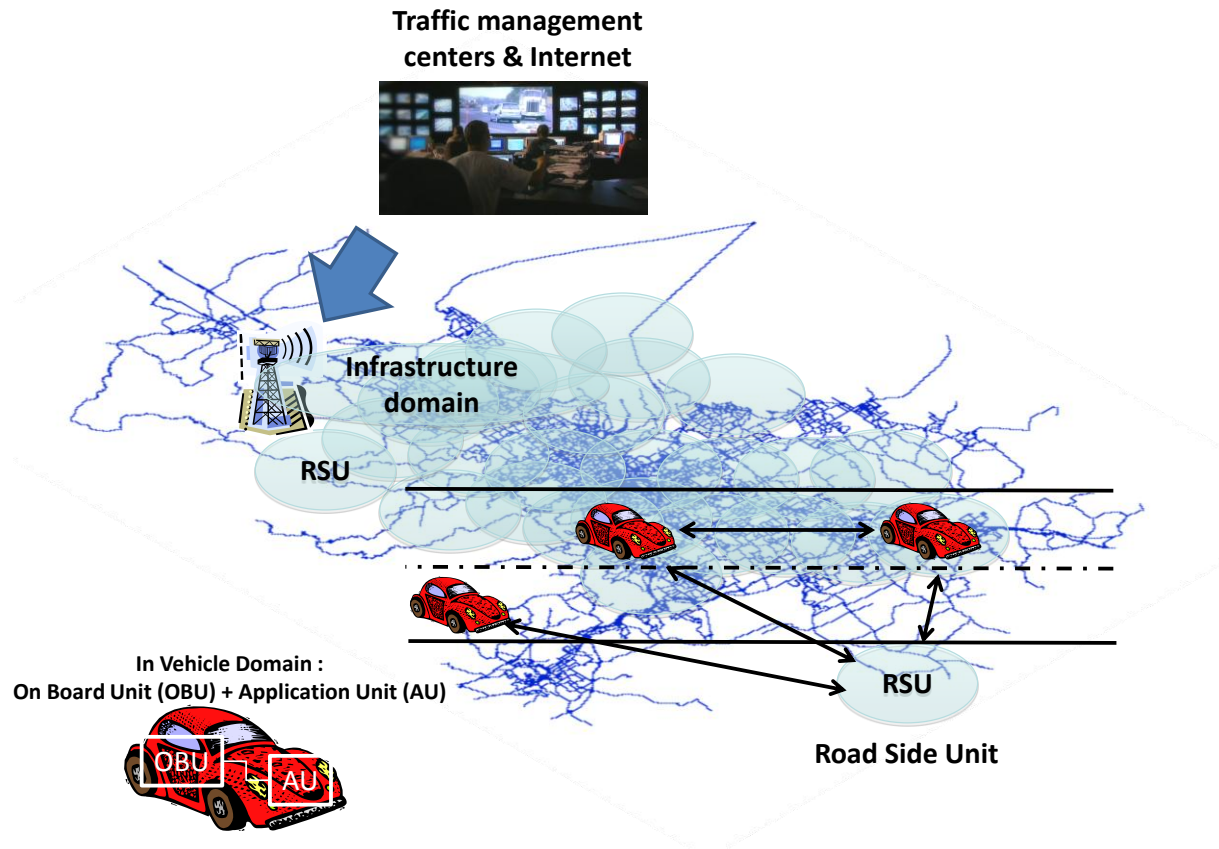
2. Cooperative systems: architecture and ITS applications

This section presents the potential applications of cooperative systems, as well as some limitations linked to their use.

2.1 Architecture of the Communication system

Actors of cooperative communication systems (Car 2 Car communication consortium 2007) are cars, who receive information and recommendations and provide data to others vehicles and to the infrastructure, road operators who retrieve traffic data and then control traffic, and potentially internet providers. Road side units (RSU) and possibly internet hotspots communicate with on board units (OBU) and with the infrastructure (servers). Within a car, an application unit (AU) is connected with the OBU via wired connection and executes applications taking advantage of OBU communication abilities (figure 1).

Figure 1: Overview of the Communication network



Within this architecture; the importance of RSU is fundamental as they are part of the vehicular ad hoc network (VANET) but are also linked to the infrastructure. RSU extend the ad hoc network by sending information to OBU, forwarding information to others RSU or running safety applications by themselves (traffic signals control for instance), or providing internet connectivity to OBU.

From a technological perspective, OBU and RSU are equipped with devices that provide wireless communication services, based on IEEE 802.11p, conventional IEEE 802.11a/b/g/n, or others radio technologies (UMTS, DSRC). IEEE 802.11p are specifically designed IEEE protocols for wireless access in vehicular networks (WAVE) (Committee SCC32 of the IEEE Intelligent Transportation Systems Council 2006), which consists in another extension of the 802.11 MAC (medium access) and PHY (physical) radio layers. The IEEE 802.11p standard is especially reserved for safety applications, whereas the others standards are mostly used for non-critical safety or non-safety applications.

The C2C ad-hoc network layer is relevant for the traffic engineering community, as the algorithms to distribute and deliver data will later influence the design of traffic control algorithms. Packet centric dissemination refers to a geographical broadcast, i.e. the information is forwarded and then distributed within a defined geographical area. Information-centric dissemination refers to single hop broadcast, where data is naturally sent and aggregated to neighbouring nodes. Multi-hop broadcast (Osafune et al. 2007) could also be used with specific safety applications.

2.2 Potential applications

The different interaction levels offer a wide range of applications which could lead to a huge transformation of the driving behaviours and traffic management. Regarding the autonomous

systems (e.g. ADAS systems), the benefits are well known, especially from a safety point of view. By providing lateral and longitudinal controls, ADAS systems allow drivers to adopt safer speeds as well as to be better informed about collision risks. The limitation of autonomous systems resides in the lack of interaction with other vehicles or infrastructures. They only provide the driver with embedded sensors informing about the direct environment. Cooperative systems expand the possibilities towards more interaction and communication. Vehicle-To-Infrastructure (V2I) communication should allow a better perception of the environment and the traffic conditions. For instance, a better knowledge of downstream traffic conditions or an assessment of the current road friction index could lead the drivers to adapt their driving behaviours to the prevailing traffic and road conditions. Although V2I communication can be viewed as a natural expansion of previous autonomous systems, its combination with Vehicle-To-Vehicle (V2V) communication represents a huge step which opens new perspectives for both drivers and traffic managers. Indeed, this kind of interactive systems can multiply the possibilities of a better traffic management. Communication with both surrounding vehicles (V2V) and infrastructure (V2I) would enable road users to have a complete view of the traffic conditions and the level of service. This includes a real time assessment of traffic conditions, traffic risk, as well as an evaluation of the current driving behaviour in terms of trajectory and risk.

From a safety point of view, we can first mention collision warning where a vehicle receives information from a downstream vehicle if a critical situation is detected. An accurate position (and headway) of all the vehicles is needed in order to detect platoon of constrained vehicles. Information should be shared between vehicles over 250 m (ideal communication range) to give them time to decelerate in a smooth way and then avoid rear-end collision. As a second safety application, crash sensing happens when collision can't be avoided, so position data length and type of vehicle should be communicated very quickly and in a reliable way to monitor air bags and all the emergency measures.

From a traffic efficiency point of view, which could obviously result into fuel consumption reduction as well, some applications come out such as ramp metering, green light monitoring, fleet targeting and more generally individual specific advice. For ramp metering the information should be shared between the merging vehicle and the traffic around him. Reliable information such as position and speed could be transmitted to the merging vehicle. In urban areas, green light monitoring enables giving an optimal speed to the driver according to the signal timing and the distance from the intersection. Accurate intersection position and signal timing data are required. This application results in fuel economy and in a decrease of congestion. Besides, for the targeting of particular fleets (for route guidance or use of reserved/emergency lanes): as some types of vehicles are less fuel consumers, and have priorities (safety for TMD trucks, effectiveness for taxis...), some specific advice could be sent by road units to these vehicles. Finally, individual specific advice would be the ultimate and more optimistic application for traffic management: where individual advices are received by each equipped vehicle to improve the traffic flow efficiency, for instance by preventing a capacity breakdown. It seems that from previous research (Yeo & Skabardonis 2009; Daganzo et al. 1999), a good synchronization of the traffic flow results in a better capacity. Ideally, microscopic choices such as lane changing manoeuvres and headway distribution as well as macroscopic ones such as dynamic OD route choice advice would have to be controlled over the network. Time headway, individual speed, and critical traffic situations should be communicated in an appropriate way, to eventually allow heading to a smoother traffic.

The embedded vehicles part of the C2X infrastructure, exchanging data each other or with the infrastructure, give power to come up with new insights about vehicle trajectories, lane changing, fuel consumption, emission. These new data sources form the core of improved traffic indicators: accurate travel time prediction, multimodal and multiobjective optimization of the network, emission or safety risk indicators.

2.3 Constraints and limitations

After an overview of the potential applications, we present here the possible constraints in terms of drivers' attention, latency time and amount of information exchanged.

First, there are technological constraints. The maximum transmit power of the C2X radio system is 32dbm and the communication range for a one hop transmission is lower than one kilometre (Car2Car Consortium 2007). Latency communication time is due to the fact that the information has to be trusted -especially for safety applications-, and therefore secured by applying cryptographic methods which could considerably increase the computational time. Moreover, anonymous data could also be required because of vehicle privacy. In high traffic conditions, the loaded data on the channel has to be controlled not to exceed the bandwidth capacity.

Because of these constraints -latency time and available bandwidth-, a centralized control that takes into account the information coming from RSU and infrastructures is not possible every single second. A local control based on a distributed approach using information from neighbouring vehicles and nearest RSU could be implemented more frequently. In both cases, the control updates obviously depend on the network, on the amount of information exchanged between OBU, RSU and infrastructure and on the complexity of the cryptographic and designed traffic control algorithms.

Secondly, this is clear that the profusion of available information is challenging to the extent that data have to be collected, prepared and transmitted in a relevant way. Hence, a consistent data fusion must be made with the inclusion of V2I and V2V information exchange, the autonomous systems etc. Then, there is a need to control the propagation of such a dense communication network in a safe and reliable way.

Other constraints come from the drivers themselves, who are not always willing to take into consideration the information they receive. An experiment project that showed a great potential gain of cooperative systems was made in the Netherlands as part of the SPITS project. But a lack of compliance from the drivers was noticed. Knoop et al. (2011) summarize three interesting points about drivers' behaviour. Of course drivers are much more receptive to a mandatory system. For voluntary systems, drivers are more receptive if they are encouraged or even punished (Wilmink et al. 2006) when they can trust the system, when they receive positive feedback and when they acknowledge by themselves a gain. For instance, a driver would be more willing to follow an acceleration advice than a decrease of speed advice.

3. Cooperative Systems Modelling

This section tackles the modelling of cooperative systems. After describing the possibilities of introducing the cooperative systems into existing traffic models, we present the challenges and the new paradigms needed to achieve a comprehensive modelling of the new complex systems. Finally, we put forward a first approach to such an objective, based on the multi-agent concepts.

3.1 Introducing cooperation into classical traffic models

In order to integrate the cooperative ideas into traffic modelling, a first approach consists in extending the existing models by taking some communication into account. In Ngoduy et al. (2009), the authors divide the vehicles into equipped and non-equipped vehicles. The equipped vehicles are able to receive information about the traffic condition downstream. This allows them to anticipate traffic jam and to adopt a deceleration phase close to low speed regions. Basically, this idea is nothing more than considering 2 classes of vehicles in a multiclass modelling framework. The multi-class gas kinetic model of Hoogendoorn et al. (1999) is modified with the incorporation of a smooth function representing the information, i.e a probability that an equipped vehicle gets a message from a vehicle downstream. The

numerical results show that the presence of equipped vehicles in this cooperative model contributes to a flow stabilization (less and smaller waves), travel time improvement or jam suppression effects. Of course, it is worth noticing that the results (such as capacity increasing) come from the model itself, and have not been validated with real world data. Nevertheless, this work draws relevant perspectives and underlines the importance of the penetration rate, i.e. the percentage of equipped vehicles. The aim would be in the future to determine a critical penetration rate above which significant improvements can be highlighted.

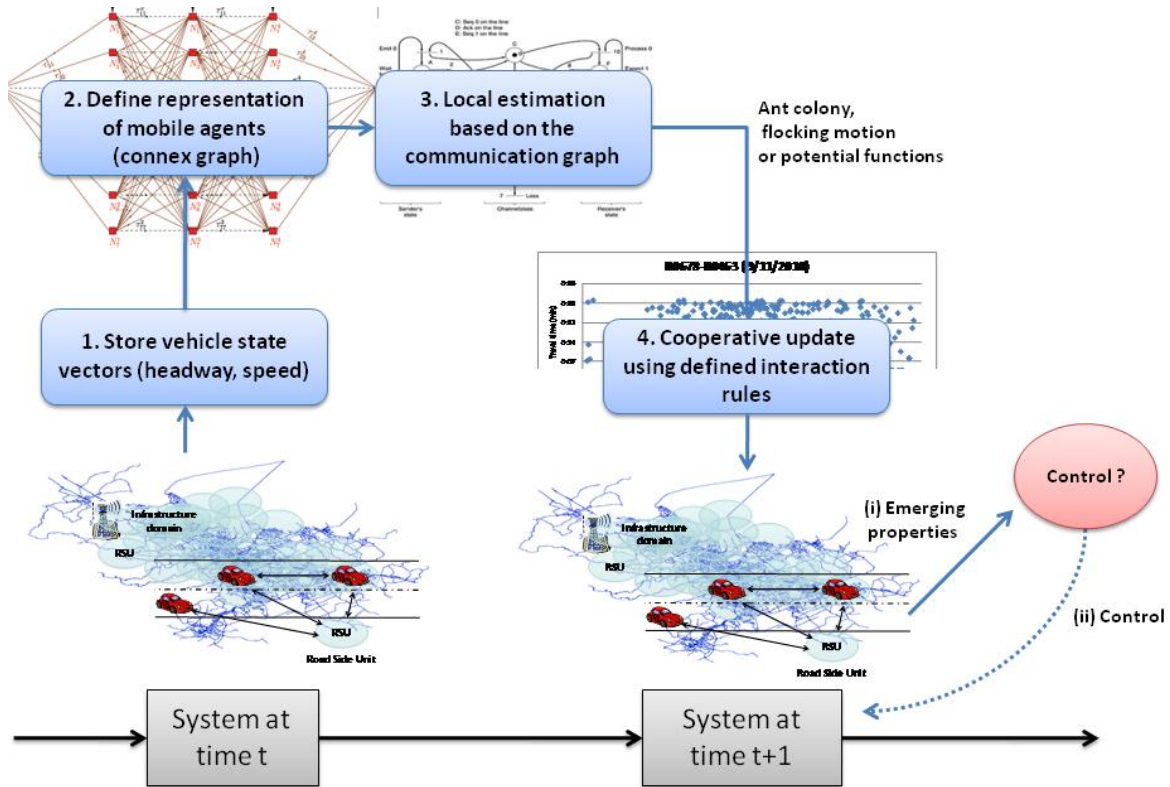
Regarding microscopic traffic models, one can view the introduction of cooperative issues as an extension of the basic follow-the-leader models. In this way, a first approach considers the vehicle as a particle not only reacting to the leading vehicle, but rather receiving information from n vehicles ahead. An example of such an extension of car following models can be found in Ge et al. (2006), and in Chen et al. (2010), where they consider anticipative information in the car following model. Again, this modification of an existing model aims to introduce more stability into the flow.

3.2 New paradigms for cooperative network modelling

Although the introduction of the cooperative concepts into micro- and macroscopic models is an essential first step, new approaches are needed to describe comprehensively the complexity of the interactions. More than a technological breakthrough, we think that cooperative systems must lead the researchers to revisit the ways of modelling and controlling traffic. First of all, one can raise the issue of a centralized versus distributed approach. The centralized approach is based on a control centre managing all the data. This centre collects and sends targeted instructions to equipped vehicles, enabling several applications. Among the applications, one can cite ramp metering, dynamic speed control, route choice advice, queue detection and reduction. In section 4, we present a single case of a centralized approach which can already bring benefits for congestion management. However, only V2I and I2V communications are considered so that the centralized approach fails to take advantage of the V2V interaction. Yet, a distributed approach could better embrace a communication network where the equipped vehicles act as agents able to adapt themselves at each time step. This last aspect is linked to a self-organizing capability of the mobile agents. At each time step, a mobile agent, that is to say a vehicle, adapts his behaviour according to the information he receives from his neighbourhood: vehicles, road side units or others. Then the challenge resides at different levels. While realistic perception and adaptation laws must be defined at the agent level, an adequate topology must be proposed at the agent network level. Thus, the distributed approach lies in local traffic state estimations by the agents that contribute to the global characterization of the system. Indeed, the real-time traffic state assessment by the different agents would allow highlighting some emerging properties which will reflect at more aggregated levels (micro-, meso-, and macroscopic levels). For the modeller and the controller, the goal is then to match the right actions with the different traffic conditions. In the next paragraph, we propose the basic concepts of a distributed multi-agent cooperative modelling.

3.3 Multi-agent cooperative modelling

Multi-agent modelling appears to be a suitable way of developing a distributed traffic modelling and control. Figure 2 describes the different steps of such a process. The goal is to update the state of each agent according to the agents' network around him. This includes an efficient evaluation of the traffic state as well as a decision making process able to cope with all the available information. As a matter of fact, the multiplicity of the interactions at the agents' level will result in emergent properties with respect to the global system. For the controller, the objective is then to highlight and understand these emergent properties at a macroscopic level. This last aspect would enable to launch some control actions onto the updated system, see Fig 2.

Figure 2: cooperative modelling process

Before reaching these objectives, the first step is to store the state vector of each single agent. At this microscopic level, the variables of interest are the speed and the headway with the previous vehicle. The second step consists of the representation of the mobile agent network by a connex graph fixing the neighbourhood of each agent. A graph representing the interaction between agents (or each group of agents) has to be defined at each time step. The edges of the graph determine the communication complexity of the system. The interaction topologies are changing dynamically (at each time step). The convergence of the system to a common desired value (safety indicator, speed) highly depends on this topology: it has been proven when talking about special movements that there is convergence if the union in time of the communication topology has a spanning tree (Wei and Beard, 2003).

From this connectivity graph, it is necessary to define the interaction rule (step 3): how will an agent perceive his neighbourhood at each time step? How will he update his variables of interest (*i.e.* his local state vector) according to the information he receives?

Different frameworks can be put forward to achieve these objective One involves the definition of an attractive-repulsive potential function. An analogy to the traffic headway (time or space gap between a leader and a constrained vehicle-follower) can be made here, where the headway is the sum of a constrained and a non-constrained term. Based on this potential function, flocking algorithms can be first considered. These methods are based on the behaviours of flocks and have already shown promising results to globally optimize a system consisting of multiple interactive agents (Choi et al. 2009). The topology of flocking algorithms is based on graph theory with proximity nets defining for each agent the neighbourhood and the associated interactions. Lattice-like structures are then used to model stability constraints and describe the collective behaviours of flocks (Olfati 2006). For instance, in traffic flow modelling, this stability could find its expression in speed and time headway harmonization.

Another approach would be based on the nearest-neighbour rule. An agent and his n followers adapt their speed cooperatively. Vicsek's leader-following architecture showed promising results (Jadbabaie et al. 2003), and these concepts seem to describe accurately the behaviours of a large group of mobile agents. This alternative is close to the flocking algorithm in the extent that the headway of a vehicle would be updated according to the headways of the vehicles present in a specific neighbourhood structure.

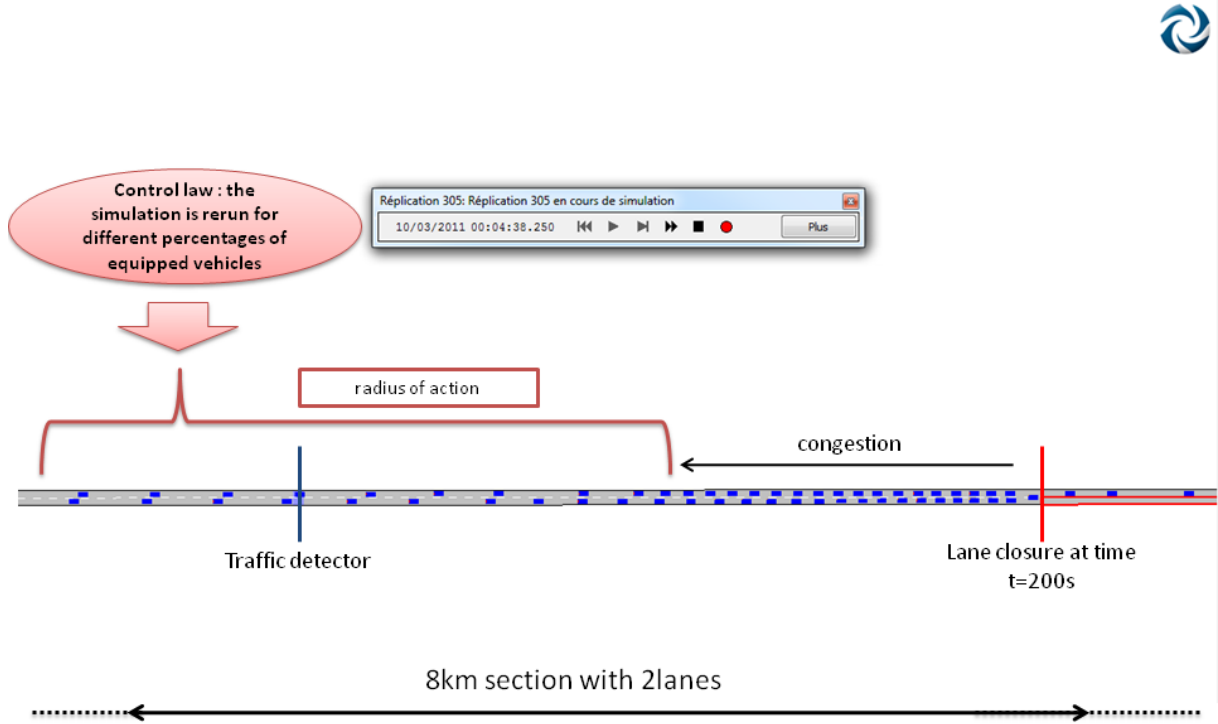
A last approach could consist in applying Ant Colonization Optimization (ACO) algorithms. A colony of insects is a perfect decentralized system with flexibility and robustness features (Dorigo et al. 1996). Instead of using classically this metaheuristic for computing shortest paths, the goal would be to model the communication in the network and to optimize it. We would model communication using the stigmergy paradigm, the environment of every single vehicle being composed of other vehicles, infrastructure, road side unit. The stigmergy resides in the use of the environment to exchange information between vehicles. Here, vehicles would behave like ants when instead of depositing pheromones they deposit information at a road side unit.

Whatever the method used, it should enable a cooperative update of the state vector of each vehicle (step 4). This microscopic update of the variables of interest will result in a collective behaviour that contains more information than the sum of each individual behaviour. Thus, the update of the system at time $t + 1$ must highlight some emerging properties for the optimization of the entire system. Basically, the objective are to describe the emerging properties at more different scales: scale of a street, scale of a district, scale of an urban network. From a modelling point of view, we aim at formally writing the link between the microscopic, mesoscopic and macroscopic models. At a macroscopic level, the results may lead to some control actions on the system, see Fig 2.

4. Active Traffic Management Case: in-vehicle dynamic adaptive speed for congestion mitigation

4.1 Description of simulation Set up

The goal of this application is to show the potential of communication by simulation and on a very simple case: a single motorway section of 8 kilometres with two lanes. By providing dynamic speed advice to the drivers and assuming that drivers respect this advice, we aim to reduce the loss of time and postpone the congestion phenomena. This basic application represents a centralized approach where a control centre can send information (speed adaptation when approaching a congested area) to the drivers. The entrance flow in the network is chosen to be 3600veh/hrs., so a quite high value if we assume the capacity to be around 4200 veh/hrs. At time $t = 200$ s of the simulation, we close a lane at position $x = 5$ km. This lane closure resides in the formation of a queue with a shock wave moving upstream. The dynamics of traffic is modelled through classic lane changing and car following models. The control law is only a modification of the car following model. A detector is put upstream the incident, and measures the occupancy, counts and speed. Figure 3 describes the configuration of the experience. The simulation is run many times with different penetration rates, i.e. with different percentages of equipped vehicles. The control principle is as follows: if congestion is detected in a radius of 2 km upstream, the information is sent to the equipped vehicles. Before detailing the cooperative control law, we describe in the next subsection how the control action is introduced into microscopic traffic modelling.

Figure 3: simulation configuration (Aimsun interface)

4.2 Microscopic traffic model used in the simulation

The Gibbs car following model is used in this simulation. According to this model, the maximum speed $v_a(n, t + \Delta t)$ that the vehicle n could reach in a simulation time Δt , given its speed of the previous time step, is defined by:

$$v_a(n, t + \Delta t) = v(n, t) + 2.5a(n) \times \Delta t \left(1 - \frac{v(n, t)}{v^*(n)} \right) \sqrt{0.025 + \frac{v(n, t)}{v^*(n)}},$$

where $v(n, t)$ is the vehicle speed at time t , $v^*(n)$ is the desired speed for the considered section, $a(n)$ is the maximum acceleration of the vehicle and Δt is the simulation time step (assumed to be equal to the reaction time).

The constrained speed by the leading vehicle $v_b(n, t + \Delta t)$ is written:

$$v_b(n, t + \Delta t) = d(n) \times \Delta t + \sqrt{(d(n) \times \Delta t)^2 - d(n) \left(2 \times \delta_n(x, s, v, t) - \frac{v(n-1, t) \Delta t^2}{d'(n-1)} \right)}$$

where $d(n)$ is the maximum deceleration of vehicle n , $s(n)$ its length, $x(n, t)$ its position at time t , $\delta_n(x, s, v, t) = x(n-1, t) - s(n-1) - x(n, t) - v(n, t) \Delta t$ and $d'(n-1)$ is the estimate of the desired deceleration of vehicle $n-1$ (leader), which is the actual deceleration times a sensitivity factor.

The applied speed to vehicles all over the network at the next time step is written:

$$v(n, t + \Delta t) = \min(v_a(n, t + \Delta t), v_b(n, t + \Delta t))$$

A constraint regarding the minimum headway, $h_{\min}(n)$, is also taken into account, such as:

$$v(n, t + \Delta t) = \frac{x(n-1, t + \Delta t) - s(n-1) - x(n, t)}{h_{\min}(n) + \Delta t} \quad \text{When } \delta_n(x, s, v, t) \leq v(n, t + \Delta t) \times h_{\min}(n)$$

The lane changing model consists roughly in a gap acceptance rule, an overtaking manoeuvre being possible when there is enough space and the speed difference between lanes is higher than a given threshold value.

4.3 Cooperative control law

The speed of the vehicles is being controlled at each time step using the data from two previous time steps. We assume a two times steps latency time (1.75 sec) to take into account the reaction time of drivers as well as the communication latency time. This later is dependent on the medium access control mechanism (MAC) in use (Yahya & Ben-Othman 2009).

Let n_{equipped} and $n_{\text{congested}}$ be two Booleans that define respectively whether vehicle n is equipped or not and whether it is in a congested situation at time t . Vehicles are randomly equipped according to a variable cooperative system market penetration rate.

The control algorithm runs in two stages. One stage consists in the detection of congestion situation. For this, we wanted to be sure to detect accurately the congestion phenomena so we did a selection on the current headway $h(n, t)$ and speed $v(n, t)$.

More specifically, we store a vehicle n as a congested one if $n_{\text{congested}}(t) = \text{true}$, where $n_{\text{congested}}(t) = \# \{h(n, t) \leq 30 \text{ and } v(n, t) \leq 15\}$.

Note that, to detect approaching situations, which are the ones of interest, we can also use the speed difference and filter it with speed or headway considerations, which would considerably reduce the amount of information needed (a vehicle just sends information if data reveals an approaching situation, *i.e.* the speed difference between leader and follower is higher than a certain value beside the low headway/speed).

Then, for each time step, we get a cluster of congested vehicles $(\Gamma_i^t)_{1 \leq i \leq \wp}$, where \wp is the total number of congested vehicles at time t , and we use the cluster of $(\Gamma_i^{t-\Delta t})_{1 \leq i \leq \wp}$ to compute a speed estimate at time $t+1$. To do so, we define an action range, *i.e.* a vehicle looks for congested vehicles in a radius of 2 kilometres, and detects the nearest congested vehicle. If there is one, and if vehicle n is not in a congested situation itself, we linearly estimate its speed according to the following equation:

$$\hat{v}(n, t + \Delta t) = v(n, t) \left(1 - \left| \frac{v(n, t) - v_{\text{nearestCong}}(n, t - \Delta t)}{x(n, t) - x_{\text{nearestCong}}(n, t - \Delta t)} \right| \Delta t \right)$$

where $x_{\text{nearestCong}}(n, t - \Delta t)$ and $v_{\text{nearestCong}}(n, t - \Delta t)$ are the position and speed of the closest congested vehicle to vehicle n . As the information needs to be processed and given to drivers, there is a time gap, and vehicles are using the information from the previous time step.

Finally, the definitive speed is taken as the minimum between this estimated speed and the previous defined speed:

$$v_{\text{control}}(n, t + \Delta t) = \min(v(n, t + \Delta t), \hat{v}(n, t + \Delta t))$$

4.4 Results

Figure 4 provides an insight of the local density perceived by the detector, and its evolution with time. The blue curve gives evidence of the benefits of the control algorithm with vehicles being more prudent when approaching the queue. The jam density is reached two time steps later at the detector. Figure 5 shows a consequent gain of time with 100% of equipped vehicles. Because of the constant flow, this gain is not consequent at the end of the incident. Slopes are parallel because of the queuing shock wave, which is the slope of the classical fundamental diagram. We can also learn from the experience and curves that 10 % of equipped vehicles are not sufficient to have a significant impact on traffic performance.

Figure 4: density at one detector for different penetration rates

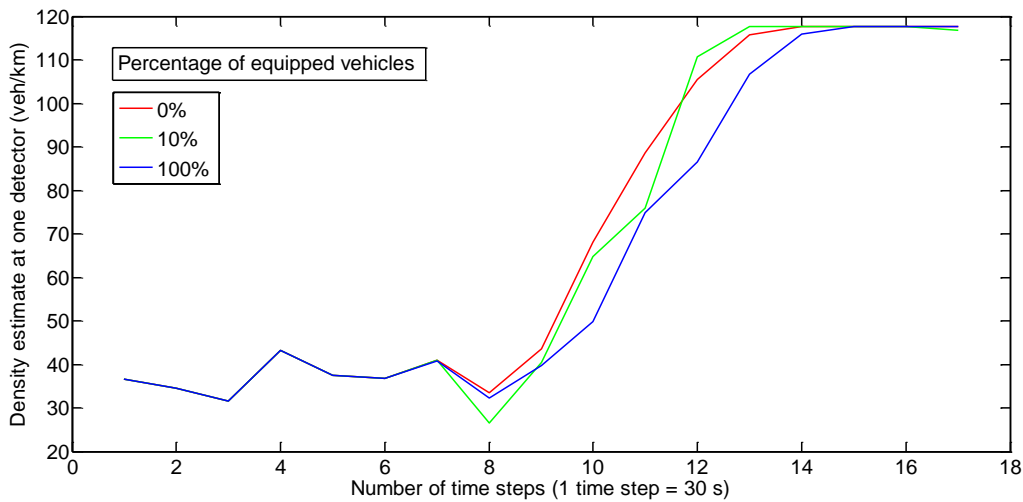
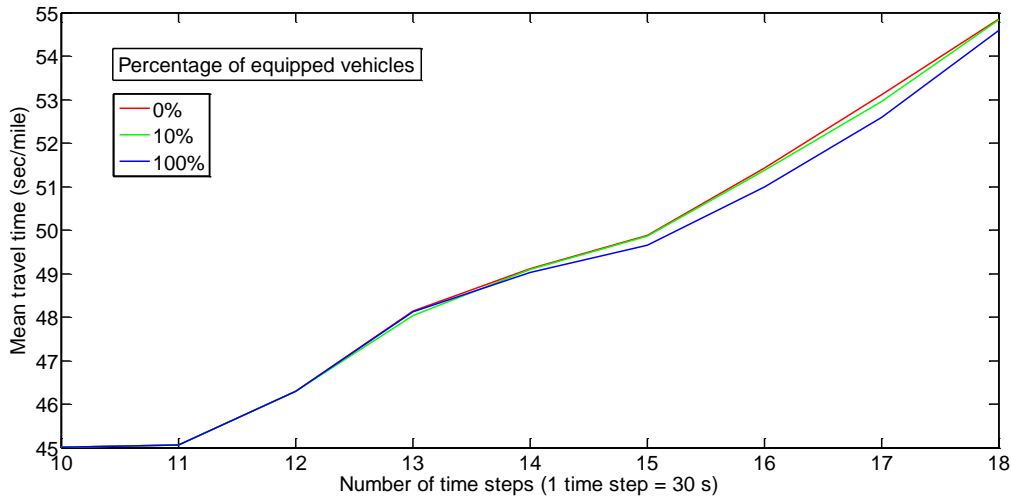


Figure 5: mean travel time over the section for different penetration rates



As a result, the congestion phenomenon is indeed postponed, reducing the travel time at the beginning of the accident. But afterwards, once the queue is formed, there is no effect, as the number of vehicles increase at the same rate, with or without control, the flow being the same. Our control algorithm also improves the traffic safety regarding rear end collisions, but this was beyond the scope of the study.

As a conclusion, we have exhibit the potential gain of cooperative systems on the simplest possible scenario. This gain is mostly due to an immediate detection of the queue and would be different with usual sensors transmitting information to a server then sending speed

recommendation to drivers (through a Variable Message Sign for instance). We believe and showed that immediate information to the vehicles allows a consequent gain of efficiency by postponing the formation of the queue, which would not be possible without these communications. Of course, we expect that such gain will increase with the complexity of the network. Dynamic speed and lane changing advice, ramp metering or route choice advice are several ways of managing traffic flow. However all the information of the network is used here to detect different traffic situations (e.g. queue formation). This is not applicable in real-work settings, where a vehicle would better make a local estimate of the traffic situation based on the limited information it receives.

5. Conclusions and prospects

In this paper, we have shed light on some of the challenges behind the advent of cooperative systems in traffic management. Cooperative systems bring new possibilities to optimize traffic management with multi-level communication between the different entities of the network: communication between the infrastructure and the car (I2C), the car and the infrastructure (C2I), and between the cars (C2C). Following the idea that these advances should be considered as a technical breakdown, we have shown how new paradigms can be put forward in order to overcome the shortcomings of existing traffic models. Indeed, although some basic cooperative concepts can be introduced into microscopic and macroscopic models without revisiting methods of traffic modelling, these kinds of frameworks are not comprehensive enough to cope with the complexity of an entire cooperative network.

We consider the merits of centralized versus distributed approaches to model the network. While a centralized approach is based on a control centre managing and sending all the information to the equipped vehicles, distributed approaches consider vehicles as agents able to adapt themselves dynamically. Taking a centralized approach, we propose in our work an application of dynamic speed advice where a centre sends targeted instructions to equipped vehicles. Results showed that congestion phenomena are indeed postponed, reducing the travel time at the beginning of the accident. With respect to distributed methods, we argue that this alternative can better take into account the complexity of the communication between vehicles. We define the basic principles of a multi-agent cooperative modelling where the agents update their variables of interest at each time step. The local optimization of the state vectors is considered using flocking, ants' colonization or nearest-neighbour techniques. As the global system is more than the addition of all its single elements, the next step is to highlight emerging properties to yield an accurate view at more aggregated levels (e.g. mesoscopic, macroscopic). In addition, these emerging properties would enable the launch of specific control actions on the system (infrastructure and equipped vehicles). Future research resides in the implementation and testing of cooperative traffic modelling. By considering road side units (RSU) as major elements of the network, the aim is to move towards semi-distributed models taking advantages of both approaches. The ultimate goal is to develop a flexible and comprehensive framework able to describe the wide range of interaction in urban and interurban networks.

References

- Bonabeau, E, Dorigo, M, & Theraulaz, G 1999, *Swarm intelligence: from natural to artificial systems*, in Oxford University Press, Santa Fe Institute Studies in the Sciences of Complexity.
- Branke J, Mnif, M, Müller-Schloer, C, Prothmann, H, Richter, U, Rochner, F, & Schmeck, H, 2006, 'Organic computing - addressing complexity by controlled self-organization' in *Proceedings of the Second International Symposium on Leveraging Applications of Formal Methods, Verification and Validation*, pages 185–191, Washington, DC, USA. IEEE Computer Society.
- Car 2 Car communication consortium 2007, in *CAR 2 CAR Communication Consortium Manifesto - Overview of the C2C-CC System*.
- Carsten, O.M.J & Nilsson, L 2001, 'Safety Assessment of Driver Assistance Systems', in *European Journal of Transport and Infrastructure Research*, 1 (3)., pp. 225-243. ISSN 1567-7141.
- Chen X & Dongfan, X 2010, 'Enhance stability of traffic flow in an extended car following model based on anticipative information', in *Logistics Engineering and Intelligent Transportation Systems (LEITS) International conference*.
- Choi, J, Oh, S & Horowitz, R 2009. 'Distributed learning and cooperative control for multi-agent systems', in *Automatica*, 45 : 2802–2814.
- Committee SCC32 of the IEEE Intelligent Transportation Systems Council 2006, in *Draft Standard for Wireless Access in Vehicular Environments (WAVE)*, IEEE 1609 - WAVE resource Manager.
- Daganzo, C.F et al. 1999, 'Possible explanations of phase transitions in highway traffic' in *Transportation Research Part A: Policy and Practice*, Vol. 33, No. 5, pp. 365 – 379.
- Dorigo, M, Maniezzo, V & Coloni, A 1996. 'Ant system: optimization by a colony of cooperating agents', in *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, 26(1): 29–41.
- Ge, H.X. Dai, S.Q. Dong, L.Y 2006, 'An extended car-following model based on intelligent transportation system application', in *Physica A* 365, pp. 543_548.
- Hoogendoorn, S. & Minderhoud, M 2001. 'ADAS impact assessment by micro-simulation', in *European journal of transport and infrastructure research EJTI*, 1 (3).
- Knoop, V. L et al. 2011, 'Individual Travelers' Advice: System Setup, Measures, and Expected Results' in *Transportation Research Board Annual Meeting 2011 Paper #11-1043*.
- Jadbabaie, A., Lin, J., & Morse, A 2003. 'Coordination of groups of mobile autonomous agents using nearest neighbor rules', in *IEEE Transactions on Automatic Control*, June 2003, 988 - 1001 .
- Lightwill, M. & Whitham, G. 1955, 'On kinematic waves. II. A theory of traffic flow on long crowded roads', in *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 229 (1178), 317-345.
- Müller-Schloer, C et al. 2006, 'Emergence in organic computing systems: Discussion of a controversial concept', in Springer Berlin / Heidelberg 4158 :1–16.
- Nguyen Vu, Q.A, Gaudou, B, Canal R, Hassas, S, Armetta, F & Stinckwich, S 2010. 'Using trust and cluster organisation to improve robot swarm mapping', in *Workshop on Robots and Sensors integration in future rescue Information system (ROSIN) in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*.

- Ngoduy, D et al. 2009, 'Continuum modeling of cooperative traffic flow dynamics', in *Physica A*, 388, 2705-2716.
- Olfati-Saber, R 2006, 'Flocking for multi-agents dynamic systems: algorithms and theory', in *IEEE Transactions on automatic control*, 51.
- Osafune T et al. 2007, 'Multi-hop vehicular broadcast', in *6th International Conference on ITS Telecommunications (ISTT)*.
- Ren, W, Beard Randal, W, & Beard AI, W 2011, 'Consensus seeking in multi-agent systems under dynamically changing interaction topologie', in *IEEE Transaction on Automatic Control*, Vol. 50, 655 – 661.
- Richards, P. I 1956, 'Shock waves on the highway.', in *Oper. Res.*, 42-51.
- Schmeck, H, Müller-Schloer, C, Çakar, E, Mnif, M & Richter, U 2010, 'Adaptivity and self-organization in organic computing systems', in *ACM Trans. Auton. Adapt. Syst.*, 5 :10 :1–10 :32.
- Schermers, G, & Malone, K. M 2004, 'Evaluating ADA technologies in the Netherlands by means of demonstration projects and micro-simulation modelling', in *Proceedings of 18th ICTCT workshop*.
- Tapani, A 2006, 'Evaluation of Safety Effects of Driver Assistance Systems Through Traffic Simulation', in *Transportation Research Record*, pp 81-88.
- Tapani, A 2007, 'Analysis of system effects of driver assistance systems by traffic simulation', in *European Conference of Transport Research Institutes*, pp 1-12.
- Wilmink, I et al. 2006. 'Explorative study to dynamic speed limits in the Netherlands' Verkenning dynamische snelheidslimieten in Nederland. *TNO, Mobiliteit en Logistiek*.
- Yahya, B & Ben-Othman, J 2009, 'Towards a classification of energy aware MAC protocols for wireless sensor networks' in *Wireless Communications and Mobile Computing*, 9 (12), 1572-1607.
- Yeo, H & Skabardonis, A 2009, 'Understanding Stop-and-go Traffic in View of Asymmetric Traffic Theory', in *Transportation and Traffic Theory 2009*, Springer, New York, pp. 99 – 115.