

Towards a Computational Transportation Science

Stephan Winter, The University of Melbourne

Monika Sester, Leibniz University Hannover

Ouri Wolfson, University of Illinois, Chicago

Glenn Geers, National ICT Australia, Sydney

1 An emerging discipline

In the near future, vehicles, travelers, and the infrastructure will collectively have billions of sensors that can communicate with each other. This environment will enable numerous novel applications and order of magnitude improvements in the performance of existing applications. However, information technology (IT) has not had the dramatic impact on day-to-day transportation that it has had on other domains such as business and science. In terms of the real-time information available to most travelers, with the exception of car navigation systems, the transportation experience has not changed much in the last 30-40 years. During this same time, the miniaturization of computing devices and advances in wireless communication and sensor technology have been propagating computing from the stationary desktop to the mobile outdoors, and making it ubiquitous. Future transportation systems, due to their distributed/mobile nature, can become the ultimate test-bed for this ubiquitous (i.e., embedded, highly-distributed, and sensor-laden) computing environment of unprecedented scale. Information technology is the foundation for implementing new transportation control and management strategies, particularly if they are to be made available in real-time to wireless devices such as cell phones and PDAs, traffic lights or dynamic signs. A related development is the emergence of increasingly more sophisticated geospatial (including spatiotemporal) information management capabilities.

Examples for this evolution are reducing congestion by providing drivers with complete, accurate, continuous and timely information about traffic conditions on the metropolitan roadways, providing travelers with timely and continuous best-route-to-destination using all available means of transportation, providing continuous, accurate and timely information about parking availability, coordinating evacuations in real-time in the event of disasters, or managing dynamic e-tolling schemes that lead to reduction of traffic delays.

While the field is moving forward with new technologies and applications, mostly subsumed as Intelligent Transportation Systems, the question arises whether the new technical possibilities also require new scientific foundations. So what is new? More and more aspects of transportation science require deep computational methods to deal with the complexity of dynamic environments. CTS is studying transport systems where people interact with systems (e.g., interfaces of driver assistance, or integrated transport information), where systems monitor and interpret traffic (e.g., mining for activity patterns, or crowd-sourcing to inform about events), or where systems manage the traffic (e.g., control

of traffic flow at traffic lights, or toll management). Today we are witnessing a fundamental change in the discipline: where (spatiotemporal transport) data was for a long time scarce, expensive, and high quality, it becomes nowadays abundant, cheap, and of low quality. Computational intensive methods are required to convert massive data streams into information when and where needed. At this interface between transportation science and computer science (including information science) better mutual understanding is needed.

We perceive in this evolution, where sensors with travelers, with vehicles and sensors in the transport infrastructure and environment will all produce a vast amount of data that could be interpreted and acted upon, an emerging discipline, or field of study and research. The emerging discipline inherits from Computer Science the aspects of distributed and decentralized computing and spatiotemporal information processing, and from Transportation Science the aspects of transportation control and management. In particular it needs scholars and practitioners that maintain and push forward an agenda and a body of knowledge that is rooted deeply in both established disciplines. We are also the first to admit that drawing the lines between the established and the emerging discipline is to some extent arbitrary. The purpose of claiming an emerging discipline is rather to focus work that otherwise is spread all over, and to foster research in this area by recognition. By no means is it intended to become exclusive or divisive. In all the areas mentioned above exemplarily or in the research agenda below is currently work done.

Wikipedia¹ states that “disciplines are defined (in part) and recognized by the academic journals in which research is published, and the learned societies and academic departments or faculties to which their practitioners belong”. Thus claiming an emerging discipline would require looking for evidence for this claim, or, alternatively, taking this understanding as a recipe for initiatives to establish a discipline.

The emerging discipline of computational transportation science (CTS) combines computer science and engineering with the modeling, planning, and economic aspects of transportation. The discipline goes beyond vehicular technology, and addresses pedestrian systems on hand-held devices, non-real-time issues such as data mining, as well as data management issues above the networking layer. CTS studies how to improve the safety, mobility, efficiency and sustainability of the transport system by taking advantage of information technologies and ubiquitous computing.

This definition of CTS shows a strong correlation with Intelligent Transportation Systems. Intelligent Transportation Systems (ITS) are information and communication systems to enrich transport infrastructure and vehicles for smarter decision making on topics such as routing, safety or environmental impact. The area of ITS is established in research and development communities and platforms world-wide, but has an applied perspective—as reflected in the ‘S’ for systems. Where academic communities look after ITS—such as in the *IEEE ITS Society* (founded 2005) and its journal, the *Transactions on ITS*—these communities actually interpret the ‘S’ as science, not systems, otherwise they would not pass scientific peer review. A similar and hence illuminating case happened in a related field: GIS stood originally for Geographic Information Systems, and it still does in industry. However, 25

¹ http://en.wikipedia.org/wiki/Academic_discipline, last accessed 5 June 2010

years after their market introduction academia was ready to define the science behind GIS, and called it Geographic Information Science (Goodchild 1992). Today Geographic Information Science has all characteristics of a discipline: an academic community, established journals (such as the *International Journal of Geographic Information Science*, or the *Journal of Spatial Information Science*), established conferences (such as *GIScience* and the *Conference on Spatial Information Theory*). We argue here that Computational Transportation Science has this potential for ITS as Geographic Information Science had for Geographic Information Systems: it is the science behind ITS. But in contrast to GIScience, the discipline we are trying to shape here cannot be named *Intelligent Transportation Science*, in analogy to ITS. First of all there is nothing such as an intelligent science, and then there is also an established discourse in Artificial Intelligence whether machines can be intelligent, which is unnecessary to open up here. So Computational Transportation Science seems to say it all.

2 History

Computational Transportation Science has made its first steps of consolidation. A PhD program on the subject, funded by the National Science Foundation, was established at the University of Illinois at Chicago in 2006. Two international workshops on CTS were held (2008 in conjunction with the 5th Annual International Conference on Mobile and Ubiquitous Systems, and 2009 in conjunction with the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems). A third one will be held with the 18th ACM SIGSPATIAL International Conference in 2010. With the first workshop appeared a preliminary publication exploring a research agenda in this area (Geers 2008). Then a Dagstuhl Seminar on Computational Transportation Science was held in 21-26 March 2010 to characterize the discipline and identify its research agenda. The seminar was attended by 25 invited researchers from USA, Australia, Germany, Belgium, and Switzerland, with nationalities also from China, India, Greece and former Yugoslavia. This report presents the highlights of this Dagstuhl Seminar. Major steps at the seminar have been:

- Collaborative definition of CTS, vision of CTS, and core research agenda for CTS
- Set up of a Wikipedia entry for the definition and vision²
- Set up of a webpage as a bulletin board for the growing community³
- Plans for the third international workshop on CTS later in 2010
- Engagement with funding bodies promoting CTS as a discipline (outreach)
- Establishing collaboration by developing some larger joint research project proposals
- Publishing the (first) core research agenda via this report

² http://en.wikipedia.org/wiki/Computational_transportation_science, last accessed 5 June 2010

³ <http://www.ctscience.org/>, last accessed 5 June 2010

3 Core research agenda of CTS

A discipline is, among other properties, characterized by a common core research agenda.

Computational Transportation Science must have some underlying long-term fundamental research problems to distinguish it from its application area, ITS. ITS, in comparison, has defined several research and development agendas that are typically short-term, such as the US DOTs strategic ITS plan (United States Department of Transportation 2009).

The following research agenda is the outcome of the discussion of the Dagstuhl Seminar on Computational Transportation Science. As such it is preliminary and biased by the composition of the participants. Nevertheless it demonstrates vision and need for this discipline. This preliminary agenda is structured into five sections: applications, knowledge discovery, decentralized computing, social computing, and societal issues.

3.1 Applications

As the name Computational Transportation Science indicates, an important aspect are computational and algorithmic aspects in CTS. The challenges lie in the diversity of sensors and thus data gathered in different spatial, temporal and thematic resolution. The high volume demands for adequate information reduction for processing. One way to solve it is to exploit the principle of locality, i.e. the fact that information is mainly relevant locally and thus can also be processed locally and need not be communicated and processed on a central server. This leads to concepts of decentralized and distributed processing.

The applications described in the following do not only rely on the fact that travelers are provided with information; on the contrary, as travelers are equipped with sensors capable of acquiring information of the local environment, they also act as data providers. This leads to a highly dynamic map of the environment which can be exploited in numerous ways. On the one hand, it provides real-time data and thus can be used for dynamic traffic assignment; on the other hand, it also enhances the perception range of individuals and allows them to “look around the corner”, or to “look through the cars in front of them”. An additional important benefit is the possibility to augment the environmental information with virtual information about the infrastructure. In this way, virtual traffic lights or virtual lane assignments can be realized to allow for a flexible traffic management.

Not only the data can be shared – but also the transportation resources can be shared. This has been the case ever since for the road network and for public transportation – however it can also be envisaged for sharing vehicles like private cars.

The applications are driven by different factors:

- Ever increasing traffic demand leading to congestions with dramatic effects on public safety and on the environment, but also on the economy due to time spent in traffic jams
- Real infrastructure is expensive and laborious to maintain; furthermore, it is ageing and has to be replaced by modern, new concepts and systems

- Cars and travelers are more and more equipped with sensors which can – among others – also capture information about themselves and about the local environment. This rich data source can be exploited.

In the following, some future applications are described:

1. Shared transportation resources: if all traffic modes are included (also private traffic), a better exploitation of the resources is achieved, with several benefits both for the users (reduced prices), the infrastructure (less congestion) and as a consequence also the environment (less pollution).
2. Collaborative travelling, for example by platooning, i.e. the virtual coupling of vehicles to form larger units like virtual trains. These structures can get priorities e.g. when crossing junctions. Within a platoon, autonomous driving is possible. Also by intersection negotiation and intelligent traffic lights, i.e., a more adaptive giving right of way depending on the current traffic situation instead of fixed schedules.
3. Infrastructure is replaced by virtual infrastructure: in this way, the real infrastructure, which has several disadvantages like ageing and expensive maintenance, can be replaced. Examples are virtual lanes to compensate different traffic volume during a day/a week; virtual traffic lights, virtual signs; it is also relevant for highly temporal and ad-hoc warnings like construction sites or aquaplaning or slippery roads.
4. Driver assistance: drivers can be warned of risks in their local environment or when risking to leave their lane. Furthermore, their visibility range can be expanded by providing highly up-to date information from areas that are currently invisible.
5. Evacuation planning: highly temporal information is provided to support and calibrate simulations
6. Autonomous driving: as a long-term goal, highly dynamic maps of the environment have the potential to support autonomous driving.
7. Dynamic road pricing: the knowledge about the current usage of roads can be used to manage traffic, e.g. by reducing prices for collaboratively used cars or platoons.
8. Smart grid, electric Cars: sharing resources opens the way to extend the flexibility of using and sharing electric cars, e.g. by dynamic planning of the electric grid resources, and of routes by considering charging facilities.
9. Road and traffic planning can be greatly enhanced by precise, high resolution travel information, which leads to adaptive traffic systems. For example, the road weather—up-to-the-minute visibility, precipitation, and pavement condition information—can be provided at high spatial resolution.

In general, the major benefits and expected properties are robustness (due to high redundancy of information), resilience (ability to recover after failure), reliability and timeliness, which is relevant both for offline and online applications describe above.

3.2 Knowledge Discovery, Filtering, and Visualization

In order to be efficient, safe and environmentally friendly a traveler must be cognizant of their inherently dynamic surroundings both through their own sensing systems and by communicating with other travelers and systems. At present travelers gain most of their situational awareness from their innate sensors (eyes, ears, etc.) perhaps augmented by delayed reports from the radio or the web.

Thus it is important to discover in a timely fashion additional information that can augment the innate sensors. Consider for example the query: what will be the expected traffic conditions at 8pm on I298 at Ontario? This query can be answered by a server that stores historical information; but additional information may be available on the web, e.g., the weather and special events such as a ball game that starts at the time. In this case it is not even clear what data and web sites are relevant to the query.

It will not be long, however, before the traveler will be inundated with real-time information coming from all distance scales over soon-to-be ubiquitous always-on wireless networks. Prioritization of messages will be critical. Hence, knowledge discovery, filtering and visualization form research challenges to devise mechanisms that makes sense of the huge amounts of heterogeneous and distributed data in particular decision making contexts. Some challenges are:

1. For the car driver the vehicle itself will not only be aware of the vehicles around it due to a plethora of on-board sensors (such as radar and computer vision systems) but also of their intentions through constant DSRC communication exchanges. Also road signs will be made redundant as the data is sent directly to the vehicle. Speed limits will be mandatorily controlled to increase the safety and efficiency of roads. Such a detailed and consolidated picture of the local environment around the vehicle has the potential to reduce the number and severity of collisions and so increase traveler safety. Other participants in traffic, such as pedestrians and cyclists, will be similarly equipped and communicating constantly with the surrounding vehicles and travelers, thus the safety of even the most vulnerable road users will be enhanced.
2. In large cities and on congested roads the data density will be vast. For the individual traveler (now taken to mean the devices and systems that are assisting a person making a journey) only a small fraction of the received data will be relevant (and even less will be useful) and some form of stream processing will be necessary just to prioritize the messages in order of immediacy and relevance let alone acting on their content. That is not to say that any of the data is useless. Indeed, it contains trends and anomalies that are useful for planning not just the next trip but also the transportation capacities required in the future. Extraction of these trends and anomalies must be automated and conveyed to the relevant user in an easily understandable form.
3. Since there is no guarantee that the data available to a traveler are of useable quality or even available when needed, filling the spatial and temporal data gap is a challenging issue. Is it

meaningful to fill the gaps with data from yesterday or even a minute ago? Can statistical machine learning techniques such as Support Vector Regression help? The answers are not clear and must depend on what the data are to be used for. After all a bus timetable is simply a prediction of often dubious reliability.

4. Visualization of the huge, multi-dimensional data sets generated will not be easy. Many users will have their own requirements and will probably want to construct queries and visualize the results using some sort of OLAP cube. It is unlikely that the mobile device of an individual user will have the computational power or storage for such a task. Will cloud computing come to the rescue? Will peer-to-peer systems help with data storage and download? – The physical presentation of the data is also an issue. An in-vehicle display cannot be too obtrusive and certainly cannot interfere with the driver's ability to control the vehicle (at least until the vehicle is fully autonomous). Questions of relevance, urgency and safety need to be addressed.

There are numerous unanswered questions raised in the paragraphs above. They are potentially solvable in isolation but all the possibilities will only be leveraged through unified study. CTS is aimed fairly at this broad field.

3.3 Decentralized Computing

While applications are concerned with what data is relevant to answer a particular query, decentralized computing is concerned with where this data resides and how to access this data. First we will explain what these questions mean in the CTS environment, and then why these questions are different than the ones answered by traditional DBMSs.

Consider for example the query: what is the average speed of traffic a mile ahead of me? Sometimes the query can be posed to a central server, but sometimes a server with this information is unavailable (e.g., because the query pertains to a congested side street that is not instrumented with speed sensors), and the query needs to be answered by polling the vehicles ahead. However, the network IDs of these nodes (the vehicles) are not known. Thus, for this query it is not known where the data resides, and how to get to it. The answer in this case may be to use short-range wireless communication such as Wi-Fi or DSRC to disseminate the query to neighboring nodes transitively. In other words, the limited transmission range of the network is used to compensate for the lack of ID knowledge.

These questions are not addressed by traditional DBMSs. The data integration problem studied by the database research community assumes that the data is always available, but the integration part is the problematic part. In distributed databases it is assumed that there are directories that map data to network IDs of computers that store the data. Such directories are appropriate for some of the data that pertains to the query, but certainly not to queries that are processed by polling other vehicles.

Research challenges on decentralized computing are:

1. Modeling and representation of highly heterogeneous data, including the context dependency of data and the reconciliation in different contexts, the (semantic) interoperability, dynamic management of interoperability, and data warehousing.

2. Methodologies/tools to orchestrate and control the information flow in and across infrastructure networks, including quality of data guarantees and control of local or partial knowledge, and quality measures for cross-layer execution of decentralized algorithms and data integration; satisfying resource constraints such as bandwidth, energy limits, or computational capabilities; aiming for global optimization in transportation from local clusters and local knowledge.
3. Novel information-theoretic formalisms and measures for complexity and efficiency, for example, data freshness / staleness, communication costs, transitions among different levels of hierarchical decentralization.
4. Data reduction and aggregation, for example, in the context of streaming, storage and management across hierarchical layers needs to be addressed, where the structure of the different layers can evolve or change over time.

3.4 Social computing

Social computing and information processing taps into the wisdom of crowds (Surowiecki 2004), and relies on the (ubiquitous) connectedness and communication ability of the members forming the society. Provided such infrastructure, cooperation in terms of computing and information processing becomes feasible and forms new research questions (Parameswaran and Whinston 2007).

While social computing is making its way into many disciplines, it is obvious how real-time social interaction between mobile and stationary individuals (people, vehicles, goods, and infrastructure) can improve transportation. From a state where every individual is acting autonomously in isolation, or with minimal (visual) interaction with their environment, it is quite a paradigm shift to think of transportation as an interconnected, communicating and cooperating complex system (e.g., Sorensen 2010).

Such a paradigm shift brings up research questions in multiple dimensions:

1. Data collection
How can data collection methods alternative to the traditional survey based collection harness computational transportation science? This involves direct and indirect collection methods such as real-time sensing or accessing pools of shared data, and issues of data integration and exchange.
2. Data sharing
How can we ensure a sustainable data flow? Why do individuals share data, what are the incentives? What type of data will be captured and shared, and what type of data needs protection?
3. Data quality assurance
How can social network based data be calibrated, or errors identified? How can trust and reliability inform an error propagation process?

4. Real time situational awareness and decision support
How can data be transformed into information, and provided where and when needed for decision support?
5. Privacy aspects: how to protect privacy when spatial information provides local information about the user? Which computational methods can be devised in order to blur the local information and at the same time still keep it useful? It should also be noted that with the ever decreasing cost of storage it may well be practical to maintain *all* the data forever. But who controls it? Should an arbitrary person or agency be able track an individual's movements? Legislation may mandate privacy but can't guarantee it. Also data privacy impacts usability. For example adding noise to the position of a vehicle would render the safety aspects of DSRC useless. Removing personal identifiers is one possible solution but is it the best?

Ultimately it is the traveler who specifies the origin and destination of their trip. Transport must be traveler-centric and any system (or combination of systems) that ignores this simple fact will have a limited life. It is the socio-economic outcomes that applications of CTS will generate that will really count in the long run.

Abstracting from social computing, other societal issues of Computational Transportation Science come up with the involvement of individuals in the information processing chain. These individuals act and interact in a larger societal context, involving also government (transportation authorities), stakeholders, and transportation providers. These groups have different roles and responsibilities, but also different values and interests.

Research questions in this area concern the complex decision making processes, economic models including novel fare models (e.g., e-tolling, e-ticketing, ride sharing, virtual fencing), and also the demands of the community for privacy.

4 Outlook

A discipline is only as good as its academic community. If this paper finds your support or meets your interests you are cordially invited to participate and engage. The infrastructure set up so far is a beginning but requires your collaboration, be it the Wikipedia entry, the CTS webpage, or the CTS workshop series. These are all small seeds that—if they grow—can lead to conferences and journals on CTS, not only in the content but also in name.

Finally, the community should shape its own academic programs or introduce core subjects on computational transportation science into the programs on transport engineering, electrical engineering, software engineering, and geographic information engineering. The spread demonstrates the inter-disciplinarity of computational transportation science, illustrates that engineering problems do not present themselves any longer wholly contained in one traditional discipline, and supports the fundamental concern that engineering disciplines have grown to be too narrow (National Academy of Engineering 2004)

5 Acknowledgements

The authors are grateful to a number of institutions that supported this work. Dagstuhl Seminars are sponsored by Schloss Dagstuhl, an institute in the Leibniz Association, Germany. Work and travel was further funded by the Australian Research Council (DP0878119), National ICT Australia, and the National Science Foundation of the USA through awards DGE-0549489 and IIS-0957394. The authors would also like to thank all contributors at the Dagstuhl Seminar, especially Steve Liang for setting up the CTS webpage and Bo Xu for creating the CTS Wikipedia entry.

6 References

- Geers, G., 2008: Some Research Questions for Computational Transportation Science, 5th Annual International Conference on Mobile and Ubiquitous Systems. Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, Dublin, Ireland, pp. Paper 2.
- Goodchild, M. F., 1992: Geographical Information Science. *International Journal of Geographical Information Systems*, 6 (1): 31-45.
- National Academy of Engineering, 2004: *The Engineer of 2020 - Visions of Engineering in the New Century*, Washington, DC.
- Parameswaran, M.; Whinston, A. B., 2007: Research Issues in Social Computing. *Journal of the Association for Information Systems*, 8 (6): 336-350.
- Sorensen, J., 2010: One in Every Crowd. *Traffic Technology International*, 2010 (2): 50-56.
- Surowiecki, J., 2004: *The Wisdom of Crowds*. Doubleday, New York, 296 pp.
- United States Department of Transportation, 2009: *ITS Strategic Research Plan 2010-2014, Research and Innovative Technology Administration (RITA)*, U.S. Department of Transportation (US DOT), Washington, DC.