Traffic Simulation and Control: challenges and opportunities for agent technology, multiagent systems, and artificial intelligence

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(and collaborators)

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Main Goal

- convince you that this is a challenging application
- convince students to jump into this application
Outline

- Motivation and introduction
- Some concepts
- Modeling and simulation
- Management and control
- Adv. travelers' information systems
- Automation of vehicles, highways, and intersections
Motivation

- transportation: key in the development of human societies
- 20\textsuperscript{th} century: congestions start
  - fast demand increasing
- problem likely to worse
  - transportation systems: high impact in the economy of any nation
Motivation

- increasing demand for mobility
- increasing demand for services, commerce and trips
  - challenges to transportation eng.
  - traffic jams
  - costs: up to 1% of GNP (EU forecast)
  - Americans lose $100 billion annually (1995) in wasted time and spent fuel while sitting in traffic
Motivation

- traffic is one of the oldest examples of complex system
  - composed by many, different actors
  - with heterogeneous goals,
  - whose actions are highly coupled
Motivation

• NOT a computer network:
  • drivers are autonomous (sometimes irrational!)
  • drivers cannot be routed
  • safety issues: bad policies have far more serious consequences
  • ...

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Introduction

- how to tackle the problem?
  - extension of the traffic network
    - economical, social, and environmental consequences
  - optimization of the existing network, intelligent methods
Introduction

• what is done today?
  • side of control:
    a) intelligent traffic lights
    b) no traffic lights !!!
  • however:
    a) expansive to maintain
    b) safe ? works in the long run? big cities?
Introduction

• what is done today?
  • side of planning
    • tolling in urban areas (London)
    • traffic restrictions in historical centers (Rom, Paris, Amsterdam)
    • restriction to circulation of given vehicles (S. Paulo, Mexico City)
  • however:
    • not popular, citizens' pockets !!!
Introduction

• more intelligent solutions:
  • providing information to the citizen (helps trip planning)

• several technologies
  • generally packed under **ITS** *(Intelligent Transportation Systems)*
Introduction

- **ITS: 3 views**
  - ATMS (advanced travel management systems)
  - ATIS (advanced travelers' information system)
- **new technologies:**
  - autonomous driving
  - automated highways
Introduction

• But...before we go to ITS...
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Basic Concepts

- ATMS:
  - control and management technologies
    - emergency handling
    - communication among devices
    - ...

Basic Concepts

- ATMS

source:
Basic Concepts

● ATIS:
  ● providing information to travelers of both highway and urban systems
  ● before and during travel
  ● examples: en-route and pre-trip driver information, route guidance, and emergency notifications
Basic Concepts

• ATIS (cont.)
  • information:
    • generated by the ATMS
    • handle by the engineering
    • sent to users via:
      • radio
      • embedded systems
      • route guidance
      • ...
Basic Concepts

- ATIS

Basic Concepts

• ITS summary:
  • can minimize effects of demand for mobility

• BUT: increase in capacity -> increase in demand :-(

• complex process: need to simulating this coupling with simulation
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Modeling and Simulation

• assignment: 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
Modeling and Simulation

• classical commuting scenario:
  • millions of commuters want to go from O to D at the same time!
  • large set of route choices
  • typical commuter: select the one with the least time
  • very complex task: commuters are likely to adjust their decisions to their past experience
Modeling and Simulation

• network analysis:
  • road users seek to optimize their individual costs regarding the trips they make by selecting their best route

• Wardrop's equilibrium (1952):
  • under equilibrium conditions, traffic arranges itself in congested networks such that all routes between any O-D pair have equal and minimum costs while all unused routes have greater or equal costs.
Modeling and Simulation

- econometric models:
  - describing and modeling the network from a macroscopic point of view, i.e. based on data sampling
  - individual utility of all participants is not known
Modeling and Simulation

- econometric models: advantages
  - yields a compact representation
  - computationally inexpensive
- disadvantages
  - do not take individual evaluation of attributes and options into account
  - individuals evaluate and select without considering others' decisions
  - thus: no adaptation of route choice
Modeling and Simulation

• a little bit better: 4-step-process
  • trip generation, destination choice, mode choice, and assignment
  • drawbacks:
    • no time-dependence (steady state flows are assumed)
    • no consistent modeling of the travelers' decision-making
Modeling and Simulation

• even better: agent-based (ABS)
  • all travelers can be modeled individually (regarding route choice, time of departure, etc.)
  • requires demographic and socio-economic data, as well as data on origins, destinations, and purpose of the trips
  • huge volumes of data with temporal dependencies
in any case: paradigm change!
- macroscopic, econometric, equilibrium based
  - good approximation
- microscopic, agent based
  - more complex: decision behavior of individuals, all actors are modelled

trade-off must be considered
Modeling and Simulation

• problems with ABS:
  • software tools for flexible and robust multi-agent simulations are currently just emerging
Modeling and Simulation

- problems with ABS:
  - joint and dynamic decision-making, contingency planning under uncertainty (e.g. due to congestion), and an increasing frequency of coordination decisions
  - ATIS not easily “simulated” due to human behavior
Modeling and Simulation

- Nagel-Schreckenberg CA model
Modeling and Simulation

- Nagel-Schreckenberg CA model
  - shortcomings:
    - driver + vehicle as single unit
    - assumption: drivers always want to drive at maximum speed
    - does not consider goals, preferences and intentions of single drivers
Modeling and Simulation

• summary: current status is
  • either MASS / QUANTITY
    • www.autobahn.nrw.de
    • online simulation of German highways as particles without trip plan (data from sensors)
  • or QUALITY
    • intelligent entities including the mental states (informational and motivational) of travelers
Modeling and Simulation

• software for simulation
  • macroscopic
    • drivers from a homogeneous population
    • no model of individuals
    • not focus here
Modeling and Simulation

- software for simulation
  - microscopic
    - commercial license:
      - Paramics
      - Dracula
      - VISIM
      - EMME2
    - open source: ITSUMO
Modeling and Simulation

- **ITSUMO**
  - database

![Diagram](image.png)

- simulator
- C++
- visualization
- Data / statistics
- Signal plans (agents)
- route decision (drivers)
- 373773738
- 848474747
- 398383838
- 388747644
- 294710135

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Modeling and Simulation
Modeling and Simulation

• summary:
  • major challenge to computer science is to develop

Large scale agent-based modeling and simulation of millions of individuals (human beings)
Excursion

- Problem
- Modeling
- Simulation
- Control
- Traffic control
- ABS
- ATIS
- Toll
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Management and Control

- traffic control by traffic lights
- traffic control by information
- traffic control by toll
- …
Management and Control

• first...
  • ... some concepts
Basic concepts in traffic control

- traffic control by traffic lights
  - first mechanical device: 1868 (London)
  - first traffic light: 1914 (Cleveland)
  - control algorithms using OR: 1960's
  - AI / expert systems: 1980's
  - MAS: open more possibilities to decentralized control
Basic concepts in traffic control

• signal-timing plan:
  • unique set of timing parameters comprising:
    • cycle length (length of time for the complete sequence of the phase changes)
    • split (the division of the cycle length C among the various movements or phases)
    • pedestrian requirements for timing
    • phase-change interval
Basic concepts in traffic control

- signal plan with 3 phases
Basic concepts in traffic control

- operation
  - pre-programmed, off-line based on historical data
  - traffic-responsive: needs detectors ($$$)
  - coordinated (synchronized, progressive, green wave)
Basic concepts in traffic control

• 4 possibilities of control of TL:
  • find optimum cycle time
  • find optimum number of phases
  • phase timing: green time according to demand of each approach (lanes)
  • find optimum offset (progressive systems)
Basic concepts in traffic control

• coordinated (synchronized, progressive, green wave)
  • in general: no progression in all traffic directions
  • plans must be selected
Basic concepts in traffic control

![Graph showing basic concepts in traffic control]

- Distance (m.)
- Time (secs.)
- 5th. st. 1200
- 4th. st. 900
- 3rd. st. 600
- 2nd. st. 300
- 1st st.
Management and Control

- well designed signal plans can achieve acceptable results
- BUT: progression in two opposing directions of an arterial is difficult to achieve (geometry)
- thus: which direction ???
- solution: flexible, short green waves
Management and Control

• classical solutions:
  • computer programs for progressive systems:
    • MAXBAND and TRANSYT (offline, OR based, 60's)
    • SCOOT (traffic responsive, centralised, 80's)
    • SCAT (traffic responsive, centralised, 80's)
    • TUC (200x)
• AI solutions
  • expert system (Paris, 80's)
  • co-learning (drivers and lights):
    • Wiering (ICML 2000)
  • stochastic game:
    • Camponogara & Kraus (EPIA 2003):
      2 intersections
  • learning from multiple sources:
    • Nunes and Oliveira (AAMAS 2004)
Management and Control

- AI solutions
  - learning classifier systems (LCS)
    - Bull et al. (2004), single intersection, traffic responsive
  - evolutionary approach + LCS
    - Rochner et al. (2006): preliminary results
  - reservation based
    - Dresner and Stone (2004): no traffic light, autonomous driving
Management and Control

• AI solutions, our group
  • 1997: game theory + reinforcement learning + evolution
  • 2004: swarm intelligence
  • 2005, 2007: distributed constraint optimization
  • 2006: model base reinforcement learning
  • 2007: stochastic game, co-learning
Management and Control

• green wave via GT+RL+GA
  • RL:
    • signal plan with best reward more likely to be selected in the future
  • GT (stochastic coordination game):
    • payoff changes stochastically
    • coordinated action better rewarded
  • GA:
    • mutation: scape no longer valid policy
Management and Control

- green wave via GT+RL+GA
  - advantages:
    - no need of a global model of traffic
    - subgroups of synchronization (instead of a long green wave)
    - no central control
    - no explicit communication or negotiation
Management and Control

• green wave via GT+RL+GA
  • disadvantages:
    • need to define payoff matrices
    • time consuming for many directions and / or complex network
Management and Control

- swarm intelligence based control
  - division of labor, task allocation
  - tasks are signal plans
  - each TL behaves like a social insect
  - emergence of green wave
  - no need of payoff matrices
Management and Control

- swarm intelligence based control
  - each individual $i$: specific threshold for each kind of task $j$
  - stimulus: concentration of pheromone
  - response threshold:
    - tendency of $i$ to perform $j$ responding to stimulus $s_j$
    - updated using a reinforcement mechanism
Management and Control

• swarm intelligence based control
  • task (plan) allocation in insect colonies
    • stimulus of plans computed
    • higher stimulus: higher probability of plan being selected
Management and Control

- swarm intelligence based control
- real network (data from Porto Alegre)
• swarm intelligence based control
  • results:
    • without synchronization: all 3 streets jammed
    • fixed synchronization (time based): only main st. is not jammed
    • dynamic synchronization via swarm intelligence: side streets less congested (balance of load)
Management and Control

• swarm intelligence based control
  • disadvantage:
    • long time for adaptation (can be critical in real time operation if traffic pattern changes too frequently)
Management and Control

- control via DCOP
  - distributed constraint optimization
    - set of distributed variables related by valued constraints
    - find values for each variable in order to optimize a global cost function
  - needs communication
  - compromise between implicit communication (swarm, GT) and classical approaches
Management and Control

• control via DCOP
  • constraints between adjacent traffic lights
    • select between possible signal plans to synchronize
      • East or West bound
      • North or South bound
  • costs are function of densities in the lanes
  • algorithms: ADOPT, OptAPO and DPOP
Management and Control

• control via DCOP

• results: groups of coordination emerge
... but: communication cost

<table>
<thead>
<tr>
<th>Alg.</th>
<th>Time (s)</th>
<th>Messages</th>
<th>Size of msg (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADOPT</td>
<td>6.30</td>
<td>2451.68</td>
<td>63.54</td>
</tr>
<tr>
<td>DPOP</td>
<td>0.21</td>
<td>112</td>
<td>147.83</td>
</tr>
<tr>
<td>OptAPO</td>
<td>2.63</td>
<td>533.84</td>
<td>20.50</td>
</tr>
</tbody>
</table>
• reinforcement learning
  • RL-CD:
    • learn (and maintain) multiple models
      • different models for different traffic patterns (contexts) -> different policies
    • how good is the forecast?
    • each partial model: measure of forecast error
    • confidence used to compare models (older models generally higher confidence)
Management and Control

• reinforcement learning
  • RL is a good idea...
  • but: non-stationarity is hard!
  • with model-based RL: no need for policy relearning
  • RL-CD: selection and creation of models on-demand
Management and Control

- summary of AI solutions: what we can now do
  - adaptation to traffic patterns
  - emergence of small coordination groups (serve several traffic directions)
  - many intersections, medium size traffic networks
  - decentralized
Management and Control

- congestion toll: difference between social cost and the private cost
  - positive: users pay toll
  - negative: users get a reimbursement
- problem: assumption about a central control entity with perfect information (to compute the toll)
Management and Control

- congestion toll:
  - no assumption of central control
  - instead: using reinforcement learning
    - Bazzan and Junges AAMAS 2006
Management and Control

- **summary: challenges for control**
- Intelligent ways to use traffic-responsive conventional traffic lights;
- Optimization and constraint processing
- Decentralized coordination of conventional traffic lights;
- Interoperability control devices;
- Mechanisms to implement congestion tolls
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ATIS

- providing information to travelers of both highway and urban systems
- before and during travel
- examples: en-route and pre-trip driver information, route guidance, emergency notifications, etc.
• can reduce travel times by giving information to help selecting the most appropriate route, mode, or departure time

• however: understanding response of users to information is still an open question (human in the loop)
ABS can facilitate the simulation of the effects of ATIS

but: needs data

- loop induced sensor data
- FCD (floating cars data): taxis
- but: GPS, communication is no reality in developing countries
ATIS

- ABS: agent architecture
  - strategical layer
  - tactical layer
• strategical layer
  • example:
    • commuter scenario: 2 routes R (shorter) and A
    • but: roadwork on R
    • which one to take? how about others? social dilemma !!!
  • solution: simple scenarios
  • long-term goal BDI-approach (beliefs, desires, intentions)
• BDI: problems
  • shall I model other drivers' models too???
  • too complex!
  • instead, direction followed:
    • first: study what kind of information to give to drivers
    • then: study how people make decisions
• SURVIVE:
  • experiments performed
  • data collected
  • our task: to simulate and replicate data from real subjects via a reinforcement learning mechanism
• SURVIVE:
  • ABS able to replicate experimental data (real subjects)
  • useful to predict other scenarios?
  • how about minority games?
• MG:
  • personalities: set of meaningful strategies
  • reduces the set of strategies to select from (much closer to how we do it)
• summary:
  
• major challenges related to ATIS
  
  • Information gathering from thousands of sensors, cameras, and GPS;
  
  • Data storage, maintenance and integration (GIS etc.);
  
  • Broadcast via mobile devices;
  
  • Data Mining of geographical data
  
  • Interoperability of devices
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Automation

- last two decades: interest regarding new technologies for automation has increased
- from manual to automated control (of vehicle and infrastructure)
- human OUT of the loop!
Automation

• conventional highway or urban system:
  • driver has the complete control over his/her route choice

• future:
  • majority of these activities will be performed automatically, and will be electronically controlled
Automation

• benefits autonomous driving
  • emission reduction
  • safe lane change
    • American interstates (1994)
      • 50% accidents caused by drivers (28% during lane change)
  • experiments (Ioannou&Bose2003):
    • 19% reduction CO, 3.4% CO2, 3.6% fuel consumption
Automation

• examples:
  • car to car communication will substitute the visual perception of the driver
  • sensors and actuators will substitute driver
  • not subject to failures due to lack of attention, alcohol and other drugs, physical, physiological and psychological problems
Automation

- developments in two main directions:
  - autonomous driving and automated vehicles
  - automate highway and road infrastructure
• but:
  • AHS and ADV do not work without reliable:
    • communication
    • sensors and actuators
    • coordination of the decentralized intelligence
Automation

• ADV: so far not a reality
  • concrete proposals from car industry and universities
• Darpa challenge
  • http://www.darpa.mil/grandchallenge/index
  • http://en.wikipedia.org/wiki/Darpa_grand_challenge
Automation

• Darpa challenge
  • 2007
    • urban
    • MUCH more difficult
Automation

- beyond Darpa challenge
- emergency vehicles: traffic lights on green as the emergency vehicles approach

pictures: Daimler-Chrysler
Automation

• beyond Darpa challenge

• remote diagnosis and maintenance of vehicle

  • vehicle could automatically transmit its individual performance data

  • if necessary service center advise driver or transmit updated software for engine adjustment
• beyond Darpa challenge

- Using DSRC, several vehicles can communicate directly with one another over a distance of some 300 yards. The white car coordinates an overtaking maneuver with the three vehicles in the right-hand lane (above). The braking signal of the white car is automatically transmitted to the red car, despite the fact that his view is obstructed by two trucks (below).
• further challenges
  • how can vehicles collaborate?
    • collaborative driving
  • how roads and junctions will look like?
  • but: several open problems
Automation

• summary: challenges related to automation
  • Development of safe and reliable sensors and actuators;
  • Communication protocols for road, highway, and intersection automation;
  • Human drivers out of the loop.
Conclusion

- more complex societies -> more demand mobility -> more difficult traffic management
- traffic engineering: requires solutions based on information technology and control engineering
Conclusion

- here: several challenges for AI, MAS, CS, IT and engineering
- researchers from different areas of computer science, traffic and engineering have to get together and join efforts in multidisciplinary teams
Conclusion

- this may not be a killing application for AI and MAS...
Conclusion

• ... but if nothing is done...
• ... it is likely that we will be killed
Collaborators
(chronological)

- J. Wahle (TrafGo)
- M. Schreckenberg (U. Duisburg)
- R. Bordini (U. Durham)
- F. Klügl (U. Würzburg)
- R. Rossetti (U. Porto)
- E. Oliveira (U. Porto)
- K. Nagel (TU Berlin)
Collaborators

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  - CAPES
  - DAAD
  - Alexander von Humboldt
Thank You!

more about our traffic projects

http://www.inf.ufrgs.br/maslab/

http://www.inf.ufrgs.br/~mas/traffic/