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16. ABSTRACT

Pricing externalities from vehicle use such as road damage, vehicular emissions (both greenhouse gases and local pollutants), and congestion has become a hot topic in the transportation sector in recent years. Road user charge pilot programs are being explored in various states in the US, cities like New York and San Francisco are following in the footsteps of Stockholm and London by announcing plans to implement congestion pricing, and numerous cities and countries have announced gasoline vehicle phase-outs or bans. In this study, we provide an overview of the academic literature related to vehicle pricing, we examine case studies of locations where pricing has been implemented, and we investigate the design choices for programs that would address each of the three externalities. Our analysis finds opportunities for integrating technology across multiple pricing programs–by relying on overlapping systems, programs can be implemented more efficiently and provide tremendous cost savings.

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IMPLEMENTING PRICING SCHEMES TO MEET A VARIETY OF TRANSPORTATION GOALS

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ABSTRACT

Pricing externalities from vehicle use such as road damage, vehicular emissions (both greenhouse gases and local pollutants), and congestion has become a hot topic in the transportation sector in recent years. Road user charge pilot programs are being explored in various states in the US, cities like New York and San Francisco are following in the footsteps of Stockholm and London by announcing plans to implement congestion pricing, and numerous cities and countries have announced gasoline vehicle phase-outs or bans. In this study, we provide an overview of the academic literature realted to vehicle pricing, we examine case studies of locations where pricing has been implemented, and we investigate the design choices for programs that would address each of the three externalities. Our analysis finds opportunities for integrating technology across multiple pricing programs–by relying on overlapping systems, programs can be implemented more efficiently and provide tremendous cost savings.

***K*eywords** vehicle pricing, congestion charges, mileage fees

1 Introduction

Passenger vehicle transportation is associated with a large number of externalities such as congestion, emissions, and road damages. For logistical and political reasons, it can be difficult to price these externalities. Traditionally, the gasoline tax has acted as a "catch-all" fee that prices both driving and fuel efficiency. Unfortunately, the gas tax suffers from both structural deficiencies and challenges from alternative fuel vehicle adoption. In the United States, the federal gasoline tax rate was last altered in 1993 (OBRA[1]) and has remained at 18.4 cents per gallon for the last 26 years. Unfortunately, this has decreased the effective revenue stream for transportation infrastructure construction and maintenance over time, due to inflation and improvements in fuel efficiency (which leads to lower fuel consumption). Indexing fuel taxes to inflation has only been achieved recently at the state-level by a few leading states such as California[2] and Oregon[3]. One of the primary reasons that gasoline taxes have remained static is that changes to the gasoline tax have been historically fraught with political challenges. For example, immediately after California passed SB1 to increase the gasoline tax and index it to inflation, a ballot proposition measure was introduced to repeal the

[1] Omnibus Budget Reconciliation Act of 1993: https://www.congress.gov/bill/103rd-congress/house-bill/2264/text

[2] Senate Bill 1 (2017): https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1

[3] House Bill 2017: https://olis.leg.state.or.us/liz/2017R1/Measures/Overview/HB2017

bill[4]. Increases to the gas tax has led to political turmoil and even civil unrest in countries such as France[5], the United Kingdom[6], and India[7].

Additionally, the advent of electric vehicle (EV) technology has led to concerns that transportation infrastructure funding will further decrease as EVs are adopted in the future. This has led states across the US to enact additional registration fees targeted towards EVs, despite research describing their drawbacks [1] and their current lack of impact to transportation infrastructure funding [2]. Nevertheless, EVs have motivated new conversation regarding alternative pricing mechanisms to replace the traditional gasoline tax–which may also be an opportunity to implement other pricing schemes. While transportation pricing, or more specifically mileage, congestion, or occupancy fees, have been long discussed in the literature (Section 2) and have begun to be implemented in the real-world (Section 3). We then analyze the possible design choices in implementing a pricing scheme to address different externalities, from data collection to payment of the fee (Section 4).

2 Literature Review

Vehicle pricing has been prevalent in the literature for several decades. Two of the most common pricing mechanisms are congestion pricing and mileage fees. In the following section we provide an overview of studies on both topics.

Congestion pricing The concept of congestion pricing, a fee enacted to capture the externalities of traffic congestion, was first introduced in the 1960's [3]. In the 1990's, several substantive studies on congestion pricing were published. Small (1992) suggested the revenue from congestion fees should be used in two ways: first, to provide travel allowances and tax reductions to decrease the regressive nature of the fee; second, to create a funding package that supplements traditional funding for new highways, improves public transit, and upgrades business centers (all of which can help mitigate congestion) [4]. While Kirstoffersson et al. (2017) argue that the most efficient implementations of congestion charges affect low-income groups disproportionately [5], a case study by Eliasson and Mattsson (2006) of a real-world congestion charge implemented in Stockholm argues that the net benefit from the revenue, if spent correctly, far outweighs the regressive component of the fee [6]. Nevertheless, congestion pricing, like gas taxes, are a politically challenging topic [7]. As recently as 2018, California attempted to pass AB 3059[8], a bill that would enable congestion pricing pilot programs in the state, but it failed to pass the Legislature. Studies have suggested improving the political acceptability of the fee by limiting them to freeways [8], offsetting fees through returning revenues to the public and restricting pricing to specific lanes [9], and increasing awareness of individual (rather than social) benefits of pricing [10].

Congestion pricing in practice has also been examined, but most studies focus on how to pursue an outcome or on the impact of implementation. For example, Börjesson and Kristoffersson (2018) present price elasticities with respect to congestion measures in Stockholm and Gothenburg and find that sensitivity to price changes were relatively low relative to the initial implementation where most of the traffic was priced off the road [11]. Lehe (2019) provides a comprehensive overview of congestion pricing in five major cities and provide four major takeaways: exemptions are highly consequential to the effectiveness of the pricing scheme, increases in fees are much milder than the initial implementation, the implementation can successfully be funded by revenues from the scheme itself, and the implementation has always been tied to an unusual political event [12]. De Palma and Lindsey (2011) reviews methods through which a congestion price can be enacted through tolling mechanisms, providing details on technologies that can be leveraged for implementation including digital photography, tag and beacon systems, in-vehicle systems, and/or satellite communications [13]. The authors point out the scope and success of any congestion pricing scheme is heavily dependent on the technology used for implementation, a conclusion that appears to be borne in practice as seen in Lehe's work. This study attempts to expand De Palma's work across all other pricing mechanisms.

[4] Proposition 6 (2018) `https://lao.ca.gov/BallotAnalysis/Proposition?number=6&year=2018`

[5] James McAuley. "France suspends fuel tax after weeks of unrest". *The Washington Post* (2018). `https://www.washingtonpost.com/world/france-suspends-controversial-fuel-tax-after-weeks-of-unrest/2018/12/04/d32577a6-f7b6-11e8-8d64-4e79db33382f_story.html`

[6] Roger Harrabin. "Fuel protests costs treasury 2bn yearly". *BBC News* (2004). `http://news.bbc.co.uk/2/hi/uk_news/3716346.stm`

[7] Nidhi Verma. "Indian opposition calls nationwide protests to take on Modi over fuel prices". *Reuters* (2018). `https://www.reuters.com/article/us-india-election-fuel/indian-opposition-calls-nationwide-protests-to-take-on-modi-over-fuel-prices-idUSKCN1LM28D`

[8] Assembly Bill 3059: `https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB3059`

Mileage fees In a similar vein to congestion pricing, there is a tremendous amount of literature on mileage fees. A mileage fee (also commonly referred to as a road user charge [RUC]) is simply a distance-based charge per mile/kilometer driven by a vehicle. Unlike congestion pricing, it is not tied directly to an externality but it indirectly addresses congestion, road use and damages, and pollution emissions, all of which increase with more miles on the road. Taxes on gasoline and diesel are perhaps the closest existing version of mileage fees. Their original implementation was designed to proxy for distance travelled based on a "user pays" principle. Litman (1999) discusses the benefits of mileage-based fees while considering how the fees can be structured (based on distance combined with weight, prorating registration/license fees, distance-based insurance, and weighted with emissions) [14]. The size of the fee can be relatively small: between $0.005 to $0.013 per mile [15] (though a full internalization of the marginal cost of driving could be as high as $0.077 to $0.091 per mile [16]). Nevertheless, public opposition (similar to fuel taxes) for a RUC is quite high [17], though participants in pilot programs have had a relatively high approval of the RUC (>90%) [18].

One of the motivations behind transitioning away from fuel taxes to a RUC is to address the transition to alternative fuel vehicles which do not pay the gas tax. Unfortunately, a uniform mileage fee also removes one of the benefits of traditional fuel taxes which encourage efficiency (and thereby environmental impacts). While Forkenbrock (2008) points out that this effect is relatively small, he also suggests that a mileage-fee can be structured to advance specific policy goals, including an incentive to operate more efficient vehicles [19]. Another concern of the RUC is the equity impacts of the fee. Several studies have indicated that a RUC does not significantly impact different distributional groups [20] or is not any more regressive than a simple gasoline tax [21] (in fact there is evidence that the RUC may be *less* regressive than a gasoline tax[9]). Further, Burris et al. (2015) indicates that the disbursement of revenue from a RUC could be structured to overcome any equity concerns [22].

Environmental Fees Lastly, the pricing of environmental impacts has been an important topic of study. Because of the correlation between the amount of driving and environmental impacts, these impacts are often viewed as secondary benefits of congestion pricing, mileage fees, and fuel taxes. Several authors point out these co-benefits with fuel taxes on green outcomes [23, 24]. Beevers and Carslaw measured the decrease in CO_2, NO_x, and PM_{10} emissions in London resulting from the congestion charging scheme implemented in 2003, all of which decreased by 10-20% [25]. Daniel and Bekka provide a similar analysis for simulated benefits if a congestion charge were to be implemented in Delaware [26].

Others advocate for modified versions of congestion/VMT fees to better incorporate environmental externalities. Greene (2011) argues that an indexed energy user fee better aligns to a greenhouse gas reduction effort than a pure mileage fee [27]. He suggests that the energy user fee complement other types of fees that would be based on congestion or weight. Several studies have proposed specific pricing mechanisms to optimally reduce environmental impacts (sometimes in addition to other externalities) [28, 29, 30, 31]. While many of the proposals on pricing rates provide novel insights on structure and impacts, almost none of these studies provide explore how they would be implemented in practice.

3 A History of Pricing Mechanisms

Many aspects of vehicle pricing and their impacts have been discussed in the literature review (Section 2). In the proceeding section we provide an overview of different pricing mechanisms that have been implemented in the real world. The distinction between different fees for vehicle pricing are not black and white. While fees can address multiple externalities, we group the existing fees based on their primary goals.

3.1 Fuel Taxes

By far the most common pricing mechanism is the gasoline/diesel fuel tax. The size of the tax varies from country to country (Figure 1) and can even vary within a country on a regional level (as evidenced at the state level in the US as seen in Figure 2). The taxes are levied on a volumetric basis (gallons in the US and liters elsewhere) and are typically collected at the terminal (storage facility after the refining, prior to distribution to stations). Due to the small number of terminals (relative to gas stations), the cost of administration and collection of the tax comprises only approximately 1% of the revenue raised from the tax. In the United States, individual states report gasoline consumption to the US Department of Transportation (DOT) and taxes are collected by the Internal Revenue Service (IRS) before disbursement. Taxes can be structured as either a sales tax (based on a percentage of price) or an excise tax (flat rate).

The amount an individual pays for a gasoline/diesel tax a function of how far he/she drives as well as the fuel efficiency of the vehicle that is being driven. In the United States, funds from fuel taxes (at the federal level and most states) must be used to fund transportation infrastructure (construction and maintenance) as well as to transportation agencies

[9]"Oregon's Road Usage Charge". Oregon Department of Transportation (2017)

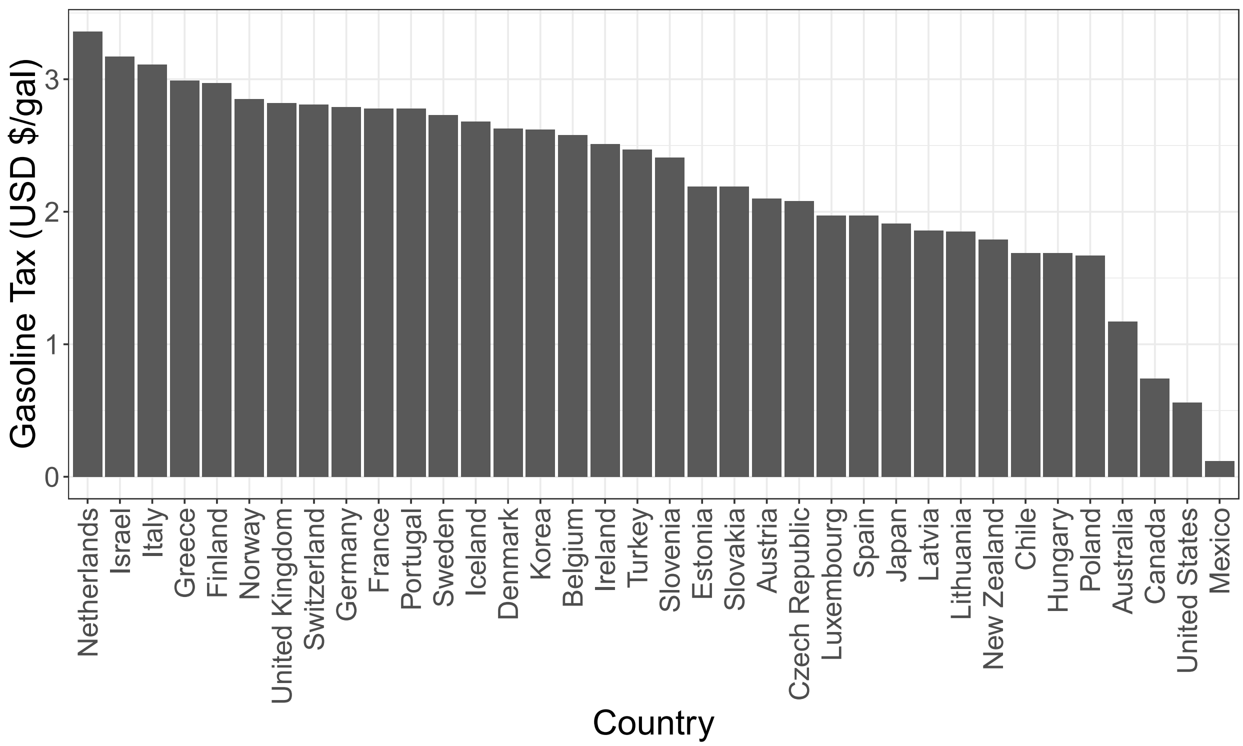

Figure 1: Comparison of gasoline taxes (in USD $ per gallon) across different countries in 2019. Note that the rate in the United States includes the weighted average of state taxes in addition to the federal tax.

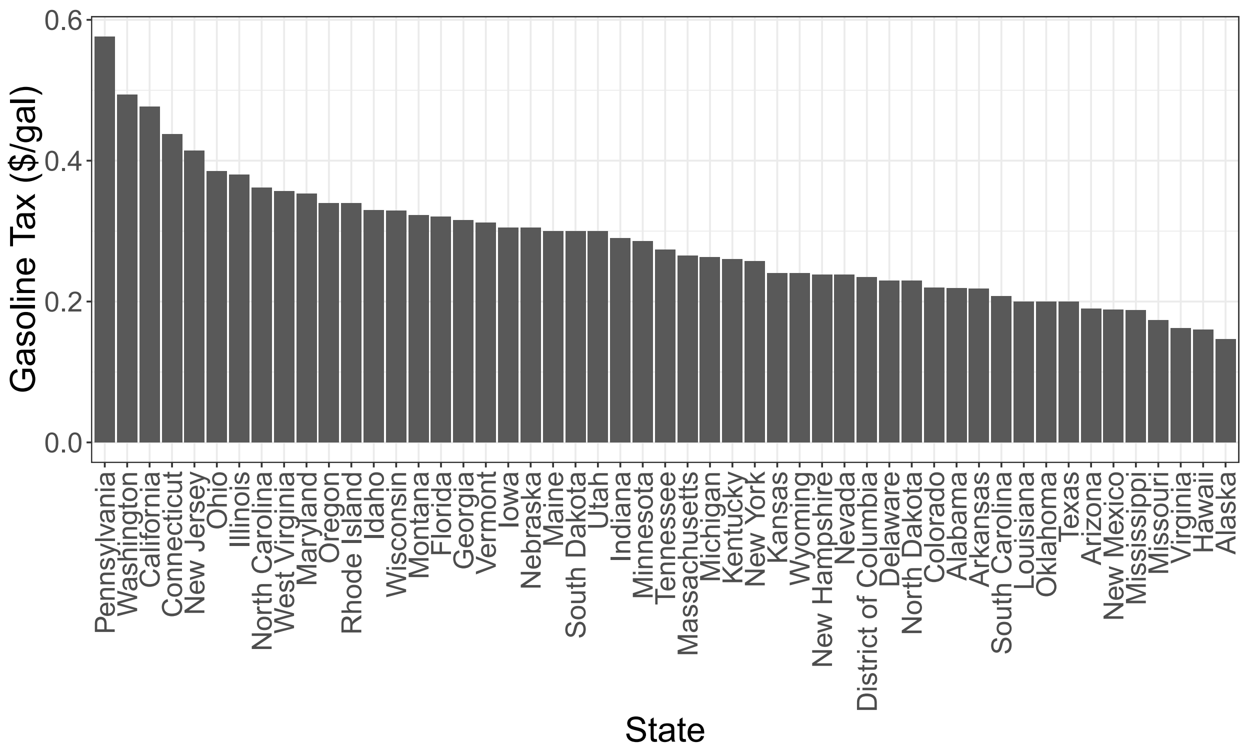

Figure 2: Comparison of gasoline taxes ($/gal) across different states in the US in 2019

(Departments of Transportation). There are exceptions to this, for example: Norway splits their fuel tax into a road use tax and a CO_2 tax, thereby directly addressing separate externalities. In other countries such as Australia, England, Germany, Italy, and Mexico, the fuel tax is not used to directly pay for their roads and instead is diverted into a general fund.

3.2 Mileage Fees

A mileage fee, commonly referred to as a road user charge (RUC), is a tax based on the distance driven by a vehicle (miles in the US, kilometers elsewhere). In the United States, the RUC has been primarily been viewed by transportation departments as a means to fund transportation infrastructure, which has traditionally come from fuel taxes. There has been some discussion on the use of a RUC to encompass other pricing purposes (such as congestion pricing), but stakeholders are somewhat averse to these discussions due to low political acceptance of the RUC[10]. However, in Europe, some mileage fees have been coupled with other vehicle pricing strategies. While literature on the subject is rich (see Section 2), this type of fee has not been widely adopted. Below, we provide an overview of implemented mileage fees and significant pilot programs of the fees.

Oregon Oregon is the first, and currently only state, to implement a road user charge in the United States. In 2001, Oregon created the Road User Fee Task Force (RUFTF) to assess alternatives to their fuel tax to generate revenues for transportation infrastructure. In 2006-2007 and 2012-2013, Oregon Department of Transportation (ODOT) ran two pilots to test implementations of a mileage fee. In the first pilot, vehicles were equipped with on-board equipment that would transfer data to pumps at gas stations when participants refueled their vehicle. In the second pilot, participants were able to choose a GPS device, a similar on-board diagnostics (OBD) device as the first study, a flat fee, or a smartphone app to collect mileage information. Following the success of the two pilots, Oregon launched a full RUC program called "OReGO", which is an opt-in mileage fee program for any residents in Oregon who wish to transition away from the fuel tax into a road user charge. Volunteers can opt into a government approved and managed system or a private sector commercial system that competes by offering value-added services.

Oregon's program has led to several key findings: perception of participants was positive, privacy concerns could be addressed, and participants could successfully be integrated into a RUC in the presence of a gasoline tax. One of the critical elements of success is the cost-effectiveness of the program, but one of the biggest drawbacks of a RUC is its relatively high cost compared to the fuel tax. Oregon's first two pilots cost $4.8 million for 387 participants–a tremendously high cost, though the program was not operating at scale. Since then, Oregon's full implementation has cost $2.3 million over two years for a total of 1,238 vehicles, an order of magnitude lower than the initial pilots but still more than the RUC brings in revenue. ODOT published a full report of their program outcomes in April 2017[11].

California In 2014, the California Legislature passed SB 1077[12], a bill that required the California Department of Transportation (Caltrans) to design and implement a pilot program[13]. The pilot program was launched in July 2016 and was administered to about 5,000 vehicles in California over the course of nine months. In order to track the miles driven by participants' vehicles, Caltrans relied on five different reporting methods: a device that plugs into a vehicle's on-board diagnostics (OBD II) port, in-vehicle telematics, a commercial vehicle mileage meter (only for commercial and fleet vehicles), GPS from a smartphone, and manual readings from odometers (by taking pictures of the vehicle odometer at set intervals). The reporting methods mirrored those of Oregon, but the pilot operated at a slightly larger scale. While the road charge rate was set at $0.018 per mile (estimated to be revenue-neutral with the average vehicle in California), no revenue was actually collected in the pilot. Instead, the pilot conducted mock invoices and payments to simulate a revenue collection process.

Similar to Oregon, the California pilot found that participants were generally had a positive perception of the program. Nevertheless, Caltrans identified critical elements of success for implementing a RUC in the future. Their suggestions included further investigation into the revenue collection process, specifically with a pay-at-the-pump model, use of in-vehicle telematics, and organizational considerations when transitioning away from a gasoline tax.

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[10] Public Workshop by the California Transportation Commission, November 11, 2018. http://ctc.dot.ca.gov/webcast/roadcharge/vod_roadcharge.asp?vodfilename=20181116_tac_1.mp4

[11] Oregon Department of Transportation. "Oregon's Road Usage Charge, The OReGO Program Final Report". April 2017. https://www.oregon.gov/ODOT/Programs/RUF/IP-Road%20Usage%20Evaluation%20Book%20WEB_4-26.pdf

[12] SB-1077 Vehicles: road usage charge pilot program https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1077

[13] California Department of Transportation and California Transportation Commission. "California Road Charge Pilot Program 2017, Final Report Senate Bill 1077." December 2017. https://dot.ca.gov/-/media/dot-media/programs/road-charge/documents/final.pdf

Minnesota In 2007, the Minnesota Department of Transportation was granted $5 million to conduct a pilot program that would transition away from the state's fuel tax [14]. The program pilot began in September 2011 and spanned a full year through October 2012 and contained a total of 500 participants. Program participants were provided a GPS-enabled smartphone to collect and transmit data as well as an OBD device that would be directly connected to the vehicle. The OBD device communicated with the phone which would then report data for several fee categories: miles travelled outside Minnesota, within Minnesota, within the Metro Zone (Minneapolis/St. Paul), and within the Metro Zone during peak periods of the day. Fees ranged from $0.01 to $0.03 per mile. Participants were able to make payments using a variety of options: by mail, online, and in person at a Minnesota Road Fee Test office.

Oceania In 1977, New Zealand passed the Road User Charges Act 1977[15], leading to the introduction of the RUC system. The RUC is primarily assessed to vehicles that weigh over 3.5 tons (though vehicles that do not pay taxes when fueling are also subject to the RUC regardless of weight). The New Zealand Transport Agency relies on a cost allocation model that balances attributing road wear with institutional complexity. The amount of the charge is determined as a function of the number of axles on the vehicle and tires per axle. The RUC is administered on the basis of 1,000 km permits: drivers essentially pay for every 1,000 km they drive rounded up. Customers are currently able to purchase a RUC license through several different channels including over the counter at NZTA agencies, directly from the Motor Vehicle Registry, online via the NZTA, by telephone/fax through service centers, and at authorized service stations/truck stops. Measurement occurs primarily through hubodometers (legally required for heavy vehicles), which count the wheel revolutions for the axle to which it is attached. Compared to more modern RUCs mileage collection methods, the hubodometer is a relatively older technology that has operational issues and can be susceptible to tampering. As a result, NZTA has considered more advanced technologies such as on-board measurement devices and tracking systems that employ GPS/cellular technologies.

Europe Several European countries have implemented versions of a road user charge, but they have primarily been applied to medium and heavy-duty vehicles, not passenger vehicles[16]. Commercial and fleet vehicles tend to have a slightly easier time standardizing for a RUC, and their lower volumes makes implementation slightly easier. Schemes that include a weight-based RUC have been implemented in Switzerland, Germany, Austria, Czech Republic, Slovakia, and Poland. Switzerland's system was implemented in 2001 for vehicles weighing more than 3.5 tonnes with a pricing system based on the total loaded weight, emissions, and miles driven. The system employs an on-board unit that collects information on mileage. One of the unique aspects is that it can be switched off by a microwave beacon at border crossings, so that miles driven out of the country are not charged. The data is downloaded by the owner on a periodic basis and forwarded to the Swiss Customs Administration which then collects the revenue. In Germany, heavy duty trucks weighing over 7.5 tonnes are assessed a mileage fee. Similar to Switzerland, Germany employs on-board units that transmit data via cellular communication using a GPS to a private operator (otherwise drivers must pay a toll by credit card). Fees are based on miles and number of axles, but not weight. Slovakia and Hungary also both employ GPS-based systems. Austria began a RUC system in 2004 for trucks and buses weighing more than 3.5 tonnes. In addition to pricing tiers for number of axles, Austria further classifies fees based on vehicle size within each axle group. The Austrian system employs a microwave transponder on-board unit (similar to Switzerland) but does not contain GPS. The devices act as a tag-and-beacon system, communicating with toll collection devices. Poland and the Czech Republic also use microwave systems similar to Austria's, though the rates are charged with different criteria. In the Czech Republic, the rates are also based on the time of day, overlapping functionality with congestion pricing.

3.3 Congestion Pricing

Congestion charges are meant to address externalities associated with traffic congestion. Congestion is typically priced either by location (in heavily congested areas) or by time (during rush hour). While the purpose of a congestion charge differs from a RUC, the systems often overlap. For example, in the aforementioned Czech Republic RUC system, mileage fees also vary by time of day to discourage travel during times of rush hour. Nevertheless, in the following section we focus on examples of pricing that were designed with the primary intent of reducing traffic on roadways.

Singapore The first congestion pricing in the world was launched in Singapore in 1975 and continued for over two decades until 1998. Singapore employed an "Area License Scheme" (ALS) that consisted of a cordoned Restricted

[14] "Vehicle Miles Traveled (VMT) Fees: Preliminary Report - Tasks 1 and 2". Texas A&M Transportation Institute. https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-14-02-P.pdf

[15] Road User Charges Act 1977. Parliamentary Counsel Office. http://www.legislation.govt.nz/act/public/1977/0124/43.0/DLM19000.html

[16] Kirk, Robert S. and Marc Levinson. "Mileage-Based Road User Charges". Congressional Research Service. June 22, 2016. https://fas.org/sgp/crs/misc/R44540.pdf

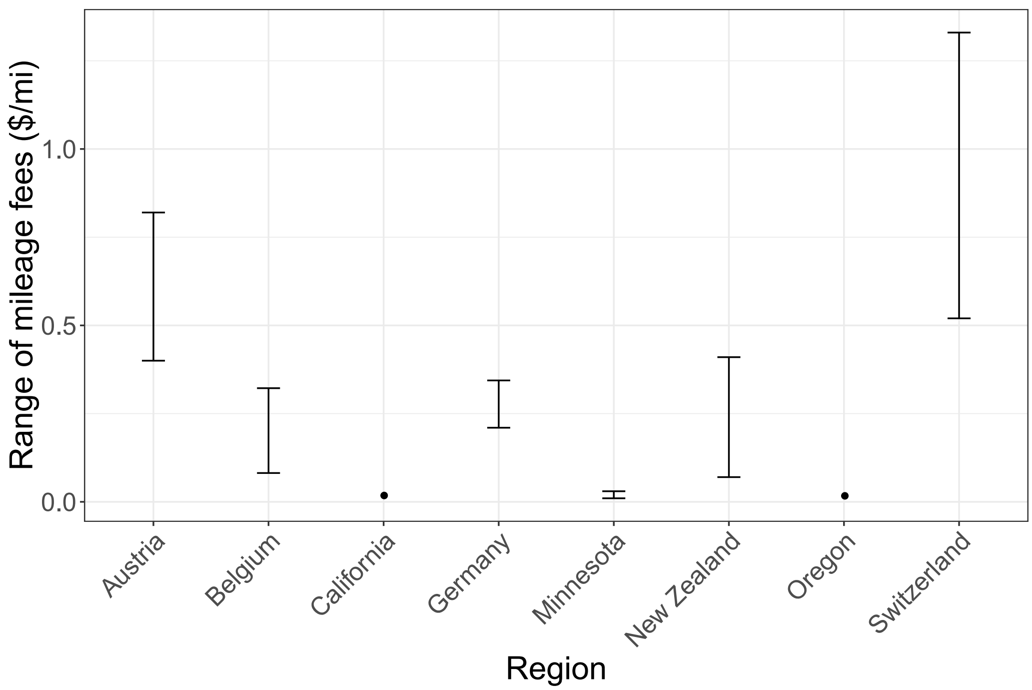

Figure 3: Comparison of road-user charge fees by different countries and by different states in the US. Rates are generally uniform per distance, or they vary by vehicle weight, number of axles, and time. The states in the US and New Zealand are applied to passenger vehicles while the European countries are applied to heavy-duty vehicles. Both the Minnesota and California RUC programs were pilots.

Zone (RZ) that would charge money to enter the RZ (but not to drive inside or exit). Additionally, vehicles would only be charged at certain times, which varied over the lifetime of the program but generally occurred during rush hour. The program was implemented using paper decals that wardens at control points would check (manually noting vehicles that lacked valid licenses). While the system is dated, compared to many of the more technologically advanced implementations discussed in this study, Singapore's congestion pricing scheme was fairly successful at reducing entries into the RZ (a 73% reduction of cars entering and a 4.5 factor increase in carpool entries within the first year [32]). Additionally, the program was fairly cost effective: in 1976 it raised $11.8 million USD while costing only $1 million USD to operate. By 1992, it raised $40 million USD in revenue while costing $3.2 million USD. In 1998, Singapore switched their congestion pricing to an electronic system as the administration of ALS increased in complexity. The system consisted of an on-board unit that sat on a vehicle's dashboard, which would be scanned at gantries when a vehicle passed by. This tag-and-beacon system is essentially an electronic toll located at control points around three contiguous cordon zones within Singapore. However, the toll rates vary by time (once again, with peak rates during periods of high congestion) and have been re-structured several times in the last two decades. The electronic system was significantly costlier than the ALS, with operational costs ranging from 20%-30% of the revenues raised.

Hong Kong Hong Kong was the first region to investigate an electronic pricing system in a series of studies from 1983 through 1985. Similar to Singapore, the system was also a tag-and-beacon system but rather than gantries, the control points outlining the cordoned zones were inductive loops embedded in the pavement that would interact with transponders placed underneath the vehicles. While the pilots were relatively successful, privacy concerns prevented the system from being implemented after the studies were concluded in 1985 [33].

Stockholm and Gothenburg, Sweden After a seven month trial period, Stockholm implemented a full-scale congestion pricing system for vehicles entering and exiting the city in 2007. This pricing scheme was initially implemented as a trial and concluded in a referendum to keep the pricing permanently in place. Despite polling quite negatively after its introduction, the referendum passed by popular vote following the trial period and the scheme was kept in place. Stockholm's system is also an electronic (radio-based), time-varying toll (tag-and-beacon) system in both directions across a cordon zone spanning the city center. The rates for congestion pricing have changed over time, and they vary based on the time of day, which part of the cordon zone is crossed (inner city, arterials, and outer artierials), and are also limited to a daily maximum. Implementation costs for the pilot were relatively high, at $282 million USD, but over time annual revenues have grown ($198 million USD in 2017) while annual costs have shrunk ($14 million USD in 2017) [6].

Following the success of the Stockholm congestion charge, the Gothenburg City Council launched a congestion tax in 2013 in order to fund several transportation projects. The scheme used the same technology and design as the Stockholm congestion charge. Again, tolls vary based on the time of day, location of control points, exemptions for tax deductions, and maximum charges over a designated period of time. The initial costs of the congestion charge system were significantly lower than Stockholm's at only $57 million USD.

London, United Kingdom In 1998, London convened a team of experts known as the Road Charging Options for London Working Group to assess pricing options. Unlike the recently implemented electronic tolling in Singapore, the London Congestion Charge launched in 2003 using an automatic number plate recognition system. More importantly, rather than developing control points for the cordon zone, the system covers all travel within the cordon zone. Cameras are located all around the city to track and identify licenses to drive within the city. Drivers must pay by midnight via phone, SMS, online, or at a designated payment machine. Also unlike other congestion schemes that have been discussed thus far, the pricing is flat rather than varying over time with a single payment that allows drivers to drive within the city for the entire day. The rate has varied quite a bit since it's initial implementation, starting at $9.8 USD in 2003 and reaching as high as $17.4 USD in 2016. One of the notable exemptions of the congestion charge are electric vehicles: both plug-in hybrids and full battery electric vehicles are granted a 100% discount. These exemptions, and similar exemptions for other "green" vehicles are a strong incentive to use clean vehicles within the city.

Other In the United States, congestion pricing has been gaining traction in several localities. In 2019, following two years of negotiation, the Governor of New York and the Mayor of New York City agreed to implement congestion pricing in New York City by 2021. Meanwhile, California introduced AB 3059[17] in 2018 to allow for four pilot programs to test congestion pricing, but the bill failed to pass. Nevertheless, the San Francisco County Transportation Board Authority voted in 2019 to conduct and implement a downtown congestion pilot pricing study.

Several countries in South America have also attempted congestion pricing schemes. For example, Brazil enacted the Urban Mobility Law[18] in 2013 that enables municipalities to implement congestion pricing. São Paolo developed a strategic plan to introduce a $2 USD per day congestion charge based on reading license plates, but it has yet to be implemented. Chile has implemented congestion pricing in Santiago de Chile on urban freeways using tag-and-beacon tolls.

3.4 Environmental Pricing

Many policies that price environmental externalities are focused on the initial purchase of the vehicle (bonus malus/feebates) or through command and control of vehicles' fuel efficiency and/or emission rates (e.g. US Corporate Average Fuel Economy Standards and Greenhouse Gas Emission standards, China's Corporate Average Fuel Consumption Standards, and EU's Fuel Economy Rules). Few pricing schemes are primarily motivated by environmental purposes, but many pricing mechanisms (both road charges and congestion pricing) are coupled with environmental goals of reducing emissions. Some environmental organizations have opposed transitioning to a road user charge because they do not incentivize fuel efficiency like the current gasoline tax. Nevertheless, we provide several examples of pricing schemes that were motivated by primarily environmental concerns.

Beijing, China In Beijing, a system of rationing road space was introduced on a permanent basis following the success of the program that was employed during the 2008 Olympic games [34]. The scheme was developed in order to restrict vehicle emissions. The policy is technically not a pricing policy, but rather a restriction on which cars are allowed on the road (subject to a fine of about $28 USD and points added to drivers licenses, which can eventually lead to suspension). When the air quality index is predicted to stay above 200 for more than 3 days, a temporary driving restriction is imposed that removes half of the city's cars off the streets. For vehicles with license plates that end on an odd number, they are allowed to drive in certain areas of the city on half of the restricted days. On the other half (alternating days), vehicle license plates that end on an even number are allowed. Electric vehicles are exempt from these restrictions. Additionally, vehicles that are registered outside of Beijing must obtain a permit (costing about $7 USD) and cannot drive in the city for more than one week.

[17] Assembly Bill 3059: Go Zone demonstration programs https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB3059

[18] Xavier, José Carlos and Renato Boareto. "The Implementation of Brazil Sustainable Urban Mobility Policy". https://thredbo-conference-series.org/downloads/thredbo9_papers/thredbo9-workshopF-Xavier-Boareto.pdf

Milan, Italy In 2008, Milan instituted an urban toll within a traffic restricted zone called the *Zone a Traffico Limitato* (ZTL) in a program known as the Ecopass. While the original program was only meant to last for one year, it was extended until the end of 2011 before being replaced by a new scheme known as Area C which converted the pollution charge to a congestion charge. Fees ranged from about $2 to $10 USD for vehicles within the ZTL, but exemptions were provided for vehicles compliant with certain European emission standards (Euro 3 and 4). Residents could also purchase annual passes that varied from about $80 to $300 USD depending on their vehicles' emissions rates. The tolls employed digital cameras at 43 electronic gates that tracked license plates. Travelers can pay by the end of the day, though the system suffered from complaints regarding lack of reliability[19]. The impacts on pollution have been well demonstrated across several studies, with measurable decreases in particulate matter, NO_x, and CO_2 [35, 36, 37, 38].

Other In addition to environmental pricing mechanisms, a large number of cities and even countries are taking a more strict approach to the externalities associated with fossil fuel. A dozen countries and over twenty cities have announced bans or commitments to bans for gasoline and diesel vehicles in order to meet national or local climate targets, in addition to reducing health risks from local emissions.

4 Implementation of Pricing Mechanisms

While there has been significant literature discussing how pricing should be structured (mainly focusing on what metric should be priced and by how much), few studies examine the logistics of implementation. We consider design aspects of pricing mechanisms that would address three externalities associated with driving: use and damage to the roads, environmental damages, and traffic congestion. Oftentimes the stakeholders associated with pricing of a single externality are not closely connected to those associated with a different externality. For example, in California the Department of Transportation spearheads efforts for a RUC while other organizations (such as cities) are the entities considering congestion pricing pilots. The primary purpose of the following section is to point out opportunities for overlap in practice and implementation.

4.1 Data To Be Collected

Pricing externalities requires data specific to the damages being caused. In Figure 4, we show the data necessary to address road use/damages, environment, and congestion (note that not every data category is necessary and that certain combinations of data can be sufficient for a particular program). For a road charge, it is necessary to know the miles travelled and direct collection of VMT is sufficient for a uniform mileage fee. However, because road damages are a function of weight, it would be possible to modify the road charge to factor in this variable as well. Additionally, it is also possible to proxy for the distance travelled by instead measuring the amount of fuel (or energy) consumed, which is the basis for the current gasoline tax. Therefore, the categories of information associated with use and damage to roads are: **fuel/energy consumed, VMT, and weight**.

Meanwhile for environmental damages, a direct measurement of the emissions coming out of the tailpipe can be used to quantify pollutant and greenhouse gases associated with driving. However, it is also possible to indirectly calculate these values. One method would be to collect VMT information and couple it with the efficiency of the vehicle, thereby allowing for a calculation of the fuel/energy consumed which can then be converted to an estimate of vehicle emissions. Alternatively, it is also possible to collect the fuel/energy consumption information directly (as in the case of the gas tax). Lastly, we also consider weighting the emissions by number of passengers–a metric that has long been discussed in academic literature and recently implemented in real-world policy (grams of CO_2 per passenger mile in SB 1014[20]). Therefore, the categories of information associated with vehicle emissions are: **direct emissions measurement, VMT and efficiency, fuel/energy consumed, and occupancy**.

The data required for congestion pricing is quite different from the previous two extenalities. Vehicle congestion occurs at specific times and locations–vehicles that contribute to said congestion should then be priced accordingly. The necessary pieces of information are location and time. Additionally, pricing can be weighted by passenger occupancy (as an incentive to encourage pooling). Therefore, the categories associated with congestion pricing are: **location, time, and occupancy**.

The choice of data associated with a particular externality is a critical decision because it informs all subsequent design choices of the pricing system. Figure 4 demonstrates this clearly: the technology used for data collection are not

[19] Balducci, Alessandro, et al. "Country Case Study: Italy - WP 8". Milan Polytechnic Dipartimento di architettura e pianificazione". March 2008. https://www.hannover.de/content/download/7973/730022

[20] California Clean Miles Standardshttps://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1014

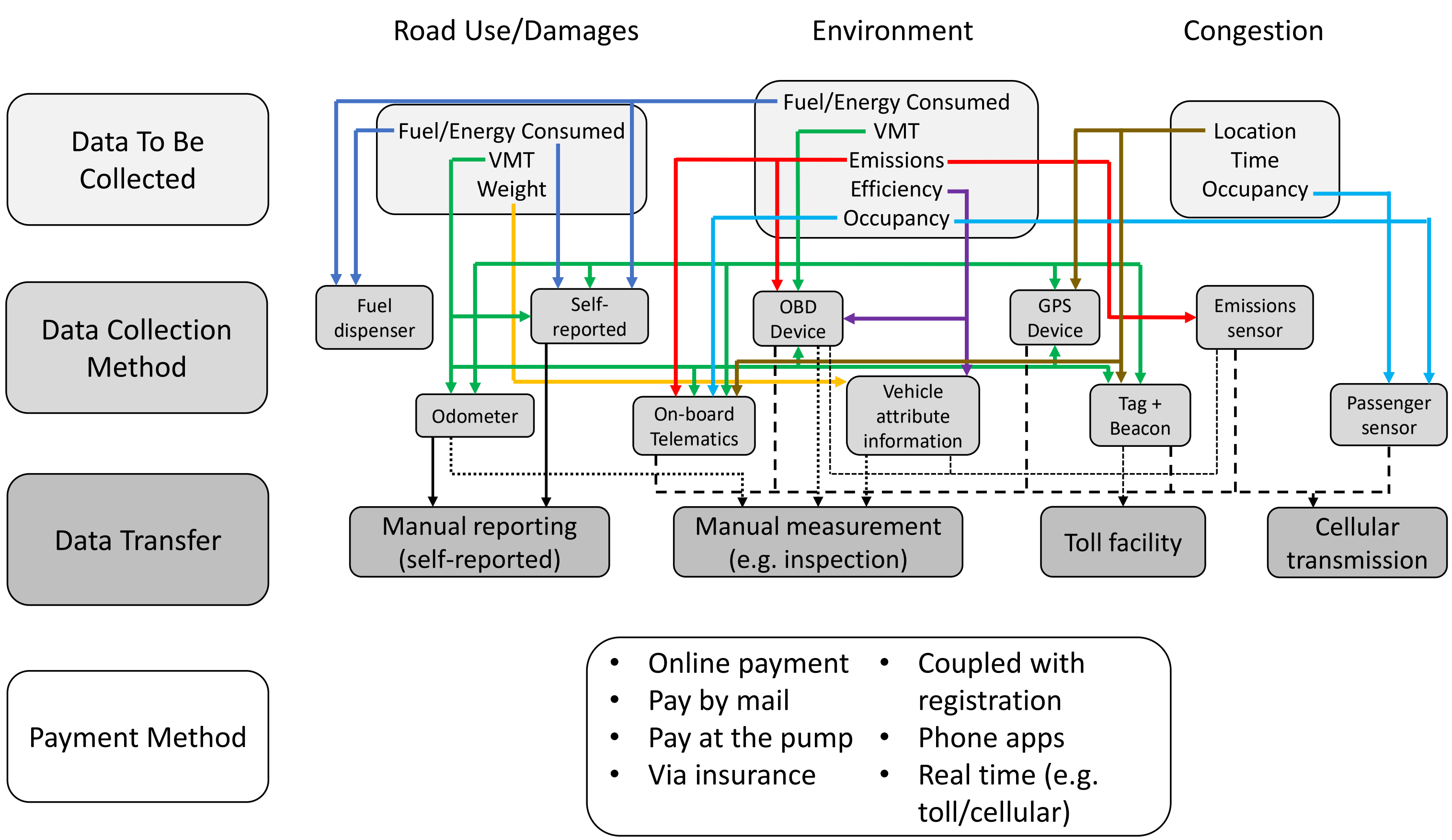

Figure 4: A schema for the possible methods of implementing pricing schemes for three externalities: road usage/damages, environmental impacts, and traffic congestion. Any pricing plan requires design choices that identifies the data that needs to be collected, the technology/method that would collect the data, the method of transferring the data to the appropriate entity, and how the fees are paid. Arrows connect each stage of the pricing scheme.

able to gather information across all categories, and therefore the technology choice is dependent on the type of data that is collected. To this end, it is important to consider where overlaps in information can improve efficiency of a system that addresses multiple externalities. For example, if the road use/damages category employs VMT data, the environmental damages category can take advantage of this information as well (when supplemented with vehicle efficiency information). Likewise, occupancy information in a system focused on environmental externalities could be used in a congestion pricing scheme. Even if a program were to implement a system addressing only a single externality, the design choice could leave the door open to address other externalities in the future.

4.2 Data Collection

The second row in Figure 4 provides an overview of data collection methods/technologies that have been employed (or theorized) to collect information for different vehicle pricing schemes. It should be noted that some methods/techologies may overlap, nevertheless we provide a list of collection methods. Fuel use information has been historically collected at the pump, which overlaps with environmental pricing but not with congestion pricing. One of the benefits of this system is that it does not require transfer of data to another party because the fees are levied at the same point of data collection–a far simpler method than many alternative technologies discussed below. Unfortunately, this method may not be a practical mechanism for alternative fuel vehicles. For example, measuring the energy associated with charging an electric vehicle requires separate meters, which would likely be a cost-prohibitive solution. Additionally, leakage would be difficult to prevent because these vehicles can be charged using standard 110 volt outlets that are not equipped with a separate meter.

Odometers The vehicle odometer measures miles travelled. Yet despite its seemingly ideal position to collect data for a RUC or for environmental pricing, in practice there are significant barriers to using an odometer for these purposes: the data from odometers are not designed to be easily transferred. Pilot RUC programs have had participants take pictures of their odometers or record them manually in a phone app–essentially a "secondary data collection" step. These constitute steps that could be very difficult to implement in widespread operation and would provide opportunities for individuals to cheat the system. Coupling the odometer with a more automated system could be more successful (such as with an on-board device or with vehicle telematics).

On-board Units We consider a suite of on-board devices–or devices that permanently reside within the vehicle. A popular method that has been deployed in many RUC pilots is a device that plugs into the on-board diagnostics (OBD) port of a vehicle. Some of the benefits of this device is that it is relatively cheap and can collect information about VMT, emissions, as well as vehicle attributes (such as efficiency and weight, via identifiers with the vehicle model). Additionally, the OBD II port was standardized for gasoline vehicles in the US starting in 1996, which means that the output signals are fairly universal. Unfortunately, many of the OBD II outputs are not standardized for electric vehicles, presenting an implementation challenge to a whole class of new technology vehicles. While the devices themselves are cheap, transmitting information can be costly if relying on transmission of data with a cellular network, which would require each individual device to have their own cellular data plan. If outfitted with GPS capabilities, the OBD device can collect location information in real time, which would be beneficial for congestion pricing schemes. In Figure 4, we separate GPS devices from OBD devices because there are also on-board GPS devices that do not rely on OBD ports to operate. Likewise, tag and beacon systems are traditionally on-board devices that communicate with an external sensor (toll booth, or sensor located in a gantry or under the pavement) and provide information that a vehicle has passed through a specific location. These systems could potentially be paired with other on-board devices (such as an OBD device or a GPS device) that would then act as an alternative avenue of transferring data rather than using a cellular signal. A modified "tag" could then serve both congestion pricing (by providing location information) and a RUC/environmental pricing scheme by transmitting relevant information to the beacon.

Occupancy Sensors The supplemental occupancy information that augments environmental and congestion pricing schemes requires a sensor that detects the presence of passengers in the vehicle. While passenger sensors already exist in vehicles today (primarily to provide warning signals to use seatbelts), the weight-based sensors may trigger if objects are placed on the seat. If there is a monetary benefit to having more passengers (i.e. through discounted environmental or congestion fees), it is unclear how easy it would be to cheat the sensors and how much drivers may be incentivized to do so.

Vehicle Telematics One avenue that potentially works across all externality pricing plans is the use of vehicle telematics. Vehicle telematics is a technology device that is integrated within the vehicle and has a wide array of functions. These include sending, receiving, and storing information via telecommunication devices, employing GPS systems for tracking and value-added services, integrating with sensors and instrumentation within the vehicle, and providing safety communications systems–to name some of the primary examples of the technology. In Figure 4, we show that the telematics system in a vehicle can theoretically collect a host of information including VMT, emissions (calculated), vehicle location (via GPS), and even occupancy. When considering unifying multiple pricing mechanisms under a single system, the flexibility of vehicle telematics makes it a prime candidate because it is one of the few methods of data collection that would be able to collect the necessary information for the three externalities. Additionally, vehicle telematics technology already have standardized protocols for communication between vehicles and roadside infrastructure[21]. However, the technology is not without its downsides. Because telematics are integrated with the vehicle, any design requirements to meet data collection and reporting requirements would need to be standardized across all automakers. There may be legitimate opposition to 1) additional standards that OEMs would be required to comply with, 2) increased costs to develop and implement the system, and 3) potential public backlash regarding privacy concerns associated with telematics. If these concerns can be alleviated, the technology represents a significant opportunity to avoid employing multiple systems, which is likely to end up costlier, for different pricing mechanisms.

One of the critical decisions that may influence the technology choice is the "coverage" of a particular pricing mechanism. While some RUC programs have operated on a volunteer basis (for example, in Oregon you opt out of the gasoline tax), a congestion price would not function unless it were applied to all vehicles in a given region. This could be seen as an opportunity to increase the rate of voluntary programs if the systems were unified: it is significantly easier for a driver participating in congestion pricing to opt into a RUC if the data collection device can serve both systems.

4.3 Data Transfer

Following the data collection process, information must be transferred to the processing entity if fees are not levied at the point of collection (as with the traditional gasoline tax). Data transfer presents a separate challenge, even for devices/methods that are robust at the data collection stage since a standardized communication protocol must be established (which may also differ between pricing schemes). Additionally, some of the data transfer methods outlined in Figure 4 would not be suited for all data collection technologies (i.e. manual reporting of a tag and beacon system). We briefly outline historic and potential methods for transmitting data below.

Manual Reporting Self-reported data has been employed in several pilot programs, but is likely too difficult to scale in a full program. In a self-reporting system, drivers report data, such as miles travelled, via a phone app, online form, or through paper forms. However, in addition to inconveniencing the driver, this method would likely increase reporting errors and create large opportunities to game the system. An alternative system that avoids wireless communication from devices would be manual measurement via a third-party. One existing example is the vehicle emissions inspection program in Pennsylvania[22] where data is collected during annual required emissions inspections from the OBD II port. A pricing scheme could piggyback on existing inspection programs and data could also be collected from the various technology devices discussed in Section 4.2 at the time of inspection. Fees could then be assessed at the same interval as vehicle inspections. Unfortunately, this method would not be feasible for real-time plans such as congestion pricing.

Tolling Systems The majority of successful congestion pricing schemes have implemented tag and beacon systems, all of which require on-board devices that communicate with sensors located at control points. This process is inherently different from a road user charge which normally does not require any location information for its operation. However, it may be possible to leverage toll facilities as "receivers" where data for a RUC or environmental pricing scheme is transmitted. This would negate the necessity for cellular data plans for the devices, but the beacon system would need to be greatly expanded from a set of control points around a cordoned zone (for the congestion pricing) to a comprehensive network across the road system of interest (for a RUC and environmental pricing).

Cellular Data Cellular transmission of data offers many advantages: real-time tracking necessary for congestion pricing, it is available in most new vehicles, and it can be universally compatible with any of the data metrics. While not all of the data collection devices/methods have cellular capability, the hardware itself is relatively cheap. Unfortunately, cellular data plans can be fairly expensive and significantly increase the cost of the program. Nevertheless, the cellular data transfer is the only mechanism we were able to identify that enables the system to take advantage of real-time technology features of the majority of the data collection devices.

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[21]IEEE 802.11p standard: Wireless Access in Vehicular Environments `https://standards.ieee.org/standard/802_11p-2010.html`

[22]PennDOT Emissions Inspection Program: `https://www.dmv.pa.gov/VEHICLE-SERVICES/Inspection-Information/Emissions-Inspection-Program/Pages/default.aspx`

5 Conclusion

The default vehicle pricing mechanism of gasoline/diesel taxes is rapidly becoming defunct: few plans account for inflation, fuel efficiency improvements continue to decrease revenue, and the adoption of electric vehicles render these fees outdated. At the same time that the transportation sector suffers from infrastructure funding shortfalls, transportation emissions are becoming an increasingly important component of climate change mitigation, and congestion continues to worsen in major cities around the world. Vehicle pricing is an economically efficient way to capture these externalities associated with the use of cars and trucks. Road user charges (mileage fees) have been explored by various states in the US and implemented internationally in Europe and New Zealand. Pricing emissions from vehicles has been implemented in cities in China and Italy. Likewise, congestion pricing has already been realized in countries such as Sweden and major cities such as London and Singapore. Importantly, numerous studies have demonstrated that almost every pricing mechanism has successfully reduced the externality they were targeting (see Section 3). As pricing becomes more mainstream and policymakers begin considering these systems, our study aims to provide context for design decisions as it relates to the integration of multiple pricing strategies.

Figure 4 is not meant to provide a comprehensive list of every technology and method that can be used to enable pricing schemes. Our goal is to demonstrate the importance of *program design* for vehicle pricing and the compatibility between data that needs to be collected, the mechanism that collects them, and how this information is communicated to the correct stakeholders. Evaluation and pilot programs of existing pricing schemes consider criteria such as cost, feasibility, and complexity when deciding an implementation strategy. To this we add compatibility. Stakeholders should consider the integration of multiple systems to be a priority as momentum for different types of vehicle pricing schemes increase.

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