Distributed and Hierarchical Management of Transportation Networks

Pavankumar Tallapragada and Jorge Cortés

Vehicular emissions currently account for a very significant portion of the Carbon dioxide and other greenhouse gas emissions. Consequently, the next generation of transportation systems not only requires the development and deployment of new vehicle designs and alternative fuels but also efficient control and management of large scale transportation network systems. Distributed and hierarchical control and planning systems are particularly suited in this context. Distributed and hierarchical systems, compared to centralized systems, have greater potential to determine local action in real-time even in massively large scale multi-agent systems such as the transportation networks. They also provide greater resilience to failures in the control and planning system. In addition, distributed and hierarchical systems have the potential to offer greater data privacy.

New technological capabilities such as Vehicle-to-Vehicle, Vehicle-to-Infrastructure communications and self-driving vehicles are enabling us to re-envision distributed and hierarchical control and planning systems for next generation transportation networks. This position paper presents three case studies to highlight potential opportunities and challenges in the design of efficient transportation networks - (i) air traffic control in the next-gen free flight aviation; (ii) traffic signalling and traffic flow management; (iii) mass and personal rapid transit networks.

1 Air traffic control in the next-gen free flight aviation

In the next-gen free flight aviation, flight-path planning would largely be executed by each flight in a distributed and automated manner. The major factors affecting the decision process in flight-path planning are existing traffic, anticipated future traffic (specially for long distance flights) and weather. While information about weather may be obtained from the ground stations or satellites, information about existing traffic (at least on a local scale) has to be gleaned in a distributed manner for real-time response. A major challenge in such a scenario is reconstructing the state of the traffic from asynchronous communications. Further, flight-path contracts or promises must be negotiated in a distributed manner with little to no arbitration from the centralized ground controllers. Long range planning could be done based on coarse information about the anticipated traffic and weather forecasts. The other challenges would be the design of the system with goal driven minimal intermittent communication and the distributed computation of socially optimal flight-paths.

2 Traffic signalling and traffic flow management

Smoother vehicular traffic flow helps reduce travel times, fuel consumption and emissions. Currently, traffic signalling at intersections is performed in an ad hoc fashion with little to absolutely no

reactivity to traffic conditions. Even when there is reactivity to traffic conditions, it is pretty much based on extremely local information. A Cyber Physical Systems (CPS) approach to the problem is to utilize the emerging technologies like Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to manage better the traffic flow. We envision a system where V2V communication could be utilized by vehicles for real-time negotiations of collision free crossings of intersections. Further, V2V and V2I communications allow a control node at an intersection to estimate the traffic density on each branch and to communicate this information with control nodes at other intersections. Thus, as a result, the control nodes at the intersections in an area could distributively set a price (in terms of travel time) for each segment of each road. This non-monetary price could in turn be used in the inter-vehicular negotiations with the aim of achieving a socially optimal 'smoothness' of traffic. In addition, the control nodes could also, if necessary, switch the direction of traffic flow on certain lanes at the time scales of a few minutes to ease the traffic. Finally, general traffic patterns and distributions do not vary day to day and thus a centralized system could set base prices and windows of price variations for different roads for different times of the day and so on. Thus, such a traffic management system is envisioned to use distributed and collaborative control at several hierarchical levels to better manage traffic.

3   Mass and personal rapid transit networks

Deployment of large scale and cost effective mass and personal rapid transit systems is probably one of the most impactful solutions for an energy efficient society and reduction in greenhouse gases. Specially in the case of bus networks, there are several trade-offs. For example, to increase the coverage of a bus network, either the fleet size or travel times have to increase, both of which increase costs. However, on the other hand, a lower coverage or a smaller fleet size implies an increased number of commuters opt for personal vehicles and there is an overall increase in travel times for everyone. Dynamic and on-demand routing of buses and shuttles (akin to shared taxis) could potentially increase the coverage while also decreasing the travel times. Such a solution requires the deployment of a fleet of shuttles to cover a dynamically changing 'anticipated demand density'. While the coverage control at the scale of a large city may be solved centrally, at a micro scale (street level) it may be necessary to have a distributed coverage control system for fast response times.

On the other hand, a very significant advantage of static routes and schedules is predictability. This is specially useful for long distance bus routes. Thus, the shuttles with dynamic schedules and routes could also be feeders to high-speed, long distance buses. However, unlike in the traditional paradigm, instead of the high-speed buses stopping at bus stations, shuttles could feed in and out commuters on the go. Such a paradigm reduces commuter wait times as well as travel times. For such a scenario to be possible, at the lowest level one needs V2V communication and interaction of possibly self-driving vehicles for feeding in and out the commuters on the go. Then, the high-speed bus and the shuttles need to collaboratively schedule meetings so that commuters' time on the shuttles is minimized. The idea of feeders feeding in and out commuters could also be applied to mass transit trains. Stretching it further, a multi-modal interaction of vehicles on the go is the ultimate challenge.

4 Fundamental challenges

Control and planning of next-gen transportation systems is a massively large scale problem. As exemplified by the scenarios discussed, distributed and hierarchical control and planning systems are required. Data of varying coarseness needs to be shared and used at different levels and scales for tractability as well as to maintain privacy. As computing and wireless devices get increasingly pervasive, it is necessary for the sake of efficient use of bandwidth and energy sources to design control systems with efficient intermittent communication. Safe operation of automated vehicles and infrastructure; network security of transport CPS are an equally important and challenging issues to be addressed.