TECHNOLOGIES FOR CONGESTION PRICING

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Under review for publication in *Research in Transportation Economics.*

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.

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 recommended 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 CBCP, which can better reflect the marginal delay costs of one’s travel choices and enable a more equitable distribution of each community’s scarce roadway assets.

INTRODUCTION

Traffic congestion is a problem in urban areas, costing citizens valuable time. Congestion costs the U.S. economy over $100 billion a year, and this number is rising (Cebr 2014, Shrank et al. 2015, Burfeind 2017), including 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 populations continue to grow, congestion is expected to increase. To combat gridlock, it is important to develop policies and technologies that reduce congestion.

Roadways are limited by their capacity, the maximum flow of traffic that can be handled by a roadway section. Capacity flows are affected by the number and width of lanes, median and merge area designs, intersection or interchange frequency, stop signs or signals, curvature, grade, and other design variables (FHWA 2017). When demand for travel rises, congestion increases, slowing travel speeds and lengthening travel times. While transportation network capacities are limited by existing infrastructure investments, demands fluctuate minute-to-minute and day-to-day. Demand can be influenced via public policy, special events, weather, and many other factors.

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, adding to the travel time of all road users (Kockelman and Kalmanje 2005). This phenomenon is represented in the supply-demand curves shown in Figure 1.

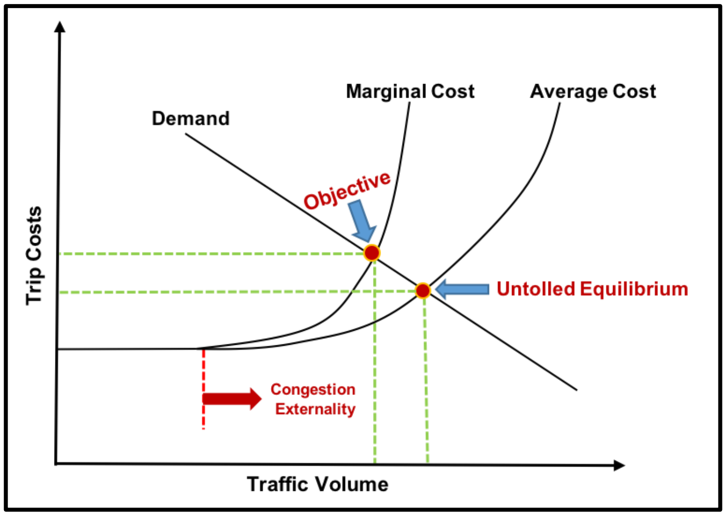

FIGURE 1 Traffic supply and demand curves, for tolled and un-tolled conditions

Congestion pricing (CP) is one potential solution to this issue. Such pricing or road tolling involves incentivizing certain link and route choices for drivers, to improve the efficiency of a congested corridor's or 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 their true cost of travel (reflecting delays they impose on other travelers), CP pushes the supply-demand equilibrium point to the left, decreasing traffic volume. Lower volume means decreased congestion and travel times on that link. Without CP, drivers face only the directly-experienced or average cost of travel, resulting in over-consumption of 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 vehicles on each roadway segment, at each time of day.

Recent developments in communication and computation technology make implementation of CP systems feasible and potentially highly cost-effective. This paper examines the technologies and policies that could be implemented in a CP 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 CP.

POLICY IMPLEMENTATION

To deliver a successful, maximally cost-effective roadway pricing system, an appropriate policy structure is needed. Some pricing policies are a vehicle-miles-traveled (VMT) tax, cordon- or area-based CP, and credit-based CP (CBCP). A VMT tax is simplest and can recover general infrastructure investment and maintenance costs; but it does not address congestion directly. Cordon-based and area-based tolling reduce travel within high-traffic areas by charging for ingress during specific times, but they are broad-based and do not reflect over-use or under-use of specific links. Rationing by license plate and day-of-week or time-of-day has also been studied (see, e.g., Nakamura and Kockelman [2002]), but can lead to perverse outcomes (Nie 2016). CP and CBCP can directly and efficiently (in an economic sense) address congestion costs by location and time. Variations in tolling can influence trip generation by time, mode choices, destination and route choices; but only CBCP is designed to address congestion costs in time and space while addressing equity implications, thereby delivering greater societal benefits.

Both a VMT tax and CBCP offer opportunities to decrease congestion and collect additional funding. With the rise of autonomous vehicles (AVs), many sources of public funding may decrease. The 25 largest cities in the U.S. reported $5 billion in auto-related revenues in 2016 (Maciag 2017). If users opt for shared AVs (SAVs), parking needs may decrease as vehicles pick up new passengers. Parking fees and tickets make up a large portion of local government revenue for infrastructure improvements in many cities. AVs will not violate traffic laws as often, decreasing revenues from traffic citations, which average $8.5 million in the largest cities (Maciag 2017). Additionally, the rise of electric vehicles will decrease revenue generated from motor fuel taxes, accounting for $16 billion spent on infrastructure or transit in 2015 (Maciag 2017). Implementation of a VMT tax or CBCP could help local governments maintain infrastructure budgets. Additionally, decreased congestion would help limit the need for maintenance and construction costs while benefitting citizens through time savings.

Vehicle-Miles-Traveled (VMT) Tax

The concept of a VMT tax involves charging users for the miles traveled on roads within the state. VMT taxes have arisen as an alternative to gas taxes as a means for states to collect funding. In most states, a gas tax is applied per gallon when travelers fill their tanks at gas stations. Increased fuel efficiency of electric and hybrid vehicles has enabled some users to use roadways without contributing to funding for roadway maintenance while costs are increasing (Caltrans 2016). Automakers continue to improve the fuel efficiency of vehicle fleets, so these challenges will become more difficult over time. A VMT fee is one way to collect taxes from all vehicles to gain funding for roadways and, potentially, to discourage excessive vehicle travel.

One way to charge 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 double-charged if they purchased gas out of state. A VMT tax can be applied only within the state operating the program using Global Positioning System (GPS) data to calculate the miles traveled within the state per vehicle. This can be accomplished using either dedicated cellular or short-range communications (DSRC) to send GPS data to a central database, where public or private entities would calculate the amount owed by each driver.

California, Washington, and Oregon have started pilot programs to test the feasibility and efficacy of a VMT program. These programs track all miles driven on public roads and charge users accordingly. The automated mileage reporting option requires in-vehicle equipment, reporting location data collected from vehicle telematics, smartphone apps, or OBD-II port devices (Caltrans 2016). An advantage of this 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 challenging, since it would require vehicles to have operational hardware that has not been modified (to reduce toll totals). Participants should be randomly audited to ensure they are not misrepresenting travel data to save money.

While VMT tax policies are 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 using GPS tracking could lay the foundation for development of more advanced transportation management policies that would require location and communication technology.

Cordon-Based Tolling

Cordon-based tolling involves charging users for entry into an enclosed area, commonly downtown business centers, to ease peak-hour traffic. Cordon-based CP has been used in many cities to reduce congestion and emissions in urban centers.

Singapore, London, Stockholm, and Milan have implemented some form of CP (Brown 2011). Singapore first introduced a manually-enforced Area Licensing Scheme in 1975, charging drivers a flat fee to enter the central business district during peak hours (ITDP 2015). Users showed their purchased license to enforcers at gantries to ensure compliance. In 1998, Singapore replaced this scheme with Electronic Road Pricing (ITDP 2015). This system requires installation of an in-vehicle unit with a smart card and DSRC system. The system has resulted in lower traffic volumes, higher average vehicle speeds, and lower carbon dioxide emissions (ITDP 2015). London also employs a cordon-based congestion charging system in the downtown area between 7:00 AM and 6:30 PM on weekdays. Payments can be made at retail outlets or electronically on the same day, or users can purchase weekly, monthly, and annual passes (Litman 2011). Cameras installed throughout the city record license plates, and users pay a fine if they do not pay for downtown road usage. Automobile usage has decreased, public transport usage has increased, and average vehicle speeds have increased in urban centers (Litman 2011). Stockholm and Milan have reported similar results (Croci 2016).

These successes suggest that cordon-based CP is a viable and valuable program to implement in cities with large traffic volumes in urban centers. As seen in these examples, cordon-based CP can be implemented with different common technologies. An advantage of this system is that installations are only needed at entry points to the congested area. While overall traffic volume may decrease, users who choose to enter the area may still choose suboptimal routes. However, cordon-based pricing is an effective means to decrease general travel volume within highly-congested areas during peak hours.

Credit-Based Congestion Pricing (CBCP)

Credit-based CP (CBCP) involves charging road users a fee that accounts for their marginal cost of congestion (Nie and Liu 2009). Current drivers make route decisions based on the shortest path or time to their destination; these decisions disregard the externality of the cost of vehicle travel to the rest of the transportation network. CBCP adds this cost into the decision-making process, making users aware of their impact on roadway congestion, and decreasing traffic along the most congested stretches of road (Kockelman and Kalmanje 2005). CBCP requires a more complex system than VMT, as technology would need to be coordinated to communicate vehicle position to a central system and route pricing to vehicle occupants. However, CBCP would more effectively accomplish the goal of changing user behavior to alleviate congestion, because it would incentivize more optimal route choice rather than reduced total miles traveled. This system would require effective two-way communication, fair pricing policies that attract users, and auditing procedures that ensure compliance.

CBCP requires communication of vehicle location and velocity data to a database, where speeds are used to evaluate congestion along a given stretch of roadway, which is then used to price routes. When certain routes are more congested, the price to travel along them increases. To alter user behavior and ensure fairness and transparency of the system, the toll operator will communicate alternative routes' prices to users. This information can be displayed early enough to allow human operators to alter their route based on this information. Vehicle location data can indicate when individual automobiles pass checkpoints along a route to toll each user. Reliable communication and accurate location data are important to ensure consistency and fairness of those tolls.

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

One major challenge with establishing a CBCP program is attracting users. Many citizens are averse to being tolled in any way. There must be sufficient incentives to volunteers to encourage opting in. One way is to provide a tax deduction that would offset the cost of tolls collected through CBCP. With that incentive, users would realize some value in joining the program.

Another issue with CP is that lower income users and people with inflexible schedules could be tolled excessively (Gulipalli et al. 2008). Equity can be improved by allocating flat budgets to individuals to spend on CP over a period (Gulipalli et al. 2008). Gullipalli et al. (2008) detail specific policy recommendations for effective CBCP management. The policy must be set appropriately to ensure efficiency, equity, and effectiveness.

TECHNOLOGY SOLUTIONS

Research has been conducted on potential technology solutions for CP systems through review of previously-published interviews and a series of expert interviews. Based on the information collected, three leading concepts have been identified for use in CP solutions: video, DSRC, and cellular. Each 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 can be employed to measure congestion and price routes. Cameras are already installed in many locations along highways and intersections, so these feeds could be harnessed to model traffic congestion. The system consists of a series of cameras on poles along roadways, a data connection to send information to a central system, and algorithms to analyze video feeds. This system would then communicate and toll users based on the pricing of each route. This could come through DSRC or cellular networks previously discussed or through license plate recognition and electronic signs indicating the toll for upcoming routes.

The major infrastructure installations would be cameras, cables, and poles along roadsides. Installations including all three components could cost $20,000-50,000, depending on camera quality and pole height (Lange 2017). Poles could be anywhere from 20 to 50 feet, and taller poles would allow for greater range while increasing costs (Lange 2017). Based on average camera ranges, one could be placed approximately every half-mile, depending on road curvature, buildings, and other obstructions (Lange 2017). A large portion of the cost is the pole itself, and individual cameras themselves can be purchased for $800-1,200 (Lange 2017). To toll individual users, video feeds would need to be of high enough quality to capture license plate numbers of passing vehicles. Processing these characters from varying angles and speeds would need to be incorporated into software evaluating the video feed.

Another challenge with video-based solutions is that 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 CP system is to alter travel behavior to alleviate congestion. DSRC or cellular solutions described in the following sections could be combined with video feeds for a comprehensive solution, but this would result in expensive and somewhat redundant infrastructure investments. Alternatively, tolls could be implemented at a limited number of locations and pricing could be communicated via electronic signs along 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 because it requires no in-vehicle installation.

One advantage of a video-based solution is that video infrastructure is already installed in many major cities. Another advantage 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 pricing to users is required. Such infrastructure can be prohibitively expensive, so it may be implemented in a limited number of locations. The challenge and cost of installing two separate systems for information collection and transmission ultimately render this solution less viable.

DSRC-Based System

Another solution is a CP system that uses Dedicated Short-Range Communication (DSRC). DSRC is a spectrum of 75 MHz in the 5.9 GHz band reserved for 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 hazards, such as stopped traffic or collisions. 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 potentially for adaptive pricing schemes in which the cost of certain routes changes often. Since the DSRC band is reserved for mobility applications, CP would 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, messages are sent from OBUs to the RSU indicating vehicles' position and speed, and this data is compiled to model the amount of congestion in a certain area. With this information, incentives for certain routes can be generated, and information can be sent back to the vehicles' OBUs. Vehicle operators decide their routes based on travel times and dynamic tolls. Using cloud-based tolling information, travelers can also delay trips or choose different destinations and modes.

Currently, most vehicles are not equipped with DSRC communication. However, DSRC is beginning to be incorporated into new vehicles, and it may be required in all new vehicles in the future 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 CP system by adding an OBU. An OBU can be small, lightweight, and can be mounted on the windshield of a vehicle with simple fasteners (Kapsch n.d.) An OBU costs about $1,500 currently, but this is likely to decrease as technology improves and production increases. OBUs can communicate position and speed, and traffic flow speed can be gathered from a limited number of vehicles. As the number of DSRC-equipped vehicles increases, the accuracy of this data and the benefits of a CP system will increase.

The other major component of a DSRC-based CP system is the installation of RSUs. RSUs have a line-of-sight range of about one kilometer. Due to the short range of RSUs, a high density of these devices would be required. Currently, RSUs are in prototype stage and cost around $3,500. With improvements in technology and mass production, that price could drop to $500-800. In addition to the cost of the RSU, the installation and maintenance costs would add up quickly. Installation cost could vary from $1,000 to tens of thousands of dollars. Higher leads and poles for RSUs would cost more money, as would connection to a communication network, especially if a data link backbone does not yet exist. RSUs will need routine maintenance for updates or replacement if external factors cause damage.

While a DSRC-based system provides fast communication between vehicles and infrastructure, it requires a large capital investment. DSRC is well-suited for transmitting small packets of data accurately in short time periods. Pairing this with a smartphone or device for route decisions would enable an effective system. However, a DSRC-based system is limited by the cost of installing units both in vehicles and in urban environments. Furthermore, installation and penetration of DSRC devices will take a long time. For this reason, some experts believe that connected vehicles (CVs) may leapfrog DSRC and go straight to 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 system challenging to implement throughout an entire network. However, DSRC solutions are viable for major bottlenecks. A pilot program could be implemented on bridges or stretches of highways that are often highly congested. Vehicles could be informed of an upcoming toll and given an alternate route option when passing the RSU. This initial installation would allow testing of an adaptive tolling scheme and route-choice data could be collected in response to CP.

Cellular-Based System

A CP system could also be created with cellular data. Information could be communicated via smartphones or devices installed in the on-board diagnostic (OBD) port in vehicles. Each of these would take advantage of the already-widespread cellular network, but use different devices which have distinct advantages and disadvantages.

A smartphone solution would require an app that would allow users to opt-in to the service to toll users and gain information about traffic conditions. Communication to the cell tower and toll operator would be included in the user's cellular data service plan. This system would allow for faster market penetration, because many people already own smartphones. Location data is collected from phones' GPS and sent to the tolling entity. One potential issue is with the accuracy of GPS currently installed in smartphones. Smartphone GPS is usually accurate enough to identify the road a user is on, but it can decrease in accuracy in urban environments (Claudel 2017). While such a system could be implemented, there may be some issues with ensuring appropriate tolling if incorrect location information is used in determining a toll.

One potential solution to this issue would be to combine the smartphone application with an inertial measurement unit (IMU) in the vehicle (Claudel 2017). An IMU is a single unit that incorporates an accelerometer and gyroscope. IMU data allows the device to calculate its position based on acceleration measurements and can bridge the gap between position estimates when the signal is blocked (Godha and Cannon 2005). While this improves the location accuracy and likelihood of fair CP, it also would require an additional installation, possibly deterring potential users.

The final cellular solution involves installing a dongle in the onboard diagnostic (OBD-II) port. A dongle is a small electronic device that traditionally collects emissions and malfunction data (Moran and Baker 2016). Such a device could receive GPS location data and communicate using cellular data (Moran and Baker 2016). Dongles could be outfitted with a more accurate GPS system to improve the resolution of the system. A GPS unit with lane-by-lane accuracy costs around $200, while road-level accuracy would be less than $50 (Dorfman 2017). The OBD-II dongle also needs a cellular communication modem. A mobile chip costs around $200 at low volume, but this price decreases at higher volumes (Sturgeon 2017). The issue with this data cost is determining who will pay the fee. Users may be willing to pay for the monetary or time benefit they gain from opting into the program. Original equipment manufacturers (OEMs) may accept the cost to collect more data on users. Departments of transportation (DOTs) could enter into agreements with carriers to provide this service to improve efficiency 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 at $3-4 per month (Dorfman 2017). This may increase at higher volumes of data, but advances in technology could decrease the cost of data. Alternatively, a third-party vendor may see an opportunity in providing the service and take on the cost.

The OBD-II dongle solution improves the problem of low-accuracy GPS included in smartphones. This would allow for increased standardization and ensure greater fairness of a CP system. The use of dongles does present some challenges, however. Users must purchase and install hardware to enable this system, and could unplug the device to avoid tolling. Additionally, the entity willing to pay for the cellular connection is not clear, and incentives to encourage that additional cost would need to exist. Additionally, older vehicles predating the OBD-II requirements would be ineligible for this program.

ADDITIONAL TECHNOLOGY CONSIDERATIONS

5G Network

While CP could be implemented with current 4G cellular communication, the development of a 5G network will increase its effectiveness. Applying CP throughout an urban transportation network may challenge the available bandwidth (Claudel 2017). While development of a widespread 5G network is far off, it will improve the performance of CVs and CP.

A 5G network is expected to be available 5-10 years from now, and there are major differences between 5G and current cellular communications. New, unlicensed frequencies of the electromagnetic spectrum are expected to be released by the FCC for use in 5G networks (Andrews 2017). 5G allows information to pass between individuals and vehicles without having to connect through a cell tower. Information about traffic, hazards, or pricing on routes could be passed backwards along sequences of vehicles on a roadway. Additionally, 5G will allow for high throughput (> 10 Gigabit per second per user) and low latency (< 1 ms RTT) communication (Fettweis 2015). Faster, larger data transfers can allow time sensitive travel information to be communicated more quickly and reliably. Vehicles can receive information in a timely manner, and the network can handle the communication required for CVs and CP more easily.

Challenges exist with the development and adoption of a 5G network. First, business models must be developed for 5G networks. The value of safety-critical applications in CVs will incentivize government entities to invest in 5G. The telecommunications sector will need to provide services, however, and their investment should be profitable. Telecommunications companies could charge individual users, automobile OEMs, or government entities depending on the value to each group. 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 continues, and it is important to stay informed about the developing value of each.

Global Positioning System (GPS)

Accurate location information from global positioning systems (GPS) is key to an effective CP system. The accuracy of this data is important for obtaining an understanding of traffic conditions and tolling individual users fairly for usage. Communication between satellites and GPS devices can often be interrupted or obstructed, especially in urban areas. This phenomenon often causes a wider location radius or inaccurate estimation of the user. High accuracy is important for CP, and varying types of GPS offer different levels of accuracy.

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

There are four GPS technologies that carry increasing levels of accuracy. The standard GPS (SPS) included in most smartphones has 1-sigma accuracy of approximately 3 meters, providing road-level accuracy (Humphreys 2017). With the addition of an antenna, wide area augmentation service (WAAS) enables 1-sigma accuracy of approximately 1.5 meters, enabling near-lane-level accuracy (Humphreys 2017).

Additionally, the United States-built GPS system does not offer as wide a bandwidth or as high accuracy as the Galileo satellite system being built by the European Union. With WAAS and good visibility, 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 areas with poor visibility. GPS L2C allows for 1-meter accuracy even in poor visibility, making lane-level CP possible even in urban centers. Current GPS systems are capable of road-level accuracy that would allow for some level of CP, and technological advancement will allow for lane-level accuracy. While high accuracy is possible, the solutions require an installation of GPS antennae plus smartphones or other devices. The accuracy of location information is a challenge to CP, but current technology is sufficiently accurate for a basic system. With correct systems in place, CP can be implemented fairly and accurately.

PRIVACY & SECURITY

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

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

For cellular and DSRC solutions using GPS data, it would be essential to offer users the opportunity to opt in rather than mandating sharing location information. Allowing the government to handle personal location information would likely deter users. A private-sector, third-party service provider could handle the data, which may ease the worries of some consumers, but data privacy would remain a concern.

Cellular communication carries the same risks that current cellular service does. 3G has known security issues, and it can be spoofed easily (Sturgeon 2017). 4G is more secure and is the most common technology insurance companies and OEMs 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 information would be necessary to prevent hacking; this would add to the overhead of implementing a CP system (Sturgeon 2017).

Malicious users could gain access to sensitive personal information if CP communications are not designed or monitored properly. Concerns about hacking into and assuming control of automated vehicles are unlikely to be valid in CP applications, since in-vehicle installations for data remittance should be designed to only “push” (rather than receive) information and should be partitioned from vehicle controls (Claudel 2017). In other words, as with CVs, communications should be separated from vehicle control programs. Security and privacy are important concerns of a location-based CP application, and must be priorities during implementation and operation. Fortunately, many systems exist, in Singapore, New York, Copenhagen, and California, with third party account managers and scrambled IDs providing privacy protections.

Furthermore, creating a centralized system for managing CP creates a single point of vulnerability subject to attack on a system-wide level. To mitigate this, a CP system can be designed to allow for decentralization, i.e. distributing responsibilities of the system across multiple hardware units in multiple locations. In doing so, a system-wide attack becomes more difficult for malicious agents, and any attack would disable only a small portion of the system at a time.

COMPLIANCE & AUDITING

To ensure compliance with a CP system, an auditing process must be created. Users could tamper with GPS location or communication devices to avoid toll payment. At the state level, vehicle inspections required by some states offer the opportunity to ensure correct device operation. A CP user who is noncompliant with the required standards could be denied vehicle approval and the incident would be reported.

While inspection may catch some malfunctioning devices, users who are intentionally avoiding fees may fix their vehicles before taking them into registration. An auditing process with external checks on location could be added to the CP policy. Cameras are one possible check on a vehicle's location. 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 CP 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 searched for in video footage. While this may not catch all people using GPS or communication jammers, it could deter people due to the chance of being caught and fined.

A HARDWARE MIGRATION PATH FORWARD

Implementation of the recommended policies requires that the implementation plan be as straightforward as possible. Consider three facets necessary for successful management schemes: impact measurement, agency communication, and driver interaction. With careful design, the technology required for the various schemas can be made modular, allowing for development of a migration plan such as in Figure 2. 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 this figure, the most basic ("bare-bones") form in this paper depends on an odometer keeping track of miles driven by a vehicle, which informs the driver of how much of an impact their driving has and must be read in person by an agent. This method's drawbacks can be a significant disincentive for those that regularly drive in a way that an odometer-based method would overcharge for their driving.

To improve upon these flaws in management, a "headless" (i.e. without a display) GPS system can be implemented to track users without any telecommunication equipment. Position tracking equipment can have various degrees of accuracy at this point, as lane-level accuracy is not yet needed. In this "low-end" VMT scenario, an in-person reading of the vehicle's mileage is still necessary, but the accuracy of such a measurement will be more reflective of a driver's impact on the road network. On the other hand, the drawback to this is that there is no method in place at this time for vehicle owners to be made aware of how many miles the GPS system has recorded until such time that a reading is taken, either by an agent or by the owner themselves.

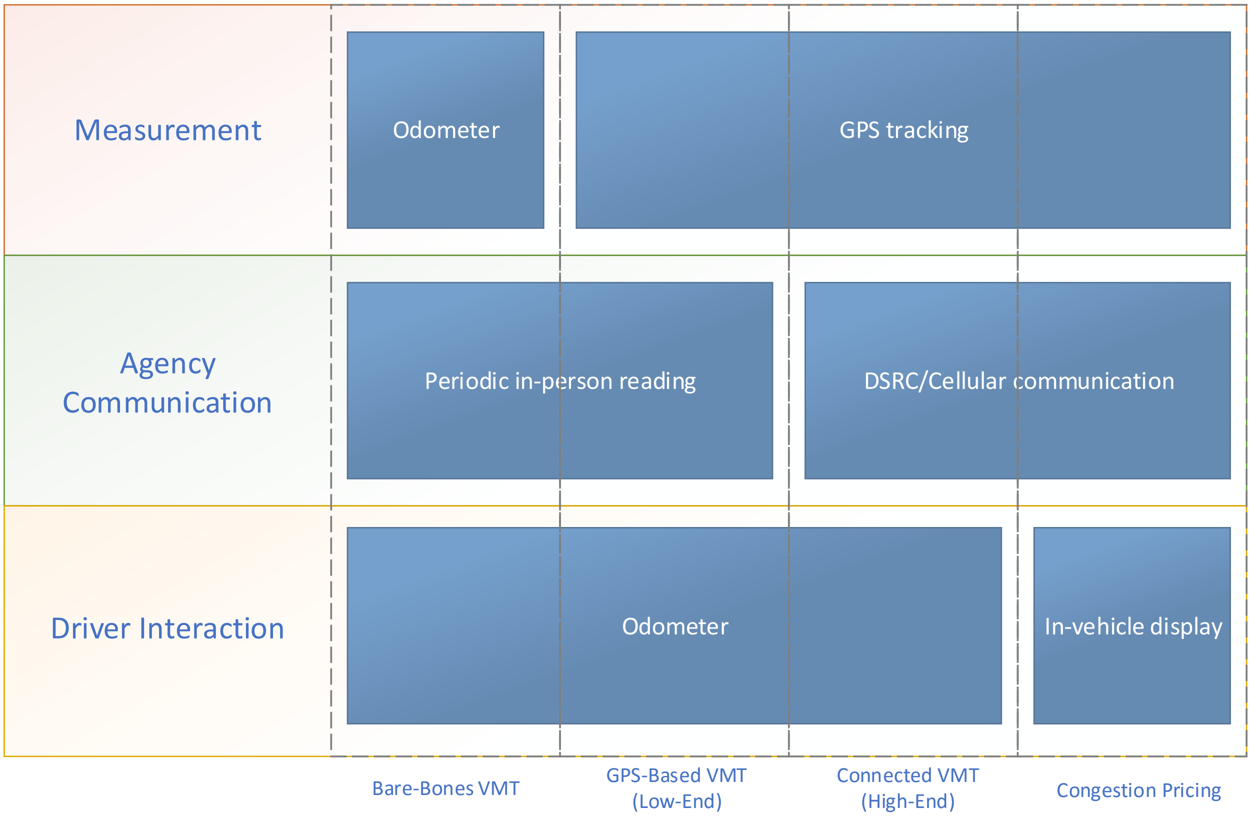

FIGURE 2 Technology migration plan for VMT and CBCP tolling schemas

Drawbacks of necessitating an in-person reading of logged mileage are addressed in the next phase of this plan – the “high-end” VMT system. This step provides for telecommunications modules (DSRC, cellular), thus allowing agencies and vehicle owners to be updated regularly regarding a vehicle’s mileage. This can be accomplished using an application or through email updates. These can limit data usage needed based on update frequency and can assist in automating the auditing process by reducing the human element. However, these do not update the driver in real time regarding their mileage, so the driver must use the odometer to measure their mileage approximately while mid-trip.

This drawback also prohibits a CBCP system, as drivers must be able to see prices in real time. To address this, a display mounted in the vehicle can provide pricing information to the driver as necessary for a CBCP implementation. A display removes the need for an old-fashioned odometer, as this functionality can be handled by the GPS and display. However, the amount of data transmitted through this system will be substantially higher than the VMT systems.

CONCLUSION

VMT fees and CBCP are related but separate types of 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 taken. CBCP would be far more effective in alleviating congestion, as this policy is focused on route selection based on congestion at a given time. However, technologies and systems required for each program are similar.

VMT fees and CBCP could be implemented with DSRC or cellular technology. VMT fees are a simpler system which could be implemented first. This allows DOTs to gain additional revenue, gain experience with collecting location data, and identify potential compliance challenges. If RSUs are placed along roadways, the location data held in-vehicle can be transferred the central databases periodically to charge VMT fees. Funds collected from VMT fees can be used to improve roadways or invest in additional technology. With this experience, entities could move into implementing CBCP 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 highly congested locations. If CBCP proves valuable, it could be expanded through cellular communication. VMT fees would be a good first step in technology-based roadway management, and CBCP could take advantage of the technology in place to further improve the efficiency of the transportation network.

Technology Recommendation

Analysis was conducted on the viability of DSRC, cellular, and video technologies for use in CP. The value of each technology is based solely on its value for CP, rather than use in CVs generally. The technologies were evaluated based on their effectiveness for this application, current market penetration, and 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 VMT fees and CBCP was also considered. First, the effectiveness of each technology when applied to CP was considered. DSRC and cellular solutions are both effective in transferring information to and from vehicles. Both systems can transfer 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 CP as it is for vehicle safety applications because routing decisions are not as time-sensitive as collision avoidance maneuvers. Video can collect congestion information to price roads, but lacks the ability to communicate information back to the users, which is required to change user behavior. A video solution must 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 and to transfer data between smartphones and other connected devices. Cameras are installed along some roads and intersections, but they are not widely distributed. DSRC is also not widely available, and RSUs would need to be installed densely along roadways. Additionally, both video and DSRC systems require installations at short intervals along the roadways, while cellular communication has much longer range. Both DSRC and cameras are recommended about every half-mile, so installing these throughout a transportation network could be costly (Lange 2017).

DSRC is recommended to be implemented at locations with high congestion in the short term as a pilot system. Bridges, highways, and other commonly congested stretches of roads are terrific locations for such pilots. RSUs could be placed a mile or two before these bottlenecks to communicate route and pricing options to travelers, and then again at section entrance, to notify OBUs of toll charges. The use of CP 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 travel costs. 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, CP can be effectively scaled to decrease congestion throughout rather than just a few key nodes.

AUTHOR CONTRIBUTION

The authors confirm the contribution to the paper as follows: study conception and design: Lewis Clements and Kockelman, K.; Data analysis and interpretation of results: Lewis Clements and Kockelman, K; Draft manuscript preparation: Lewis Clements, Kockelman, K. and Alexander, William. All authors reviewed the results and approved the final version of the manuscript.

ACKNOWLEDGEMENTS

The authors thank the Texas Department of Transportation (TxDOT) for financially supporting this research (under research project 0-6838, "Bringing Smart Transport to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas"). The authors also acknowledge Dr. Baruch Feigenbaum, Bertus Pretorius, and graduate student William Alexander for their review and feedback on this work. We also thank the experts who took time to be interviewed: Dr. Christian Claudel, Purser Sturgeon, Matthew Dorfman, Dr. Jingtao Ma, Phil Eshelman, Dr. Yong Zhao, Raymond Lange, and Dr. Todd Humphreys.

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