Cooperative intelligent vehicles: Are we there yet?

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With the proliferation of transportation research in the domain of cooperative intelligent vehicles, our society must prepare for the imminent introduction of such technology onto our highways. However, before such an endeavor is undertaken, it is necessary to examine the timeframe for its adoption by asking the quintessential question: "Are we there yet?" In this essay, several challenges related to adoption of connected vehicles arising on technological, social and legal fronts, including the effect of penetration rate on system-wide performance, are discussed along with potential remedial measures.

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A JOURNEY TO UTOPIA…

Humanity has traveled far on a long, winding highway in the quest for automotive innovation. As a people and as a transportation research community, our journey on this highway is fueled in part by the dreams of a *utopian* destination, where human ingenuity conceives technology and is rewarded with an immaculate safety record and zero congestion incidents. With the recent and remarkable advances made by communication and cooperative vehicles technology [1] [2] [3], we have good reason to believe that such a utopia may finally be within our grasp. But today, we need the little kid in the back seat to ask us a clichéd-yet-innocent question. Today, as we stand on the verge of a revolutionary advance in automotive technology, we must listen to that little voice which inquires, “Are we there yet?”

The question is not an affront to our technological prowess, but instead a humble query about the time frame required for the adoption of cooperative vehicles technology. Lest we be hasty and make bold predictions about the future that tomorrow holds [4], the query should serve as a gentle reminder that it is wise to stand back and reflect upon the ground realities of today. As we develop technology that will alter the way humanity travels, the question persuades us to assess our readiness and provide a realistic scenario for its adoption on a market-wide scale.

PIT STOPS: ADDRESSING CHALLENGES TO MARKET-WIDE ACCEPTANCE

Research organizations and leading car manufacturers have demonstrated the unbounded potential of connected vehicles for improving passenger safety [5] [6] and alleviating congestion [7], amongst other applications [8] [9]. However, market-wide deployment of cooperative intelligent vehicles on our roadways faces several challenges and barriers. While these challenges may broadly be categorized into the following domains – technological, social and legal – such a straightforward classification is not really representative of reality. By far, the single biggest challenge to deployment of cooperative intelligent vehicles remains the apparently “high” penetration rates required for guaranteeing their success.

Determining and/or minimizing the necessary penetration required to enable this technology remains a ***technological*** challenge. Inextricably linked to this problem is the ***social*** challenge of molding public opinion to perceive the potential benefits of connected vehicles technology and accept it in sufficient numbers to ensure its success. A ***legal*** challenge that may follow as penetration rates of connected vehicles increase is that potential damages and liability may be distributed, and current laws are not clear on how to handle such a form of distributed liability. The following sections discuss each of these challenges in detail and present some remedial measures that may facilitate and hasten the arrival of connected vehicles technology on our roadways.

TECHNOLOGICAL CHALLENGES

Since the advent of intelligent vehicle technology, such as adaptive cruise control (ACC), transportation researchers have been interested in determining the impact of its introduction on system-wide traffic performance. Analytical research by Darbha [10] and Ioannou [11], and numerical simulations by Helbing [12], Kesting [13] and van Arem [14] point to an improved traffic flow with the introduction of ACC in traffic flow. Recent analytical results by Jerath [15] show how ACC penetration rate affects congestion and system-wide traffic flow. The results indicate that relatively little improvement in congestion and traffic flow occurs at low penetration rates. Recent research on connected vehicles by Ergen [16] indicates that limited penetration may be sufficient to deploy V2V (vehicle-to-vehicle) applications in dense traffic. On the other hand, research by Kafsi et al., which makes use of network and percolation theory [17], suggests that at low market penetration, the connectivity of a vehicular ad-hoc network may be low due to “background” (un-connected) traffic. Similarly, research by Khabazian [18] indicates that vehicles entering the traffic stream at high velocities are unlikely to find a connected vehicle network and would most likely require a longer communication range. These and other works [19] indicate that determining the minimum necessary penetration that would ensure the success of connected vehicles remains an open problem and technological challenge to deal with.

While active research on analyzing connectivity in cooperative vehicles continues, the transportation research community must also ***work towards facilitating the spread of connected vehicles technologies***, by either:

(a) Building strategies to substantially increase penetration rates, or

(b) Developing technologies that function as 'force multipliers' and produce significant impact despite low penetration rates.

An important strategy that may help in achieving high penetration is by keeping a low cost of entry for the end-user. By ***building connected vehicles technology atop existing personal mobile devices*** that end-users already possess, we can not only lower cost and reduce dependence on specialized hardware, but also facilitate scaling in a manner that is not possible through the use of V2I (vehicle-to-infrastructure) strategies. Specifically, with the current improvements in data transfer speeds and the onset of 4G LTE (Long Term Evolution) cellular technology, the time may be ripe to consider the use of personal mobile devices for V2V communication [20]. It may also be desirable for leading car manufacturers to consider partnerships with mobile device manufacturers such as Apple, Samsung, HTC, Motorola etc., along the lines of the partnership between Ford and Microsoft that led to the Sync communications system.

On the other hand, the transportation community may also look towards building 'force multiplier' technologies that allow a significant impact on system-wide performance characteristics despite low penetration rates. Unfortunately, even the best scenarios in this approach require some form of infrastructure deployment that could soon become defunct as penetration rates begin to rise. However, the deployment of V2I may be a necessary step in pushing towards the critical penetration rate that may further lead to market-wide acceptance. While spatial connectedness may not be achieved with low penetration rates, it may be possible to achieve temporal connectedness through the use of infrastructure communication devices. Temporal connectedness may be used to store information, such as traffic and congestion patterns collected over time, and relay the same to a passing connected vehicle. It is unlikely that V2I communication at low penetration rates will prove sufficient to enable active passenger safety applications. While the aforementioned technological hurdles are being actively tackled, the transportation research community must also focus on the social aspect of the problem.

SOCIAL CHALLENGES

Market penetration of new technology is a widely researched subject [21] [22] [23] and the study of how a new technology propagates through the market is essential for understanding how to maximize the penetration rate of cooperative vehicles. According to the theory of ***technology adoption lifecycle***, the various users in contact with a technology can be categorized into five classes: innovators, early adopters, early majority, late majority, and laggards [21]. The strategy adopted by Tesla Motors (the 'innovator') presents a good example of the technology adoption lifecycle. The company's initial focus on 'early adopters' dictated the development of the Roadster, while later its focus shifted towards the 'early majority' and led to the development of the more affordable Model X and Model S.

In the context of the connected vehicles market, the players in the 'innovators' category are the research institutions and leading car manufacturers. At the present state in the adoption lifecycle, when the new technology is about to be released into the market, the innovators should focus on the 'early adopter' demographic and its needs. If the early adopters find the technology favorable and are able to attain a critical mass, then the initial success of the technology will be communicated through various channels (media outlets, blogs and even word-of-mouth) to the next and larger section of the public, the early majority. On the other hand, if upon the introduction, the early adopter community finds the technology to be either sub-par or unfit for their needs, it may not reach the critical penetration rate that would ensure its success.

Car manufacturers are on the right track of addressing the needs of early adopters, as is evident from several new models that offer integration with the end-users' smartphones. However, in order to ensure that the 'early adopters' understand and correctly perceive the benefits of connected vehicles technology, the innovators should ***provide additional connected vehicle services that the early adopters may find beneficial***. Specifically, providing applications for groups of early adopters traveling together so that they may be able to form a platoon and attain greater fuel efficiency may present the technology in a favorable light. Additionally, applications that obtain traffic updates about upstream congestion and suggest alternative paths may also be viewed favorably, as could applications that provide real-time weather updates (icy road, thunderstorm warnings etc.) from further down the highway that allow the driver to take any necessary precautionary measures. Upstream traffic flow updates transmitted to the connected vehicle may be used to adapt the cruise control algorithm and subsequent fuel savings may be prominently displayed to the early adopter to emphasize the benefits of the new technology. Some of these services will require V2I integration, unless some form of long-range connectivity can be established over a 4G LTE network.

LEGAL CHALLENGES

As public opinion is swayed in favor of connected vehicles technology, the penetration rate is bound to increase. At this point the system may exhibit complex macroscopic behavior due to human-computer interactions or interactions between various algorithms deployed on different connected vehicles [15] [24]. Such complex behavior may result in traffic incidents that could have ***distributed liability*** and damages. Recent developments, such as the introduction of autonomous vehicles terminology into the Nevada legislative framework [25] and the bill introduced by Senator Padilla in the California legislature for regulating autonomous vehicles [26], show that lawmakers are actively considering guidelines for new automotive technology. However, there is a long way to go before a robust legislative framework for connected vehicles is realized. Nevertheless, the transportation research community should build upon this promising start and ***play a proactive role in helping draft the legislative framework for distributed liability*** in a connected vehicles system. Specifically, the technology must be robust enough to avoid malicious packets sent over the network. In addition, ownership tokens should be provided to all network packets so that liability may be correctly assigned later, if required. Further, algorithms aboard each connected vehicle should track trust indices that quantify the trust in each network packet received, and these indices should also be used to assign liability to each connected vehicle itself. While the legal framework remains a quagmire that we are only now beginning to explore, the momentum built up by the technology and associated research builds a strong case for pushing through with it.

GETTING "THERE": SETTING EXPECTATIONS FOR MARKET-WIDE ACCEPTANCE

While we continue to move steadily and develop connected vehicles technology, we remain perhaps a few decades removed from the promise of a utopia with an immaculate safety record and zero congestion incidents, as evinced from the arguments presented above. However, as we iron out the kinks in the adoption of connected vehicles technology, we will pass several milestones along the way that will keep the technology centered and focused in the public eye. Each new step will bring the technology closer to market-wide acceptance and each milestone should help set the expectations of the timeframe for achieving the next milestone. As we progress on the highway of automotive innovation, we must continually evaluate our state of readiness and should occasionally listen to the little voice which ever so innocently asks us: "Are we there yet?"

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