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Is It Cost-Effective to Share Roadside Infrastructure for Internet Access?*

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***Abstract*—Vehicular networks have the potential to improve road safety using Dedicated Short Range Communications (DSRC) technology, but substantial investment in roadside units (RSUs) is required. DSRC can be simultaneously used for safety and non-safety applications. If local governments share RSUs deployed for safety or smart streetlights with other kinds of service providers, then the respective costs can also be shared, thereby reducing costs for the government. We estimate that government could save about one fifth the nationwide cost of safety RSUs in the U.S. if they are shared with Internet service providers. We also estimate an increase in social welfare from sharing. The prices that maximize government savings and social welfare may differ. However, we find that maximizing government savings results in near-optimal social welfare.**

Keywords*— *Connected Vehicles; Roadside Infrastructure Cost; DSRC; Intelligent Transportation Systems

I. Introduction

Vehicular networks may soon be widely deployed using DSRC technology, primarily for car safety. In-vehicle routers allow both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links between cars and RSUs placed near roads. RSUs can support safety applications such as crash avoidance, and non-safety applications such as in-vehicle Internet access [1], [2].

This paper is about cost savings from infrastructure sharing, when it is deployed by government agencies and shared with private parties. The cost of RSUs may slow adoption of V2I safety applications. While V2V may be mandated in the U.S. [3], RSUs for safety will cost billions of dollars nationwide and probably won't be deployed until state and local governments choose to pay [4]. If there are ways to reduce RSU deployment cost, DSRC safety benefits 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 [5]–[8], 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 [7].

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 [9]. 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, it has been shown [10] that roadside microcells provide Internet access at a lower cost than cellular networks, assuming greenfield deployment of either infrastructure. [11] 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 paper, 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 paper 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-

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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.

One aspect of our method is an engineering-economic model 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 method is a detailed packet-level simulation model of TCP/IP connections between cars and Internet-connected RSUs using DSRC, under a variety of design choices, to estimate the 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.

II. 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. This network has been transferring about 3 TB/month, and in downtown, where most of the RSUs are located, up to 70% of data is carried via DSRC. We used a dataset with measurements of data transferred over DSRC and cellular, and GPS position data of 430+ buses and 420 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.

III. METHOD

To determine how sharing affects government savings and social welfare, Porto data is used in the simulation model to estimate throughput of the DSRC vehicular network, under varying quantities of RSUs and vehicles. The simulated throughput is then used as input to the engineering-economic model. 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 simulation and engineering-economic models are described below.

A. Throughput estimation

We estimate 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 ns-3 network simulator [12]. The simulation model is described in greater detail in [11] and [13]. 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.

The network is simulated with vehicles changing positions each 5 seconds. During a 5 s interval, throughput is simulated over a network of non-moving nodes. Then vehicle positions are changed and the process is repeated for the next interval. Vehicles 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. Antenna height is 7 meters for RSUs, 3 m for buses, and 1.5 m for other vehicles.

Steady-state throughput is estimated for each 5 s interval. This is our estimate of the vehicular Internet data that is offloaded from macrocells at peak hours.

We assume four 10 MHz DSRC channels are available for non-safety traffic, and each OBU and RSU is equipped with four radios. The channel to be used at each hop of a connection is chosen as the least used channel in the area simulated.

We assume that half of DSRC-equipped cars are exchanging traffic at a constant rate at any given time, and all DSRC-equipped cars act as relays for other cars.

Each vehicle connects to an RSU through TCP/IP with a Maximum Segment Size of 2244 bytes [14]. IP packets are routed through connections with up to three hops. If a vehicle can reach several RSUs through one-hop, then the hop with the least path loss is selected. If all connections have multiple hops, then we select one randomly among the connections with the fewest hops.

A hop is used between two nodes only if received signal strength exceeds 15 dB above the sensitivity threshold (-94 dBm). This is the criteria determined empirically in the Porto network. When the hop is used, packets are received at an error rate as in [15],[12]. The transmitted power is 14.6 dBm [16]-[17], and the gains of the transmission antennas are 16 dBi and 5 dBi for the RSUs and vehicles, respectively, which are consistent with Porto settings. The received signal is calculated according to the propagation loss model from [18] (urban microcell B1 variant). The difference between the median simulated loss and the median loss measured in Porto buses is below 5 dB for most distances shorter than 200 meters. (More than 95% of the hops observed in the Porto network are shorter than 200 m.)

B. *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.

1) *Costs of DSRC and cellular infrastructure*

As in [11], 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. [19]. 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 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 km^2 is $NPVB = \rho_{savedtowers} {}^{*} C_{tower}$ [11]. C_{tower} is the average NPV per macrocell tower and $\rho_{savedtowers}$ is the total number of towers "saved" per km^2, given by

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

where *bpsOff* is the peak-hour, downstream DSRC throughput per km^2, $FR \geq 1$ 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.

2) *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.

3) *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 km^2 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 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}. The value for c_u in Table I is assumed as the incremental cost of backhaul to provide Internet access on safety RSUs. (In [20] 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 [21], [22]. Because of this, we assume a positive GP causes an "avoided" excess burden $AEB=GP{}^{*}0.4$.

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 [4], [23]), 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 using k-means clustering [13], [24]. The algorithm divides a given number of vehicle positions into k regions, and then finds the RSU location for each region that minimizes the sum of the distances between the vehicles and the RSU.

5) Base Case Scenario

The base case numerical values for the assumptions are listed in Table I. Table II lists the assumed number of vehicles for each population density. These assumptions apply for the results in section IV unless otherwise stated. (For further justification of these numerical assumptions, see [11] and [13].)

Moreover, in the base scenario 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 [4].

TABLE I. BASE CASE NUMERICAL ASSUMPTIONS

Assumption	Value
Discount rate	7%, real [25]
Time horizon	10 years (see [11])
Penetration of DSRC	25% of all vehicles in Table II [26]
Data traffic per DSRC-equipped vehicle on the road	400 kbps [27]: 50% of cars are endpoints for 800 kbps, 50% are relays only
Share of downstream traffic	90% of data from RSU to vehicle [9]
Macrocellular spectrum efficiency s_{sector}	1.4 bps/Hz/sector [28] (downstream average)
Sectors per macrocell $N_{sectors}$	3 [29]
Macrocellular bandwidth bw	70 MHz (downlink per sector [11])
Reuse factor FR	1 (macrocellular frequency reuse) [30]
Unit cost of macrocellular tower C_{tower}*	$750,000 (e.g. [8]): NPV of capital and operating expenses (Capex and Opex) over time horizon (see [11])
Cost of one DSRC Internet-only RSU c_{io}*	$14,000 ([4] and others, NPV of Capex and Opex over time horizon [11])
Cost of to upgrade one safety RSU for Internet access c_u*	$1,400 (see 0
Density of safety RSUs N_{sa}	0.2 per 1,000 people [4], [23]

* Monetary values in 2014 U.S. dollars

TABLE II. NUMBER OF VEHICLES ON THE ROAD AT PEAK HOURS PER CAPITA AND PER KM^2, AS A FUNCTION OF POPULATION DENSITY [11]

Population	Vehicles owned		Vehicles on the road at peak hours	
per km^2	per capita	per km^2	per capita	per km^2
10	1	10	0.1	1
200	0.75	150	0.04	8
1000	0.65	650	0.04	40
2000	0.6	1200	0.04	80
3000	0.6	1800	0.04	120
5000	0.46	2300	0.04	200
12000	0.24	2900	0.033	400

IV. RESULTS AND DISCUSSION

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.

All these results depend on average throughput, which is determined as follows. The throughput for each simulated condition of RSU density, vehicle density and data rate is derived by averaging throughput for at least 1000 vehicles over 50 seconds. Assuming that the 50-50-second throughputs of the vehicles are mutually independent, then the confidence interval is within 7-15% of the mean throughput.

A. 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 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.

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.

B. *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.

C. *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.

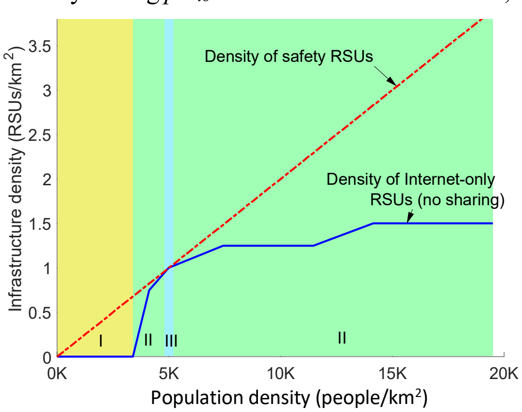

Fig. 1. RSU density as a function of population density. The background colors represent which condition (I, II or III) applies for each population density.

D. *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). In III.B we noted 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 $SW+AEB$.

E. *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 [31]), 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

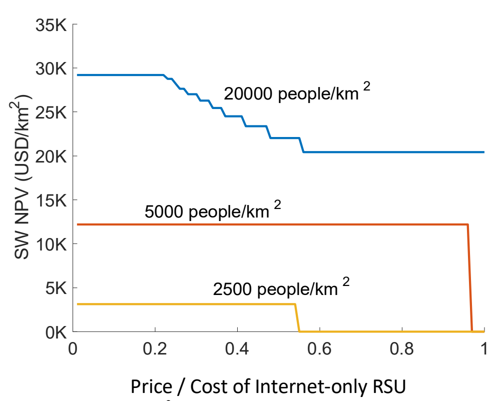

Fig. 2. 10-year NPV per km^2 of social welfare from sharing SW as a function of price for sharing safety RSUs. Each curve refers to a different pop. density.

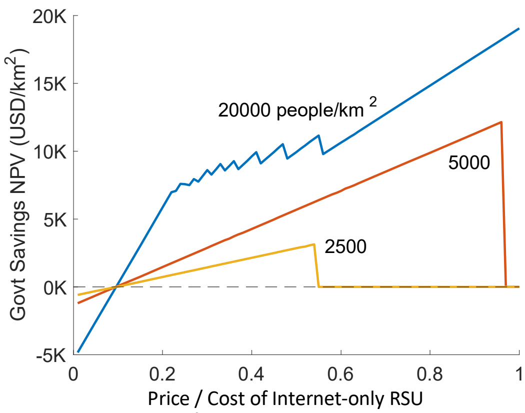

Fig. 3. 10-year NPV per km^2 of government savings from sharing *GP* as a function of price for safety RSUs. Each curve refers to a different pop. density.

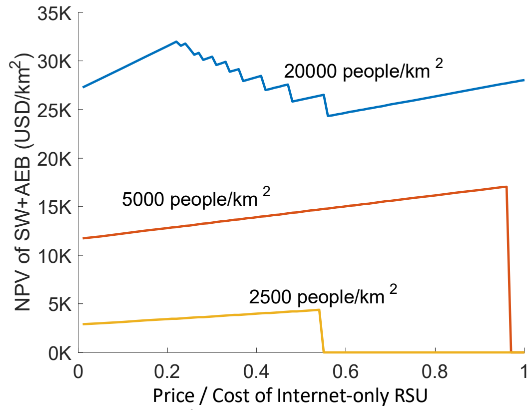

Fig. 4. 10-year NPV per km^2 of social welfare from sharing plus the avoided excess burden (*SW+AEB*), as a function of price for sharing of safety RSUs. Each curve refers to a different population density.

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.

F. *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.

V. Conclusion

In this paper 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-

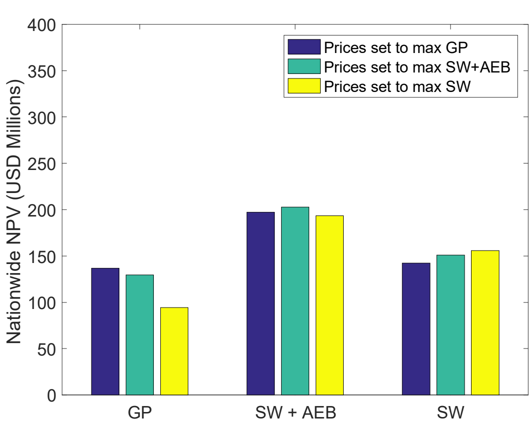

Fig. 5. 10-year NPV, summed over U.S. census tracts, of *GP*, *SW*, and *SW+AEB* from sharing of safety RSUs. Prices are chosen at each census tract to maximize *GP* (blue bars), *SW+AEB* (green), or *SW* only (yellow).

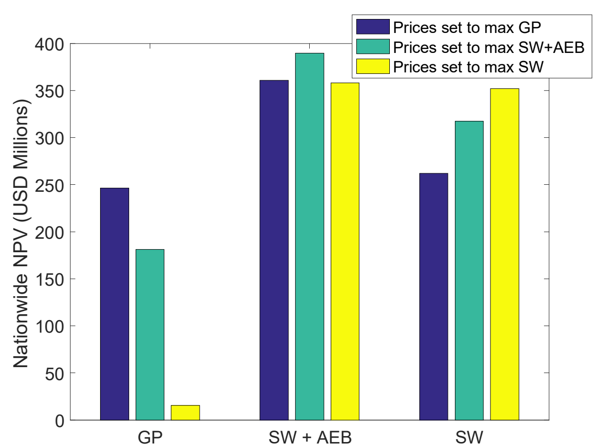

Fig. 6. 10-year NPV, summed over U.S. census tracts, of *GP*, *SW*, and *SW+AEB* from sharing of smart streetlights.

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 18% 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.

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REFERENCES

[1] S. Zeadally, R. Hunt, Y.-S. Chen, A. Irwin, and A. Hassan, "Vehicular ad hoc networks (VANETS): status, results, and challenges," *Telecommun. Syst.*, Dec. 2010.

[2] C. Campolo and A. Molinaro, "Multichannel communications in vehicular Ad Hoc networks: a survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 158–169, May 2013.

[3] U.S. Department of Transportation, *Federal Motor Vehicle Safety Standards; V2V Communications - Notice of Proposed Rulemaking (NPRM)*. 2016.

[4] J. Wright, J. K. Garrett, C. J. Hill, G. D. Krueger, J. H. Evans, S. Andrews, C. K. Wilson, R. Rajbhandari, and B. Burkhard, "National Connected Vehicle Field Infrastructure Footprint Analysis," US DOT - FHWA, 2014.

[5] R. Hallahan and J. M. Peha, "Compensating Commercial Carriers for Public Safety Use: Pricing Options and the Financial Benefits and Risks," in *39th Telecommunications Policy Research Conference, 2011. www..ece.cmu.edu/~peha/papers.html*.

[6] R. Hallahan and J. M. Peha, "Quantifying the costs of a nationwide public safety wireless network," *Telecommun. Policy, 2010. www.ece.cmu.edu/~peha/papers.html*.

[7] J. M. Peha, "A Public-Private Approach to Public Safety Communications," *Issues Sci. Technol. Natl. Acad. Press. 2013. www.ece.cmu.edu/~peha/papers.html*.

[8] R. Hallahan and J. M. Peha, "The business case of a network that serves both public safety and commercial subscribers," *Telecommun. Policy, 2011. www.ece.cmu.edu/~peha/papers.html*.

[9] Sandvine, "Global Internet Phenomena Report 1H," 2014.

[10] N. Lu, N. Zhang, N. Cheng, X. Shen, J. W. Mark, and F. Bai, "Vehicles Meet Infrastructure: Toward Capacity–Cost Tradeoffs for Vehicular Access Networks," *IEEE Trans. Intell. Transp. Syst.*, 2013.

[11] A. K. Ligo, J. M. Peha, P. Ferreira, and J. Barros, "Comparison between Benefits and Costs of Offload of Mobile Internet Traffic Via Vehicular Networks," in *43rd Telecommunications Policy Research Conference, 2015. www.ece.cmu.edu/~peha/papers.html*.

[12] "ns-3 Network Simulator." [Online]. Available: https://www.nsnam.org/. [Accessed: 10-Jul-2015].

[13] A. K. Ligo, J. M. Peha, and J. Barros, "Throughput and Cost-Effectiveness of Vehicular Mesh Networks for Internet Access," in *IEEE Vehicular Technology Conference, 2016. www.ece.cmu.edu/~peha/papers.html*.

[14] Z. Wang and M. Hassan, "How much of dsrc is available for non-safety use?," in *Proceedings of the fifth ACM international workshop on VehicularAr Inter-NETworking - VANET '08*, 2008.

[15] M. Lacage and T. R. Henderson, "Yet another network simulator," in *Proceeding from the workshop on ns-2: the IP network simulator - WNS2*, 2006.

[16] A. Cardote, F. Neves, S. Sargento, and P. Steenkiste, "A statistical channel model for realistic simulation in VANET," in *IEEE Vehicular Networking Conference (VNC)*, 2012.

[17] F. Bai, D. D. Stancil, and H. Krishnan, "Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers," in *Proceedings of the 16th MobiCom*, 2010.

[18] J. Meinilä, P. Kyösti, T. Jämsä, and L. Hentilä, "WINNER II Channel Models," in *Radio Technologies and Concepts for IMT-Advanced*, M. Döttling, W. Mohr, and A. Osseiran, Eds. Wiley, 2009.

[19] U.S. Department of Transportation, "Planning for the Future of Transportation: Connected Vehicles and ITS," 2015.

[20] D. D. Clark, W. Lehr, and S. Bauer, "Interconnection in the Internet: the policy challenge," in *TPRC: The 39th Research Conference on Communication, Information and Internet Policy*, 2011.

[21] R. K. Triest, "The relationship between the marginal cost of public funds and marginal excess burden," *Am. Econ. Rev.*, 1990.

[22] J. J. Laffont and J. Tirole, *Competition in Telecommunications*. MIT Press, 2000.

[23] FHWA, "Highway Traffic Signals - FHWA MUTCD," *Frequently Asked Questions - Part 4*, 2016. [Online]. Available: http://mutcd.fhwa.dot.gov/knowledge/faqs/faq_part4.htm#tcsgq3. [Accessed: 12-May-2016].

[24] A. W. Moore, "K-means and Hierarchical Clustering," 2001. [Online]. Available: http://www-2.cs.cmu.edu/~awm/tutorials/kmeans.html. [Accessed: 30-Jul-2015].

[25] Office of Management and Budget, "Circular No. A-94 Revised," *The White House*, 1992. [Online]. Available: https://www.whitehouse.gov/omb/circulars_a094/. [Accessed: 02-Aug-2015].

[26] J. Harding, G. Powell, R. Yoon, J. Fikentscher, C. Doyle, D. Sade, M. Lukuc, J. Simons, and J. Wang, "Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application." U.S. DOT NHTSA, 2014.

[27] Deutsche Telekom, "Connected cars get big data rolling," 2013. [Online]. Available: http://www.telekom.com/media/media-kits/179806. [Accessed: 03-Apr-2015].

[28] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution: From Theory to Practice*, 2nd ed. Wiley, 2011.

[29] M. U. Sheikh, "Aspects of Capacity Enhancement Techniques in Cellular Networks," Tampere University of Technology, 2014.

[30] J. Wannstrom and K. Mallinson, "HetNet/Small Cells," *3GPP*, 2014. [Online]. Available: http://www.3gpp.org/hetnet. [Accessed: 09-Aug-2015].

[31] United States Census Bureau, "QuickFacts - United States," 2015. [Online]. Available: http://www.census.gov/quickfacts/table/PST045214/00. [Accessed: 02-Aug-2015].