Next Generation Multi-Modal Traffic Management Systems: Cyberphysical Challenges

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The Cyberphysical Future

At the end of this decade, one may imagine a highly instrumented transportation infrastructure on which heterogeneous vehicles are traveling and competing for space. These vehicles will fall into the following categories:

- Passenger vehicles, small, intermediate and large, including:
  - Single occupancy vehicles (SOV), high occupancy vehicles (HOV)
  - Automated vehicles (wirelessly connected to infrastructure-based systems) (AV)
  - Non-automated vehicles (wirelessly connected to infrastructure systems) (WCV)
  - Individually controlled and managed (as most of the vehicles are now) (ICV)
- Trucks, – also categorized as AV, WCV and ICV based-trucks
- Buses, which would mostly be WCVs
- Light rail, trams – mostly WCVs but travel only where they can be guided by rail tracks or overhead power lines
- Emergency vehicles – that should not stop enroute to service (Fire and ambulance), mostly WCVs
- Priority vehicles – that prefer not to stop enroute to service (for repairing essential services, incident removal, transferring patients to urgent care, etc; buses and VIP vehicles may be included here too), also mostly WCVs.

Enormous amounts of data are generated from these vehicles and from the infrastructure, every fraction of a second, from

- In-pavement (intrusive) detectors
- Overhead and roadside (non-intrusive) sensors
- Vehicle sensors (e.g., electronic toll tags, cameras and on-board systems)
- Transportation infrastructure, e.g., traffic controllers located at intersections and freeway ramps

These data are collected, parsed, managed and worked-on, all **in real-time**, to negotiate the competition among vehicles vying for the infrastructures' right s of way, and then to provide the appropriate right of way to individual and platoons of vehicles, **also in real-time**.

The objectives and constraints for this next-generation traffic management system include

- Minimize real and/or perceived delays (e.g., a minute of delay, yet moving, may be perceived as more desirable that a minute spent unmoving, waiting at a red traffic light)
- Maximize safety
- Maximize privacy of data collected that can identify individuals (only when appropriate and necessary, because some data such as type of vehicle (SOV vs HOV) being driven is needed for operating a traffic management system that favors HOVs)

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* He is the PI on the NSF Cyberphysical Systems (CPS) grant 1239396. His research team is developing ***MIDAS*** (Managing Interacting Demands And Supplies) – A CPS system for *Proactive Traffic Management to Enhance Mobility and Sustainability*. MIDAS will bring together data from smart-phone type devices, as well as geographical databases and traffic management system data to provide proactive controls and advisories, allowing drivers to make better route choices, especially in the presence of congestion, whether recurrent or non-recurrent. Appropriate methodologies for congestion pricing or reward systems are also planned in MIDAS to influence travel demand. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the above organizations.

- Maximize sustainability through more efficient use of non-renewable fuel sources
- Minimize “costs” to users and operators which would include direct costs as well as indirect costs such as the installation, rollout and maintenance of the system and its components,
- Improve livability and health – through stress reduction for drivers/passengers/users, through better air quality, through more beneficial use of spaces and infrastructure, and, in general, through making the area more “livable”.

The objectives are appropriately weighted and/or traded off to make automated management actions or assist decisions related to the various categories of vehicles (see above) and on their usage of the multimodal transportation networks and systems.

But the challenges to reach this transportation vision are many and major.

Cyber-physical Challenges

Challenges in designing the next generation traffic management system exist in three aspects of Cyber-physical systems (CPS) transportation systems: the physical world, which is governed by the physics of transportation systems (multi-modal traffic flow, travel behavior, latencies, etc), the cyber realm that is governed by distributed computing and .communications, and societal dynamics governed by human organizations and behavioral decision-making. These challenges include:

- ***“Big Data” Problems***: How can we handle large amounts of data, recognize patterns and mine it effectively, using data-driven algorithms to make predictions on the states of the systems and networks and subsequently deciding on control and traffic management actions – all using streaming data in real time.
- ***Large-scale optimization and/or constraint satisfaction algorithms***: Given hundreds of thousands of heterogeneous vehicles traveling the roads in a metropolitan network, within several categories of vehicles (see above), each category defining vehicle/behavioral dynamics and priority in using the network infrastructure, the traffic management problems become rather large and complicated. What makes them even more challenging is the constraint that some of the decisions must be made within a split- second, while others may have time constraints on the order of minutes and hours. Control and decision variables include traffic signal timings, ramp metering rates, travel advisories via dynamic message signs, route advisories, route guidance (i.e., navigation) for drivers, congestion pricing/rewarding (more on this below), variable speed limits, managed lanes (e.g., lane restrictions and variable tolls), road gating where possible and appropriate, and in-vehicle information, advisories and controls.
- ***Communication networks and protocols***: Large amounts of data needed to be communicated from fixed local locations (e.g., roadside traffic controllers), moving platforms (e.g., vehicles) and remote locations (e.g., cloud computing systems), in a reliable and timely manner. In addition, after the computation of required decisions and controls, they need to be communicated to actuators (e.g., traffic controllers and ramp meters), to information providers (e.g., for variable message signs and in-vehicle displays), and to “decision-makers” who are the using the transportation network (drivers, passengers, traffic managers, transit service providers and WCVs and AVs), again, in a reliable and timely manner, especially information/data needed for time-critical decisions.
- ***User and societal acceptance***: Even when a technologically advanced system is available, a successful rollout will depend on several factors before users will use it and society will accept it. These factors include:
    - *Privacy of data*: Is sensitive and private data being sent and used in the system secure and kept private?

- *Driver behavior*: Are the advisories and guidance received by drivers accurate and done in an acceptable manner that is not distracting to the driver?
- *Driver and passenger stress*: Do these systems decrease stress levels of the driver and any passengers using the network? Here we would also include ease of use and user-friendliness of the system.
- *Acceptance of traffic managers*: Is the job of the traffic operators and mangers at least as manageable as now, while making the movement of various categories of vehicles safer, more sustainable, and performing better as measured through the system's objectives and constraints (see above list)? Is the installation and maintenance of this new advanced technological system manageable and cost-effective?
- *Acceptance of other stakeholders*: There are many stakeholders that rely upon the transportation network, including freight companies, emergency managers, transit systems, emergency services, healthcare providers, pick-up and delivery services, automobile companies (including for AVs, WCVs, and ICVs), repair service providers, communication providers (for cable, electricity, etc.) and governmental service providers. The operations of these stakeholders will definitely be affected, but it is anticipated it will be for the better. Can the stakeholders accept this technology easily?
- *Roll-out of the system*: The next generation CPS-enabled traffic management system, if promising and viable, will be gradually introduced to the public and users, who will learn to use the system, who will start reacting to the system (tolls and rewards will influence which routes the vehicles will take which, in turn, will influence the traffic benefits the vehicles will receive); and the system will continuously adapt to new traffic patterns and leaned driver behaviors. Suitable fail-safe system/software engineered procedures, based on human and organizational behaviors factors, must be included, using real-time data mining, pattern recognition and re-enforced learning approaches to keep the increasing user base from leaving the system during the roll-out period.

- ***Making the business case****:* As with the introduction of other technologies that have had a broad impact upon society, such as the *Internet*, *personal computers ,and wireless and mobile telephony;* and most recently with *smartphones and mobile computing,* a business case must made where the technology is gradually introduced into the market, possibly with loss leaders during initial rollouts, until market penetration takes hold and finally there are enough users to make the system useful for a large number of users, and beneficial and/or profitable for the system providers, users, and the society.

To address the above challenges, a multi-disciplinary team of researchers are needed to develop and introduce such a system, including computer scientists, communication engineers, operations research and control systems engineers, transportation engineers, social scientists, human factors researchers, industrial engineers, and business and marketing researchers.