Technologies for Safe & Efficient Transportation

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Can Sharing Infrastructure with ISPs Make Deployment of Safety Infrastructure Affordable?

FINAL RESEARCH REPORT

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DISCLAIMER

Problem statement

Vehicular networks may soon be widely deployed using Dedicated Short Range Communications (DSRC) technology, primarily for car safety. In-vehicle communications devices allow both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links between cars and roadside units (RSUs) placed near roads. RSU infrastructure is required to support certain safety applications, such as warnings of weather or road hazards to nearby vehicles. Moreover, V2I communications also support mobility, environmental, and other non-safety applications such as Internet-based car infotainment (Zeadally et al. 2010; Campolo and Molinaro 2013).

However, the cost of RSU infrastructure may limit or slow the adoption of V2I safety applications. While V2V may be mandated in the U.S. (U.S. Department of Transportation 2016), RSUs for safety will cost billions of dollars nationwide and probably won't be deployed until state and local governments choose to pay (Wright et al. 2014).

Approach

This project is about cost savings from infrastructure sharing, when it is deployed by government agencies and shared with private parties.

If there are ways to reduce RSU deployment cost, benefits from safety and other V2I applications may be experienced sooner by more people. For example, governments might save by sharing safety RSUs with Internet Service Providers (ISPs) for a fee.

Although government agencies often deploy infrastructure only for their own use, previous work has shown other instances where government can save by sharing communication infrastructure with commercial companies. For example, as shown in (Hallahan and Peha 2011a, 2010; Peha 2013; Hallahan and Peha 2011b), a highly cost-effective way to provide communications capabilities for emergency responders such as firefighters and police involves sharing infrastructure between government and commercial cellular providers. This approach was adopted in FirstNet, a nationwide network for emergency responders which Congress funded in 2012 with $7 billion (Peha 2013).

A similar approach might consist of governments sharing DSRC RSUs with ISPs. Some claim that demand for mobile Internet has grown sharply and will continue to do so (Sandvine 2014). That includes in-vehicle Internet access, which is currently served mainly by macrocells, and therefore cellular

infrastructure would continuously need expansion where networks are capacity-limited. Although that extra capacity is costly, previous work has been shown that vehicular networks could provide Internet access at a lower cost than cellular networks. For example, (Ligo et al. 2015) shows that ISPs can provide Internet access at lower cost using DSRC networks than through expanding cellular infrastructure in some regions, if ISPs deploy RSUs that function as Internet gateways. If ISPs could use government RSUs for less than the cost of their own RSUs, then ISPs might offer DSRC-based Internet in more locations. Thus, there is an opportunity to share dual-use RSUs that benefit both safety and Internet access.

Moreover, governments may widely deploy other types of infrastructure that could be shared. One example is the deployment of "smart" streetlights with communications capability, which aid municipal services such as surveillance, air quality monitoring, etc. Those streetlights may be opportunities for ISPs of cheap access to power, poles, and backhaul, while possibly being available in more locations than safety RSUs. In this project, we also consider sharing of smart streetlights.

By sharing safety RSUs or streetlights, governments might charge prices that either maximize government savings, or maximize overall social welfare. The contributions of this project are to quantify government savings and increased social welfare from sharing, and the prices the government would charge an ISP to maximize either government savings or social welfare. To the best of our knowledge, this is the first work that quantifies the benefits of sharing DSRC infrastructure with ISPs. We consider the scenario where vehicles are equipped with onboard units (OBUs) in response to a Dept. of Transportation mandate. In-vehicle Internet access is increasing sharply, and ISPs must decide whether to expand cellular capacity or to deploy RSUs to offload part of the traffic demand. These RSUs can either be deployed for Internet only by the ISP, or shared. In this scenario, the ISP pays to share government infrastructure. However, the results are also applicable to some other sharing arrangements, such as joint deployment through a public-private partnership.

We analyze government infrastructure expenses, ISP infrastructure expenses, and government revenues from ISPs. We estimate these without sharing, and with sharing as a function of the price government charges to share an RSU. We assume that ISPs design their systems to carry a given volume of traffic, and ISPs choose the cost-minimizing approach, which can be any combination of deploying their own DSRC RSUs that serve as Internet gateways, sharing safety RSUs or smart streetlights with government for a fee, and deploying traditional macrocellular infrastructure.

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Methodology

We employ an engineering-economic model to determine how sharing affects government savings and social welfare. One aspect of our model is to estimate RSU costs, government revenues from ISPs, and the resulting government savings and increased social welfare from sharing. Some of these costs depend on how much traffic can be offloaded from a macrocellular network to a vehicular network as a function of RSU quantity. Thus, another aspect of our model is a detailed packet-level simulation of wireless connections between cars and Internet-connected RSUs using DSRC, under a variety of design choices, to estimate the data throughput of the vehicular network. To make this simulation more realistic, many of the assumptions underlying our simulation come from actual measurements of an actual, citywide vehicular network operating in Portugal.

In this model we assume that DSRC throughput equals the vehicular Internet traffic offloaded from macrocells at peak hours, thus reducing the number of towers needed in capacity-limited cellular networks. Thus, if the cost of DSRC is less than that of cellular to carry a given amount of data, the ISP is better off by deploying RSUs. Moreover, DSRC costs for the ISP are affected by whether RSUs are shared by the government, and at what price.

From the engineering-economic model we derive the pricing strategies that maximize either government savings, social welfare, or a combination of both. We also estimate the resulting savings and welfare increase under those strategies, for varying population densities. The dataset, simulation and engineering-economic models are described below.

Dataset

We use data from a real DSRC network that is operating in Porto, Portugal, as of March 2015. OBU-equipped buses offer free Wi-Fi to passengers, and route data over multihop connections to reach one of 27 DSRC RSUs connected to the Internet. RSUs are placed in locations with high vehicle traffic. When a vehicle cannot connect to an RSU, data is sent over cellular. We used a dataset with measurements of data transferred over DSRC and cellular, and GPS position data of 400+ buses and 400 taxis. Porto data is used in three ways. First, GPS positions are used to determine the positions of the vehicles in the simulation. Second, strength of the signal received from RSUs is measured in the buses. This measurement is verified to be compatible with the simulated signal strength, on average. Third, coordinates of intersections are used for modeling RSU locations.

Moreover, we used 2010 data about U.S. census tracts (United States Census Bureau 2015), to

compute nationwide results as described below.

Throughput estimation from network simulation

We estimate data throughput per unit of area of the DSRC vehicular network to be used in the engineering-economic model. This throughput is estimated via packet-level simulation from the physical to the transport layer using the open-source ns-3 network simulator. The assumptions for the simulation are as follows. A bidirectional connection is established between each OBU-equipped vehicle and one RSU which serves as a gateway to the Internet. A vehicle can connect to an RSU either directly or through multiple hops with other vehicles acting as relays. The throughput per unit of area is defined as the sum, across all OBU-equipped vehicles, of the data throughput achievable between each vehicle and an RSU it is communicating with. Vehicles in the simulation are positioned according to the GPS logs of buses and taxis over 20 km^2 in Porto, and the positions of cars other than buses are also derived from the GPS logs of taxis.

Engineering-economic Model

In our model, when Internet traffic is carried over the DSRC vehicular network at peak hours, fewer macrocellular towers are needed than in a scenario without DSRC. If the avoided cost of macrocells exceeds the cost of DSRC, then this difference is a profit for the ISP from DSRC. If the cost of DSRC exceeds that of avoided cells, then the ISP is better off by not deploying DSRC for Internet access. Therefore, if RSU sharing reduces DSRC cost for the ISP, then its profit is higher than in the absence of sharing. We assume the ISP will adopt the RSU deployment strategy that maximizes profit. We also assume that the amount of Internet traffic does not depend on whether it is carried over macrocells or RSUs (shared or not). Thus, ISP revenue does not depend on strategy, so the ISP strategy that maximizes profit also minimizes cost. If this strategy includes shared RSUs, then government savings and increased social welfare are possible. The modeling of costs, ISP strategy, government savings and social welfare from sharing are described below.

Costs of DSRC and cellular infrastructure

As in (Ligo et al. 2015), we consider the case where DSRC spectrum is already allocated for vehicular safety, and there is a mandate to equip cars with OBUs for safety, as may occur in the U.S. (U.S. Department of Transportation 2015). In this scenario, spectrum and OBU costs are incurred for safety and RSU costs are the only costs that matter for non-safety purposes.

We define avoided cost of macrocells as the cost of additional cellular towers deployed if the

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traffic carried by the vehicular network would instead be carried on a capacity-limited, macrocellular network. That avoided cost depends on the throughput estimated as in III.A, and its net present value (NPV) per km² is $NPVB = \rho_{savedtowers} * C_{tower}$ (Ligo et al. 2015). C_{tower} is the average NPV per macrocell tower and $\rho_{savedtowers}$ is the total number of towers "saved" per km², given by

$$\rho_{savedtowers} = \frac{bpsOff * FR}{s_{sector} * bw * N_{sectors}} \qquad (1)$$

where *bpsOff* is the peak-hour, downstream DSRC throughput per km², $FR \geq 1$ is the frequency reuse factor, s_{sector} is the average downstream spectral efficiency in bps/Hz/sector, *bw* is the total downstream bandwidth per ISP, and $N_{sectors}$ is the number of sectors per tower.

ISP strategy for using shared and Internet-only RSUs

Cost for the ISP per unit of area is $C_{isp} = p.N_{sh} + c_{io}.N_{io}$ where *p* is the price per shared RSU and N_{sh} and N_{io} are the densities of shared RSUs and Internet-only RSUs that minimize cost. c_{io} is the cost the ISP bears to deploy an Internet-only RSU by its own. N_{sh} and N_{io} also affect *bpsOff*, and thus determine the avoided cost of macrocells. Therefore, the ISP chooses N_{sh} and N_{io} to minimize cost for the ISP.

We find N_{sh} and N_{io} according to the following procedure. We determine a large number N of possible Internet-only locations using the k-means algorithm. Then we simulate scenarios of Internet-only RSUs, with the quantity of RSUs varying up to N. We obtain scenarios with Internet-only and shared RSUs by substituting Internet-only locations with the closest locations of either safety RSUs or smart streetlights. If there are S safety or streetlight locations, S scenarios are simulated with the quantity of shared RSUs varying from 1 to S. After the scenarios are simulated, we choose the set of shared and Internet-only RSUs that result in the highest total avoided cost of macrocells minus total cost for the ISP.

Social welfare and government savings from sharing

Sharing can increase the social welfare derived from DSRC-based Internet access. That increase per unit of area is

$$SW = SW_{sh} - SW_n \qquad (2)$$

where SW_{sh} and SW_n are the social welfare from Internet per unit of area with and without sharing, respectively. SW_n is

$$SW_n = B_n - C_n \qquad (3)$$

where C_n is the cost of Internet-only RSUs that would be deployed and B_n is the avoided cost of macrocells per km² under the ISP strategy that maximizes profit, without sharing. SW_{sh} is

$$SW_{sh} = B_{sh} - C_u - C_{io} \qquad (4)$$

where B_{sh} is the avoided cost of macrocells when RSUs can be shared, C_{io} is the cost to deploy

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Internet-only RSUs in this case, and C_u is the cost to upgrade safety RSUs or streetlights for sharing, per unit of area. C_u is defined as $C_u = N_{sh} * c_u$, where c_u is the cost to upgrade a safety RSU or streetlight for sharing. Thus, Cu is proportional to the density of shared RSUs N_{sh}. c_u is assumed as the incremental cost of backhaul to provide Internet access on safety RSUs. (In (Clark, Lehr, and Bauer 2011) the backhaul cost is about \$1/Mbps/month. The NPV results from incurring costs for 16 Mbps of capacity. The throughput/RSU is below 16 Mbps in more than 95% of the simulations).

Government savings from sharing is $GP=(p–c_u)*N_{sh}$. A positive GP results in a secondary positive effect. Each dollar of GP means that a dollar less is required from public funds to finance safety RSUs or streetlights. For each dollar raised for public funds, there is a social burden arising from taxation known as the excess burden of taxation, which has been estimated to be between \$1.3 and \$1.5 (Triest 1990; Laffont and Tirole 2000). Because of this, we assume a positive GP causes an "avoided" excess burden $AEB=GP*0.4$.

Locations of shared and Internet-only RSUs

Government savings and social welfare from sharing depends on the quantity and locations of safety RSUs or streetlights that can be shared. The assumptions for both types of infrastructure are described below.

For safety RSUs we assume that 0.2 RSUs per 1,000 inhabitants are deployed (which is consistent with (Wright et al. 2014), (FHWA 2016)), which are placed at the intersections with the highest average quantity of vehicles at peak hours. We also assume that placement and quantity of safety RSUs do not depend on whether they are shared.

We also examine the case where other types of public infrastructure such as "smart" streetlights can be shared. We assume that smart streetlights can be upgraded to provide DSRC-based Internet access and are ubiquitous, so they are available at the locations that would be chosen by an ISP deploying its own RSUs (intersections or not).

With sharing of either safety RSUs or streetlights, the ISP may also deploy its own Internet-only RSUs. We assume that an ISP determines possible locations for Internet-only RSUs (intersections or not) based on the number of vehicles nearby at peak hours.

Base Case Scenario

The base case numerical values for the assumptions are listed in Table I. In this project, we consider RSU sharing with ISPs. However, the method applies to any provider of IP-based traffic that would typically be carried over macrocells, such as mobility and environmental applications envisioned in (Wright et al. 2014).

TABLE I. BASE CASE NUMERICAL ASSUMPTIONS

Assumption	Value
Discount rate	7%, real (Office of Management and Budget 1992)
Time horizon	10 years (see (Ligo et al. 2015))
Penetration of DSRC	25% of all vehicles in Table II (Harding et al. 2014)
Data traffic per DSRC-equipped vehicle on the road	400 kbps (Deutsche Telekom 2013): 50% of cars are endpoints for 800 kbps, 50% are relays only
Share of downstream traffic	90% of data from RSU to vehicle (Sandvine 2014)
Macrocellular spectrum efficiency s_{sector}	1.4 bps/Hz/sector (Sesia, Toufik, and Baker 2011) (downstream average)
Sectors per macrocell $N_{sectors}$	3 (Sheikh 2014)
Macrocellular bandwidth bw	70 MHz (downlink per sector (Ligo et al. 2015))
Reuse factor FR	1 (macrocellular frequency reuse) (Wannstrom and Mallinson 2014)
Unit cost of macrocellular tower C_{tower}*	$750,000 (e.g. (Hallahan and Peha 2011b)): NPV of capital and operating expenses (Capex and Opex) over time horizon (see (Ligo et al. 2015))
Cost of one DSRC Internet-only RSU c_{io}*	$14,000 ((Wright et al. 2014) and others, NPV of Capex and Opex over time horizon (Ligo et al. 2015))
Cost of to upgrade one safety RSU for Internet access c_u*	$1,400 (see III.C.2)
Density of safety RSUs N_{sa}	0.2 per 1,000 people (Wright et al. 2014), (FHWA 2016)

* Monetary values in 2014 U.S. dollars

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Findings

In this section we show the RSU deployment strategy that maximizes ISP profit, the pricing strategies of a government that seeks to maximize either social welfare *SW* or savings *GP* when charging a profit-maximizing ISP for shared RSUs, and the national implications of those government strategies.

ISP strategy for using shared and Internet-only RSUs

In this subsection we discuss the ISP strategy, i.e. the densities of shared RSUs N_{sh} and Internet-only RSUs N_{io} that minimize cost, considering sharing of safety RSUs.

First, we found that data throughput of a shared safety RSU is less than 5% different from the throughput at an Internet-only RSU for 95% of them. Thus, if an Internet-only RSU is cost-effective in a location, and there is a safety RSU or streetlight available for sharing nearby, then the ISP will use the shared RSU as long as $p < c_{io}$ (i.e. the price of sharing is lower than the cost of an Internet-only RSU).

We also found that the ISP strategy is affected by conditions that vary with population density. That is, there is a different cost-minimizing strategy under each of three mutually-exclusive conditions, defined by two densities. One is the density of shareable locations N_{sa}, i.e. the density of safety RSUs or streetlights that can be shared with ISPs. The other is the density of Internet-only RSUs N_n that minimizes ISP cost under no sharing. We label those conditions I, II and III, as shown in Fig. 1.
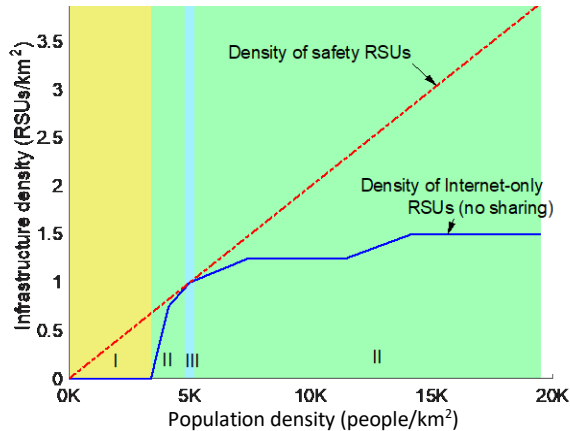

Fig. 1. RSU density as a function of population density. The background colors represent which condition (I, II or III) applies for each population density.

Condition I is $N_n = 0$, i.e. in the absence of sharing the ISP strategy is to not deploy any Internet-only RSU. However, if the price of shared RSUs is lower than the avoided cost of macrocells, then the ISP will deploy a non-zero density of shared RSUs N_{sh} in those locations.

Condition II is $N_{sa} > N_n > 0$, i.e. for a price lower than the avoided cost of macrocells the ISP strategy is to use more RSUs than it would deploy without sharing (N_n).

Condition III is $N_n \geq N_{sa} > 0$, i.e. the density of Internet-only RSUs N_n that minimizes ISP cost under no sharing is higher than the density of shareable locations. In that case, an ISP would profit from deploying N_n, but there are not as many shareable locations as the ISP would deploy. Thus, the ISP strategy is to use all shared RSUs as long as $p < c_{io}$ (the price of sharing is lower than the cost of an Internet-only RSU). Also, the ISP may deploy Internet-only RSUs in locations not served by safety RSUs.

Fig. 1 shows N_{sa} for safety RSUs and N_n, both as a function of population density. The graph shows that $N_{sa} > N_n$ (i.e. condition I or II) for most population densities. However, there is a narrow range of population densities around 5,000 people/km^2 where condition III holds.

Government strategy to maximize social welfare SW

This subsection discusses the pricing strategy that maximizes social welfare when sharing safety RSUs. The derivative of Equation (4) with respect to the density of shared RSUs N_{sh} implies that SW is maximized by setting price $p=c_u$. (The base case cost of an Internet-only RSU c_{io} is $14,000, and the cost to upgrade a safety RSU for Internet is c_u is $1,400. Thus, the optimal p/c_{io} is 0.1.) Fig. 2 shows that for sharing of safety RSUs, SW is maximized for $p=c_u$, but remains at its maximum for other prices as well. This is because there is a range of prices where all safety RSUs are shared. That flexibility to achieve maximum social welfare at multiple prices may help also accomplish goals other than welfare, such as government savings examined in the following subsection.

For population densities where condition I holds, there is a limit for the price p above which SW is zero. This is because there is no deployment of RSUs for p near c_{io}, since the avoided cost of macrocells is below the cost of RSUs. The curve for 2,500 people/km^2 illustrates an example population density under condition I. For condition II SW is maximum for $p=c_u$, but then SW falls with p. This is shown in Fig. 2 for 20,000 people/km^2. SW is maximum for p/c_{io}=0.1 (i.e. $p=c_u$) and for higher prices sharing (and SW) decrease, but all safety RSUs are shared and SW remains maximum for $0 < p/c_{io} < 0.22$. Where condition III holds, if $p<c_{io}$, all safety RSUs are shared and SW is maximum. This is illustrated in Fig. 2 for 5,000 people/km^2.

Thus, a government seeking to maximize SW can set $p=c_u$ (or p/c_{io}=0.1 in the base case) under all
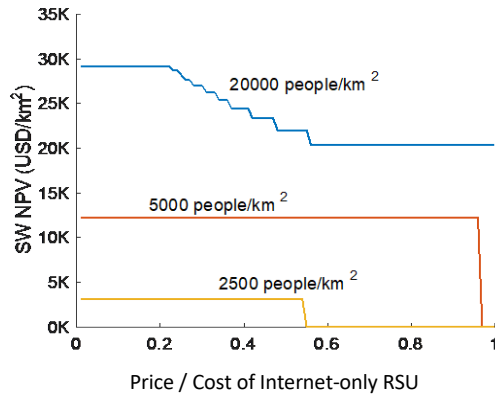
conditions.

Fig. 2.   10-year NPV per km^2 of social welfare from sharing SW as a function of price for sharing safety RSUs. Each curve refers to a different pop. density.

Pricing strategy to maximize government savings GP

The sharing price p determines how much of the cost saving from sharing RSUs increases either ISP profit or GP. This subsection discusses what p a government sets to maximize GP, considering sharing of safety RSUs.

In areas where condition I holds, there is a price limit above which GP = 0. Fig. 3 illustrates that for 2,500 people/km^2. The government would charge p/c_{io}=0.55 for maximum savings. For condition II, there are more safety RSUs than the number of Internet-only RSUs that would be deployed under no sharing. A large quantity of shared RSUs are deployed at a low price, but fewer shared RSUs are used as they become more expensive for the ISP. In Fig. 3, in the curve for 20,000 people/km^2 GP is maximized by setting p/c_{io} close to 1. For condition III, all safety RSUs are shared as long as $p<c_{io}$ (the price of sharing is lower than the cost of an Internet-only RSU). In this case, a government would again charge p close to c_{io}, which is illustrated in Fig. 3 for the population density of 5,000 people/km^2. In any case (I, II or III), adopting a price strategy of charging the maximum price the ISP can bear is optimal for sharing of safety RSUs.
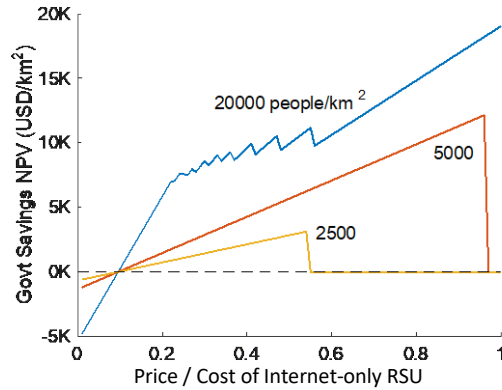
Fig. 3. 10-year NPV per km^2 of government savings from sharing GP as a function of price for safety RSUs. Each curve refers to a different pop. density.

Government trade-offs and the avoided excess burden AEB

In many regions, maximum government savings GP and maximum social welfare SW cannot be achieved with the same price. Indeed, $p=c_u$ (i.e. price equals the cost to upgrade a safety RSU for Internet) is optimal for SW while the p that maximizes GP varies with population density. Thus, there is a trade-off between maximizing SW and maximizing GP for some population densities.

One way to reconcile the two objectives is to consider avoided excess burden (AEB). We presented before the AEB that results from non-zero GP. Thus, aside from the objectives of maximizing GP or SW, a third possible objective for the government might be to maximize $SW+AEB$, which is a hybrid objective that depends on both GP and SW.

Fig. 4 shows that $SW+AEB$ does not always increase monotonically with price p, considering sharing of safety RSUs. Therefore, while we showed before that SW is maximum for $p=c_u$ (i.e. $p/c_{io}=0.1$), the pricing strategy that maximizes $SW+AEB$ depends on population density. However, Fig. 4 suggests that charging the maximum price the ISP can bear is near optimal, i.e. the $SW+AEB$ obtained with such a strategy is not more than 10 or 20% lower than the maximum possible $SW+AEB$. Thus, a strategy of maximizing GP is similar to a strategy of maximizing $SW+AEB$.
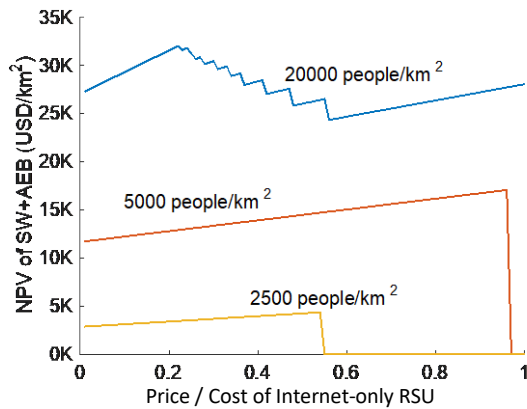
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Fig. 4.   10-year NPV per km^2 of social welfare from sharing plus the avoided excess burden (*SW+AEB*), as a function of price for sharing of safety RSUs. Each curve refers to a different population density.

Nationwide Government Profit and Social Welfare

In this section, we quantify the effects of sharing safety RSUs nationwide. We assume the population density variation of the U.S., and that all census tracts determine their pricing strategies to either maximize social welfare *SW*, maximize government savings *GP*, or maximize *SW* plus avoided excess burden *AEB*.

GP, *SW* and *AEB* were calculated for each U.S. census tract (2010 data (United States Census Bureau 2015)), and then summed nationwide. Penetration, data rates and other assumptions are fixed in the base values. Fig. 5 shows that the 10-year NPV of nationwide *GP* is close to $150 million when the pricing strategy is to maximize *GP*. Assuming a safety RSU has the same cost c_{io} of an Internet-only RSU, then the cost of nationwide RSU deployment for safety in 20% of the signalized intersections (see III.B) would be about $850 million. Thus, Internet access could save about 18% of the investments in safety DSRC RSUs that will be incurred by local governments.

On the other hand, Fig. 5 shows that nationwide *SW+AEB* is just 2% lower when maximizing *GP* is the objective, compared to *SW+AEB* when the objective is to maximize *SW+AEB*. Thus, if state/local governments lean to the objective of maximizing *GP*, the nationwide impact in *SW+AEB* seems to be small.
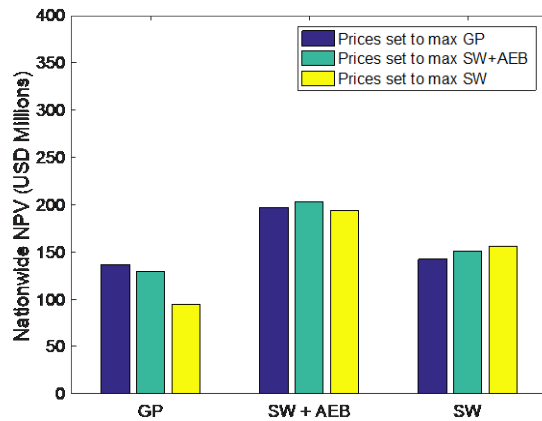
Fig. 5. 10-year NPV, summed over U.S. census tracts, of *GP*, *SW*, and *SW+AEB* from sharing of safety RSUs. Prices are chosen at each census tract to maximize *GP* (blue bars), *SW+AEB* (green), or *SW* only (yellow).

Sharing of smart streetlights

For the preceding results we assume sharing of safety RSUs. For this subsection we assume instead that smart streetlights are shared as RSUs.

The density of streetlight RSUs will always exceed the density of RSUs that maximizes ISP profit in the absence of sharing N_n. In this case, there is no population density where condition III applies, so any location will either fit in condition I or II. The density of shared RSUs N_{sh} is higher in the case of streetlights than of safety RSUs, especially when price is low such as in locations under condition I. (When p/c_{io} approaches one, N_{sh} is similar with either streetlights of safety RSUs.) The result is that both *GP* and *SW* (and hence *SW+AEB*) are higher for streetlights than safety RSUs for several population densities.

Fig. 6 shows nationwide results for smart streetlights. The graph shows that the maximum NPV of nationwide *GP*, *SW* and *SW+AEB* are all higher than the nationwide results with sharing of safety RSUs (Fig. 5), which indicates the advantage of having more locations with sharing opportunities in the streetlight case.
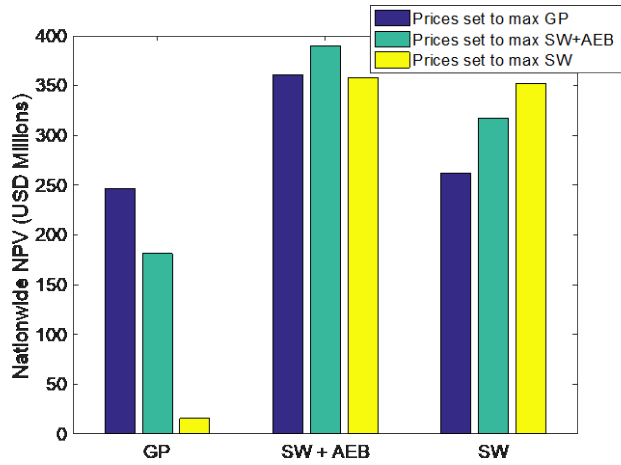
Fig. 6. 10-year NPV, summed over U.S. census tracts, of *GP*, *SW*, and *SW+AEB* from sharing of smart streetlights.

Conclusions and recommendations

In this project we show that sharing DSRC RSUs deployed for safety with ISPs would result in savings for the government who owns them, and these savings could be used to offset the investment in safety infrastructure. Likewise, sharing of other infrastructure such as smart streetlights could result in government savings. Sharing would also enhance social welfare, when compared to RSUs being deployed independently by ISPs for Internet access only.

Moreover, we show that the pricing strategy a government should adopt to charge an ISP for sharing depends on location, w.r.t. population density. If price is lower than the cost of Internet-only RSUs, then an ISP is likely to deploy more RSUs with sharing than without it. In particular, shared RSUs are deployed in locations where Internet-only RSUs are not cost-effective. Thus, sharing allows DSRC-based Internet over more areas of the country than it would be the case without sharing.

For sharing of safety RSUs, government savings from sharing are maximized when the price to share is close to the cost of Internet-only RSUs, for locations where Internet over DSRC is cost-effective even without sharing. However, for places with lower population densities, there is a price above which it is not cost-effective for ISPs to deploy RSUs, so there is no revenue for the government. For a nationwide deployment, we estimate the savings as about one fifth of the total investment in safety RSUs.

If a government chooses to maximize social welfare, the optimal price equals the cost to share RSUs. This often differs from the pricing strategy that maximizes government savings. However, the effect of such a trade-off in nationwide social welfare plus the avoided excess burden of taxation *SW+AEB* is limited. If state and local governments choose to maximize savings, the resulting *SW+AEB* is close to maximum.

Publications and presentations that resulted from the project

The following papers were published, or were accepted for publication, in peer-reviewed conferences:

[1] A. Ligo, J. Peha, and J. Barros, "Throughput and Cost-Effectiveness of Vehicular Mesh Networks for Internet Access," IEEE 84th Vehicular Technology Conference, 2016. Available at www.ece.cmu.edu/~peha/papers.html

[2] A. Ligo, J. Peha, and J. Barros, "Is It Cost-Effective to Share Roadside Infrastructure for Non-Safety Use?," IEEE 85th Vehicular Technology Conference, 2017. (This paper was produced during the project and was accepted to appear in the conference in February 2017.) Available at www.ece.cmu.edu/~peha/papers.html

The following presentations were performed during the project:

[1] J. Peha, KEYNOTE: "Cars, Broadband, Internet: And why the road to innovation may go through Washington DC, " IEEE Consumer Communications and Networking Conference, 2015

[2] J. Peha, KEYNOTE: "Wireless Communication and Municipal Governments – Looking Forward", to appear in 2017 Conference of Pennsylvania State Association of Burroughs.

[3] J. Peha, "Spectrum Sharing in Smart Cities," NSF Future Wireless Cities Workshop, Feb 2016

[4] A. Ligo and J. Peha, "Cost-Effectiveness of Using Connected Vehicle Infrastructure for Internet Access," Symposium of the Traffic21 Institute/T-SET University Transportation Center Consortium, 2016.

[5] A. Ligo and J. Peha, "Cost-Effectiveness of Using Connected Vehicle Infrastructure for Internet Access," MASITE-ITSPA Annual Conference, 2016. (MASITE: Mid-Atlantic Section of The Institute of Transportation Engineers; ITSPA: Intelligent Transportation Society, Pennsylvania)

Other outcomes resulting from the research project

The PI has met with various senior government officials, including the Chairman of the U.S.

Federal Communications Commission and many staff experts, to present our results and discuss the opportunities and challenges in vehicular networks.

The PI of this project has been invited to serve as an (unpaid) advisor to the City of Pittsburgh on deployment of wireless technology for smart city applications such as transportation. In this way, the PI is putting research results and concepts to work for the benefit of Pittsburgh and its citizens.

Other information

The funding agreement number of the project: 45

4.   The RH Display ID for the project: ???

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