White paper on

"Design and Evaluation of the Connected Vehicle Systems: Safety, Mobility and Fuel Economy"

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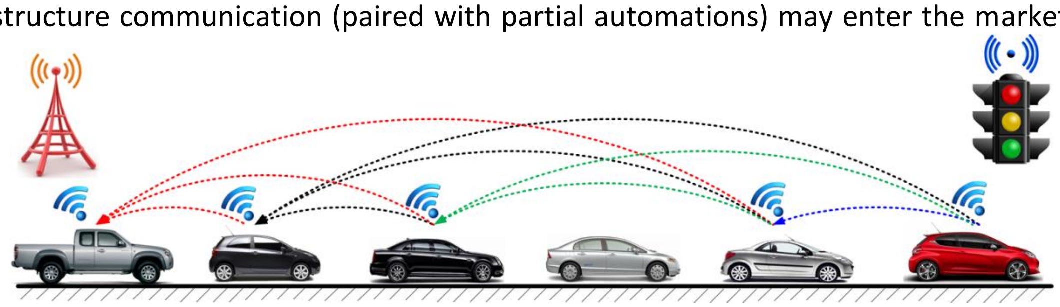
Potential benefits of vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2I) communication

Vehicular traffic is one of the most complex interconnected cyber-physical systems created by mankind. Vehicles are controlled by human operators who sense the environment, i.e., the motion of other vehicles, traffic signals, and road conditions, make decisions based on the collected information, and actuate the cars accordingly. The great advantage of such systems is the high level of flexibility they provide: one can go wherever he/she wants whenever he/she wants. However, such freedom may be reduced when safety of vehicles are compromised (causing accidents), when mobility becomes limited (typically by other vehicles) and when fuel consumption becomes a concern. Indeed such limitations are intimately linked: accidents may lead to sever reduction in mobility while accidents are more likely to occur at the tails of stop-and-go jams. Traffic congestion also have a negative effect on fuel economy. With the current steady growth of automobile population road transportation may become unsustainable within one or two decades [1].

There are (at least) two principal ways to mitigate these problems. One is to automate vehicles and potentially make them fully automated which is indeed pursued by many automakers. This definitely can have a positive impact on safety and may also impact mobility and fuel economy. However, the truth is that even a fully automated vehicle can get stuck in traffic jams since, similarly to conventional vehicles, it only observes its immediate environment. Another approach is to connect vehicles to each other and to the road infrastructure which can be achieved by using ad-hoc wireless communication like DSRC (that operates at 5.9GHz using IEEE 802.11p protocols). Based on the positive outcome of the Safety Pilot project [1] launched in 2012, NHTSA is expected to start regulating DSRC and may eventually require that all vehicles manufactured in US shall be equipped with DSRC. Indeed, connectivity and automation shall work in conjecture. However, while fully automated vehicles are only expected to be available within a decade (in the luxury category), applications that use vehicle-to-vehicle and vehicle-to-infrastructure communication (paired with partial automations) may enter the market as early



as next year and may be spread widely due to the low cost of these technologies. In the near future, we may use connectivity to completely redesign road transportation and create new cyber physical systems with improved safety, mobility and fuel economy.

Challenges of connected vehicle design

Designing the arising complex systems comprised of a large variety of vehicles superimposed by communication networks is a very challenging task. First of all, when designing automated vehicles (without connectivity) the final high-level goal is clear: create a vehicle that drives itself without human supervision. In contrast, for connected vehicles there exist a large variety of applications that may lead to design conflicts. For example, a vehicle designed to minimize fuel consumption may have negative impact on mobility (as it may be more sluggish). There are two typical approaches currently taken for connected vehicle design and we believe that none of them are feasible for the arising large-scale systems.

One approach (typically taken by automakers) is to work out simple scenarios involving two communicating vehicles (e.g. two vehicles approaching an intersection trying to avoid collision) and handle these cases one by one. While the penetration of connected vehicles is low such scenarios may occur (though their probability is very low). However, for higher penetration of connected vehicles typical scenarios will become much more complex and involve much more than two vehicles. Consequently, each car must handle a large number of (possibly conflicting) wireless messages sent by neighboring vehicles. Thus the point-wise design explained above becomes unfeasible in the arising connected environment.

Another approach (typically proposed for transportation management) is to monitor every vehicle in the system and use a centralized optimizer to guide the vehicles (route them, recommend speed etc.). Clearly, this requires every single vehicle to be equipped with the technology and a huge investment on the infrastructure side which would place these systems into the distant future. Also, the driver acceptance of such fully guided systems is expected to be low in the US. Moreover, one must accept that introducing connectivity will increase the heterogeneity in the arising systems that consist of human-driven and (partially) automated vehicles, some of which may not be equipped with communication devices; see the figure above. On the top of being heterogeneous, transportation systems will remain severely under-actuated even for high level of connectivity.

Establishing the core principles for connected vehicle design

We believe that to make connected vehicle technologies broadly applicable and to make sure that they benefit transportation early on, both of the above approaches must be changed. On one hand, we need to provide automakers with clear design principles that take into account the traffic environment in the connectivity range (occupied by mostly human driven vehicles). Indeed such design must be robust against packet drops and communication latencies. Moreover, the high-level of modularity of transportation systems must be preserved allowing drivers to join or leave the system which eliminates approaches that focus on fixed network structures with vehicles having designated roles (e.g. platoon leader). Instead, one must consider multi-vehicle configurations with ad-hoc connectivity as the first design step. The established principles shall be created by considering simplified (but not oversimplified) models of automobiles and wireless communication and shall move the auto industry from point-wise toward network-based design. The impact of such paradigm change on road transportation is expected to be similar to the impact of VLSI design on the computer industry.

On the other hand, we also need to provide transportation agencies with clear principles that can be followed when designing and evaluating the behavior of the arising large-scale connected systems (that is expected to be a very different environment compared to the existing non-connected traffic). To control these under-actuated systems one must rely on their natural dynamics and actuation must happen in a decentralized way. Such strategy can lead to early benefits and may result in smoother operation compared to fully-actuated systems (compare the walking gate of a human versus that of a fully-actuated robot). Moreover, transportation agencies shall also be able to harmonize applications that are developed by automakers at the level of small ad-hoc vehicle networks and evaluate these in large-scale systems. For example, a connected application that benefits the fuel economy of a group of vehicles may impact mobility of large-scale systems negatively, and in turn may increase fuel consumption. This is expected to result in trade-offs and may require additional consensus protocols between connected vehicles (e.g. to avoid rerouting all of them to the same low-capacity route).

Qualification of the Author

Professor Gábor Orosz has been studying transportation systems for more than a decade. He has applied techniques from nonlinear dynamics and control and time delay systems to large-scale multi-vehicle system. He has given the first rigorous mathematical explanation to a long-lasting problem of bistable traffic flow [3] and recently his interest turned toward the dynamics and control of connected vehicles [4]. He is currently collaborating with Toyota Motor Co and Navistar.

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