TECHNOLOGIES FOR CONGESTION PRICING

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ABSTRACT

Congestion pricing of high-demand roadways seeks to influence travelers' route choices, trip timing, modes, and destination choices, to keep vehicles moving and avoid excessive congestion. This paper describes the use of various technologies to enable more advanced and cost-effective congestion pricing applications, and a credit-based policy to ensure equitable network access for all travelers.

Video-based systems require cameras to capture the state of traffic, plus some form of communication back to users. Both DSRC and cellular-based systems use GPS data to price roads and toll users based on traffic conditions. DSRC employs roadside units (RSUs) to receive and send messages to in-vehicle DSRC units. A cellular-based system could use communications from cellular towers in combination with a smartphone, on-board diagnostics port (OBD-II), or pre-installed cellular chip. DSRC is a valuable technology to pilot congestion pricing at highly congested locations, such as bridges and major highways, while cellular communications enable congestion pricing across entire networks.

VMT taxes can be relatively simple, or variable in space and time, facilitating transportation-agency cost recovery. A next step for roadway management is congestion pricing (CP), to better reflect the marginal delay costs of one's travel choices. When coupled with travel credits, CP can better ensure welfare gains for most travelers.

INTRODUCTION

Traffic congestion is a major problem in all major urban areas, costing citizens valuable time. Congestion is caused by an excess of vehicles on part of a roadway at a given time, leading to vehicle speeds that are slower than the normal "free flow" speeds of that roadway (FHWA

2017). Congestion costs the U.S. economy over $100 billion a year, and this number is rising over time (Cebr 2014, Shrank et al. 2015, Burfeind 2017). This includes the direct costs of the value of fuel and time wasted as well as the indirect costs from the increased cost of doing business. As economies and populations continue to grow, congestion is expected to increase. In order to combat increasing gridlock, it is important to develop policies and implement technologies that reduce congestion.

Roadways are limited by their capacity, which is the maximum flow of traffic that can be handled by a given roadway section. Capacity flow values are affected by the number and width of lanes, median and merge area designs, intersection or interchange frequency, presence of stop signs or signal lights, curvature, grade, and other design variables (FHWA 2017). When demand for travel rises, congestion sets in, slowing travel speeds and lengthening travel times. Congestion can be recurring or non-recurring. Recurring congestion is the result of normal traffic volumes in a typical environment (Hallenbeck et al. 2003), such as peak times of day every weekday upstream of key bottlenecks (like bridge crossings) in urban environments. Non-recurring congestion is caused by unusual events or conditions that result in capacity losses or added demand. Vehicle collisions, construction zones, inclement weather, and special events (like professional football game days) can all result in non-recurring congestion by temporarily reducing capacity or exceeding existing corridor capacities. While transportation network capacities are inflexible due to the limitations of the existing infrastructure, travel demands fluctuate minute to minute and day to day. Since the size of roads and freeways cannot be varied to match demand, demand must be influenced to reduce congestion. Travel demand can be influenced randomly by special events, weather, and other factors, but it can be actively managed by implementing public policies.

Without regulation and pricing, the demand-supply equilibrium for roadway space settles at a suboptimal point, because users only consider the direct costs of congestion on their personal travel time (Komanoff 2017). Users ignore the additional marginal cost of their travel on the transportation network, which adds to the travel time of all road users (Kockelman and Kalmanje 2005).

Congestion pricing is one potential solution to this issue. Such pricing or road tolling involves incentivizing certain link and thus route choices for drivers, to improve the overall efficiency of a congested corridor's or congested network's roadways. By charging a higher price to travel on highly-congested roadway sections or offering tax credits for traveling through less-congested areas, system managers can encourage choices that decrease system-wide costs and improve social welfare or net community benefits. By confronting users with the true cost of their travel (reflecting the delays they impose on other travelers, behind them, essentially), congestion pricing pushes the supply-demand equilibrium point to the left, decreasing traffic volume. Lower volume means less congestion and lower travel times on that link. Without congestion pricing, drivers face only the directly experienced or average cost of travel, resulting in over-consumption of what truly is a socially more expensive good than they realize. With appropriate pricing in place, travel choices become less sub-optimal, and ideally reflect the full cost of added vehicles on each roadway segment, at each time of day.

Recent and emerging developments in communication and computation technology make widespread implementation of congestion pricing systems feasible and potentially highly cost-effective. This paper examines the technologies and policies that could be implemented in a congestion pricing system. With information gathered from various expert sources, this work provides recommendations for the best mix of technology and policy in several transport settings, as well as a roll-out strategy for congestion pricing.

POLICY IMPLEMENTATION

In order to deliver a successful and maximally cost-effective roadway pricing system, an appropriate policy structure is needed. A few major pricing policies are a vehicle-miles-traveled (VMT) tax, zone-based charges, and congestion pricing (CP). A VMT tax is simplest, and can fittingly recover general infrastructure investment and maintenance costs, for example; but it does not address congestion directly. Zone- or area-based tolling reduces travel within high-traffic areas by charging for ingress or egress during specific times of day, but they are broad-based and do not reflect over-use or under-use of specific links or VMT imbalances across users or by time of day. Rationing by license plate and day of week or time of day has also been studied and used (see, e.g., Nakamura and Kockelman [2002]), but can lead to perverse outcomes (Nie 2016). CP can directly and rather efficiently (in an economic sense) address congestion costs by location and time of day. Variations in tolling can influence trip generation by time of day, mode choices, destination and route choices. And *credit-based* CP (CBCP) – wherein CP revenues are returned uniformly to travelers to use for a base level of “free” travel each month - directly addresses congestion costs in time and space while also addressing equity implications, thereby delivering greater societal benefits.

All types of road tolls offer the opportunity to reduce congestion while collecting revenues. With the rise of autonomous vehicles (AVs), some sources of public funding may fall. For example, the 25 largest U.S. cities reported $5 billion in auto-related revenues in 2016 (Maciag 2017). If users opt for *shared* autonomous vehicles (SAVs), parking demand may fall, as vehicles pick up new passengers. Parking fees and parking tickets make up a sizable share of *local* government revenue used for infrastructure improvements in many cities (Clements and Kockelman 2017). AVs will not violate traffic laws as often, decreasing revenues from traffic citations, which average $8.5 million per year in the largest U.S. cities (Maciag 2017). Additionally, use of hybrid and plug-in electric vehicles (which most AVs may be, due to high power demands on board) will lower revenues (per VMT) from federal and state motor fuel taxes, which accounted for $16 billion spent on local U.S. infrastructure or transit in 2015 (Maciag 2017). The implementation of a VMT taxes and/or CP tolls can help local, state, and federal governments maintain and supplement infrastructure budgets. Additionally, decreased congestion reduces infrastructure maintenance expenses and need for new construction while benefitting citizens through time savings.

Vehicle-Miles-Traveled (VMT) Tax

The concept of a VMT tax involves charging users for the number of miles traveled on roads within a state or other jurisdiction. VMT taxes have arisen as an alternative to the gas tax, which is the main source of U.S. state and other nation’s transportation budgets. The increased fuel efficiency of electric and hybrid vehicles allows some users to use roadways with little to no contribution highway maintenance funds, for which costs are increasing (Caltrans 2016). Hopefully, automakers and consumers will continue to improve fleet fuel economy, so these budgeting challenges will rise over time. A VMT fee is one way to collect appropriate taxes from all vehicles to gain sufficient funding for roadways and, potentially, to discourage excessive vehicle travel.

One way to charge users for the number of miles traveled is through odometer readings at yearly vehicle inspections. However, this policy assumes all miles traveled are within the state, and some users would be getting double charged if they traveled and purchased gas out of state. A VMT tax can be applied only within the state operating the program by sending Global Positioning System (GPS) data to calculate the number of miles traveled within the state by each vehicle. This can be accomplished by using either dedicated short-range communications (DSRC) or cellular communication to send the GPS data to a central database, where a public or private entity would calculate the amount of money owed by each driver.

California, Washington, and Oregon have started pilot programs to test the feasibility and efficacy of a VMT tax program. These programs track all miles driven on public roads and charge users accordingly. The California Road Charge Pilot program plans to analyze a variety of means for collecting road usage data, with and without the need for electronic vehicle location data (Caltrans 2016). Users can choose from four types of monitoring systems: time permit, mileage permit, odometer charge, and automated mileage reporting. In a time or mileage permit system, the user pre-pays for the right to drive for a certain period of time or number of miles, while the odometer charge allows the participant to pay a per-mile fee based on odometer readings (Caltrans 2016). The automated mileage reporting option requires in-vehicle equipment, which reports location data collected from vehicle telematics, smartphone apps, or OBD-II port devices (Caltrans 2016). An advantage of this more advanced option is that participants will not be charged for out-of-state or private road travel (Caltrans 2016). Enforcement of this advanced method can be somewhat challenging, since it requires vehicles to have operational hardware that has not been modified (to reduce toll totals). Participants will need to be randomly audited to help ensure they are not misrepresenting their travel data to save money. The Oregon Department of Transportation (ODOT) has implemented a similar pilot, which involves actual payment rather than simulated payment, with a program called OreGO. The permanent program currently accepts 5,000 volunteers, who are also given an option between a GPS tracking and a series of non-tracking options such as odometer readings.

While VMT tax policies are currently in their infancy, they may become increasingly necessary with the rise of more fuel-efficient vehicles. Additionally, they enable more equitable charges for road usage for all types of vehicles. The development of pilot and permanent VMT fee programs that use GPS tracking could lay the foundation for the development of more advanced transportation management policies that would require this location and communication technology.

Zone-based Tolling

Zone-based tolling involves charging users for entry into, exit from, or travel within an enclosed area, commonly downtown business centers, to ease traffic at peak hours. There are three main types of zone-based tolling: cordon, area, and zonal (Chu 2008). Cordon charges are fees levied for crossing a boundary entering or exiting an urban center. Area tolls charge for all trips within the designated boundary, whether they originate outside the boundary and cross into or originate inside the charge zone and never cross the boundary. Zonal charges involve mini-cordons in and around an urban center, where fees are charged for entry into each mini-cordon, at flat or variable rates.

Zone-based congestion pricing has been used in cities around the world as a means to reduce congestion and emissions in urban centers. Singapore, London, Stockholm, Gothenburg, and

Milan have all implemented some form of zone-based congestion pricing (Brown 2011). Singapore first introduced a manually-enforced cordon charge known as the Area Licensing Scheme in 1975, which charged drivers a flat fee to enter into the central business district during peak hours (ITDP 2015). Users showed their purchased license to traffic wardens at one of 22 control points to ensure compliance. In 1998, Singapore replaced the manual Area Licensing Scheme with Electronic Road Pricing (ITDP 2015). This system requires installation of an in-vehicle unit with a smart card and a DSRC system. The Singapore cordon-based congestion pricing system has resulted in lower traffic volumes, higher average vehicle speeds, and lower carbon dioxide emissions (ITDP 2015). London employs an area charge in the central downtown area between 7:00 AM and 6:30 PM on weekdays. Payments can be made at retail outlets or through electronic means on the same day, or users can purchase weekly, monthly, and annual passes (Litman 2011). Video cameras installed throughout the city record license plates, and the user pays a fine if they do not pay for downtown road usage. Drivers pay for travel within the downtown center whether or not they cross the boundary. Automobile usage decreased, public transport usage increased, and average vehicle speeds increased in urban centers (Litman 2011). However, average traffic speeds decreased and reached pre-charge levels by 2007, as London issued congestion charge exemptions and overall roadway capacity fell due to increased construction (Lehe 2019). Stockholm and Milan have reported positive results, as average vehicle speeds have increased since implementing zone-based charges (Croci 2016).

These successful programs around the world suggest that cordon-based congestion pricing is a viable and valuable program to implement in cities with large traffic volumes in dense urban centers. As seen in these examples, cordon-based congestion pricing can be implemented with different technologies that have been around for years. An advantage of this type of system is that installations are only needed at entry points to the congested area. While overall traffic volume may decrease, the users who choose to enter the restricted area may still choose routes that are suboptimal to the congestion of the roadway system. However, cordon-based pricing is an effective means for reducing traffic volumes within highly congested areas during peak periods.

Congestion Pricing (CP) & Credit-Based Congestion Pricing (CBCP)

Congestion pricing (CP) involves charging road users a fee that reflects the marginal cost of congestion they cause others, like those behind them in the traffic stream (Nie and Liu 2010). Current drivers make route decisions based on the shortest path or time to their destination, without considering the overall network costs of their choices. CP adds this cost into the decision-making process, making users aware of their impact on travel times for others, thereby reducing traffic along the most congested stretches of road (Kockelman and Kalmanje 2005). CP requires more implementation details than a flat VMT tax, since technology must calculate marginal tolls and communicate evolving prices to travelers. However, CP much more effectively alleviates congestion, because it incentivizes more optimal route, mode, time of day, and destination choices rather than simply incentivizing lower VMT. Such a system does require effective two-way communications, a fair pricing policy that attracts users, and an auditing procss to ensure compliance.

Credit-based congestion pricing (CBCP) is a special case of CP policy, wherein all travelers (e.g., adult vehicle owners in a region) receive a travel credit or budget to use every month or so. Any form of CP requires observation of vehicle speeds or counts and travel times in order to evaluate the average or evolving state of congestion and marginal delay costs of added travelers along any congested stretch of roadway. This information is used to price routes, with tolls rising as travel times and thus marginal delay costs (changes in travel time multiplied by the number of vehicles present) rise with added demand. In order to alter user behavior and ensure fairness and transparency of the congestion pricing system, the toll operator should communicate the pricing of alternative routes to the users via DSRC or cellular systems. This information can be displayed on a smartphone or other device early enough to allow travelers (or, in the longer term, self-driving vehicles) to alter their routes based on this information and their personal value of time (ideally for the specific trip they are undertaking). Tolling totals are kept on each vehicle's private device and reported to active roadside or other local readers (e.g., when paying for fuel) to protect traveler privacy in terms of travel locations. Reliable communication and accurate location data are important for ensuring tolling consistency and fairness.

Based on the value of each individual's value of time and the time constraints of their travel, users can choose to take an alternative route in exchange for a lower cost or continue on the same path for a larger fee. While many people may choose to continue along their route and pay the fee, others will be influenced by this charge and opt to take a different route or travel at off-peak times, which will alleviate congestion along the most congested roadways.

A key challenge in establishing a CP programs is the lack of strong public support. Many citizens are averse to being tolled in any way (Podgorski and Kockelman 2006), but no one has yet experienced credit-based tolling (in part because road managers wish to hang onto all revenues, especially when gas taxes and other fees do not cover expenditures transportation agencies wish to undertake - but also because it can be difficult to draw a line on credit eligibility). Moreover, it takes some time to install CP technology on most or all vehicles. One way to manage transition towards device installation is to charge a relatively high, flat VMT fee for those not using the more advanced technology. This will help incentivize a faster shift to the new system (like an on-board dongle, as discussed below). Local governments also could provide users with more travel credits and/or a tax deduction to offset installation costs (e.g., 1 hour of time investment plus $50 for the dongle). Regardless of approach, the pricing system should be designed thoughtfully in order to ensure the cost is enough to alter travel behavior without deterring too many users. Gullipalli et al. (2008) detail more specific policy recommendations for effective CBCP management. Having a citizen-led committee to craft CP and CBCP policies also helps ensure greater support, transparency, efficiency, equity, and effectiveness.

Currently, a number of variably-tolled lanes exist across the U.S. and elsewhere in the world, while adjacent lanes are kept "untolled", as "general purpose" lanes (TTI 2017, ULI 2013). Keeping adjacent lanes untolled helps avoid public pushback, since travel credits are not provided (as they would be in CBCP policies). These variably-tolled lanes are often "HOT" lanes, where high-occupancy vehicles (with 2+ or 3+ persons, depending on the location and time of day) do not have to pay the toll. But enforcement of HOV status is very costly, and effectively impossible (due to window tints and belted dummies or dolls stymying police views and pets showing up on heat sensors). Moreover, HOV and HOT policies rarely achieve much of a vehicle-occupancy shift, and are instead used by HOVs that would have existed regardless of the policy's implementation (e.g., family members or friends wanting to travel together). HOV lanes require special entrances and exits, and separated HOT lanes required additional right of way and construction costs, which are very difficult to afford and add in our network's most congestion locations (Dahlgren 2002). Credit-based CP policies across all congested lanes/locations is likely to be much more cost effective, physically practical, and behaviorally effective than HOT lanes. But variably-tolled lanes using radio-frequency identification (RFID) transponder-type technologies already exist in 15 or more U.S. locations, with tolls to keep traffic moving, at either pre-determined (scheduled) intervals or dynamically, alongside the rise and fall of observed demand in those special lanes.

TECHNOLOGY SOLUTIONS

For this paper, research was conducted on the potential technology solutions for a congestion pricing system through a review of previously-published interviews and a series of expert interviews. Based on the information collected during this research, three leading concepts have been identified for use in a congestion pricing solution: video, DSRC, and cellular. Each of these solutions requires a different mix of technologies, and each has its own advantages and disadvantages. The specifications, cost, and value of each of these systems are discussed below.

Video-Based System

Video is one technology that could be employed to measure congestion and price links or routes accordingly. Video cameras are already installed in many locations along highways and at intersections, so these feeds could be harnessed to create a real-time model of traffic congestion. The system would consist of a series of video cameras on poles along major roadways, a data connection to send the information to a central system, and algorithms to analyze the video feed. This system would then need a means to communicate with and charge toll users based on the pricing of each route or link. This could come through the DSRC or cellular networks previously discussed or through license plate recognition and electronic signs indicating the toll for upcoming routes or boundaries.

The major infrastructure installations would be the camera, cable, and pole along the roadside. Installations including all three of these major components could cost $20,000-50,000, depending on the quality of the camera and pole height (Lange 2017). The camera can differ based on which features are included, such as the ability to zoom and pan. The pole could be anywhere from 20 to 50 feet, and taller poles would allow for greater range but also would increase cost (Lange 2017). Based on the average range of cameras, one could be placed approximately every half-mile, depending on the road curvature, buildings, and other obstructions (Lange 2017). A large portion of the cost is the pole itself, and the individual video cameras themselves can be purchased for $800-1,200 (Lange 2017). In order to toll individual users, the video feed would need to be of high enough quality to capture license plate numbers of passing vehicles. This may require multiple cameras at one location, or a very high-quality, high-speed camera. The processing of these characters from varying angles and speeds would also need to be incorporated into the software evaluating the video feed.

One major challenge with a video-based solution is that the pricing information cannot be communicated to travelers through the same system with which traffic data is collected. Communication of pricing to travelers is essential, as the goal of a congestion pricing system is to alter travel behavior to alleviate congestion. The DSRC or cellular solutions described in the following sections can be combined with the video feed for a comprehensive solution, but this requires multiple, expensive and somewhat redundant infrastructure investments. Alternatively, tolls could be implemented only at a limited number of locations and the pricing could be communicated via electronic signs on the side of the road or above highways. While this additional infrastructure investment limits the number of locations that tolls can be placed, it increases the number of users that can participate in the program because it requires no in-vehicle installation.

One advantage of a video-based solution is that the video infrastructure is already installed in many places in major cities. Another advantage of a video-based solution is the relative ease of obtaining higher levels of market penetration without every user needing a communication device in his/her vehicle. Despite these advantages, additional infrastructure to communicate the real-time pricing to users will be required. Such infrastructure can be prohibitively expensive if added everywhere, so it normally would be implemented in a limited number of locations. The challenge and cost of installing two separate systems for information collection and transmission ultimately render a video-based solution less viable.

DSRC-Based System

Another possible solution is a congestion pricing system that uses Dedicated Short-Range Communication (DSRC). DSRC is a spectrum of 75 MHz in the 5.9 GHz band that has been reserved for use in vehicle safety and mobility applications (ITS 2017). DSRC is currently being used in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications to alert drivers of potential hazards, such as stopped traffic or collisions. The low latency communication of two-way messages makes DSRC useful in time-sensitive situations (ITS 2017). Fast communication is essential for safety applications such as crash avoidance, and it would also be useful for adaptive pricing schemes in which the cost of traveling certain routes changes often. Since the DSRC band is reserved for mobility applications, congestion pricing may be a useful allocation of this bandwidth.

A DSRC system will require roadside units (RSUs) installed along roadways, along with on-board units (OBUs) installed in vehicles. As vehicles pass the RSUs, a message is sent from the vehicle’s OBU to the RSU indicating the vehicle’s position and speed, and data from all vehicles’ messages is compiled to model the amount of congestion in a certain area. With this information, incentives for certain routes can be generated, and this information can be sent back to the vehicles’ OBUs via RSU messaging. Vehicle operators decide which route(s) to take based on travel times and dynamic tolls. Using cloud-based tolling information, travelers can also delay their trips or choose different destinations and modes.

Currently, most vehicles on the road are not equipped with DSRC communication. However, DSRC is beginning to be incorporated into some new vehicles, and it may one day be required in future vehicles, along with GPS. Some experts expect that both may be required by the National Highway Traffic Safety Administration (NHTSA) within the next 5-7 years (Sturgeon 2017).

Conventional vehicles could take advantage of a congestion pricing system by adding DSRC connectivity through installation of an OBU. An on-board DSRC unit can be small, lightweight, and it can be mounted on the windshield of a vehicle with Velcro or other simple fasteners (Kapsch n.d.) Such a specialized OBU can cost over $1,000 to manufacture currently, but this price falls dramatically as production volumes rise, for regional applications. OBUs can communicate position and speed, and relatively accurate traffic flow speed can be gathered from a limited number of vehicles. As the number of vehicles equipped with DSRC increases, the accuracy of this data and the benefits of a CP system increase.

The other major component of a DSRC-based congestion pricing system is the installation of RSUs. RSUs have a line-of-sight range of about one kilometer. Due to the short range of DSRC RSUs, a high density of these devices would be required. Since communication is limited by line of sight, dense urban environments would require RSUs to be more compact or placed higher, with longer poles and leads. Billboards, buildings, and other objects could block the signal even within a short distance. Currently, RSUs are in the prototype stage and cost around $3,000. With improvements in technology and mass production, that price could go down to $500-800. In addition to the cost of producing the RSU, the installation and maintenance costs would add up quickly. The installation cost could vary from $1,000 to tens of thousands of dollars based on a variety of factors. Higher leads and poles for RSUs cost more money. Connection to a communication network will also increase costs, especially if a data-link backbone does not yet exist. RSUs also need routine maintenance for updates or replacement if weather or other external factors cause damage.

While a DSRC-based congestion pricing system would allow for fast communication between vehicles and infrastructure, it does require a large capital investment. DSRC communication is well-suited for transmitting small packets of data accurately in short periods of time. Pairing this communication with a smartphone or device for route decisions would enable an effective congestion pricing system. However, a DSRC-based system is limited by the cost of installing DSRC units both in vehicles and in dense urban environments. Furthermore, the installation and penetration of DSRC devices in infrastructure and vehicles will take a long time. For this reason, some experts believe that connected vehicles may leapfrog DSRC and go straight to using 5G cellular communication. Benefits can be realized with the installation of a limited number of RSUs at highly congested areas, but the long time frame is an important consideration.

The large monetary and time investments make a DSRC-based congestion pricing system challenging to implement throughout an entire transportation network. However, DSRC solutions are viable for installation at major bottlenecks. A pilot program could be implemented on bridges or stretches of highways that are often highly congested at certain hours. Vehicles could be informed of an upcoming toll and given an alternate route option when passing the DSRC unit. This initial installation would allow testing of an adaptive tolling scheme and route choice data could be collected in response to congestion pricing.

Cellular-Based System

Of course, CP systems can also rely on cellular data. Information can be communicated via smartphone or a device installed in the vehicle's on-board diagnostic (OBD) port. Each of these solutions exploits the already-widespread cellular network, but uses different devices, with distinct advantages and disadvantages.

A smartphone solution will require an app that allows users to opt-in to the service. Acceptance of the agreement allows tracking of the user's location for tolling and for providing information about traffic conditions and evolving toll rates. This type of system enables rather fast market penetration, because most drivers already own smartphones. Users can download the application that connects them to the congestion pricing system, rather than needing to install additional hardware. But they must keep their cell phones on and charged, and be sure to engage the app for each trip. Enforcement can be challenging when relying on ad hoc cell phone use. In addition, smartphone GPS using LTE/4G cellular has not been accurate enough to identify positioning on ramps or roads, especially in dense urban environments (Claudel 2017). But 5G cellular is being rolled out across cities and carriers, and will be able to enable such accuracy, including for reliable lane-by-lane variable-pricing applications.

To further improve vehicle-location accuracy, manufacturers and those retrofitting existing vehicles can combine smartphone applications with installation of an inertial measurement unit (IMU) in the vehicle (Claudel 2017). The IMU's accelerometer measures the linear acceleration along three axes (Graves 1997). Its gyroscope, also known as an angular rate sensor, outputs three signals describing the angular rate about each of the axes (Graves 1997). IMU data allows the device to calculate its position based on the acceleration measurements, and it can bridge the gap between position estimates when the signal is blocked (Godha and Cannon 2005).

Another cellular solution involves installing an OBD-II dongle in the OBD port. A dongle is a small electronic device that traditionally collects emissions and malfunction data (Moran and Baker 2016). Such a device can receive GPS location data and communicate using cellular data (Moran and Baker 2016). It can be outfitted with a more accurate GPS system to improve the resolution of the congestion pricing system. A GPS unit with lane-by-lane accuracy may cost around $200, while one with road-level accuracy may be less than $50 (Dorfman 2017). The OBD-II dongle will also need a cellular communication modem. While a mobile chip costs around $200 at low production volume, this price falls quite a bit at higher volumes (Sturgeon 2017). The major issue with this data cost is determining who will pay the fee. Users may be willing to pay for the monetary or time benefits they gain from opting in to the program. Original equipment manufacturers (OEMs) may accept the cost in order to collect more data on the users. Departments of transportation (DOTs) can enter into agreements with cell carriers to provide this service to improve the efficiency of or gather funding from their transportation network. The cost of a small data plan purchased at high volume by an OEM or DOT is estimated to be $3 to $4 per month (Dorfman 2017). This may increase at higher volumes of data communicated, but advances in technology could also decrease the cost of data. Alternatively, a third-party vendor may see an opportunity in providing the service and take on the cost of data communication.

The OBD-II dongle solution improves the problem of low-accuracy GPS included in current smartphones. This solution would allow for increased standardization and ensure greater fairness of a congestion pricing system. The use of OBD-II dongles does present some challenges, however. Users would need to purchase and install the hardware to enable this system, and they could unplug the device to avoid tolling. Additionally, the entity that would be willing to pay for the cellular connection is not clear, and sufficient incentives to encourage that additional cost would need to exist. Another issue is that the inclusion of OBD ports by OEMs is mandated by emissions standards, so many electric vehicles do not come equipped with the appropriate hardware (Dorfman 2017). So, if congestion pricing were implemented through OBD installations, electric vehicles would either need to start including a similar port or their users can not participate in the congestion pricing program. Additionally, much older vehicles – ones that pre-date the OBD requirements -- would need special retrofits and added technology (like a simple mobile phone) to participate.

ADDITIONAL TECHNOLOGY CONSIDERATIONS

5G Network

While some level of congestion pricing can be implemented with current 4G or Long-Term Evolution cellular communication, the emergence of 5G networks will increase CP effectiveness.

Applying congestion pricing throughout an urban transportation network places a large data load on current networks and may challenge the available bandwidth (Claudel 2017).

A 5G network already exists in many cities and nations, across various carriers, like AT&T in the U.S. It should become available to nearly all of the U.S. and many other nations within 5 to 10 years, and there are a few major differences between 5G and current cellular communications. New, unlicensed frequencies on the electromagnetic spectrum, such as millimeter wave spectrum (> 25GHz), were recently released in the U.S. by the FCC for use in 5G networks (Brodkin 2019). 5G allows for information to pass between individuals and between vehicles without having to connect through a cell tower. Information about upcoming traffic, hazards, or road pricing on routes ahead can be passed backwards along sequences of vehicles on a roadway. Additionally, 5G allows for high throughput (> 10 Gigabit per second per user) and low latency (< 1 ms Real Time Text) communication (Fettweis 2014). Faster, larger data transfers can allow important, time sensitive travel information to be communicated more quickly and reliably. Vehicles can receive congestion, safety, and road pricing information in a timely manner, and the network will be able to handle the communication required for connected vehicles and congestion pricing more easily.

There are certain challenges with the development and adoption of 5G networks for vehicles. First, a business model must be developed for Low-density locations. The public value of safety-critical applications in CVs may be sufficiently valuable for government entities to help deliver 5G in rural settings. The private telecommunications sector will need to provide the service, however, and their investment will need to be profitable. Telecommunications companies may charge individual users, automobile OEMs, and others based on the value to each groups. GM has installed DSRC in some vehicle models, while Daimler (Mercedes-Benz) has focused more on preparing its vehicles for 5G (Sturgeon 2017). The debate between 5G and DSRC will continue, and it is important to stay informed about the developing value of each when considering CVs and congestion pricing.

Global Positioning System (GPS)

Accurate location information from global positioning systems (GPS) is key to an effective congestion pricing system. The accuracy of this data is important for obtaining a good understanding of the traffic conditions and tolling individual users fairly for road usage. The communication between satellites and GPS devices can often be interrupted or obstructed, especially in dense urban areas. This phenomenon often causes the device to produce an inaccurate estimation of the user's location. High accuracy is important for congestion pricing, and there are varying types of GPS that offer different levels of accuracy.

Road-level accuracy is relatively easy to achieve with the current standard of GPS, and it should be sufficient for most forms of congestion pricing. Road-level accuracy would allow users to be tolled for travel on a certain route or stretch of road. Lane-level accuracy would enable greater precision and allow for specially assigned lanes, which could incentivize high-occupancy travel. While this would be a nice feature to add in some areas, it is not essential to effective congestion pricing.

There are four combinations of GPS satellites and technologies that carry increasing levels of accuracy. The standard GPS (SPS) included in most smartphones has 1-sigma accuracy of approximately 3 meters. The standard lane is also around 3-meters, so this provides enough accuracy for roads that include at least two lanes in either direction (Humphreys 2017). 31 SPS satellites are currently in orbit, providing sufficient coverage. With the addition of an antenna, wide area augmentation service (WAAS) enables 1-sigma accuracy of approximately 1.5 meters (Humphreys 2017). This service allows for nearly lane-level accuracy, but there would be significant potential error.

Additionally, the United States-built GPS system does not offer as wide a bandwidth or as high accuracy as the Galileo satellite system being expanded by the European Union. With WAAS and good visibility, the Galileo GPS offers 1-sigma accuracy of 1 meter (Humphreys 2017). This system is sufficiently accurate to collect lane-level accuracy but could present some issues in dense urban areas with poor visibility. There are currently 24 Galileo satellites in orbit (22 usable, 2 in testing), and many more expected in orbit within five years (European GNSS 2019). The ideal GPS system would be GPS L2C, which allows the GPS to communicate with a smartphone over Bluetooth. 19 of the 31 SPS satellites are currently equipped with L2C capability, and all 31 are expected to be L2C compatible within 5 years (Humphreys 2017). GPS L2C allows for 1-meter accuracy even in poor visibility, making lane-level congestion pricing possible even in dense urban centers. Table 1 summarizes the types of GPS and their accuracy capabilities.

TABLE 1. GPS Accuracy Specifications (Humphreys 2017)

Type of GPS System	**1-Sigma Accuracy (meters)**	**Level of Accuracy**
Standard Positioning Service (SPS)	3	Road-level
SPS + Wide Area Augmentation (WAAS)	1.5	Near lane-level
Galileo + WAAS	1 (good visibility)	Lane-level
SPS or Galileo + L2C	1 (poor visibility)	Reliable lane-level

The current GPS systems are capable of road-level accuracy that would allow for some level of congestion pricing, and the advancement of GPS technology will allow for lane-level accuracy. While high accuracy is possible, the solutions do require an installation of a GPS antenna in addition to a smartphone or other device. So, the accuracy of location information is a challenge to congestion pricing, but current technology is sufficiently accurate for a basic system. With the correct systems in place, congestion pricing can be implemented fairly and accurately.

PRIVACY & SECURITY

Privacy and security are major concerns when handling personal location data of a large pool of users. The privacy and security issues with each solution differ based on the method of data collection and communication used. These potential problems are important when evaluating the reliability and safety of congestion pricing applications.

For a video-based system, there is some concern about capturing images of users and non-users along roadways at all times. Monitoring users who do not opt in to the congestion pricing service seems to be a small invasion of privacy. However, cameras are installed along many roadways, and are not an illegal invasion of privacy in many places (Claudel 2017). While video cameras may cause some backlash from citizens who are especially concerned about privacy, the concern is not as great as applications using GPS location data.

For cellular and DSRC solutions that use GPS location data to track the routes of users, the privacy concern is greater. For these location-based applications, it would be essential to offer users the opportunity to opt in rather than mandating sharing of location information. Allowing the government to handle personal location information at all times would likely deter some users. A private-sector, third party service provider could handle the data, which may ease the worries of some consumers, but data privacy would still be a concern.

Cellular communication would carry the same risks that current cellular service does. 3G has known security issues, and it can be spoofed relatively easily (Sturgeon 2017). 4G is more secure and is the most common technology insurance companies and OEMs currently use for vehicle monitoring (Sturgeon 2017). While location and speed information are anonymized for many DSRC safety applications, applications that toll individual users cannot be truly anonymous. Encryption and decryption of user information would be necessary to prevent hacking, and this would add to the overhead cost of implementing a congestion pricing system (Sturgeon 2017).

Malicious users could gain access to sensitive personal location information if the CP communications are not robustly designed or monitored properly. Concerns about people hacking into and assuming some control of automated vehicles are unlikely to be valid in CP applications, since in-vehicle installations for data remittance should be designed to be only "push" (rather than receive) information and should be partitioned from vehicle controls (Claudel 2017). In other words, as with connected vehicles, communications should and will be separated from vehicle control programs. Security and privacy are important concerns of a location-based congestion pricing application, and they must be priorities during implementation and operations. Fortunately, many road-pricing systems do exist, in Singapore, Stockholm and Southern California, with third-party account managers and scrambled IDs providing meaningful privacy protections.

Furthermore, creating a centralized system for managing CP policy creates a single point of vulnerability that could be subject to attack on a system-wide level. To mitigate this, a CP system can be designed with great care to allow for decentralization, by distributing the system's various responsibilities across multiple hardware units in multiple locations. In doing so, a system-wide attack becomes more difficult for a malicious agent, and any such attack would likely disable only a small portion of the system at any given time.

COMPLIANCE & AUDITING

In order to ensure compliance with a congestion pricing system, an auditing process would need to be created. Users could tamper with the GPS location or communication devices in order to avoid toll payment. At the state level, vehicle inspections required by some states for registration offer the opportunity to ensure correct operation of the devices. If a congestion pricing user is not compliant with the required standards, he could be denied vehicle approval and the incident would be reported.

While inspection may catch some malfunctioning devices, users who are intentionally avoiding fees would likely fix their vehicles before taking them into registration. An auditing process with an external check on location could be added to the congestion pricing policy. Video cameras are one possible check on a vehicle's location. A few video cameras at major bottlenecks could capture vehicle license plates, and this information could be matched with the location data transmitted by the vehicle. If the GPS data does not indicate the same vehicle location at the time and date the video was captured, the user would be noncompliant with the congestion pricing system. The vehicle would then be investigated for tampering, and a fine would be issued to the user of that vehicle if it is found to be illegally altered.

While it is not economically feasible to audit every vehicle regularly, a selection of vehicles could be audited periodically. A portion of license plate numbers would be chosen, and this number would be searched for in video footage. While this would not necessarily catch all people using GPS or communication jammers, it would likely deter people due to the chance of being caught and fined.

A HARDWARE MIGRATION PATH FORWARD

To ensure successful implementation of policies recommended, the implementation plan should be as straightforward as possible. Three key facets for successful management schemes are: impact measurement, agency communication, and driver-system interactions. This section proposes a potential migration path forward that improves these facets incrementally. With careful design, the technology required for the various schemas discussed in this paper can be made modular, allowing for the development of a migration plan like that shown in Figure 1. This plan allows for the reuse of hardware until such point as it becomes obsolete, when it can be replaced by technology that can provide for more advanced management methodologies.

As illustrated in Figure 1, the most basic (“bare-bones”) VMT Tax requires an odometer read. This method’s drawbacks, discussed above, can be a significant disincentive for those that regularly drive outside the taxed region, so an odometer-based method may overcharge for many owners (and undercharge others, who register their vehicles elsewhere but spend significant distance in the taxed region). To improve upon this, a “headless” (i.e., non-displayed) GPS system can be implemented which would track users without any form of telecommunications equipment. The position tracking equipment can be of various levels of spatial accuracy, since lane-level accuracy is not yet needed. (Such hardware will be valuable later in this process, and sufficient planning should allow for an easy upgrade to achieve this.) In this VMT Tax scenario, a reading of the vehicle’s mileage is still needed, but its accuracy will be much more reflective of a driver’s impact on traffic congestion within the taxed region or state. One downside to this approach is that the vehicle owner(s) may not appreciate mileage until the reading is taken, but reading stations may be common (and remotely managed for most vehicles, at existing gantries and gas pumps, for example).

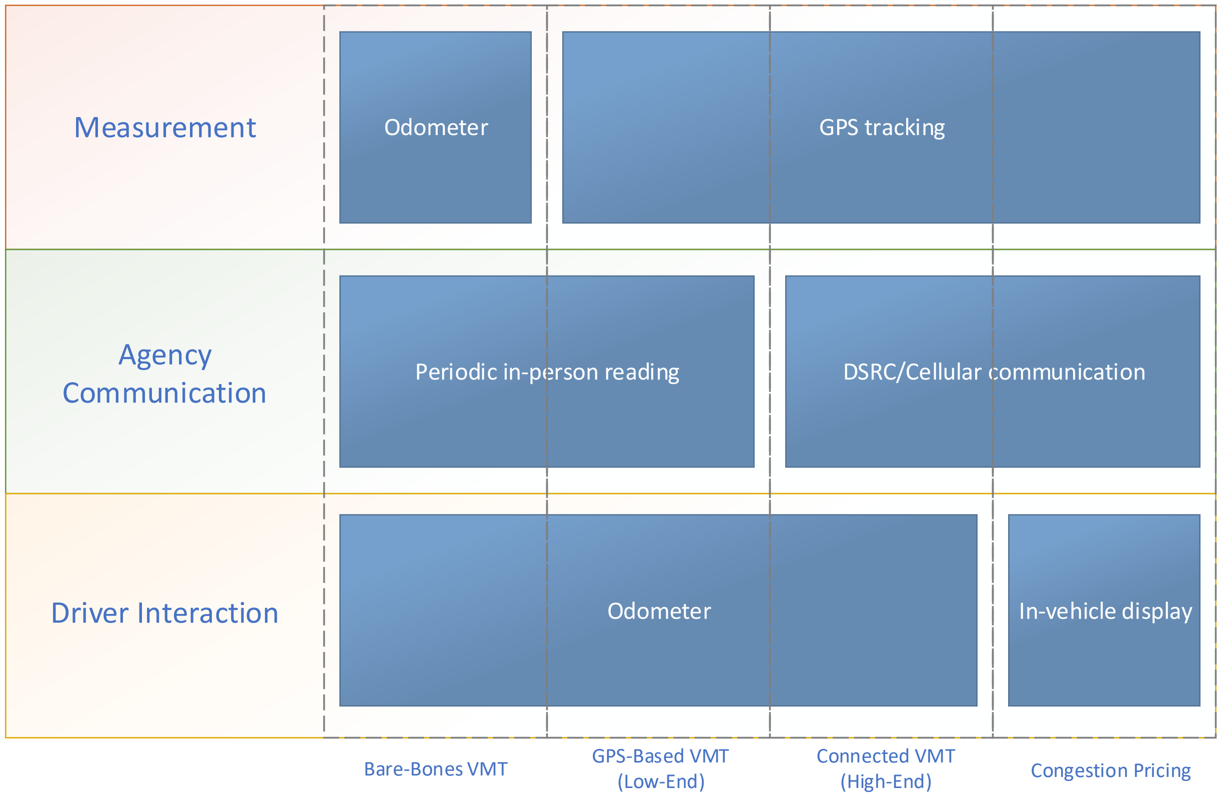

FIGURE 1. Technology Migration Plan for VMT and CP Tolling Schemas

A "high-end" VMT Tax system would rely on an instantaneous or regular telecommunications module (via DSRC or cellular), as discussed earlier, allowing agencies and vehicle owners to be updated regularly on mileage and perhaps location. This can be accomplished using an application or text and/or email updates. Such methods limit data or bandwidth use and can assist in automating the auditing process by reducing human intervention in the tax-reporting process. Additional messaging will be needed to keep drivers apprised on taxes owed and paid.

A proper CP system will need travelers and drivers to appreciate tolls in real time and in advance, at least approximately, to plan trips and tours. To address this need, the system's final addition is information online/in the cloud to access at any time of day and ideally displayed to drivers within the vehicle. The amount of data transmitted through this real-time road-pricing system is much higher than that of a flat VMT Tax system, and locational accuracy of GPS modules becomes rather key, to avoid tolling the wrong rate, from a nearby and parallel link, for example, or in urban canyons, where added positioning information will be needed (as satellites become obscured). Regardless, such advanced modules are not needed during the transition phases, and can be deployed as technology and other resources become available.

CONCLUSION

VMT fees and CP are related, but distinctive, transportation policies. VMT fees primarily help state and local governments gain funding for roadways with declining revenue from the gas tax, with a small possible congestion benefit. Some users may opt to travel fewer miles with their VMT being monitored, but this does not alter the routes they will take. CP should be far more effective in alleviating congestion, as this policy emphasizes location or link selection by time of day, based on local congestion delays. However, the technologies and systems required for each program are similar.

VMT fees and CP can be implemented with DSRC or cellular technology. VMT fees are a simpler system, so they could be implemented first. This would allow DOTs to gain additional revenue, gain experience with collecting vehicle location data, and identify potential compliance challenges. If DSRC units are placed along major roadways, the location data held in the vehicle can be transferred to the central database periodically to charge VMT fees. The funds collected from VMT fees can be used to improve roadways or invest in additional technology. With this experience, the same entities could move into implementing CP for additional benefits to the transportation network. The same DSRC units could be used to collect information on vehicle speed and location and communicate route pricing at these highly congested locations. If the CP program proves valuable, it can be expanded through cellular communication. VMT fees are a good first step in technology-based roadway management, while CP can take advantage of the technology in place to further improve transportation network use efficiencies.

Technology Recommendation

This paper analyzed the viability of DSRC, cellular, and video technologies for use in roadway pricing. The value of each of these technologies is based solely on its value for addressing congestion delays, rather than use in connected vehicles generally. The technologies were evaluated based on their effectiveness for this application, current level of market penetration, and the scalability throughout a transportation network. These criteria were evaluated on a scale representing their relative values. The ability of each technology to be applied to the major policies of VMT fees and credit-based CP (CBCP) was also taken into account.

First, the effectiveness of each technology when applied to congestion pricing was considered. DSRC and cellular solutions are both similarly effective in transferring information to and from vehicles. Both systems are able to transfer small data packets known as basic safety messages (BSMs), which include vehicle location and speed. DSRC currently allows for lower latency communication, but this is not as important for congestion pricing as it is for vehicle safety applications because routing decisions are not as time-sensitive as collision avoidance maneuvers. Video can collect congestion information in order to price roads, but it lacks the ability to communicate information back to the users, which is required to change user behavior and reduce congestion. A video solution would need to be combined with electronic signage indicating the price of upcoming routes or with DSRC or cellular communication. This limits the scope of a video-based solution since it requires costly, redundant technology. Therefore, cellular or DSRC solutions will be most effective for the longer term.

Cellular technology is widespread in urban centers, as it employs cell towers that enable long-distance communication. The infrastructure is already in place for 4G communication around the world, in developed nations, and it is currently used to transfer data between smartphones and other connected devices. Video cameras are installed along some stretches of roads and intersections, but they are not widely installed along roadsides throughout cities. DSRC is also not widely available, and RSUs would need to be installed densely along roadways. Additionally, both video and DSRC systems would require installations at short intervals along the roadways, while cellular communication has much longer range. Both DSRC units and video cameras are recommended about every half-mile, so installing these throughout a transportation network could be costly (Lange 2017).

DSRC is recommended for locations with high congestion in the short term, as a pilot system. Bridges, major highways, and other commonly congested stretches of roads are terrific locations for such pilots. RSUs could be placed a mile or two before these major bottlenecks to communicate route and pricing options to arriving travelers, and then again at section entrance, to notify on-board devices of toll charges. The use of congestion pricing at each region's most congested points and corridors will encourage use of alternative routes, driving at off-peak times of day, and/or changes in trip destination, mode and generation decisions, in order to reduce the travel costs. In the long term, however, cellular systems will be more effective in tolling entire urban transportation networks. With the ability to toll large areas using cellular networks, congestion pricing can be effectively scaled to decrease congestion throughout a network rather than just a few key nodes or on a few links. Such widespread traffic demand management can be crucial in avoiding spillovers from targeted pricing, given how extensive road networks and route substitutes are. Potentially more important, is the option of credit-based congestion pricing (CBCP), to ensure everyone has reasonable access to the network and a region's travel options, regardless of income. A combination of VMT fees for system maintenance (and some scheduled expansions, if needed) along with CP where all CP revenues are returned as travel credits, is likely to be the long-term solution, as the gas tax erodes in many states, thanks to more travelers shifting to electric vehicles and hopefully a less environmentally unsustainable future.

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