Traffic as a Complex System: Four Challenges for Computer Science and Engineering

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Abstract. *The increasing demand for mobility in our society poses challenges not only to traffic engineers and urban planning experts, but also to computer scientists, control engineers, and other researchers involved with information technology. There is no turnkey solution for the problem of traffic congestion in metropolitan areas, but several new tools and technologies are being developed to address the following challenges in traffic engineering: modeling and simulation of traffic systems; providing information to the users via travelers' information systems; management of the system; and automation (of vehicles, highways, and intersections). These challenges are outlined here with the aim of proposing new research directions to computer scientists and electronic and computer engineers interested in the field of intelligent transportation systems.*

1. Introduction

The second half of the last century has seen the beginning of the phenomenon of traffic congestion. This has occurred because the demand for mobility in our society has increased constantly. Besides, transportation and economic growth are closely tied: according to studies conducted by the European Union (Delphy Study on Future and Mobility), the volume of goods and people transported follows the growth of the GDP. The major problem with this is that the increase in transportation volume generates traffic congestion. In metropolitan areas, traffic congestion is a phenomenon caused by too many vehicles trying to use the same infrastructure at the same time. The consequences are well-known: delays, air pollution, decrease in speed, and unsatisfaction which may lead to risk maneuvers thus reducing safety for pedestrians as well as for other drivers.

The increase in transportation demand can be met by providing additional capacity. However, this might no longer be economically or socially attainable or feasible. Thus, traffic engineering seeks to improve the existing infrastructure, without increasing the overall nominal capacity, by means of an optimal utilization of the available capacity.

Also, safety in traffic has become a key issue. Statistics from European Union show that around 50.000 fatalities occur per year in Europe. In Brazil, the situation is even worse: according to the director of the Urban Mobility Department of the National Transport and Urban Mobility Board, Mr. R. Boareto in an interview in 2004 to the online edition of Folha de S. Paulo (November 18, 2004), 30.000 fatalities and 320.000 injuries occur in traffic accidents in Brazil, per year. He compares these figures to war scenarios!

Specifically regarding urban environments, the increasing urban mobility poses challenges to traffic engineers, urban planning experts, and researchers involved with optimization and information technology. Taking the city of São Paulo as an example, in 29 of June 1996, a record of 242 kilometers of traffic jam was registered. Since then, similar levels of congestion have been registered many times, caused by heavy rain, strikes in public transportation etc. Due to the lack of timely information to users of the traffic system (public transportation, trucks and vehicle drivers) this problem tends to increase.

In order to alleviate the traffic congestion and increase safety, many, complementary, measures can be taken: improving the management systems by use of recent developments in the areas of telecommunication and information technology, improving the management via control techniques, and increasing the automation level in highways, in vehicles, and in urban areas. Ultimately the goal is to reach completely autonomous driving in order to eliminate the human factor associated with driving, and accidents.

Given all these facts, figures, and statistics, it is not surprising that urban mobility is one of the key topics affecting both the policy-makers and the citizens/tax-payers. Especially in medium to big cities, the urban space has to be adapted to accommodate the increasing needs of the commuters. Several measures have been adopted in the last years, such as congestion charging in urban areas (London), restriction of traffic in the historical center (Rome, Paris, Amsterdam), alternace of vehicles allowed to circulate in a given day (São Paulo, Mexico City), and many others which seek to impose a sustainable mobility. However, these measures impact the daily life of many commuters and tax-payers, as they restrict the freedom of movement. In order for the above mentioned measures to be better accepted, it is desirable to compensate tax-payers by providing services and information in order to help them to better plan his/her commuting needs. This can be achieved with techniques from the area of information technology (IT), and Intelligent Transportation Systems (ITS).

It is generally believed that information-based ITS strategies are among the most cost-effective investments that a transportation agency can make. Moreover, in the near future, ITS tend to be much more dependent on information technology and control and electronic engineering. However, the challenges ahead are immense as traffic is admittedly a complex system composed by many, different actors, with heterogeneous goals, whose actions are highly coupled. This is in fact the reason why vehicular traffic is quite different from traffic in computer networks: vehicles are driven by human beings with a high level of *autonomy*. Packages can be routed while drivers are free to even ignore detour information aimed at diverting them from traffic congestion.

Therefore, no obvious solution exists for problems of traffic management, which, in fact, are known for decades and have been the focus of research by mathematicians, physicists, and engineers. Perhaps, only multidisciplinary teams will be able to tackle the problem and mitigate its effects.

In the present paper I claim that these multidisciplinary strategies can be categorized in four main directions of interest for computer science and engineering:

1. Modeling and simulation of traffic systems: the availability of data and the increase in hardware processing capacity now allows fine-grained modeling of all participants of the traffic system (e.g. model of individual drivers' decision-making), as well as the use of microscopic and agent-based simulation paradigms.
2. Advanced travelers' information systems to provide information to the users: high-

way advisory radio, variable message signs, telephone information services, Web/Internet sites, kiosks with traveler information, personal data assistant devices, and in-vehicle devices.

3. Management and control of the system: modern toll systems that charge users in heavy loaded roads and reimburse users in more free roads; intelligent traffic lights; intelligent intersections *without* traffic lights; etc.
4. Automation of vehicles, highways, and intersections: GPS, car to car communication; adaptive cruise control; autonomous and/or collaborative driving; automated highways; collaborative driving, etc.

Tools and technologies related to these four main directions will be discussed here in the next four sections. At the end of each one, main computational methods are mentioned, which can be targeted in order to address those challenges. Due to lack of space, not all concepts can be detailed here. The reader is referred to [Bazzan and Klügl 2007].

2. Modeling and Simulation of Traffic Systems

An *assignment problem* is the problem of how to model the distribution of the traffic in a network considering demands between several locations, and the transportation supply and capacity in that network. Notice that this is a different problem in respect to computer networks, where one is interested in distributing the traffic (packages) efficiently. Transportation engineers need to model or reproduce, as accurately as possible, the *actual* distribution of users in a network.

Assignment methods must consider not only the distribution of traffic in a network, but also a set of constraints related to cost, time, and preferences of the road users. An example of traffic assignment is related to a classical commuting scenario: several commuters want to go from several origins to several destinations, around a specific time of the day. The network offers a large set of route choices. A typical commuter will then select the one with the least time, although other criteria can be used. Given that thousands or millions of commuters make the same decision each day, the modeling of the assignment of commuters to routes becomes a very complex task, especially given that the commuters are likely to adjust their decisions to their past experience and to the information they may gather. On the other hand, transportation authorities also collect information about the state of the network. Unfortunately, given topological constraints, it is not possible to change the supply in a high flexible way so to entirely match the demand. Therefore, transportation authorities must employ methods such as optimization.

Classically, this is done via network analysis. To this aim, it is assumed that individual road users seek to optimize their individual costs regarding the trips they make by selecting the “best” route. This is the basis of the traffic network analysis based on Wardrop’s equilibrium [Wardrop 1952]: when the equilibrium is reached, no user is better off by changing route. This analysis is based on the fact that participants chose the alternative that has the best utility for him/her.

These so-called econometric models aim at describing and modeling the network from a macroscopic point of view, i.e. based on data sampling, since the individual utility of all participants is not known. Econometric approaches have several advantages that make them attractive for describing route choice, which is an important step in the assignment problem. The most important advantage is that it yields a compact representation and it is computationally inexpensive (at least in its basic version). However, this compactness is based on homogeneous utility functions. Therefore, it cannot take individual evaluation of attributes and options into account. Moreover, every road user is assumed to evaluate and select on its own, without considering others' decisions. This way, econometric models do not account for participants' ability to adapt or evolve strategies for route choice, nor for the fact that they may have incomplete or imperfect information.

One of the most used computational tools is the so-called 4-step-process, consisting of: trip generation, destination choice, mode choice, and assignment. Assignment includes both route choice and a very basic traffic flow simulation, that are alternated until an equilibrium is reached. The two main drawbacks of the 4-step-process are: first, there is no time-dependence (steady state flows are assumed). Second, there is no consistent modeling of the travelers' decision-making. That means, for example, that while the trip generation module knows about households, income, daily plans, the route choice module only knows the starting and ending point of a trip.

Therefore the first challenge in modeling assignment in transportation networks is to move from macroscopic, econometric models, to activity-based demand generation (ABDG). Here, all travelers of the region under consideration are modeled individually regarding their travel-related decision-making throughout the day. The model requires demographic and socio-economic data, as well as data on origins, destinations, and purpose of the trips. For computer science this means processing huge volumes of data with temporal dependencies.

ABDG can be combined with agent-based approaches. In fact, some attempts have already been done. However, modeling decision-making throughout the day is difficult when the traffic flow simulation is time-*in*dependent. Therefore, for consistent modeling also the assignment part needs to be made dynamic.

Another problem is the estimation of the state of the whole traffic network from partial sensor data. Although many schemes exist for incident detection, there are few deployments of large scale traffic state estimation. One exception can be seen in `www.autobahn.nrw.de`. It uses a traffic microsimulation to extrapolate between sensor locations. The particles (vehicles) used in the simulation are quite simple and they do not know their destinations and their daily plans. This was a necessary simplification to make the approach work, but future approaches need to overcome this simplification since the effects of information systems on drivers are difficult if not impossible to estimate without modeling the drivers, possibly via agent-based simulation (ABS). This new paradigm for simulation is an alternative approach to simulation based on equations (sometimes referred as equation-based model). An agent-based simulation model consists of a set of agents that encapsulates the behavior of the various individuals. The execution of the model emulates the entire behavior of the system.

Agent-based approaches intends to allow the simulation of more "intelligent" entities including the mental states (informational and motivational) of the travelers. However, until now agent-based simulations with high-level agents on the scale required for traffic simulation of real-world networks have not been developed. The main reason is that the software tools for flexible and robust multi-agent simulations are currently just emerging.

Ultimately, in order to make traffic simulations at the microscopic and agent-based level, one may have to consider travel alternatives, joint and dynamic decision–making, contingency planning under uncertainty (e.g. due to congestion), and an increasing frequency of coordination decisions. The influence of providing information to the drivers on the actual traffic state cannot be modelled without understanding travelers' route choice behavior and how they learn traffic patterns after using the same traffic network for a given time.

Besides modeling, another important aspect is which paradigm to use to simulate the network. Simulation paradigms are normally classified according to the level of detail they use to represent the system. A microscopic model describes both the system entities and their interactions at a high level of detail. A mesoscopic model generally represents most entities at a high level of detail but describes their activities and interactions at a much lower level of detail than would a microscopic model. A macroscopic model describes only entities and their activities and interactions at a low level of detail. For example, the traffic stream may be represented in some aggregate manner such as a statistical histogram of flow rate, density and speed. Macroscopic models are helpful only when is satisfied with a coarse prediction.

Software based on microscopic models are costly to develop and to maintain. Besides, it requires a number of parameters that need to be calibrated. Moreover, traditional macroscopic, mesoscopic, and even microscopic simulation approaches have a hard time to model flexible behavior of traffic participants. The ABS paradigm provides more powerful modeling tools for drivers decision making.

In summary, adequate modeling and prediction of traffic flow will become more and more important as advanced travel information systems such as dynamic route guidance systems, are being increasingly deployed. To be effective, such systems have to make assumptions about the travel demand, and hence about travel choices. In particular, the behavior of people in reaction to the information provided (as discussed in the next section) alters the traffic situation and, potentially, makes the predictions obsolete.

Therefore, the first major challenge to computer science is to develop:

Large scale agent-based modeling and simulation of millions of individuals

3. Advanced Travelers' Information Systems

Advanced Traveler Information Systems (ATIS) aim at providing information to travelers of both highway and urban systems. Information about the transportation network before and during travel is transmitted to the traveler using infrastructure-provided equipment as well as personal assistants and vehicle-based devices. En-route and pre-trip driver information, route guidance, and emergency notifications are examples of ATIS.

ATIS can reduce travel times by giving users the information needed to select the most appropriate route, mode, or departure time for a given trip. With this information individuals can make choices that reduce their travel time while reducing the total network delay. Traveler information is particularly beneficial in situations when travelers are unaware of travel conditions on the highway network. These conditions could include incidents or bad weather. Even under normal conditions, these types of systems can benefit travelers who are unfamiliar with the area.

One of the challenges of ATIS is to be integrated with an adequate modeling of assignment (see last section) and with control of traffic flow (see next section). This becomes more and more important, for instance, for dynamic route guidance systems. The more reliable the information that a driver gets about the network (e.g. alternative routes, detours, load of the network, and even expected travel time), the more his/her actions – e.g. his route choices – depend on what s/he believes about the decisions of the other road users. A commuting scenario is normally characterized by a driver facing a repeated situation regarding route selection. However, currently drivers' private information and their reaction to it is neither registered nor considered in any forecast system.

Understanding individual travel behavior is essential for the design of ATIS according to [Adler and Blue 1998, Barfield and Dingus 1998] ands. However, the response of users to information is still an open question (e.g., [Ben-Akiva et al. 1991, Bonsall 1992]). Basically, one challenge is to develop efficient microscopic modeling and ABS tools. Moreover it is not clear whether more information is beneficial [Ben-Akiva et al. 1991]. Drivers confronted with too much information may become overloaded in the sense that information processing turns too difficult and users develop simple heuristics to solve the problem.

However, simple heuristics and overreaction by the drivers have catastrophic effects. In the city of S. Paulo, on the eve of a holiday, the CET once recommended users to plan their trips to Santos for the late hours of the night. This has caused immense jams around 3 a.m. because people overreact to the recommendation and decided to postpone their trips all together. This way, it is necessary to plan the type and frequency of the recommendations, and try to anticipate the effects of the information broadcasted. If possible, the behavior of the drivers has to be incorporated in the forecast (e.g. [Ben-Akiva et al. 1991, Bonsall 1992]).

Multi-agent techniques have been used for modeling and simulation of the effects of the use of these technologies, as well as the modeling of behavioral aspects of the drivers and reaction to information. Details can be found in [Balmer et al. 2004, Bazzan et al. 1999, Bazzan and Klügl 2005, Burmeister et al. 1997, Elhadouaj et al. 2000, Klügl and Bazzan 2004, Wahle et al. 2002].

In order to generate a recommendation or an advice, data must be gathered, especially volume of traffic and speed of vehicles. The main mean to collect this data is via induced loop sensors. This method has the disadvantage that they must be buried under the road. Alternatives based on image processing are being investigated but these are challenging since the images involve movement of objects and weather and luminosity issues. Another possibility (for restrict applications only) is to use data collected from so-called floating cars. These are vehicles such as taxis equipped with GPS (originally for help and advice to taxi drivers but nowadays used for other purposes as well). In Stuttgart, for instance, a fleet of approximately 700 taxis (data from 2003) circulate with GPS that deliver, each 30 seconds or so, position and speed to a controlling center. This center collects information from this and other sources and feeds an information and control system. Similar projects are operational in cities such as Vienna, Berlin, and Nürnberg. In order to estimate the benefits for Brazilian cities, one must only reason about the taxi fleet of S. Paulo for instance: 32689 vehicles (source: CET, December of 2006).

In terms of when information is broadcasted, ATIS may be classified in different ways. One classification distinguishes between recommendation of route *before* the trip (pre-trip recommendation) and *during* the trip (en-route). Depending on this, the broadcast can be made via radio, TV, internet, cell phone and other mobile devices, VMS or on-board devices. VMS are panels where messages are written according to the specific situation. These are use to give en-route information. The use of VMS has increased a lot in the last years given the increase in traffic jams, and also because it is popular among drivers, who can have fast and direct access to information in order to make decisions during their trips. Typical messages are road work announcements or detours and incident messages.

By using VMS, both rough information as well as route recommendation may be broadcasted. However, as said, the manager of the system must be careful before given route recommendations that may cause the recommended route to be overloaded due to overreaction of the drivers. If "bad" recommendation occurs frequently, drivers tend ignore the recommendation as they perceive it as not valuable, wrong, or as a tentative to divert them to alternatives that are better for the overall balance in the network. This kind of problem was simulated in [Klügl and Bazzan 2004, Bazzan and Klügl 2005].

In any case, drives seem to prefer rough information that allow them to make their own decisions. However, it is questionable whether rough information is of any help for drivers. In order to use rough information and translate it into alternative routes, the driver must know the network very well. Moreover the driver tends to make myopic decisions, especially if the information received is just local information.

Despite these issues, there have been several reports about benefits of ATIS. Surveys performed in the Seattle, Washington, and Boston metropolitan areas indicate that 30%–40% of travelers frequently adjust travel patterns based on travel information. Of those who change travel patterns, about 45% change route of travel and another 45% change time of travel; an additional 5%–10% change travel mode.

In summary, the major challenges for computer science regarding ATIS are:

- Information gathering from thousands of sensors, cameras, and GPS;
- Data storage, maintenance and integration (GIS etc.);
- Broadcast via mobile devices (interfaces, etc.);
- Interoperability of on-board and on-route devices.

4. Management and Control of Traffic Systems

Given the current developments in communication and hardware, computer-based traffic control and management of the traffic system is now a reality. Nowadays the term "advanced transportation management systems" (ATMS) is used to denote the set of all control and management technologies.

The main goals of ATMS are: to maximize the overall capacity of the network; to maximize the capacity of critical routes and intersections which represent the bottlenecks; to minimize the negative impacts of traffic on the environment and on energy consumption; to minimize travel times; and to increase traffic safety. Besides, modern philosophies of ATMS also attempt to efficiently manage the communication between driver, vehicle, and roadway components (e.g. traffic signals).

In order to achieve ATMS goals, devices to control the flow of vehicles have been used. The installation of the first mechanical device for street crossing in front of the Houses of Parliament in London in December 10th, 1868 and the first traffic light in Cleveland in 1914 are milestones worth noting. From then on, the most widely employed traffic flow management concept is the use of traffic signals. This can vary from hard-wired logic to computerized control, either centralized or decentralized.

Signalized intersections are controlled by signal-timing plans which are implemented at traffic signals. A signal-timing plan (signal plan for short) is a unique set of timing parameters comprising basically the cycle length (the length of time for the complete sequence of the phase changes), the split (the division of the cycle length C among the various movements or phases), pedestrian requirements for timing, and the phase-change interval. Traffic signals are ubiquitous in medium to big cities. In São Paulo, for instance, there are more than 5000 signalized intersections (source: CET, June 2006).

There are several concepts of computer-based ATMSs. The most basic is the computer sends out commands that control the signals[1] (isolated or in an arterial), receiving no feedback. Thus the traffic signal plans are not responsive to the actual traffic conditions. Signal plans are generated off-line based on historical or earlier traffic data, not in a real time fashion. The second concept for ATMSs is similar to the former but uses detectors that feed information back to the central computer. However, this information is not used to influence the current plan selection, just for off-line creation of other plans. In full actuated operation, every lane of every approach must be monitored by a detector. Green time is allocated according to information from the detectors and programmed rules established in the controller. In this type of operation, the cycle length, sequence of phases, and green time split may very from cycle to cycle.

Another concept is operating coordinated systems (also called synchronized or progressive systems). The goal here is *to synchronize the traffic signals along an arterial* in order to allow platoon of vehicles, traveling at a given constant speed, to cross the arterial without stopping at red lights. Thus, coordination here means that if appropriate signal plans are selected to run at the adjacent traffic lights, a "green wave" is built so that certain vehicles do not have to stop at certain intersections.

Well designed signal plans can achieve acceptable results in *not completely congested streets in one flow direction*. However progression in two opposing directions of an arterial is difficult to achieve, if not impossible, in almost all practical situations. The difficulty is that the geometry of the arterial is fixed and with it the spacing between adjacent intersections. Only in very special cases the geometry allows progression in opposite directions. Synchronization in four directions is, for practical purposes, impossible.

First generation of coordinated systems are based on computation of synchronized signal plans for fixed times of the day such as morning and afternoon rush hours. Even if the computation itself is not manual, this is a complex task that requires a lot of expert knowledge, as well as historical data. Once the traffic expert can generate a library of plans, the next task is to decide which one to select under each situation. This is effective

[1]The terms intersections, crossing, junction, traffic signal and traffic light are used here interchangeably since in each intersections, *only one signal-timing plan* runs in a set of traffic lights so that the set of traffic lights must be seen as a single entity.

only in networks with well-behaved traffic patterns. In second generation coordinated systems, plans are computed in real time, based on forecasts of traffic conditions using detector data as input to a prediction algorithm. A third generation mentioned in the literature, namely highly responsive control, is based on the relaxing of a cycle-based system. It is of course much more difficult to maintain a progressive pattern where cycle length or phase splits are allowed to vary. This can be overcome with queue management at critical intersections, requiring a high number of detectors. Due to all these difficulties, systems of the third generation are not yet deployed.

The common reality is that, if a coordinated system is implemented at all, it is almost always a fixed-time, manually operated one. This is so because the computer controlled traffic responsive system relies on detectors. These are unaffordable for huge cities in developing countries, not robust, and of difficult maintance (since buried). In fact, at any given time, most of the detectors (even in Europe) are out of order. Despite this, some successful cases of use of computer-controlled coordinated systems are reported in Washington DC, Toronto, Sydney, and UK.

Some algorithms were proposed in the sixties and seventies to analyze traffic patterns and to set coordination in arterials. The most known is TRANSYT, an *off-line* optimization tool [TRANSYT-7F 1988]. SCOOT [Hunt et al. 1981] and SCATS [Lowrie 1982] work similarly but are both based on traffic responsive operation. A new approach is TUC (*Traffic-responsive Urban Traffic Control*) [Diakaki et al. 2002], conceived for large scale networks. Authors report positive results compared to a situation with fixed time synchronization. On the other hand, the computation is centralized and the conflits are solved either by a traffic expert or by a priori rules, in a clear contrast with a trend of decentralization of control.

Thus, approaches are necessary that seek to replace the traditional arterial green wave by "shorter green waves" in *segments* of the network, as these can be computed in a distributed way. Of course in some key intersections conflicts may appear because in almost all practical situations, synchronization in more than one traffic direction is not possible. Hence the challenge is to decide dynamically which direction is synchronized.

An additional problem for an integrated control of traffic is the interoperability between hardware from several vendors, e.g. traffic light controllers. Different manufacturers and models all use proprietary technologies. Middleware were proposed in [de Morais et al. 2004] to serve as an interface between traffic management applications and control devices, allowing the integration of different specifications of controllers in a single system, many issues remain open as this middleware is restrict to the case of traffic light controllers.

There has been far more reports about benefits of ATMS than about benefits of ATIS, possibly because ATIS are more recent than ATMS, a established research field. Some examples are: The Maryland CHART program is expanding automated surveillance with lane sensors and video cameras. The evaluation of the initial operation of the program shows a benefit/cost ratio of 5.6:1, with most of the benefits resulting from a 5% (2 million vehicle-hours per year) decrease in delay. The Automated Traffic Surveillance and Control (ATSAC) Program in Los Angeles, a computerized signal control system, reported an 18% reduction in travel time, a 16% increase in average speed, and a 44% decrease in delay. The city of Toronto, Ontario, Canada, evaluated SCOOT on two corridors and the central business district network, resulting a 8% decrease in travel time as well as a 17% decrease in delay.

Regarding new technologies and future challenges, due to space limitation, I discuss here two directions that deal with different aspects of the control problem: congestion toll (and its effect) as a mechanism to balance the load in highway networks, and intersection without traffic lights (to be used by autonomous vehicles, which are discussed in the next section).

Normally, control strategies aim at achieving the *system* optimum (minimization or maximization of some *global* objective criterion). However, this does not imply the Wardrop's *user* optimum. In general, traffic control authorities are interested in the system optimum, while the user seeks its own optimum.

Road pricing and specifically congestion tolls are concepts related to balancing marginal social costs and marginal private costs. It has been speculated that road pricing improves the efficiency of network equilibrium [Arnott et al. 1990] as negative external effects of road user i over others is accounted for. This way, road pricing has been proposed as a way to realize efficient road utilization i.e. to achieve a distribution of traffic volume as close as possible to the system optimum. Congestion toll is one of the road pricing methods: considering the system optimum, a toll is computed which is the difference between the marginal social cost and the marginal private cost. Notice that this difference can be negative meaning that drivers actually get a reimbursement. This mechanism is not to be confunded with toll charging for the sake of covering costs of road maintenance or simply for profit.

A state-dependent toll pricing system is discussed in [Kobayashi and Do 2005]. They provide the calculations of which are the system optimum in terms of traffic volume in each case as well as the drivers expected welfare (average over all drivers). In [Bazzan and Junges 2006] this method is compare with the distribution of traffic volume which is achieved when drivers make their route choices based on the toll they receive, in a bottom-up, agent-based approach for adaptive route choice. First, an agent computes an expectation of the costs he will have if he selects a certain route. With a certain periodicity, it updates this heuristic according to the rewards he has obtained on the routes he has taken so far. Since the rewards include the toll payed (or amount reimbursed), simulations performed showed that congestion tolls are useful to internalize the costs drivers impose to others when they act greedily.

Regarding intersections without traffic lights, one should notice that conventional traffic lights as we know today were designed as an interface for human beings (drivers). However, when autonomous driven vehicles (called ADV here) are deployed, a scenario expected to be reality in a few decades, the traffic light as we know today will have to be changed. Once vehicles are autonomous (e.g. driven by sensors and actuators), also the interfaces and *modus operandi* will have to be changed. The basic idea is that autonomous vehicles are equipped with communication devices. Up to now, the automobile industry is concerned with car to car communication (see next section). However, once the basic infrastructure is there, it will be possible to use it to make vehicles and control equipment to communicate as well. Then, once these entities can communicate, several protocols can be thought in order to make control at intersections more intelligent.

One draft proposal deals with specific aspects of how vehicles could use the intersection. This so-called reservation-based intersection control [Dresner and Stone 2004] is proposed in for a simplified version of real-world intersection without conventional traffic lights. The reservation is performed as follows: first, the ADV informs the intersection manager (IM): the time it will arrive at the intersection, the velocity, direction, maximum and minimum acceleration and other vehicles properties. Then, the IM simulates the journey of the ADV, given the IM's knowledge about other similar reservations. If the space requested by the ADV (for a given time) is already occupied, then the request is rejected, in which case the ADV must decelerate and try again. If the request is accepted, it must be kept or canceled by the ADV (in case it cannot be met).

Up to now the protocol is very simple and has many open questions. To begin with, vehicles have limitations in their freedom of turning, changing lanes, and movement. A second issue is that it is not clear what happens if the driver has to make last *second* changes, whether the ADV is really committed to the deceleration, what happens if conventional vehicles participate in the system as well, and what happens outside the look of the intersection manager after ADV's have to decelerate in response to a deny of request. As soon as conventional guided vehicles are present, these are likely to disturb the nice dynamic shown in the simulations (see `http://www.cs.utexas.edu/~kdresner/aim/oldsim/`), especially in what regards lane changing.

This issue of mixed traffic (i.e. ADV *and* conventional, human-driven vehicles) is a key one. As long as only autonomous vehicles are present in the traffic, we can expect very low level of failures, assuming that those sensors and actuators reach the desired level of reliability, a reasonable assumption given the current developments in this area (e.g. sensors used in airplanes, airports, etc.). This aspect is very important in developing countries. In Brazil for instance, a significant part of the fleet is very old and does not even comply with safety issues. It is therefore not realistic to expect autonomous vehicles to be the majority of the fleet in the next decades, an important condition for such a reservation-based system to work (see [Dresner and Stone 2007] for details).

Traditionally, the area of control and management of traffic is the one where computer science has given more contribution. However, some challenging issues remain for AI, distributed systems, middleware, and for computer and electronic engineering:

- More intelligent ways to use actuated conventional traffic lights;
- Decentralized coordination of conventional traffic lights;
- Interoperability of control devices;
- Mechanisms to implement congestion tolls;
- Automated intersections.

5. Back to the future: Automation of vehicles, Highways, and Intersections

In the last two decades, the interest on new technologies for automation has increased tremendously. The main direction has been the transition from manual to automated control (both regarding the vehicle as well as the transportation infrastructure). This transition is expected to have two main effects: i) how the actors will work, and ii) how they are to be integrated. For example, in a conventional highway or urban system, the driver has the complete control over his/her route choice, given that the control (path choice, speed, lane changing, etc.) is made by the driver. In the future, the majority of these activities will be performed automatically, and will be electronically controlled. For example, it is assumed that car to car communication will substitute the visual perception of the driver. Once the automatic control is sufficiently reliable, they are likely to improve performance and safety. Sensors and actuators are not subject to failures due to lack of attention, alcohol and other drugs, physical, physiological, and psychological problems. Of course sensors and actuators do fail but good control over their state and preventive maintenance can drastically reduce the likelyhood of accidents. A hint of this is that most of the accidents in aviation are caused by human failures, not by sensors and actuators. An example of the benefits of autonomous driving is that once the driving task is automated, vehicles can travel in platoons with minimum gaps between them.

In order to reach this level of automation, developments must evolve in two main directions: automation in vehicles and automation in the road infrastruture.

Regarding the latter, there are proposals of reservation of lanes for vehicles having autonomous driving technology. Entering and leaving these lanes would still be performed manually but, once the autonomous driven vehicle (ADV) reaches the reserved lane, all driving operations would be performed automatically, including lane changing.

Therefore, an important side of the automation process regards automated highway systems (AHS). These will be responsible for vehicles acceleration, deceleration, limiting access of given vehicles to given portions of the network, safety, etc. In this case, it is very important that ADV and AHS can communicate efficiently. This communication is key for the coordination of all actors involved.

Although AHS are very important, the first step is to increase the automation level in the vehicles themselves, so that they can later profit from the automated highways. Thus, the automobile industry is investing massively in these issues. Initially this industry is concerned with safety and confort. Just to mention some improvements, parking help, ABS, and the so-called Cruise Control (driver sets the speed while acceleration is automatic) are taken for granted when American consumers buy a new car.

The next step is to deploy adaptive cruise control and automated driving. However, in order to do this, several questions are still open as for instance what kind of interfaces with the driver must be developed.

Regarding car to car communication, the proposals are based on two-way communication. For instance, when a vehicle detects another stopped vehicle, it can communicate this fact to others, thus permitting them to plan and decelerate smoothly, what reduces the fuel consumption and air pollution. The frequency of transmission as well as communication protocols are still open questions. It is expected that the data transfer rate be superior to 1 Mbps.

Regarding sensors and actuators, these are of two main types: longitudinal and lateral. As for the longitudinal, these must measure distance and relative speed between a given vehicle and those ahead and behind. Specifically, a vehicle ahead must be detected with fine accuracy: speed changes around 2 MPH (3.5 Km/h) must be detected. In terms of lateral control, several types of sensors are already used such as those based on on-board cameras and image processing. Specifically for road detection, magnetic devices that work as markers or guides for vehicles are already used. A description of different types of technologies as well as their advantages, disadvantages, applicability, and minimum requirements for safety can be found in [Ioannou and Bose 2003].

These new technologies also aim at a better utilization of the capacity of the network. This is a more complex matter and involves middleware as well as software and intelligence. Besides the fact that intelligent intersection are necessary, another key point must be highlighted: while human drivers are generally *not* collaborative (on the contrary, road rage is an increasing phenomenon), automated vehicles can be designed to collaborate and serve the collectivity and react to global measures (e.g. network balance). Collaborative driving by platoon formation is just one proposal ([Hallé and Chaib-Draa 2005]).

In summary, the automobile industry as well as universities and research institutes are already making tremendous progress that will enable autonomous driving. This is an unavoidable direction of future research given that manual driving is reaching its limitations: roads, streets, highways are increasingly jammed; drivers seek risk maneuvers that cause more and more accidents. Autonomous driving is likely to eliminate the human-failure component associated with current driving styles. Moreover, it will help to save millions of men-hours as people will be able to use their time for other activities while the car is driven automatically.

This is not a far reality though. Concrete proposals exist and DARPA is sponsoring the DARPA Urban Challenge (`http://www.darpa.mil/grandchallenge/index.asp`) with 57 teams from 6 countries. The program is conducted as a series of qualification steps leading to a competitive final event, scheduled to take place on November 3, 2007. In 2005 the Stanford team won the previous setting of this competition, by having an autonomous vehicle successfully completing a 131.2 mile course in the Mojave Desert, ahead of four other teams. An astonishing accomplishment (worth 2 million dollars!).

The last challenge, automation, can then be summarize as follows:

- Development of safe and reliable sensors and actuators;
- Protocols for road, highway, and intersection automation;
- Human drivers out of the loop.

6. Conclusion

The more societies and economies become complex and coupled, the more difficult is the management of the traffic. Traffic engineering now requires solutions that are based on information technology and control engineering. This paper has outlined several challenges for subareas of computer science, information technology and engineering, aggregated around four main areas involving ITS. In order to tackle most of those challenges, it is obvious that researchers from different areas of computer science, traffic and engineering have to get together and join efforts in multidisciplinary teams.

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