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Connected Vehicle Infrastructure for a Smart City

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FINAL RESEARCH REPORT

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Final Report:

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1 Problem Description

Connected vehicle technologies have been tested and deployed for several types of applications. One category is related to communications among vehicles and fixed infrastructure of roadside units to enhance road safety by avoiding crashes or mitigating the severity of accidents. On the other hand, non safety-critical applications may range from mobility enhancement such as congestion management, map downloads and updates, to Internet services such as video streaming, file sharing and messaging among car passengers. Connected vehicles form mesh networks of short-range connections among vehicles and between vehicles and roadside units. These connections are collectively referred to as vehicle-to-everything, or V2X.

The long-term goal of this research is to provide credible and quantitative results that shed light on the most cost-effective strategies for wireless smart city technology, infrastructure and spectrum to support connected vehicles. During this project (# 173) we have addressed major issues that recently arose in the connected vehicle landscape regarding proposed rules for spectrum allocation and sharing (with and without a mandate to deploy V2X devices in cars). Moreover, to help municipalities decide which technology to deploy, we are doing work on the impact of the performance of V2X applications, and how V2X performance is affected by different V2X technologies and design choices. Technologies include dedicated short range communications (DSRC), which is the technology that has been considered and evaluated by the U.S. DOT for the last several years, and the emerging cellular vehicle-to-everything (C-V2X) technology. V2X design choices may include spectrum usage and density of V2X infrastructure.

Spectrum is a costly resource, and it has been recently debated whether spectrum currently allocated for connected vehicles should use by other types of devices (such as unlicensed Wi-Fi devices connected to the Internet). Since 1999, 75 MHz of spectrum was first allocated to Intelligent Transportation Systems (the so-called "ITS band")(U.S. Federal Communications Commission 2004), when demand was relatively low for spectrum at those high frequencies. That is no longer the case. Other industries would now like to reclaim some of the ITS spectrum entirely, to share the ITS spectrum with connected vehicles, or a bit of both. The Federal Communications Commission (FCC) has an ongoing proceeding (Lansford, Kenney, and Ecclesine 2013) in which it is considering several such plans. In this project we have evaluated what is the socially optimum amount of spectrum that should be allocated for ITS, and whether and how such spectrum should be shared with non-V2X devices.

Another issue that has been hotly debated is what V2X technology or technologies should be deployed. This technology must work well for both safety-critical and non-safety-critical applications. DSRC is no longer the only technology that one might consider to support short-range communications with connected vehicles and roadside infrastructure. Cellular operators have already been increasing reliance on microcells and femtocells in recent years, but in the past these devices have been problematic for vehicles because handoff times are far too slow for a device that is moving at 50 miles per hour, and end-to-end latency in the cellular network may be too high to satisfy requirements of road safety applications (Lee et al. 2017). More recently, standardization bodies in the cellular industry such as the 3GPP have been advancing a set of standards known as cellular vehicle-to-everything (C-V2X) that includes V2V, V2I, and vehicle-to-base stations. With more options, it is no longer clear whether DSRC, C-V2X, or even some combination of technologies is the best option. Moreover, the cellular technology itself is in flux. For example, unlike DSRC, the initial release of C-V2X was not suitable for high-data-rate users that are explicitly considered in our previous research (Ligo and Peha 2019, 2018), but the latest releases may be. For the portions of the standard that are complete, deployment can still take many forms that have yet to be determined. We are investigating some of these issues, and their implications for decisions about connected vehicle infrastructure and spectrum.

2 Approach

The first objective was to assess how much spectrum should be made available for vehicular communications. The U.S Federal Communications Commission (FCC) has allocated 75 MHz of spectrum in 5.9 GHz for DSRC V2V and V2I communications. Given that this spectrum could be allocated for other uses, we evaluate how much spectrum should be made available for ITS. Is 75 MHz too much for ITS? Or should more be allocated? We assume that a certain amount of spectrum is sufficient to serve road safety applications, and then explore whether adding spectrum would result in an economic benefit of offloading Internet traffic from cellular onto V2X networks. Our previous work has shown that deploying V2X infrastructure for offload is cost- effective in urban areas (Ligo et al. 2017). This will likely be relevant for the foreseeable future. Although macrocellular capacity continues to increase as carriers expand infrastructure and regulators allocate more spectrum, it is unclear whether cellular capacity will increase dramatically in the near future for highly mobile users. Moreover, mobile Internet traffic has grown 18-fold in the past 5 years (CIsco 2017), justifying alternative approaches such as data offload. We have also shown that it is even more cost- effective if infrastructure is shared between Internet access and safety applications (Ligo and Peha 2018). However, the work in (Ligo et al. 2017; Ligo and Peha 2018) considered the bandwidth allocated for ITS as fixed and not shared. In contrast, this project focuses on spectrum management; we examine the economic benefit of adding spectrum to offload Internet traffic. If the marginal benefit of adding one unit of spectrum exceeds its opportunity cost (i.e. the foregone benefit of using that spectrum for something else), then that unit is worth allocating for ITS. With this approach, we estimate the ITS bandwidth that maximizes benefit minus cost. In addition, we examine how that estimate changes with uncertain factors such as data rates of Internet traffic and penetration of V2X devices in vehicles.

The second objective of this project was to examine whether all that spectrum allocated to ITS should be used exclusively by DSRC devices or shared with non-vehicular devices. This question has been hotly debated in FCC proceedings. For example, it has been proposed that part of the ITS band should be used exclusively by DSRC devices while unlicensed devices are allowed in the other part (Qualcomm 2013). For our analysis, we considered the scenario in which DSRC-based safety messages are transmitted over spectrum that is not shared for other types of communications, while additional spectrum is used to transmit DSRC-based communications other than safety (i.e., Internet data). We considered the possibility of sharing the spectrum between ITS and other kinds of devices on a co-equal basis, how this might affect the performance for all systems involved, and how efficient spectrum would be used when compared to other spectrum management paradigms.

The third objective of the project is to determine how the performance of V2X communications for safety-critical applications is affected by technology or design choices. This objective is relevant and current given the uncertainty around which V2X technology (DSRC, C-V2X or some combination) should be deployed for safety-applications. The most critical safety applications are based on the ability of vehicles to transmit information about their, position, speed, acceleration and other kinematic conditions to other cars nearby in a frequent basis (typically 10 times per second). Communications errors and delays of various natures prevent that state information about a vehicle reach other cars. Rather, there is a non-zero interval from the time the state a vehicle changes (e.g. braking) until information about that change reaches another vehicle nearby. We have developed an approach to estimate how much that interval affects the effectiveness of some safety applications. For example, a safety application may warn the driver as soon as the application detects a change in state of vehicles nearby that require an action of the driver to avoid an accident, such as to reduce speed. Our approach informs how the delay in receiving state information from other vehicles impacts the ability of the driver to act. Moreover, we are currently evaluating how the interval from the time the state a vehicle changes until information about that change reaches another vehicle nearby varies with technology, road conditions such as vehicle density, and design choices such as amount of spectrum used for a safety application.

3 Method

Our general method is threefold: (i) collect extensive data from large connected vehicle deployments in the U.S. and Europe, (ii) run detailed packet-level network simulation, and (iii) develop extensive engineering-economic models to estimate performance, and sometimes relate that performance to costs, of different deployment strategies related to spectrum and V2X technology choices.

In this project we have developed two instances of this general method, one to address the objectives related to spectrum management and the other instance to address issues related to safety-critical V2X communications. Each of the two instances of the method are described below.

3.1 Method for Analysis of Spectrum-related Issues

We have developed packet-level simulation software that uses location data from more than 900 vehicles from Portugal, to simulate a mesh network comprised by DSRC-equipped vehicles that connect to roadside units (RSU) to gain access to the Internet. We use this simulation to estimate the rate of Internet data that can be carried through the DSRC channels not occupied by safety messages, under different conditions. To estimate economic gain as a function of throughput, we assume that mobile devices can use either cellular services or networks of connected vehicles, and that every bit carried on the vehicular network is one less bit on the cellular network. In a capacity-limited cellular network, a reduction of data from mobile devices that must be carried in the busy hour allows each cell tower to provide adequate capacity over a larger area, thereby reducing the number of costly towers that a cellular operator needs to cover a given region. We define the benefit of offload in a given scenario as the cost savings from reducing the number of cell towers. This is compared to the costs of DSRC RSUs, which quantity is assumed to be the one that maximizes the difference between benefits and costs.

To consider the impact of spectrum policy, we designed the packet-level simulation to support different amounts of spectrum and three different types of sharing: one based on coexistence, and two based on cooperation. In practice, the more spectrum allocated for intelligent transportation systems, the more likely that spectrum will be shared. In some scenarios, some or all of the spectrum used for intelligent transportation systems may also be used by devices that share without cooperation, meaning that they are sources of interference and congestion. In other scenarios, these devices cooperate, perhaps relaying a packet from a moving vehicle to a roadside unit, in accordance with the technical standard.

3.2 Method for Analysis of Performance of Different V2X Technology Choices on Safety-critical Applications

We have been developing models that relate the performance of V2X technology choices with the performance of safety-critical applications. Most of those applications rely on information exchanged between vehicles and infrastructure through the "Basic Safety Message" (BSM) (SAE International 2016). The BSM is a standardized "awareness message" that vehicles equipped with V2X technology are intended to transmit at fixed intervals (typically 100 ms) to nearby vehicles and RSUs. Each message conveys information about the state of the transmitting vehicle, which include its location, speed, acceleration, heading, and other kinematic data. Upon receiving BSM's from a transmitting vehicle, safety-critical applications in nearby cars should determine the need to take action. For example, one application evaluated by the U.S. DOT is the Forward Collision Warning, which "warns the driver of an impending rear-end collision with a vehicle ahead in traffic in the same lane and direction of travel" (U.S. Department of Transportation 2016), or perhaps trigger an autonomous braking function for vehicles that have such a capability. The effectiveness of a safety application in taking action and preventing an accident depends on whether it receives BSMs in a timely fashion and from a safe distance from the transmitting vehicle. On the other hand, communications errors due to propagation characteristics and data congestion (depending how many cars are transmitting BSM, at what intervals and the amount of spectrum available) may result in BSMs being either lost or received with a delay. As a result, whenever a vehicle presents a change in its state (e.g. sudden braking or deceleration) that may require action from nearby vehicles, there is a non-zero interval between the state change and other vehicles successfully receiving BSMs with updated information about that change. In addition, this update interval depends on the distance that separates a transmitting and a receiving vehicle. This interval may delay the safety-critical application action, which may impair the ability of such applications to prevent accidents. In this project, we have been developing models that associate the communications-related update interval with measures that inform the effectiveness of safety applications. With those models, we are able to quantify how much the V2X-related update intervals are relevant for given safety-critical applications. We have been doing this modeling in an application per application basis.

Some of the aforementioned models of safety-critical applications depend on the typical speeds and accelerations of the vehicles transmitting and receiving BSMs, and how those speeds and accelerations change during the interval it takes for information from one vehicle be successfully received by others. We have been measuring real speeds, accelerations and their changes over varying intervals using the dataset "Safety Pilot Model Deployment Data" made available by the U.S. DOT for public use. This refers to a large deployed pilot of connected vehicles in Ann Arbor, MI exchanging BSMs using DSRC technology. The dataset contains detailed BSM logs that include GPS position, speed, acceleration, heading, and other BSM fields specified in the connected vehicle standards.

In addition, to assess the impact of V2X performance on the effectiveness of safety applications, we need estimates of the actual intervals associated with different V2X technologies (e.g. DSRC, C-V2X), under different conditions of vehicle density, distance between transmitting and receiving vehicles or propagation environment (highway, urban, etc.), and under different V2X-related design choices such as the amount of spectrum allocated and the density of V2X infrastructure, if any. We have been obtaining V2X update intervals using network simulation. For the simulation we have been using and building upon the publicly available V2X simulation software described in (Cecchini et al. 2017), which allows us to compare DSRC and C-V2X technologies under varying conditions and design choices.

4 Findings

We have three main groups of findings related to spectrum issues. The first is related to how much spectrum should be available for ITS. Second, we discuss whether ITS spectrum should be shared with unlicensed devices, as has been proposed by the FCC and others. In the third group of findings, if ITS spectrum is to be shared, what sharing scheme should be implemented. For the analysis, we consider the scenario in which safety messages are transmitted over spectrum that is not shared for other types of communications. V2X and unlicensed devices may share spectrum on a co-equal basis to carry non-safety-critical information, such Internet traffic.

On how much to allocate for ITS, we found that if spectrum is allocated exclusively, there are realistic scenarios where allocating spectrum far in excess of what is used for safety enhances social welfare, and there are also realistic scenarios where too much spectrum has already been allocated for ITS. The bandwidth that maximizes social welfare is sensitive to uncertain factors such as the penetration of devices in vehicles, data rates (particularly those to unlicensed devices), characteristics of the cellular network, and the opportunity cost of 5.9 GHz spectrum. For example, in scenarios of higher data rates and penetration, adding 40 MHz enhances social welfare if the opportunity cost is about $0.45 per MHz-pop or less. On the other hand, if data rates of Internet traffic and penetration of devices in vehicles do not reach the levels assumed, or macrocellular networks are expanded with cheaper or more efficient technologies than current cell towers, then it might be that it is not cost-effective to allocate any spectrum in excess to what is allocated for safety. Because of this uncertainty, allocating spectrum exclusively runs the risk of not providing enough spectrum for welfare-enhancing ITS.

This uncertainty becomes less problematic if ITS spectrum is shared. We found that it is highly efficient to share spectrum allocated for ITS with unlicensed devices. We have found that V2X and unlicensed devices coexisting in shared spectrum might require up to 50% less bandwidth than is required to achieve the same throughputs in shared bands. This is true for scenarios that we believe represent the relevant range of population densities, penetrations of vehicular devices and data rates of Internet traffic, and whether unlicensed devices are located indoors or outdoors. While sharing is spectrally efficient when usage of V2X and unlicensed devices are predictable, it is even better in the scenarios where data rates and/or penetration are much lower than expected due to the uncertainty discussed above, because even if spectrum being added exclusively for ITS might not be justified, shared spectrum is still well used by unlicensed devices.

When V2X and unlicensed devices are sharing spectrum, we consider three possible sharing schemes. The first is coexistence, where V2X and unlicensed devices sense each other transmissions, but devices of one type try to avoid interference without explicit cooperating with devices of the other type. (This is similar as one of the proposals to the FCC to share the ITS band.) In the second sharing scheme, unlicensed devices act as access points to the Internet both for unlicensed and V2X traffic, which we call backhaul cooperation. In the third scheme, unlicensed devices do not act as access points for V2X traffic, but rather act as part of the vehicular mesh. In this scheme, hotspots relay traffic between vehicles and RSUs or other vehicles, which we call relay cooperation. Backhaul cooperation has the potential to further improve the efficiency of sharing ITS spectrum, when compared to the simpler coexistence scheme. However, the magnitude of this advantage is sensitive to the conditions where sharing takes place. For example, backhaul cooperation requires less bandwidth than coexistence for lower population densities, which are representative of most of the U.S. distribution, but the difference in bandwidth is significant only if those locations have widespread presence of outdoor hotpots such those of metropolitan Wi-Fi networks. With few outdoor hotspots, the bandwidth required with backhaul cooperation is not significantly less than with coexistence. Such deployment of outdoor hotspots is unlikely for sparsely populated areas. Given that such a cooperation scheme would require regulatory efforts that are probably far more complex than a mandate for coexistence (Peha 2009), it is unlikely that the benefits of cooperation outweigh the cost of implementing it. Moreover, we found that the other cooperation scheme examined in this chapter (relay cooperation) does not produce results that are significantly different from those of the simpler coexistence scheme. Therefore, a nationwide mandate of a sharing scheme such as relay cooperation over coexistence would probably not be worth the extra technical and regulatory cost.

In the recent policy debate over ITS spectrum, it has generally been assumed that the size of the ITS band would remain fixed at its current level, and the question is whether to share with unlicensed devices. If the bandwidth available to vehicles is fixed, we have found that the throughput achievable with V2X devices coexisting with unlicensed devices in shared spectrum can be significantly lower than the throughput in exclusive spectrum (up to 2/3 lower, depending on the scenario). However, there is no reason why the bandwidth of the ITS band cannot be increased if we allow unlicensed devices to share the ITS band. If spectrum policymakers wish to give V2X better throughput than they could achieve in the existing ITS band after unlicensed devices are allowed to coexist, then policymakers could change regulations to increase the size of the ITS band while still giving unlicensed devices access. In other words, while unlicensed devices gain access to the ITS band, V2X devices could use the adjacent unlicensed bands for non-safety-critical traffic. (Again, sharing the ITS band might exclude the portion of the ITS band reserved for safety messages.) Under these circumstances, V2X and unlicensed devices would achieve the same throughput performance in shared spectrum while using less bandwidth overall. Such an approach would likely be implemented with the coexistence sharing scheme rather than with cooperation. While it might be reasonable to require cooperation from unlicensed devices as a condition to operate in the ITS band, the small improvement in throughput and required bandwidth (if any) of cooperation over coexistence is not likely worth the complexity of the former. Moreover, unlicensed devices do not cooperate in the bands in which they already operate, which would make cooperation in these bands even harder to implement.

Besides, we have found the throughput to unlicensed devices in shared spectrum to be not much lower than in exclusive spectrum. Therefore, sharing spectrum allocated for ITS with unlicensed devices effectively represents extra bandwidth for those devices, without compromising their throughput performance.

Finally, we have made progress on evaluating the impact of the performance of V2X technology choices on safety-critical applications, although further work remains. We have modelled the Forward Collision Warning (FCW) safety application and have been assessing the impact on V2X performance on FCW under several mobility scenarios. We have identified two categories of mobility scenarios so far. One is probably representative of some of the cars traveling in highways. They move with speeds that are constant on average, and the averages of vehicles close to each other are roughly similar. However, instantaneous speeds and accelerations fluctuate around the average, either because of other cars nearby, curves, road slope, wind, or slight changes in drivers acceleration/braking behavior over short periods of time. In this category of mobility scenarios, we have found that the acceleration of a car may experience small changes in very short periods of time (in the order of hundreds of milliseconds). If there is an update interval for an acceleration measurement to be successfully received by a car nearby, then there may be a mismatch between the instantaneous acceleration of a vehicle transmitting BSMs and the last information received by vehicles nearby about the transmitter's acceleration. This mismatch between current and last received acceleration may result in wrong or outdated determination of actions by the FCW application. However, we have found that the variation in acceleration does not change significantly with the update interval for intervals between 100 ms to 500 ms, while it changes significantly for intervals above 1 second. That means that for the FCW application in this category of mobility scenarios, different V2X technologies and design choices will result in similar performance as long as the update delays with different technologies and choices remain within 500 ms. (We have also found that variations in speeds and positions are not substantially different than predicted even after intervals of several seconds, assuming that vehicles nearby predict the transmitter's position and speed using constant-acceleration kinematic equations.) The fluctuations in speeds and accelerations for several scenarios were obtained from the U.S. DOT's "Safety Pilot Model Deployment" dataset.

However, we have found different results in the second category of mobility scenarios. In this category, we consider the case of cars moving in the same lane and then the leading car brakes abruptly with a "hard braking" intensity. As in any other scenario, there is a non-zero update interval between the braking event and information about the event is received at the other vehicle. We have found that after a "hard braking" event, accelerations and speeds may change significantly even with update intervals as little as 200 ms. Such a level of update intervals may be hard to achieve, considering that BSM's are typically generated every 100 ms and additional delays are expected due to communications errors where one or more BSMs are not successfully received, or scheduling when BSM transmissions are delayed because several cars trying to transmit BSMs simultaneously may congest the wireless medium.

We are currently using detailed, packet-level network simulation to determine the expected update delays under varying conditions of distance between vehicles, vehicle density, V2X technology (DSRC or C-V2X) and other conditions. We have found that for distances shorter than 100 meters, the update delay has an average around 50-60 ms with standard deviation of 50 ms, for DSRC communications and high vehicle density (highway with 200 vehicles/km). At larger distances the update delay can be significantly higher and exceed 1 second. However, distances larger than 100 m between vehicles may have limited impact at least for the FCW applications. We have been continuing the analysis to evaluate difference between V2X technologies and scenarios.

5 Conclusions

At the federal level, our research has impact on the current debate about the use of spectrum for Intelligent Transportation Systems. While it has been recently proposed that spectrum is shared between vehicular and unlicensed devices, transportation authorities have concerns that such sharing may cause harmful interference to vehicular communications. Our ongoing research suggests that as long as safety messages are transmitted on exclusive spectrum, the FCC could allow vehicles and unlicensed devices to share spectrum for non-safety communications in a highly efficient way.

Our work will also inform the current debate about whether DSRC or C-V2X is the best technology to be deployed in vehicles and RSU infrastructure for safety-critical applications. We have found that the effectiveness of the FCW application seems to be insensitive to V2X update delays under "normal" conditions, i.e. vehicles traveling in highways without abrupt braking. In this case, if the main difference among V2X technologies and design choices is on the update delay, then any particular V2X choice may have limited impact on FCW effectiveness. On the other hand, this may not be the case for a "hard braking" scenario, in which the update delay may have significant impact on FCW effectiveness. In the future, we will evaluate how the update delay varies across V2X technology and design choices, and we will consider additional applications and additional scenarios.

6 Recommendations

Regarding the use of ITS spectrum, we recommend sharing the portion not needed for safety-critical communications with unlicensed devices, because this would enhance the utilization of spectrum significantly.

Moreover, our results support the idea of sharing some (but perhaps not all) of the ITS spectrum with other kinds of devices. If such sharing leads to an unacceptable degradation of performance for connected vehicles, it appears to be more effective to allow DSRC to use spectrum currently available only to unlicensed devices than to prevent unlicensed devices from accessing spectrum available only to connected vehicles. In its proceeding, the FCC has not considered the idea of allowing DSRC devices and unlicensed devices to share both the ITS band and the adjacent unlicensed band, but our results show that this deserves consideration. Nevertheless, more research is needed in this area.

We are currently evaluating the impact of V2X technologies and design choices on connected vehicle safety-critical applications. Our preliminary conclusions are that the performance of given V2X choices may have limited impact on the effectiveness of the FCW application under "normal" conditions, while V2X update delay may significant affect FCW under "hard braking" scenarios. We are currently evaluating the differences in update delay performance of different V2X technologies and design choices under varying conditions, which will result in future recommendations. Moreover, further work is needed to evaluate the impact of V2X technologies and design choices on other safety-critical applications, such as the Do Not Pass Warning (DNPW), Left Turn Assist (LTA), Intersection Management Assist (IMA), and other connected vehicle applications.

7 References

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8 Products

Ph.D. Dissertation

Alexandre Ligo. "Connected Vehicles for Internet Access: Deployment and Spectrum Policies," Carnegie Mellon University, Pittsburgh, PA, 2018.

This Ph.D. dissertation was submitted, defended and posted during project #173. The dissertation details all results and conclusions contained in this report, as well as the results of the previous projects sponsored by Traffic21 / Mobility21.

Published Papers

1. Alexandre Ligo and Jon M. Peha, "Spectrum for V2X: Allocation and Sharing," accepted to appear in *IEEE Transactions on Cognitive Communications and Networking*. https://ieeexplore.ieee.org/document/8712390
2. Alexandre Ligo and Jon M. Peha, "Cost-Effectiveness of Sharing Roadside Infrastructure for Internet of Vehicles," *IEEE Transactions on Intelligent Transportation Systems*, Volume 19, Issue 7, July 2018, pp. 2362-2372. https://users.ece.cmu.edu/~peha/infrastructure_sharing_for_Internet_of_vehicles.pdf
3. Alexandre Ligo, Jon M. Peha, Pedro Ferreira and Joao Barros, "Throughput and Economics of DSRC-Based Internet of Vehicles," *IEEE Access*, vol. 6, pp. 7276–90, 2018. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8241368
4. Alexandre Ligo and Jon M. Peha, "Spectrum for Intelligent Transportation Systems: Allocation and Sharing," *Proceedings of IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN),* Seoul, South Korea, October 2018. https://ieeexplore.ieee.org/document/8610408
5. Alexandre Ligo and Jon M. Peha, "Spectrum Policies for Intelligent Transportation Systems," *Proceedings of 45th Telecommunications Policy Research Conference (TPRC)*, Arlington, VA, September 2017. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2943688

6. Alexandre Ligo and Jon M. Peha, "Is It Cost-Effective to Share Roadside Infrastructure for Non-Safety Use?," *Proceedings of IEEE 85th Vehicular Technology Conference (VTC),* Sidney, Australia, June 2017. http://users.ece.cmu.edu/~peha/Sharing_Roadside_Infrastructure_VTC_2017.pdf

Public Presentations

1. Jon M. Peha, "Sharing Connected Vehicle Infrastructure Between Governments and Internet Service Providers," presented at ASCE International Conference on Transportation & Development (ICTD), July 2018.
2. Jon M. Peha, "Smart City Technologies for Local Governments," to be presented at Fall Conference of Townships, Boroughs & Authorities, Sept. 2018.
3. Jon M. Peha, "Connected Vehicles for Internet Access: Implications for Governments and ISPs," presented at Traffic 21 Seminar, Oct. 2018,
4. Jon M. Peha, KEYNOTE: "Wireless Communication and Municipal Governments – Looking Forward," Pennsylvania State Association of Boroughs, August 2017.
5. Alexandre Ligo and Jon M. Peha, "Spectrum Policies for Intelligent Transportation Systems," presented at *45th Telecommunications Policy Research Conference (TPRC)*, Arlington, VA, September 2017.
6. Alexandre K. Ligo, "Spectrum for Intelligent Transportation Systems: Allocation and Sharing," presented in IEEE International Symposium on Dynamic Spectrum Access Networks, October 2018.
7. Alexandre Ligo, "Is It Cost-Effective to Share Roadside Infrastructure for Non-Safety Use?," presented at *IEEE 85th Vehicular Technology Conference (VTC),* Sidney, Australia, June 2017.

9 Datasets

U.S. DOT Connected Vehicle Safety Pilot Model Deployment Data. Available for public use at https://catalog.data.gov/dataset/safety-pilot-model-deployment-data

U.S. DOT Connected Vehicle Safety Pilot – Ann Arbor, MI map data. Available for public use at https://www.a2gov.org/services/data/Pages/default.aspx

10 Other Information

10.1 ORCID Identification of Project Investigators

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