TECHNOLOGIES FOR CONGESTION PRICING

Lewis M. Clements
Undergraduate Research Assistant
Department of Mechanical Engineering
The University of Texas at Austin
lewisclements@utexas.edu
Phone: 210-787-9945

Kara M. Kockelman
(E.P. Schoch Professor in Engineering
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
kkockelm@mail.utexas.edu
Phone: 512-471-0210

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ABSTRACT

Traffic congestion is a challenging problem in major urban areas, increasing time use and fuel consumption. Congestion pricing is a strategy that seeks to influence route choice, timing, or volume of travel in order to decrease congestion. New developments in technology enable the possibility of more advanced congestion pricing strategies. This paper explores and evaluates the technologies and policies that could be employed for congestion pricing. Technologies evaluated include video, dedicated short-range communication (DSRC), and cellular communication. Potential policies include a vehicle miles traveled (VMT) tax and credit-based congestion pricing (CBCP).

A video-based system would require video cameras to be placed approximately every half-mile to capture the state of traffic and some form of communication back to users. Whether by electronic signs, DSRC, or cellular, this additional component limits the potential value of a video-based system. Both DSRC and cellular-based systems would use Global Positioning System (GPS) location data to price roads based on traffic conditions and to toll individual users based on route choice. DSRC would employ roadside equipment (RSEs) to receive and send messages to in-vehicle DSRC units. These units would have to be installed every half-mile and in each vehicle. 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 would be a good technology to pilot congestion pricing at highly congested areas, such as bridges and major highways, while cellular communication would enable congestion pricing to be implemented throughout a transportation network.

A VMT tax is a policy that would enable governments to collect money for roadway improvement as an alternative to the gas tax, and it could decrease some roadway usage. California, Washington, and Oregon have pilot programs, which use GPS-based location data to measure road usage. VMT fees would allow states and operating entities to gain experience with location data and these communication systems while gaining funding to maintain roadways.
The next step for roadway management would be CBCP, which charges road users a fee that accounts for the marginal cost of congestion they cause by traveling along a particular route. CBCP would be an effective way to re-direct congestion from the most crowded routes or to cause users to travel at off-peak times.

**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 was estimated to incur $300 billion in economy-wide costs in the U.S. in 2013, and this cost is expected to rise as population increases (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.

Vehicle collisions, construction, and inclement weather can all decrease the potential speed within a given roadway. Roadways are limited by their capacity, the maximum amount of traffic that can be handled by a given roadway section, and this is affected by number of lanes, merge area, and the grades and curves of the roadway (FHWA 2017). The other factor that affects the congestion within a roadway is the volume of traffic demand at a given time. While highway capacity is limited by the available roadway real estate, traffic demand fluctuates and can be influenced by human behavior and decisions.

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). This phenomenon is represented in the supply-demand curve shown below in Figure 1.

![Traffic Supply-Demand Curve, Tolled and Un-tolled](image)

**FIGURE 1. Traffic Supply-Demand Curve, Tolled and Un-tolled** (Levinson and Rafferty 2004)

Congestion pricing (CP) is one potential solution to this issue. Congestion pricing involves incentivizing certain route choices for drivers to improve the overall efficiency of an urban area’s roadways. By pricing highly-congested roadways higher, or offering tax credits for traveling
through less congested areas, transportation systems can encourage routes that decrease the
system-wide cost of travel choices. Developments in communication and computation
technology have made the implementation of a congestion pricing system possible. This paper
examines the technologies and policies that could be implemented in a congestion pricing
system. With the information gathered from interviews and literature, it seeks to make a
recommendation for the best mix of technology and policy as well as a roll out strategy for
congestion pricing.

POLICY IMPLEMENTATION

In order to harness the installed technology infrastructure to operate a successful congestion
pricing system, the appropriate policy structure will need to be in place. There are different
types of road usage policies that vary in complexity and potential benefits. The two major types
of policies that could be used are a vehicle-miles-traveled (VMT) tax and credit-based
congestion pricing. A VMT tax is simpler, but credit-based congestion pricing could offer
greater societal benefits.

Vehicle-Miles-Traveled (VMT) Tax

The concept of a VMT tax involves charging users for the number of miles traveled on roads
within the state. VMT taxes have arisen as an alternative to the gas tax, which is a means for
states to collect funding and limit emissions. 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 DSRC or cellular communication to send the
GPS data to a central database, where the 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. 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). 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 pilots 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.

**Credit-Based Congestion Pricing (CBCP)**

Credit-based congestion pricing (CBCP) involves charging road users a fee that accounts for the marginal cost of congestion they cause (Nie and Liu 2009). Current drivers make route decisions based on the shortest path or time to their destination, and these decisions do not take into account 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 the roadway congestion, and decreasing the volume of traffic along the most congested stretches of road (Kockelman and Kalmanje 2005). CBCP would require a more complex system than a VMT tax, but it would more effectively accomplish the goal of changing user behavior to alleviate congestion. Such a system would require effective two-way communication, a fair pricing policy that attracts users, and an auditing procedure that ensures compliance.

CBCP requires communication of vehicle location and velocity data to a database, where vehicle speeds are used to evaluate the state of congestion along a given stretch of roadway. This information would be used to price routes. When certain routes are more congested, the price to travel along these routes would increase. In order to alter user behavior and ensure fairness and transparency of the congestion pricing system, the toll operator will communicate the pricing of alternative routes to the users via DSRC or cellular communication. With human operators, this information can be displayed on a smartphone or other screen ahead of time in order to allow them to alter their route based on this information. The vehicle location data can indicate when individual automobiles pass checkpoints along a route in order to toll each user. Reliable communication and accurate location data is important to ensure the consistency and fairness of those tolls.

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.

One major challenge with establishing a CBCP program is the attraction of users. Many citizens are averse to being tolled in any way. There would have to be sufficient incentives to the volunteers to encourage them to opt in. One way to do this is to provide users a tax deduction that would offset the cost of tolls collected through CBCP. With that monetary incentive, users would realize some value in joining the program. One possible issue with congestion pricing is that lower income users and people with inflexible schedules could be tolled excessively (Gulipalli et al. 2008). Equity can be improved by allocating a flat budget to each individual to spend on congestion pricing over a certain period of time (Gulipalli et al. 2008). Gulipalli et al. (2008) details more specific policy recommendations for effective CBCP management. It is essential that the policy be set appropriately to ensure efficiency, equity, and effectiveness.

**TECHNOLOGY SOLUTIONS**
Research has been 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 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 cable to send the information to a central system, and algorithms to analyze the video feed. This system would then need to have a means to communicate and toll users based on the pricing of each route. 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.

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 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 $800-1200 (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 the 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 the 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 could be combined with the video feed for a comprehensive solution, but this would result in 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 that it would be easier to attain a higher level of penetration without every user needing a communication device in the vehicle. Despite these advantages, additional infrastructure to communicate the real-time pricing to users would be required. This infrastructure would be prohibitively expensive in
addition to the video infrastructure, or could only be implemented in a limited number of locations. The challenge and cost of installing two separate systems for information collection and transmission make 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). The low latency communication of two-way messages makes DSRC useful in time-sensitive situations (ITS 2017). Since the DSRC band is reserved for mobility applications, congestion pricing would be a useful allocation of some of the bandwidth.

DSRC units would need to be installed both in vehicles and in infrastructure, with roadside equipment (RSEs). As vehicles pass the RSEs, a message is sent from the vehicle to the RSE indicating the vehicle’s position and speed, and data from all of the vehicle messages would be compiled to model the amount of congestion in a certain area. With this information, incentives for certain routes could be generated, and this information could be sent back to the vehicles via a message from the RSEs. The vehicle operator would then make a decision about which route to take based on the pricing and delay of an array of options.

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 is likely to be required in connected vehicles (CVs) 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 the congestion pricing system by adding DSRC connectivity through installation of an on-board unit. An on-board unit would cost about $1500 currently, but this price is likely to decrease as technology improves and production volume increases. On-board DSRC units 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 congestion pricing system will increase.

The other major component of a DSRC-based congestion pricing system is the installation of RSEs. RSEs have a line-of-sight range of about one kilometer. Due to the short range of DSRC RSEs, a high density of these devices would be required. Since communication is limited by line of sight, dense urban environments would require RSEs 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, RSEs are in the prototype stage and cost around $3500. With improvements in technology and mass production, that price could go down to $500-800. In addition to the cost of producing the RSE, the installation and maintenance costs would add up quickly. The installation cost could vary from $1000 to tens of thousands of dollars based on a variety of factors. Higher leads and poles for RSEs would cost more money. The additional connection to a back-hall system if not already installed would also cost more money. RSEs will 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 display 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 CVs may leapfrog DSRC and go straight to using 5G cellular communication. Benefits can be realized with the installation of a limited number of RSEs at highly congested areas, but the long time frame is an important consideration.

**Cellular-Based System**

A congestion pricing system could also be created with the use of cellular data. Information could be communicated via a smartphone or an on-board device installed in the on-board diagnostic (OBD) port in the vehicle. Each of these solutions would take advantage of the already-widespread cellular network, but they use different devices, which each have distinct advantages and disadvantages.

The smartphone solution would require an app that would allow users to opt-in to the service. This acceptance of the agreement would allow the user’s location to be tracked in order to toll users and gain information about traffic conditions. The communication to the cell tower and to the toll operator would be included in the user’s cellular data service plan. This type of system would allow for faster market penetration, because many people already own smartphones. Users could download the application that connects them to the congestion pricing system, rather than needing to install additional hardware. Location data would be collected from the phone’s GPS and sent to the tolling entity. One potential issue is with the accuracy of the 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 dense urban environments. Smartphone GPS is not accurate enough to monitor lane-by-lane traffic reliably (Claudel 2017). While such a system could be implemented, there would likely be some issues with ensuring appropriate tolling if incorrect location information is used to determine how much a user is charged.

One potential solution to the location accuracy issue would be to combine the smartphone application with the installation of an inertial measurement unit (IMU) in the vehicle (Claudel 2017). An IMU is a single unit that incorporates an accelerometer and a gyroscope. The accelerometer measures the linear acceleration along three axes (University of Maryland n.d.). The gyroscope, also known as an angular rate sensor, outputs three signals describing the angular rate about each of the axes (University of Maryland n.d.). The 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). While this does improve the location accuracy to improve the likelihood of fair congestion pricing, it also would require an additional installation, possibly deterring potential users.

The final cellular solution involves installing an OBD-II dongle in the onboard diagnostic (OBD) port. A dongle is a small electronic device that traditionally collects emissions and malfunction data (Moran and Baker 2016). Such a device could be configured to receive GPS location data and communicate using cellular data (Moran and Baker 2016). The dongle could 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 would cost around $200, while one with road-level accuracy would be less than $50 (Dorfman 2017). The OBD-II dongle would also need a cellular communication modem. A mobile chip costs around $200 at low volume, but this price
would decrease 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 benefit
the 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) could
enter into agreements with cell carriers to provide this service to improve the 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 to be $3-4 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 was implemented only through
OBD installations, electric vehicles would either need to start including a similar port or their
users could not participate in the congestion pricing program.

ADDITIONAL TECHNOLOGY CONSIDERATIONS

5G Network

While some level of congestion pricing (CP) could be implemented with current 4G or LTE
cellular communication, the development of a 5G network will increase the effectiveness of CP.
Applying congestion throughout an urban transportation network would put a large load on the
current networks and may challenge the available bandwidth (Claudel 2017). While the
development of a functioning, widespread 5G network is many years down the line, it will
further improve the performance of connected vehicles (CVs) and congestion pricing (CP).

A 5G network is expected to begin to be available 5-10 or more years from now, and there are a
few major differences between 5G and current cellular communications. New, unlicensed
spectrum will be used at the high and low ends, millimeter wave spectrum and microwave
spectrum (Andrews 2017). There will be a densification of communication with pico-cells,
femto-cells, and coordination between cells and Wi-fi (Andrews 2017). Additionally, a virtual
network will replace actual circuits, leading to greater integration with sensors and the internet of
things (IoT). 5G would allow 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 could be passed backwards along strings 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
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 many challenges with the development and adoption of a 5G network. First, a business model must be developed for the distribution of a 5G network. The public value of safety critical applications in CVs will provide value for government entities to invest in 5G. The private sector telecommunications will need to provide the service, however, and their investment will need to be profitable. Telecommunications companies could charge individual users, automobile OEMs, or government entities depending on the value to each of these groups. The ideal way in which to structure a profitable case for 5G is unclear at this point, but it will need to be determined before benefits can be realized.

Global Positioning System (GPS)

Accurate location information from the 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 fairly tolling individual users 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 a wider location radius or inaccurate estimation of the user. 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 (HOT). 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 meter (Humphreys 2017). This service allows for nearly lane-level accuracy, but there would be significant potential error. In Europe, the Galileo satellite system has a wider bandwidth and offers greater accuracy than standard GPS in the U.S. 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 11 Galileo satellites in orbit, and 30 satellites are expected to be in orbit within five years. 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.

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. So, the accuracy of location information is a challenge to CP, but
current technology is sufficiently accurate for a basic system. With the correct systems in place, CP 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 release of location information. Allowing the government to handle personal location information at all times would likely deter some users.

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 what insurance companies and OEMs currently use for vehicle monitoring (Sturgeon 2017). While location and speed information is anonymized for many DSRC safety applications, anonymization may not be used for applications that toll individual users.

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 communications used for congestion pricing are not made robust or monitored properly. While some users may be concerned about the possibility of people hacking into and taking control of vehicles, this would not be a concern for congestion pricing applications, as the installation could be made to be push-only. Security and privacy are major concerns of a location-based congestion pricing application, and they must be priorities when implementing congestion pricing.

**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 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, the 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 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 selection of 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 who are using GPS or communication jammers, it would likely deter people due to the chance of being caught and fined.

CONCLUSION

VMT fees and CBCP are related, but they are separate types of policies. VMT fees primarily help cities gain funding for roadways with declining profits 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 would take. CBCP would be far more effective in alleviating congestion, as this policy is focused on route selection based on the congestion at a given time. However, the technologies and systems required for each program are similar.

VMT fees and CBCP could both 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 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 these highly congested locations. If the CBCP program 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 for use in congestion pricing. The value of each of these technologies is based solely on its value for congestion pricing, 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 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

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 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 these highly congested locations. If the CBCP program 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.

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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

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 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 these highly congested locations. If the CBCP program 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.

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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 or requires costly, redundant technology. Therefore, a cellular or DSRC solution would be most effective.

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, 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 installed along roadsides throughout cities. DSRC is not installed almost anywhere right now, and roadside units 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 to be implemented at locations with high congestion in the short term, as a pilot system. Bridges, major highways, and other commonly congested stretches of roads would be the ideal location for such pilots. The use of congestion pricing at the most congested areas would encourage people to take alternative routes or drive at off-peak times in order to reduce the cost of their travel. 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 rather than just a few key nodes.

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