Cost-Effectiveness of Sharing Roadside Infrastructure for Internet of Vehicles

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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 safety RSUs. In the case of sharing smart streetlights, we find that nationwide benefits could be up to one third higher than with sharing of safety RSUs. The prices that maximize government savings and social welfare may differ. However, we find that maximizing government savings results in near-optimal social welfare. The benefits of sharing would increase significantly if Internet traffic or DSRC penetration grow over time, as expected.**

***Index Terms*—Connected Vehicles, Internet of Vehicles, DSRC, Intelligent Transportation Systems, Roadside Infrastructure Cost, Smart Cities, Safety RSUs, Smart Streetlights**

I. Introduction

CONNECTED vehicles may soon be widely deployed using Dedicated Short Range Communications (DSRC) technology, which is an important element of Intelligent Transportation Systems. In addition to supporting safety applications, DSRC gives each vehicle the ability to collect, disseminate, and receive information about the vehicle surroundings, and gives the vehicle and its passengers the ability to interact more fully on the Internet [1], [2]. Some have called this the "Internet of Vehicles".

This paper is about cost savings from infrastructure sharing, when it is deployed by government agencies and shared with private parties. In-vehicle routers allow both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links between cars and roadside units (RSUs) placed near roads. While V2V may be mandated in the U.S. [3], RSU cost may slow adoption of V2I applications. RSUs for safety will cost billions of dollars nationwide and probably will not be deployed until state and local governments choose to pay [4]. If RSU cost can be reduced, DSRC safety may be experienced sooner by more people. We show that governments might save by sharing safety RSUs with Internet Service Providers (ISPs) for a fee.

Moreover, governments may widely deploy other types of infrastructure that could be shared. As illustrated in Fig. 1, one example is the deployment of "smart" streetlights with communications capability, to aid services such as surveillance, air quality monitoring, etc. Those streetlights may be opportunities for ISPs of cheap access to power, poles and backhaul, and possibly available in more locations than safety RSUs. In this paper, we also consider sharing of streetlights.

By sharing safety RSUs or streetlights, governments might charge prices to maximize either government savings or social welfare. The contributions of this paper are to determine the prices the government would charge an ISP to achieve either goal. We consider the scenario where the U.S. Department of Transportation (DOT) mandates vehicles to be equipped with onboard units (OBUs). In-vehicle Internet is increasing sharply, and ISPs must decide whether to expand cellular capacity or to deploy RSUs to offload part of the 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 a public-private joint deployment.

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 minimize cost by choosing 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 macrocells.

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 macrocells 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

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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 paper, Section II describes related work, while Section III outlines the data used. In Section IV we describe the model and methodology. Results are discussed and sensitivity analysis is performed in Section V. Section VI concludes the paper.

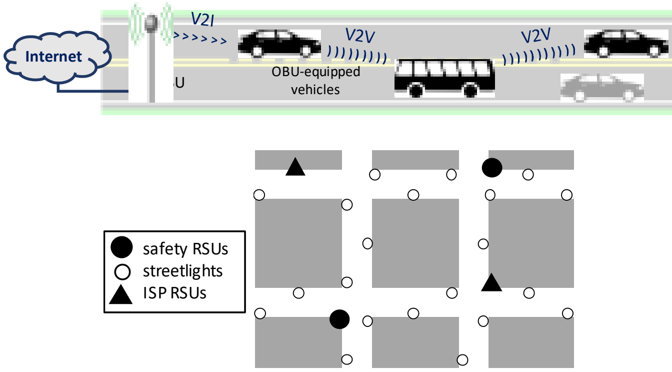


Fig. 1. Representation of a vehicular connection to an Internet-connected RSU. An ISP may deploy its own RSUs, and it may use safety RSUs or smart streetlights shared by the government.

II. Related Work

Although government agencies often deploy infrastructure only for their own use [5], previous work has shown other instances where government can save by sharing infrastructure with commercial companies. For example, as shown in [6]–[9], a highly cost-effective way to provide communications for emergency responders 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 [8].

Similarly, governments might share DSRC RSUs with ISPs. Some claim that demand for mobile Internet will grow sharply [10]. That includes in-vehicle Internet access, which is currently served mainly by macrocells that would continuously need expansion where networks are capacity-limited. Although that extra capacity is costly, previous work has shown that vehicular networks could provide Internet access at a lower cost than cellular networks. For example, it has been shown [11] that roadside microcells provide Internet access at a lower cost than cellular networks, assuming greenfield deployment of either infrastructure. It also has been shown [12] 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 benefit in sharing dual-use RSUs for both safety and Internet access. To the best of our knowledge, this paper is the first that quantifies that benefit.

III. Dataset

We use data from a real DSRC network operating in Porto, Portugal, as of March 2015 [13]. 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. 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 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.

IV. Method

To determine how sharing affects government savings and social welfare, Porto data is used to simulate throughput of the vehicular network, under varying quantities of RSUs and vehicles. That throughput is then used in an engineering-economic model, from which we derive government savings, social welfare. We also examine the pricing strategies that maximize either savings, welfare, or a combination of both.

A. Throughput Simulation

We simulate throughput at packet-level in physical, link, network and transport layers using the ns-3 network simulator [14]. The simulation model is described in greater detail in [12], [15]. Bidirectional packet streams flow 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, as in Fig. 1. When a vehicle is not within three hops of a RSU, the vehicle will switch to a ubiquitous cellular service.

The throughput per unit of area (in bps/km^2) is defined as

$$R = \sum_{i=1}^{V} R_i \qquad (1)$$

where V is the density of OBU-equipped vehicles per km^2, and R_i *is* the data throughput at the transport layer, achievable between vehicle i and an RSU it is communicating with.

In the simulation, vehicles change positions each 5 seconds. During a 5 s interval, throughput is simulated over non-moving nodes. Then vehicle positions are changed and the process is repeated for the next interval. R_i is obtained by averaging the throughputs to vehicle i over the intervals simulated.

Passenger cars, taxis and buses are positioned according to the GPS logs of taxis and buses over 20 km^2 in Porto. Each simulated bus follows the same trajectory as a real bus. We randomly select this bus and a start date and time, and then use its actual GPS measurements. Each of the remaining vehicles follows the same trajectory as a real taxi. For these, we similarly select a random taxi, and a random start day and time.

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.

The band allocated for DSRC in the U.S. is divided in seven 10 MHz channels, of which three are reserved for safety applications and for control of operation of the other channels

[2]. We assume the four remaining channels are available for non-safety traffic, and each OBU and RSU is equipped with four radios. Multiple radios allow different channels to be used simultaneously, so multi-radio OBUs can increase channel utilization and throughput compared to single-radio OBUs. Therefore, if RSUs that act as Internet gateways are deployed, and cars must be equipped with OBUs anyway, then users have much to gain by getting multi-radio OBUs rather than single-radio OBUs. Moreover, we believe the cost difference is likely to be quite small. For example, Chen et al suggest that if certain technical problems can be solved, then this cost will be small, and "there is every reason" to expect the use of more radios than is strictly necessary [16]. Nevertheless, it is possible that OBUs with fewer radios will be deployed, which would lead to somewhat lower throughputs than we report in this paper.

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 [17]. Each vehicle connects to an RSU through TCP/IP with a Maximum Segment Size of 2244 bytes [18]. Each RSU is a gateway to the Internet, but in the simulation we treat the RSU as if it were the endpoint of a TCP connection rather than a gateway. 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. The channel to be used at each hop of a connection is chosen as the least used channel in the area simulated.

The media access control (MAC) sublayer in DSRC is the one specified in IEEE 802.11p, with all packets transferred having the same IEEE 802.11p user priority level. RTS/CTS is not used. In the physical layer, 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 Porto. When the hop is used, the modulation is chosen according to SNIR such that physical bitrates reach up to 27 Mbps per channel. The transmitted power is 14.6 dBm [19]-[20], 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 urban microcell B1 propagation loss model from [21], which is suitable for frequencies in the 5.9 GHz band used for DSRC. In this model, signal loss depends on antenna height, which we assume is 7 meters for RSUs and 1.5 m for other vehicles. 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 m. (More than 95% of the hops observed in the Porto network are shorter than 200 m.)

B. Engineering-economic Model

In our model, DSRC throughput equals the traffic offloaded from macrocells. Therefore, 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. Otherwise, the ISP is better off by not deploying DSRC for Internet access. On the other hand, DSRC costs for the ISP are affected by whether RSUs are shared by the government, and at what price. 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. Also, 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. All costs are defined as the sum of upfront and ongoing costs over the base case time horizon, which are discounted to present values using the base case discount rate.

1) Costs of DSRC and cellular infrastructure

As in [12], 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. [3]. In this scenario, spectrum and OBU costs are incurred for safety and only RSU costs 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. The net present value (NPV) per km^2 of the avoided cost of macrocells is [12]:

$$AC_{tower} = c_{tower}\, N_{savedtowers} \tag{2}$$

where c_{tower} is the average NPV per macrocell tower and $N_{savedtowers}$ is the density of towers "saved" per km^2, given by

$$N_{savedtowers} = \frac{R_{off}\, K}{\eta_{sec}\, B\, N_{sec}} \tag{3}$$

where R_{off} is the peak-hour, downstream DSRC throughput per km^2. R_{off} is the downstream portion of the throughput R defined in (1), which results from the network simulation. $K \geq 1$ is the frequency reuse factor, η_{sec} is the average downstream spectral efficiency in bps/Hz/sector, B is the total downstream bandwidth per ISP, and N_{sec} is the number of sectors per tower.

2) Locations of safety RSUs and smart streetlights

The ISP strategy in deploying RSUs, government savings and social welfare from sharing depends on the quantity and locations of safety RSUs or streetlights that can be shared.

For the former we assume the density of safety RSUs that can be shared is $0.2\, P\, /\, 1000$ (based on [4], [22]), where P is the population density. Safety RSUs are placed at the intersections with the highest average quantity of vehicles at peak hours. This assumption is consistent with [4], which found that a significant number of crashes are intersection-related and high-volume intersections are likely to have the highest number of crashes. We also assume that placement and quantity of safety RSUs do not depend on whether they are shared.

We also examine sharing of smart streetlights, which we assume can be upgraded to provide DSRC-based Internet access and are ubiquitous. Therefore, they are available at the locations that would be chosen by an ISP deploying its own RSUs (intersections or not). We name the density of locations that can be shared (either safety RSUs or streetlights) as N_{sa}.

3) ISP strategy for using shared and Internet-only RSUs

Cost for the ISP per unit of area (km^2) is

$$C_{ISP} = p\, N_{sh} + c_{io}\, N_{io} \quad (4)$$

where p is the price per shared RSU, c_{io} is the cost the ISP bears to deploy an Internet-only RSU by its own, and N_{sh} and N_{io} are the densities of shared RSUs and Internet-only RSUs per km^2 that maximize ISP profit $(AC_{tower} - C_{ISP})$. Note that N_{sh} and N_{io} affect not only C_{ISP} but also the avoided cost of macrocells AC_{tower}, because N_{sh} and N_{io} affect throughput.

For sharing of safety RSUs in a given scenario of population density, DSRC penetration and other assumptions, we find the N_{sh} and N_{io} that maximize $(AC_{tower} - C_{ISP})$ according to the following procedure. We run the simulation with the density of RSUs $N_{sh} + N_{io}$ ranging from 0 to 10 RSUs/km^2. and with the density of shared RSUs ranging from 0 to $min\{$density of safety RSUs, $N_{sh} + N_{io}\}$. For each density, we calculate throughput and costs, and thereby determine the optimal N_{sh} and N_{io}.

For each RSU density, RSUs are initially placed where they are likely to result in the most throughput. Thus, RSUs should be set in places with a large number of vehicle positions at peak hours. More specifically, RSUs are placed using the *k-means* clustering heuristic [23], with peak-hour vehicle positions as the input. The algorithm divides a number of observations (vehicle locations, in our case) into regions, and finds the centroid for each region that minimizes the sum of distances between the observations and the centroid. An RSU is placed at each centroid. If all RSUs are Internet-only, then the RSUs remain at these locations. For cases where some RSUs are shared, RSUs are moved to be collocated with safety RSUs until the desired density of shared RSUs is reached. If j RSUs are to be moved, then we move the RSUs that are closest to an unshared safety RSU. For the case of sharing of smart streetlights, the locations of shared RSUs are the same as the Internet-only RSUs, because streetlights are assumed to be ubiquitous.

4) Social welfare and government savings from sharing

As outlined in Section I, governments might choose prices for sharing RSUs that maximize either social welfare or government savings. Social welfare is the level of well-being in a society. In basic economic theory, it is the sum of all benefits experienced, minus the total cost to provide those benefits, regardless of who benefits and who incurs the costs. In this paper, we examine how RSU deployment impacts welfare. We assume that both total Internet traffic carried and the availability of safety-enhancing applications do not depend on the number of RSUs deployed or shared, so consumer benefit is not affected by RSU strategy. As a result, social welfare is maximized by carrying that traffic and supporting those safety applications with the combination of RSUs and macrocells that result in the lowest overall cost. In contrast, if governments choose to maximize government savings, they would seek to collect as much as possible from ISPs, without considering how RSU strategy might benefit Internet users and providers. As a result, governments that maximize government savings may deploy a different number of shared RSUs and share RSUs at different prices from those governments that maximize social welfare.

In our model, social welfare is increased when DSRC-based Internet access is provided at a lower cost than using macrocells for vehicular users. The increase in social welfare when there is no sharing SW_n (NPV per km^2) is given by

$$SW_n = AC_{tower,n} - C_n \quad (5)$$

where $AC_{tower,n}$ is the avoided cost of macrocells (NPV per km^2) under the ISP strategy that maximizes $(AC_{tower,n} - C_{ISP})$, calculated with (2), in the absence of sharing. C_n is the cost (NPV per km^2) of Internet-only RSUs that would be deployed in the absence of sharing, and given by $C_n = c_{io}\, N_{io}^{nosharing}$. $N_{io}^{nosharing}$ is the density of Internet-only RSUs deployed when there is no sharing. The increase in welfare under sharing is

$$SW_{sh} = AC_{tower,sh} - C_u - C_{io} \quad (6)$$

where $AC_{tower,sh}$ is the avoided cost of macrocells (NPV per km^2) calculated with (2) when RSUs can be shared, and $C_{io} = c_{io}\, N_{io}^{sharing}$ is the cost to deploy $N_{io}^{sharing}$ Internet-only RSUs in the sharing case. C_u is the cost to upgrade safety RSUs or streetlights for sharing, per km^2. C_u is defined as

$$C_u = c_u\, N_{sh} \quad (7)$$

where c_u is the cost to share a safety RSU or streetlight.

Sharing results in a net increase in social welfare if and only if the increase under sharing SW_{sh} exceeds the increase when there is no sharing SW_n. The net increase (NPV per km^2) is

$$SW = SW_{sh} - SW_n \quad (8)$$

The price p affects the density of RSUs N_{sh}, which affects social welfare. The lower p, the greater is N_{sh}. However, if p is lower than the cost to share c_u, then the ISP will deploy RSUs which marginal $AC_{tower,sh}$ is lower than their marginal cost, and this decreases social welfare. To find the pricing strategy that maximizes social welfare, we differentiate (6) w.r.t. N_{sh}:

$$\frac{\partial SW_{sh}}{\partial N_{sh}} = \frac{\partial AC_{tower,sh}}{\partial N_{sh}} - \frac{\partial C_u}{\partial N_{sh}} - \frac{\partial C_{io}}{\partial N_{sh}} = \frac{\partial AC_{tower,sh}}{\partial N_{sh}} - c_u \quad (9)$$

as long as the variation of C_{io} w.r.t. N_{sh} is negligible. From the above, SW_{sh} is maximized when $\frac{\partial AC_{tower,sh}}{\partial N_{sh}} = c_u$. Since the ISP will deploy shared RSUs as long as $\frac{\partial AC_{tower,sh}}{\partial N_{sh}} \geq p$ (i.e. the macrocell cost avoided by an additional RSU exceeds the price to the ISP), then SW_{sh} (and SW) is maximized when $p = c_u$.

Government savings from sharing is

$$GS = (p - c_u)\, N_{sh} \quad (10)$$

The price p that maximizes GS is not obvious, because (10) depends on N_{sh}, which is also affected by p.

Besides, a positive GS results in a secondary effect. Each dollar of GS means that a dollar less is required from public funds (raised from taxes) to finance safety RSUs or streetlights. Taxation causes a social burden known as the excess burden of taxation, which has been estimated to be between 0.3 and 0.5 of public funds raised [24]. If government savings means less taxes, then the excess burden is also reduced. We call this reduction an "avoided" excess burden, or AEB. We assume a positive GS causes an AEB of

$$AEB = 0.4\, GS \quad (11)$$

5) Base Case Scenario

The base case numerical values for the assumptions used in the model are listed below. (For further justification of these numerical assumptions, see [12], [15].) These assumptions apply for the results in Section V unless otherwise stated.

Monetary values. The monetary values are in constant 2014 dollars. Benefit and cost NPVs are calculated at a real discount rate of 7% [25] over a horizon of 10 years [4].

Population density. We make the simplifying assumption that population density is constant throughout the region being analyzed. The base case density is 5000 people/km^2, which is representative of cities like Porto, Boston or Chicago [26].

Number of vehicles on the road at peak hours per capita. Assumed as in Table I, which is calculated as the product of vehicles owned per capita [26], fraction of time vehicle is in use and ratio of peak-hour usage to average usage [27]. We consider usage at peak hours because our calculation of the avoided cost of macrocells is based on capacity-limited cellular networks, and it is peak-hour usage that determines how much capacity a cellular carrier needs, and thus the cost that the carrier incurs.

DSRC Penetration in vehicles. Assumed as 25% of the number of vehicles in Table I. This is reasonable for a decision-maker looking 5 to 10 years ahead in the context of a mandate to deploy DSRC in all new cars [3].

TABLE I. NUMBER OF VEHICLES ON THE ROAD AT PEAK HOURS PER CAPITA AND PER KM^2, AS A FUNCTION OF POPULATION DENSITY [12]

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

Data traffic per DSRC-equipped vehicle on the road. At any 5-second interval during the peak hour, 50% of the DSRC-equipped vehicles on the road are endpoints for data being continually at 800 kbps (*total* downstream and upstream). This is consistent with predictions that vehicular traffic will reach 5 GB/month in the coming years [28].

Share of downstream traffic. While a vehicle is transferring data, 90% of the data flows downstream (RSU to vehicle) [12].

Unit cost of macrocellular tower c_{tower}. The NPV of cost per macrocell tower over 10 years is $750,000 [6], [12].

Macrocellular spectrum efficiency η_{sec}. The downstream average efficiency of a macrocell is 1.4 bps/Hz/sector (LTE-FDD rel. 8 [29]). While technologies such as LTE-A will be more efficient, usage of less efficient ones also continues [30].

Sectors per macrocell N_{sec}. Assumed as 3 [12].

Macrocellular bandwidth B. A tower deployed in a capacity-limited region is constrained by a downlink bandwidth of 70 MHz per sector [31].

Macrocellular frequency reuse K. Assumed as 1 [12], [29].

Unit cost of DSRC RSU c_{io}. The average NPV over 10 years of a DSRC RSU is $14,000, based on [4]. However, in Section V we will consider variations of 25% from that value, as conditions about infrastructure availability vary. For example, the city of Porto deployed RSUs with Capex between $1,200-4,000, by using existing structures (traffic poles, buildings, etc.) already equipped with energy and backhaul access. On the other hand, costs can be significantly higher if new poles, energy and communications infrastructure must be built entirely.

Unit cost to share RSU for Internet access c_u. The average NPV is $1,400, assumed as the incremental cost of backhaul on safety RSUs is streetlights. In [32] 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.)

Densities of safety RSUs or smart streetlights are as in Section IV.B.2. 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 [4].

V. 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 GS when charging a profit-maximizing ISP for shared RSUs, and the national implications of those government strategies. Moreover, we perform sensitivity analysis to show the impact of the most important assumptions on nationwide results.

Results depend on average throughput, which is determined as follows. For each simulated condition of RSU density, vehicle density, data rate and other network parameters, throughputs R_i (see Section IV.A) are obtained for at least 1000 vehicles by simulating the vehicular network. Assuming that throughputs R_i are mutually independent, then the confidence interval is within 7-15% of the mean throughput to a vehicle.

A. ISP strategy for using shared and Internet-only RSUs

In this Section we discuss the ISP strategy, i.e. the densities of shared RSUs N_{sh} and Internet-only RSUs N_{io} that maximize the ISP profit from RSU deployment $(AC_{tower} - C_{ISP})$.

First, we found that throughput of a shared safety RSU is less than 5% different from the throughput of an Internet-only RSU for 95% of them. This is shown in Fig. 2. 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

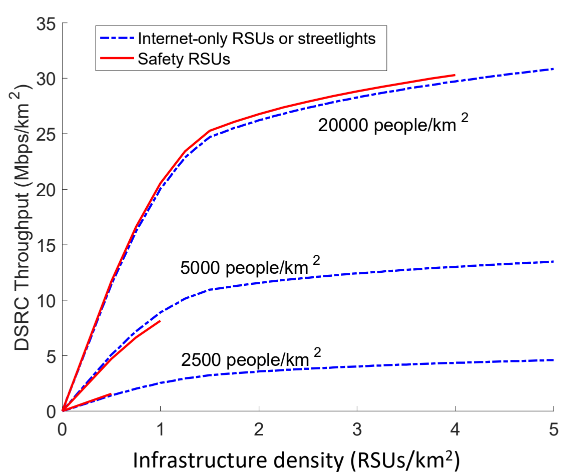


Fig. 2. Throughput as a function of RSU density, for different population densities. The dashed lines show throughput from Internet-only RSUs, which is the same as the throughput of RSUs located at smart streetlights, while the solid lines show throughput of Internet data through sharing of safety RSUs. There are less safety RSUs than Internet-only RSUs because it is assumed that there are 0.2 safety RSUs per 1000 people.

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 strategy under each of three mutually-exclusive conditions, defined by the RSU densities N_{sa} and $N_{io}^{nosharing}$ (see IV.B.4). We label those conditions I, II and III, as shown in Fig. 3.

Condition I is $N_{io}^{nosharing} = 0$, i.e. in the absence of sharing the ISP strategy is to not deploy Internet-only RSUs. However, if the price of shared RSUs is lower than the avoided cost of macrocells, then the ISP deploys a density of shared RSUs N_{sh}.

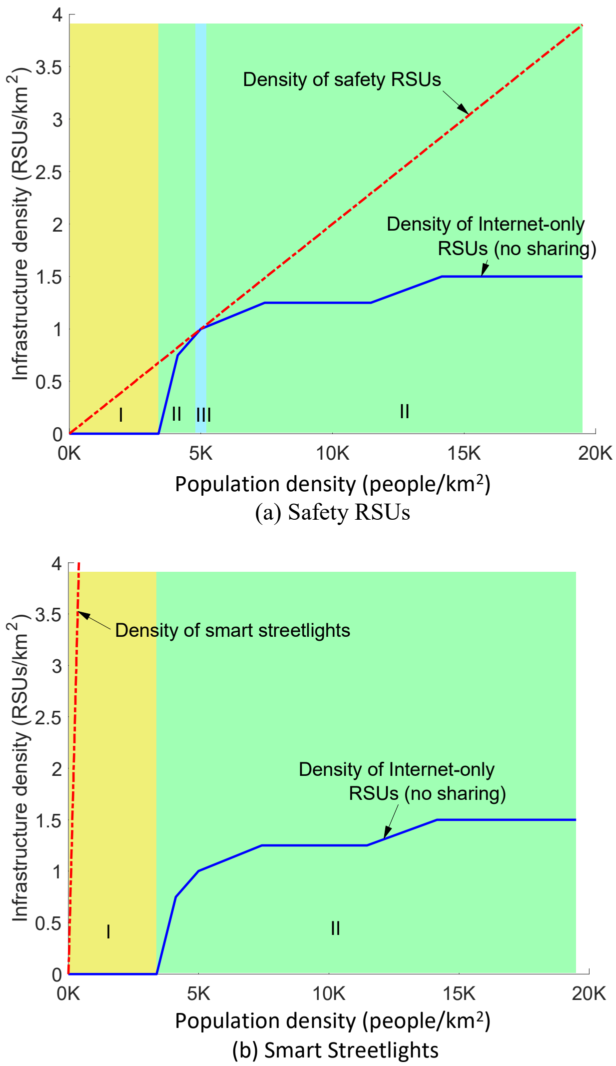
Condition II is $N_{sa} > N_{io}^{nosharing} > 0$. For a price lower than the avoided cost of macrocells, the ISP strategy is to use more RSUs than it would deploy without sharing ($N_{io}^{nosharing}$).

Condition III is $N_{io}^{nosharing} \geq N_{sa} > 0$, i.e. the density of Internet-only RSUs $N_{io}^{nosharing}$ that maximizes ISP profit under no sharing is higher than the density of shareable locations. In that case, an ISP would profit from deploying $N_{io}^{nosharing}$, 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 $p < c_{io}$. Also, the ISP may deploy Internet-only RSUs in locations not served by safety RSUs or smart streetlights.

Fig. 3 (a) shows N_{sa} for safety RSUs and $N_{io}^{nosharing}$, both as a function of population density. The graph shows that $N_{sa} > N_{io}^{nosharing}$ (i.e. condition I or II) for most population densities. Condition I applies for population densities below 4,000 people/km^2, while condition II applies for most populations above that density. However, there is a narrow range of population densities around 5,000 people/km^2 where condition III holds. On the other hand, Fig. 3 (b) shows that the density of smart streetlights will always exceed $N_{io}^{nosharing}$, thus there is no population density where condition III applies.

B. Government strategy to maximize social welfare SW

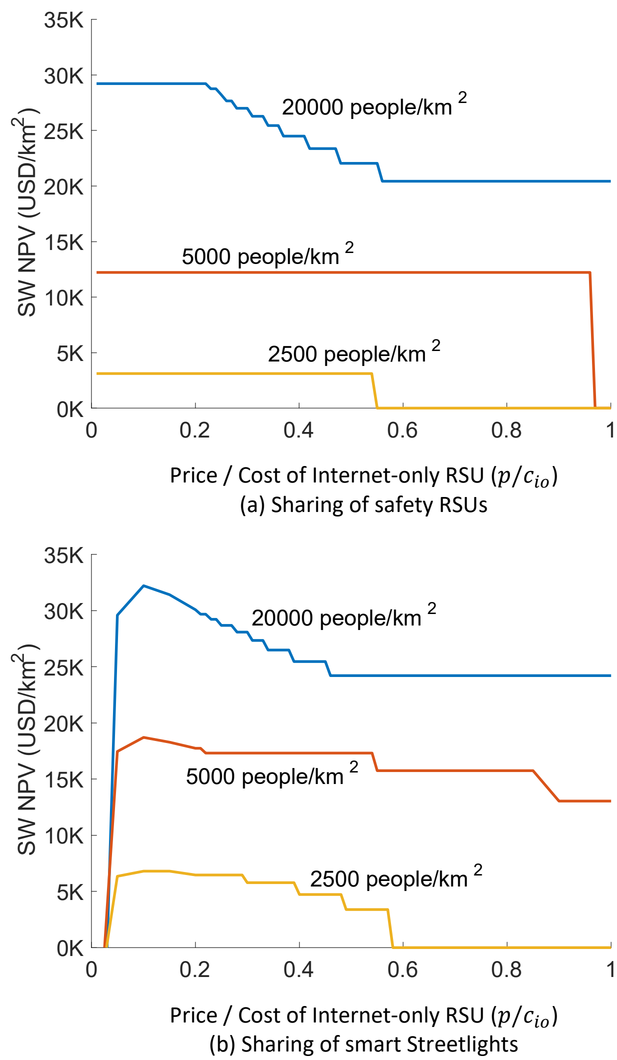
This Section discusses the pricing strategy that maximizes social welfare from sharing. In Section IV.B we show that *SW* is maximized by setting price $p = c_u$. (Since c_{io} = \$14,000 and c_u = \$1,400, the optimal p/c_{io} is 0.1.) Fig. 4 (a) shows that for sharing of safety RSUs, *SW* is maximized for $p = c_u$, but remains at its maximum for other prices as well. This is



(a) Safety RSUs

(b) Smart Streetlights

Fig. 3. RSU density as a function of population density. The solid line is the density $N_{io}^{nosharing}$. The dashed line is the density N_{sa}. The background colors represent which condition (I, II or III) applies for each population density.



(a) Sharing of safety RSUs

(b) Sharing of smart Streetlights

Fig. 4. 10-year NPV per km^2 of social welfare from sharing *SW* as a function of price for sharing, for different population densities.

because there is a range of prices where all safety RSUs are shared.

For population densities where condition I holds, there is a limit for the price p above which SW is zero. This is because no RSUs are deployed at p near c_{io}, since the avoided cost of macrocells is below RSU cost. The curve for 2,500 people/km^2 illustrates one population density under condition I. For condition II SW is maximum for $p = c_u$, but then falls with p. This is shown for 20,000 people/km^2. For safety RSUs (Fig. 4 a) SW is maximum for $p/c_{io} = 0.1$ (i.e. $p = c_u$) and for higher prices sharing and SW decrease. For condition III, if $p < c_{io}$, all safety RSUs are shared and SW is maximum. This is illustrated in Fig. 4 (a) for 5,000 people/km^2.

For streetlights, Fig. 4 (b) shows that SW is maximized for $p = c_u$ and decreases for other prices, although there is still a range where SW is close to maximum. Moreover, the maximum SW from sharing streetlights, as shown in Fig. 4 (b), is higher than the maximum SW from sharing safety RSUs in Fig. 4 (a). This is because there are less safety RSUs than the quantity the ISP would use at the optimal price. That relative gain in SW from sharing streetlights instead of safety RSUs is larger for lower population densities than for higher population densities,

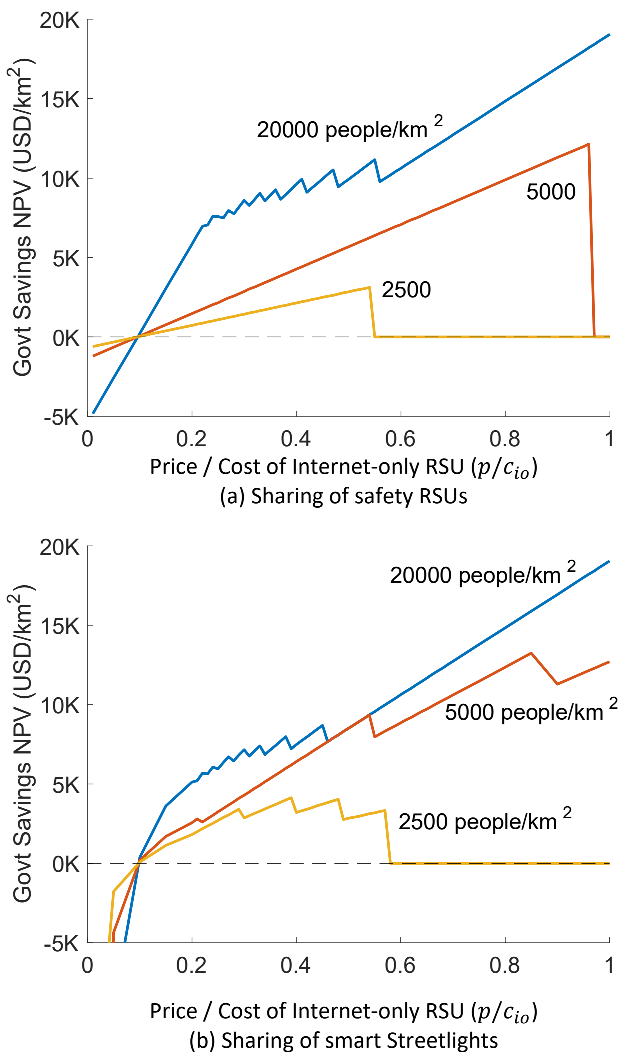


Fig. 5. 10-year NPV per km^2 of government savings from sharing GS as a function of price, for different population densities.

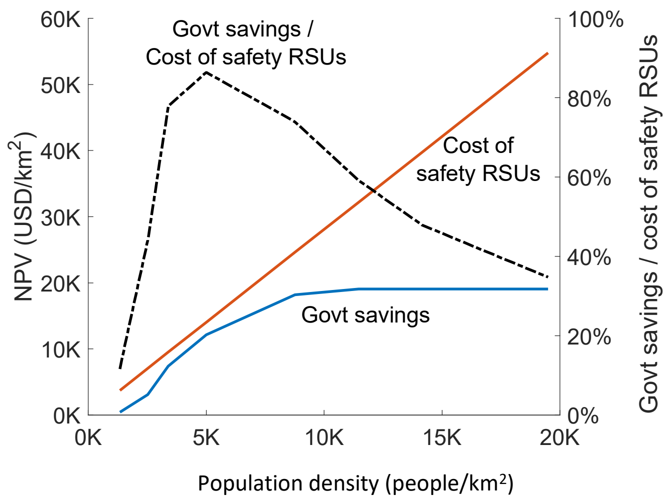


Fig. 6. 10-year NPV per km^2 (left axis) of government savings from sharing, and the cost of safety RSUs. The right axis refers the ratio between savings and cost of safety, shown in the dashed line.

because of the diminishing incremental benefit per additional RSU. For example, the maximum SW from sharing streetlights is twice that from sharing safety RSUs at 2,500 people/km^2, while that gain is only 10% higher at 20,000 people/km^2.

In summary, a government seeking to maximize SW can set $p = c_u$ under all conditions. However, the magnitude of SW shown in Fig. 4 may differ for assumptions other than those considered. For example, as discussed in IV.A we believe that OBU cost does not change much when more radios are used for Internet access, when compared to less radios. If this cost difference is otherwise high, then OBUs will likely be deployed with fewer radios, resulting in a somewhat lower SW.

C. Pricing strategy to maximize government savings GS

The sharing price p determines how much of the cost saving from sharing RSUs increases either ISP profit or GS.

In areas where condition I holds, there is a price limit above which $GS = 0$. Fig. 5 illustrates that for 2,500 people/km^2. The government would charge p/c_{io} of about 0.5 for maximum savings. For condition II, 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. For 20,000 people/km^2 GS is maximized by setting p/c_{io} close to 1 in the case of sharing safety RSUs (Fig. 5 a). This is also true for streetlights (Fig. 5 b, see 5,000 and 20,000 people/ km^2). For condition III (5,000 people/km^2 in Fig. 5 a), all safety RSUs are shared as long as $p < c_{io}$. In this case, a government would again charge p close to c_{io}. In any case (I, II or III), adopting a price strategy of charging the maximum price the ISP can bear is optimal.

The GS resulting from charging the maximum price the ISP can bear is similar between sharing of safety RSUs and sharing of smart streetlights. This is because at the maximum price the ISP can bear, the ISP is going to deploy the same quantity of shared RSUs regardless of type (safety RSUs or streetlights).

Also, in Fig. we show that for sharing of safety RSUs at locations with densities around 5,000 people/km^2 (condition III), the ratio between government savings and the total cost of safety RSUs can be over 80%, because most or all RSUs can be shared at a high price. However, for other population densities, the ratio is lower because of the price limits discussed above. For higher population densities such that the quantity of safety RSUs is higher than the optimal number of Internet-only RSUs, the safety locations with less Internet benefit are not used.

D. Government trade-offs and avoided excess burden AEB

In many regions, government savings GS and social welfare SW cannot be maximized at the same price. While $p = c_u$ is optimal for SW, the p that maximizes GS varies with population density. Thus, there is a trade-off between maximizing SW and maximizing GS for some population densities.

One way to reconcile the two objectives is to consider avoided excess burden (AEB – see Section IV.B). Thus, aside from the objectives of maximizing GS or SW, a third possible objective for the government might be to maximize $SW + AEB$, a hybrid objective that depends on both GS and SW.

Fig. shows that $SW + AEB$ does not always increase monotonically with price p. The pricing strategy that maximizes $SW + AEB$ depends on population density. However, Fig. 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 $SW + AEB$. Thus, a strategy of maximizing GS is similar to maximizing $SW + AEB$. Moreover, $SW + AEB$ from sharing of streetlights (Fig. b) is higher than $SW + AEB$ from sharing of safety RSUs (Fig. a).

E. Nationwide Government Savings and Social Welfare

In this Section, we quantify the nationwide effects of RSU sharing. 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 GS, or maximize SW plus avoided excess burden AEB.

GS, SW and AEB were calculated for each U.S. census tract (2010 data [26]), then summed nationwide. Penetration, data rates and other assumptions are fixed in the base values. For sharing of safety RSUs, Fig. (a) shows that the 10-year NPV of nationwide GS is close to \$200 million when the pricing strategy is to maximize GS. Assuming (i) there are about 310 thousand signalized intersections in the U.S. and safety RSUs would be deployed in about 20% of those intersections ([4], Table 7) in the period of analysis, and (ii) a safety RSU has the same cost c_{io} of an Internet-only RSU, then the cost of

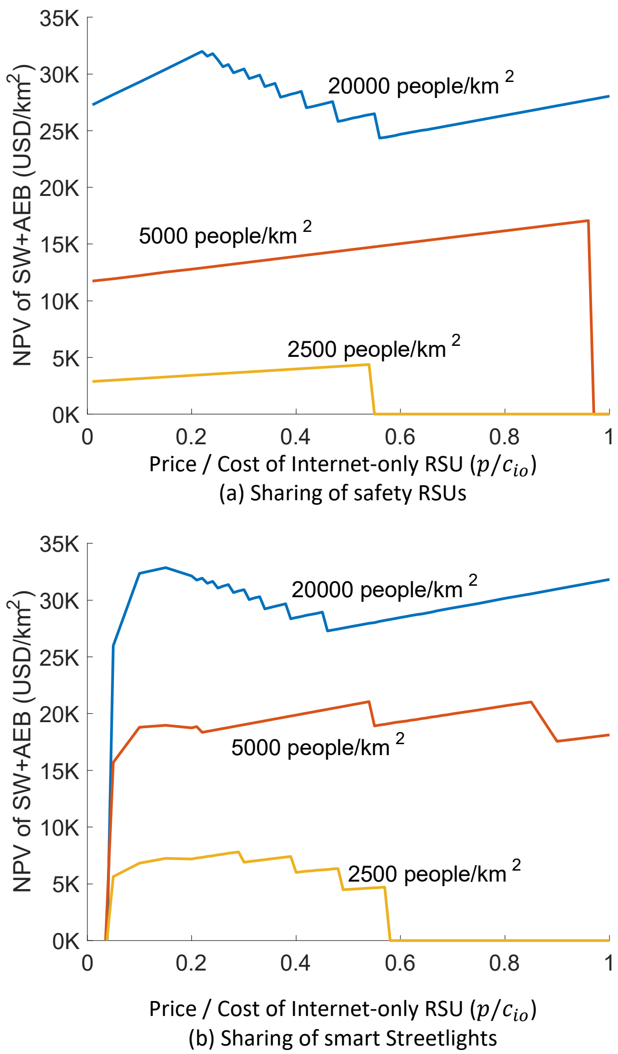


Fig. 7. 10-year NPV per km² of social welfare plus the avoided excess burden (*SW+AEB*) as a function of price, for different population densities.

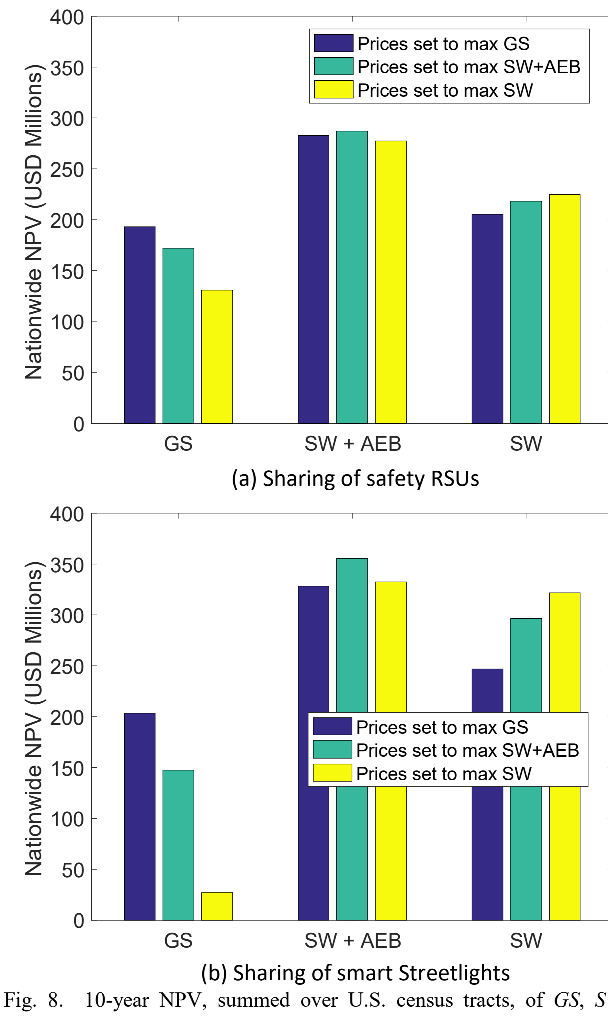


Fig. 8. 10-year NPV, summed over U.S. census tracts, of *GS*, *SW*, and *SW+AEB*. Prices are chosen at each census tract to maximize *GS* (blue bars), *SW+AEB* (green), or *SW* only (yellow).

nationwide deployment of safety RSUs would be about $310000 \times 0.2 \times \$14000 = \$850$ million. Thus, Internet access could save about \$200 million / \$850 million = 23% of the investments in safety RSUs by local governments.

On the other hand, Fig. (a) shows that nationwide $SW + AEB$ for sharing of safety RSUs is just 2% lower when maximizing GS 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 GS, the nationwide impact in $SW + AEB$ seems to be small.

Fig. (b) shows nationwide results for smart streetlights. The graph shows that the maximum NPV of nationwide SW and $SW + AEB$ are higher than the nationwide results with sharing of safety RSUs, which indicates the advantage of having more locations that can be shared in the streetlight case. For example, nationwide $SW + AEB$ with the price strategy to maximize GS is \$270 million from sharing of safety RSUs and \$360 million from sharing of streetlights, or 33% higher than the former. This is because the density of shared RSUs N_{sh} is higher for streetlights than for safety RSUs, especially when price is low such as in locations under condition I.

F. Sensitivity analysis

The results presented above depend on the numerical assumptions in Section IV.B.5. Some of those are expected to increase over time, such as Internet data rates and OBU penetration in vehicles. Other assumptions are uncertain, such as the costs c_{io}, c_u, and of macrocells. This Section investigates the robustness of the results w. r. t. the assumptions that are most likely to vary, are most uncertain or have the most impact.

Fig. shows the effects of variations (one assumption at a time) on the nationwide social welfare plus the avoided excess burden $SW + AEB$. The variations are shown for safety RSUs in Fig. (a) and for smart streetlights in Fig. (b). The graphs show that data rate per OBU has the highest effect on nationwide $SW + AEB$ from sharing of either safety RSUs or streetlights. The reasons are twofold. First, we considered a variation for data rates that is higher than the variation for the other assumptions. This is because it has been reported that the volume of mobile Internet traffic has grown 70% per year [33], and thus estimates of data rates over multiple years are uncertain. On the other hand, it is also uncertain whether the current growth in mobile Internet will hold in the future for vehicular users. Hence, we consider variations of up to twice and down to half the base data rate in Fig. . The second reason for the high impact of data rates on results is that higher rates both raise savings GS and welfare from sharing SW in a location. Moreover, data rate determines the number of RSUs to deploy (shared and not shared). There are locations where DSRC is not cost-effective at the base data rate, but eventually become cost-effective as data rates increase. A consequence is that the variation in nationwide $SW + AEB$ is more than proportional to the variation in data rate per OBU-equipped vehicle. For example, Fig. shows that if data rates are twice the base rate, nationwide $SW + AEB$ is 7 times the base value for sharing of safety RSUs and 18 times for streetlights.

That also explains why varying the penetration of OBUs in vehicles has a significant impact. For sharing of safety RSUs an increase of 25% in penetration results in an increase of 20% in nationwide $SW + AEB$. However, we considered a variation in penetration much smaller than the variation in data rates because the growth in the former is expected to be relatively low, even in the case of a mandate. (The US DOT estimates that penetration would reach 50% no earlier than 2026 [3].)

Uncertainty may also have a major impact. Regarding the cost of macrocells, the more expensive is the cost of a tower, the higher is the benefit of Internet over shared RSUs. For example, land and legal costs can be major components, which vary by location. Hence we consider a variation of plus or minus 50%. If a macrocell costs on average half of the base assumption, then Fig. shows a high reduction in $SW + AEB$ (although $SW + AEB$ is still greater than zero). That would mean less savings and a smaller increase in social welfare than predicted with base assumptions, and DSRC-based Internet

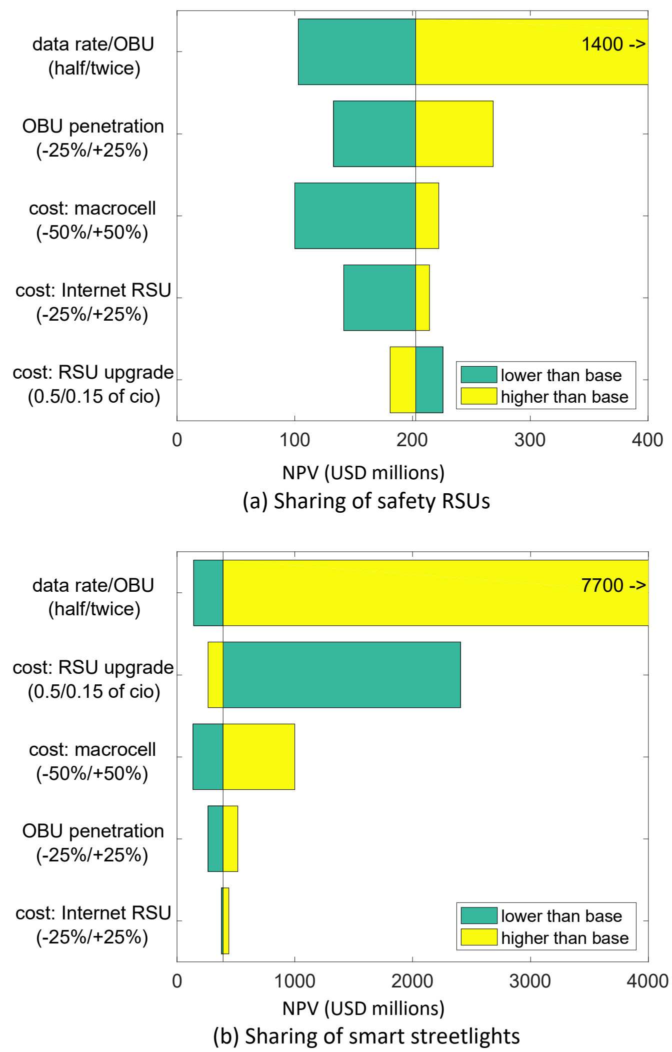


Fig. 9. 10-year NPV, summed over U.S. census tracts, of social welfare from sharing SW plus the avoided excess burden of taxation AEB. Prices are chosen at each census tract to maximize *SW+AEB*. The vertical line in each graph is the nationwide result with the assumptions in base values. Each horizontal column refers to a variation in one of the numerical assumptions (data rate per OBU, OBU penetration, c_{io} or c_u), and the values in parentheses indicate the range of variation in the assumption.

might be cost-effective in fewer locations than predicted.

The uncertainty in the other factors seems to have limited effect on nationwide results. Regarding c_u, even if it is 50% higher than the base value, the variation in nationwide $SW + AEB$ is less than 20% either for sharing of safety RSUs or streetlights. This is partly because we believe c_u is relatively small compared to c_{io}, and hence the nationwide results should be robust to the uncertainty in c_u. The uncertainty on the cost of an Internet-only RSU c_{io} should be high, because deployment can be cheap in locations with mounting structure, energy and backhaul available, while c_{io} can be much higher than the base value in locations with no such infrastructure. Fig. (a) shows that 25% cheaper Internet-only RSUs cause a roughly proportional decrease in $SW + AEB$, because the optimal price to share is near c_{io} for a wide range of population densities. However, Fig. (b) shows that variations of 25% in c_{io} have negligible effect on nationwide results for streetlights.

For data rates or OBU penetration higher than the base values, and at low sharing prices, one may conclude (wrongly) that benefit exceeds the cost for the ISP and trigger deployment of shared RSUs even for population densities close to zero. Actually, cellular networks in sparsely populated areas are likely to be coverage-limited instead of capacity-limited, implying no benefit of offload. For this paper, we assumed that benefit is zero for population densities below 10 people/km^2. This is reasonable because for a random sample of U.S. counties, those with population densities below 10 people/km^2 have shown average cell radius of tens of km, while most counties with more than 10 people/km^2 have lower and decreasing cell range as population density increases (which is an indication that those cells are capacity-limited).

VI. Conclusion

In this paper, we show that sharing DSRC RSUs deployed for safety or smart streetlights with ISPs would result in savings for the government who owns them, and these savings could be used to offset investment. 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.

Government savings from sharing safety RSUs or smart streetlights 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 ISPs do not deploy RSUs, so there is no revenue for the government. For a nationwide deployment, we estimate the savings as 23% of the total investment in safety RSUs. In addition, we found that maximum government savings are similar between safety RSUs and streetlights. The reason is that at the prices that maximize savings, ISPs will be indifferent between their own RSUs or shared ones, regardless the latter are safety RSUs or streetlights.

If a government chooses to maximize social welfare, the optimal price equals the cost to share RSUs. At this price, social welfare from sharing is different between sharing of safety RSUs and smart streetlights. Welfare is maximized at prices where the ISP will deploy many more shared RSUs than the ISP would deploy on its own. Because there are more streetlights than safety RSUs, SW is higher for streetlights than safety.

The pricing strategy that maximizes government savings often differs from the strategy that maximizes social welfare. 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.

Moreover, we found that nationwide $SW + AEB$ is one third higher for sharing of smart streetlights than for sharing of safety RSUs, when the price strategy is to maximize savings.

If a government chooses to maximize savings, it probably has inaccurate information about the maximum price the ISP can bear. For each location, there is a price limit above which the ISP will not deploy any shared RSU, and this limit depends on the population density of the location and costs experienced by the ISP. These costs are unknown to governments. If more than the maximum price is charged, then the ISP will choose not to share. That is why governments may choose to maximize savings and charge less than the maximum price the ISP can bear. If that happens, governments would still experience $SW + AEB$ within 20% of its maximum.

Some of the numerical assumptions adopted in this work are likely to increase over time, while others are uncertain. A sensitivity analysis revealed that cheaper macrocells may result in lower nationwide $SW + AEB$. On the other hand, if data rates or OBU penetration grow over time as expected, nationwide $SW + AEB$ increase more than proportionally to that growth. Moreover, we found that uncertainty in factors such as the cost of an Internet-only RSU and the cost to upgrade safety RSUs or streetlights have limited effect on nationwide results.

In the future, we plan to extend our work by examining other policy issues related to DSRC-based Internet of vehicles. One is to evaluate government savings and social welfare of an expanded set of possible shared locations, e.g. intersections without access to backhaul. (In this case, some RSUs might be gateways to the Internet, while others act merely as relays in the vehicular mesh.) Moreover, we will investigate spectrum policies such as how much spectrum should be allocated for DSRC, whether the part of that spectrum not used for safety should be shared with unlicensed devices, and if so how much.

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