POLICY BRIEF

Impacts of Road Pricing on Passenger Vehicle Use and Greenhouse Gas Emissions

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Program Description

This project reviews and summarizes empirical evidence for a selection of transportation and land use policies, infrastructure investments, demand management programs, and pricing policies for reducing vehicle miles traveled (VMT) and greenhouse gas (GHG) emissions. The project explicitly considers social equity (fairness that accounts for differences in opportunity) and justice (equity of social systems) for the strategies and their outcomes. Each brief identifies the best available evidence in the peer-reviewed academic literature and has detailed discussions of study selection and methodological issues.

VMT and GHG emissions reduction is shown by effect size, defined as the amount of change in VMT (or other measures of travel behavior) per unit of the strategy, e.g., a unit increase in density. Effect sizes can be used to predict the outcome of a proposed policy or strategy. They can be in absolute terms (e.g., VMT reduced), but are more commonly in relative terms (e.g., percent VMT reduced). Relative effect sizes are often reported as the percent change in the outcome divided by the percent change in the strategy, also called an elasticity.

Summary

Strategy Description

Road pricing is a form of travel demand management designed to affect the amount, time, or place that people drive. Road charges are levied through tolls, cordons, or based on distance driven.

Behavioral Effect Size

Most estimates find that a 10% increase in the toll fees results in a 3% decrease in traffic volume on the tolled facility. The estimate for heavy-duty vehicles is slightly larger, between 3 and 4%. Cordon pricing has a large immediate effect at implementation. Traffic entering the tolled area decreases between 4.5 and 9%. In most cases, the effect strengthens over time. The effect of distance-based pricing on heavy-duty vehicles is small to non-existent because vehicle miles traveled reduction is not the primary goal.

Strategy Extent

Road pricing can be implemented at various scales, ranging from very local applications (e.g., a single bridge) to distance-based pricing systems coordinated across national borders. Most strategies work at the city level on a network of roads or a central business district. The effects of road pricing are highly variable based on the urban spatial structure, type of facility, pricing technology, and travel patterns and mode share.

Strategy Synergy

The main strategy synergy with road pricing is the availability of public transit. The research shows that in the absence of public transit the effect of cordon pricing weakens over time; the

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effect strengthens where pricing revenues support transit. An analog in moving freight onto rail has been challenging, but incentives to invest in cleaner truck fleets have been effective.

Equity Effects

The equity effect for individual users is influenced by the availability of alternative transportation options, like transit, as well as the presence of toll exemptions or discounts designed make the pricing structure more progressive. In the absence of alternatives, the extra cost acts as a regressive tax on drivers. However, road pricing is progressive on the whole when it reduces pollution, decreases travel time, and makes roads safer, all impacts that tend to burden marginalized communities more heavily.

Strategy Description

Road pricing (or charging), when used as travel demand management, is designed to affect the amount, time, or places that people drive. An alternative use of road pricing emphasizes revenue generation rather than altering travel behavior, such as where pricing is used as a replacement for or complement to fuel tax revenue.

There are three types of road pricing strategies in use today:

- Link or point charging: Drivers are charged for access to a segment of road or facility (e.g., freeway, bridge, or tunnel).
- Cordon charging: Drivers must pay to enter an area defined by a system of toll points (usually the central business district). This strategy has also been used to create low emissions zones.
- Distance-based charging: Drivers are charged a price based on the distance they drive. This strategy has only been deployed for commercial, heavy-duty vehicles.

Each strategy can be further refined to vary with congestion and vehicle emissions, type, or occupancy. Congestion charging uses variable pricing to increase the cost of driving at times when roads are most congested (either based on the time of day or based on real-time congestion). Vehicle-based charging uses variable pricing based on the level of greenhouse gas emissions vehicles emit, charging more for polluting cars and trucks, the number of axles on the vehicle (to similarly charge larger vehicles differently), and the number of occupants. This brief focuses on link and cordon charging, as distance-based charging is not wide-spread and discussed more fully in the *Gas taxes, distance-based charges, and transportation network company charges* policy brief.

Strategy Effects

Behavioral Effect Size

Tolls along links or at points on roads or highways have the longest history of application and are the only road pricing strategy that is widely used in the United States. The impact of toll roads is characterized by a high degree of heterogeneity. In addition to country differences, variations in income, trip purpose, payment method, the location of the tolled link (in a tourist area, for example), and modeling approach are some of the factors for which researchers have estimated elasticities. In addition, few studies examine the effect of the initial toll rate because it is usually set by policy and consistent comparison is complicated by variation in rate setting rules (Kweun, 2017). Table 1 focuses on general or average elasticity, which does not differentiate between conditions. Research on tolls focuses on traffic volume (the number of vehicles passing through the toll), because calculating impact on vehicle miles traveled would require information that is not easily collected.

Even at the extremes, the effect of tolls is inelastic; the effect size from a 10% increase in toll rate ranges from a 0.4% to 8.3% decrease in traffic volume at the toll, with most estimates falling between 2% and 4% decreases. Bain (2017), in a review of consultant reports based on primary data, finds an average elasticity of traffic volume of -0.25 with nearly 80% of estimates between 0 and -0.5.

Studies that assess the long-run impact of toll charging all find that elasticity increases with time. Estimates range from a 2.8% to 13.1% decrease in traffic volume for a 10% increase in price. Kweun (2017), in a review of studies based on dynamic panel data analysis, found that the average long-run elasticity was -0.78, corresponding to a 7.8% decrease in traffic volume for a 10% price increase. Matas and Raymond (2003) and Odek and Brathen (2008) attribute this trend to the ease with which drivers could find un-tolled alternative routes. Higher initial rates, though less studied, are associated with a greater sensitivity to toll price changes (Kweun, 2017).

The impact of tolls on truck volume ranges between -0.3 and -0.4. Elasticities for heavy-duty vehicles tend to be slightly higher than for cars but the small number of studies and the greater variation between truck types means that evidence is insufficient to establish a comparison (Bain, 2017). Elasticities for trucks vary depending on the type of truck (e.g., 2-axle or 5-axle), whether they are operated independently, the size of the operating firm, the distance they travel, and the nature of the goods they transport.

Table 1. Impact of toll road on traffic volume

Study	Study location	Study years	Vehicle type	Results
Gomez et al. (2015)	Toll roads throughout Spain	1999-2011	Passenger cars	-0.19 to -0.4 (SR)
Burris & Huang (2013)	Interurban and metropolitan tolls in the US	2000-2010	Passenger cars	-0.3 (SR)[1]
			Heavy-duty vehicles	-0.30 to -0.35
Kweun (2017)	64 US toll roads in 15 states	2004-2013	Passenger cars	-0.04 (SR) and -0.28 (LR)
Odek & Brathen (2008)	Urban Motorways in Norway	1995-2005	All	-0.55 to -0.76 (SR) and -0.75 to -0.9 (LR)
Matas & Raymond (2003)	72 segments of toll roads in Spain	1981-1998	All	-0.21 to -0.83 (SR) and -0.33 to -1.31 (LR)
Gomez & Vassallo (2015)	14 toll roads in Spain	1990-2007	Heavy-duty vehicles	-0.33
Bari et al. (2015)	SH130 in Austin, TX	2008-2011	Heavy-duty vehicles	-0.39

Cordon charging typically applies to a specific part of an urban area, often focused on the central business district. Table 2 differentiates between estimates at the initial implementation and in the longer run as a response to changes in pricing. A new cordon's initial impact on the volume of traffic entering the area ranges from -0.47 in London to -0.87 in

[1] SR denotes short-run estimates and LR refers to long-run estimates. All estimates refer to the change in the number of vehicles utilizing the segments where tolls are installed.

Gothenburg. A 10% increase in the cost entering the cordoned area would result in a decrease in incoming traffic of 4.7% to 8.7%.

There are two measures of longer-term impact. The first focuses on how traffic volume evolves over time in reference to traffic volume before the implementation of the cordon. In Sweden, long-run adaptation varied by market. The elasticity in Stockholm went from -0.69 after the introduction of the cordon to -1.24 six years later. A significant uptick in transit use accounts for much of this increase. In car-reliant Gothenburg, the elasticity decreased from -0.87 in the first year to -0.69 two years later. Gothenburg is a smaller city with fewer transit options leading to more people opting to drive into the cordon over time. Despite the greater car reliance, a significant number of commuters switched to using transit, but the shift among discretionary travelers is less clear due to confounding factors (Börjesson &Kristoffersson, 2015). On the whole, evidence suggests a possible decline in total trips into the cordoned area, but the data were not definitive.

The second longer-term impact evaluation focuses on how traffic volume changes in response to subsequent price changes to cross the cordon or expansions of the cordoned area. Changes in pricing after the cordon was installed resulted in much smaller adjustments compared to the initial impact. In Stockholm and Gothenburg, a 10% increase in price led to a 2.8% and 1.6% decrease in incoming traffic (Börjesson and Kristoffersson, 2018). A similar decrease in the effect was observed in London where a 10% increase in price initially resulted in a 4.7% decrease in traffic entering the cordon but the same 10% price increase three years later led to a 1.6% decrease in incoming traffic (Evans, 2008). The expansion of the cordon area also comes with a lower elasticity. In London, the expansion of the original cordon resulted in a decrease of 0.6% in traffic entering the newly cordoned area (Ouali, 2021). Gibson and Carnovale (2015) used the unexpected and temporary suspension of the cordon in Milan to estimate a -0.3 elasticity.

Table 2. Impact of cordon tolls on traffic volume entering the cordon area (Estimates only include chargeable vehicles.)

Study	Study location	Study years	Timing	Results
Börjesson (2018)	Stockholm and Gothenburg, Sweden	2006-2015	Initial and long-term	-0.69 to -0.87 (SR) -0.52 to -1.24 (LR)
Börjesson & Kristoffersson (2018)	Stockholm and Gothenburg, Sweden	2015	Subsequent price change	-0.28 and -0.16
Croci (2016)	Milan, Italy	2008	Initial	-0.44 to -0.66 depending on vehicle type
Gibson & Carnovale (2015)	Milan, Italy	2008-2012	Suspension and reintroduction	-0.3
Luk (1999)[2]	Singapore	1975	Initial	-0.39 to -0.58
Olszewski (2007)	Singapore	1975-2006	Subsequent price change	-0.21 to -0.31
Evans (2008)	London	2003-2007	Initial and expansion	-0.47 and -0.42
			Price change	-0.16

[2] The study by Luk (1999) assumes the introduction of cordon charging corresponds to a 200% price increase.

Distance-based charging remains relatively uncommon due to technical and political challenges. Small-scale experiments and pilots have been completed in several locations in the U.S. and internationally (more details on these studies in the *Gas taxes, distance-based charges, and transportation network company charges* policy brief), but full-scale implementations have been limited to the heavy-duty freight sector in several European countries. Table 3 reports the results of a few estimates of the impact on the freight sector with a range of 0 to a 10% reduction in tonne-kilometer at the time of the fee introduction. Gomez et al. (2018) find no significant effect on VMT in an analysis of all countries that levy a distance-based fee on trucks.

A study of the impact of the distance-based fee in Switzerland found a 23% reduction in VMT compared to a business-as-usual counterfactual and a 32% increase in efficiency (measured in average ton per truck) after the introduction of the fee (iMONITRAF, 2010). Another study found no reductions in Germany and small decreases of 3% and 10% in Austria and the Czech Republic when comparing the year of introduction to the previous year (de Jong et al., 2010). The multi-pronged nature of distance-charging policies likely led to the lack of effect. In Germany, for example, the per-km fee was paired with generous subsidies to upgrade to cleaner trucks that would benefit from lower fees.

Table 3. Impact of distance-based pricing on traffic volume

Study	Study location	Study years	Vehicle type	Results
Gomez and Vassallo (2018)	12 European Union countries	1995-2015	Heavy-duty vehicle	No significant impact on t-km in most countries[3]
iMONITRAF! (2010)	Switzerland	2000-2005	Heavy-duty vehicle	23% below projected VMT without fee
de Jong (2010)	Germany, Austria, and Czech Republic	1995-2009	Heavy-duty vehicle	0.5% to 10% reduction in t-km after introduction of fee

Greenhouse Gas Emission Reductions

One of the goals of cordon charging and distance-based pricing is to reduce pollution. As noted above, distance-based pricing policies have approached the goal through incentives to upgrade trucks to cleaner environmental standards. The policy in Germany led to 10% of the heavy-duty vehicle fleet in the most polluting classes being replaced with cleaner trucks within one year (Broaddus & Gertz, 2008). The policy also leads to significant improvements in efficiency so that even if VMT is unchanged, fewer trips are empty or partially empty loads (Broaddus & Gertz, 2008; iMONITRAF!, 2010).

A review of cities that implemented cordon pricing or tolls found reductions in pollution, with CO_2 emissions dropping by 13% to 20% within the cordon area and by 1% to 3% across the entire metropolitan area (Cavallaro et al., 2018).

Reductions across the metropolitan areas tend to be smaller because, while congestion within the cordon typically decreases, some drivers may switch to taxis, reroute and increase VMT to avoid the charge—leading to more traffic outside the cordon and potentially offsetting some of the environmental benefits.

[3] t-km is tonne-kilometer, a measure that combines the tonnage trucks transport and distance.

Extent

Scale of application: Road pricing approaches vary widely in scale from a toll on a short segment of freeway to comprehensive, international distance-based charging. Each approach has a set of geographic constraints. Tolls can form a national network but are limited to a finite number of roads and are usually implemented in areas of high freeway traffic volume. Cordon-charging areas have only been implemented around central business districts, usually in large cities. Gothenburg (around 500,000 people) is the smallest city to implement and maintain cordon pricing (some smaller cities like Trondheim, Norway, have abandoned the policy). Technology for distance-based charging imposes no geographic limit but is constrained by political boundaries and private road networks. On-board technology can accurately differentiate between public and private roadways, different types of roads (freeway vs. arterials), and when a user crosses state lines. Some European countries have coordinated to create standardized pricing for heavy-duty vehicles that cross borders (Gomez & Vassallo, 2018).

Efficiency or cost: Cordon pricing is highly efficient. Stockholm recovered initial costs in one year and annual costs are 7% of revenues (Börjesson, 2018). Even in the smaller system of Gothenburg, the ratio is 11%. The more expansive London system recovered initial cost in 3.3 years and operates with a 30% cost efficiency rate (Börjesson, 2018). Tolls also operate with varying efficiency, but a review of the literature on operational costs found that costs tend to be between 12% and 20% of revenues (Odek, 2018).

Time and speed of change: Tolls and cordon pricing strategies can be very quick to implement. The technology for each strategy is well established and has reached maturity. The infrastructural needs are relatively small and unobtrusive, usually requiring only the installation of sensors or cameras at strategic locations. The main implementation delays are due to institutional and political obstacles. New York City introduced a plan for cordon charging in 2003 that became operational in 2025. Distance-based charging likely has a still longer timeline for implementation. The Netherlands planned a distance-based road charge in 2008 that has gone through several plan iterations with following administrations but no implementation. On-board tracking technology is the most viable technology to create a comprehensive and reliable system. The technology, whether through a retrofitting of cars, manufacturer onboard technology, or the use of smart phones, needs to clear a high hurdle to gain political acceptance.

Location within the region: The impact of tolls varies depending on their location and the type of facility they charge. Tolls on bridges and tunnels are common and tend to have lower passenger vehicles elasticity than tolls on roads (Kweun, 2017). The lower elasticity of bridges and tunnels is due to the lack of alternatives to using these facilities. Urban roads with few alternatives similarly have lower elasticity.

Cordon pricing has only been used around central business districts. The expansion of the cordon area in London had a much lower magnitude effect than the original implementation because the expansion was fully integrated with the initial area and residents within the new zone benefitted from a 90% discount on the charge.

Differences between regions: The differences in elasticities are larger between types of facilities and various pricing and payment mechanisms (electronic payments have lower elasticity) than they are between regions. Tolls on bridges or on comparable roads have an impact of similar magnitude in different regions or countries. The same is true of cordon pricing where differences are attributed to the pricing mechanism (e.g., tied to emissions in Milan) rather than the cities. The lower elasticity in Gothenburg, the only cordon-charging city without a dense public transit system, suggests that cordon-charging in more sprawling cities that offer few transit options would be less successful in curbing congestion.

Equity

Road pricing affects equity through multiple mechanisms (Plotnick et al., 2009). At the individual level, road pricing increases the cost of travel by charging for the use of the tolled facility and may add travel time for those who seek alternative routes or use transit instead. For the users of tolled facilities and people within a cordon, there are gains in the form of lower congestion and shorter travel time, and lower exposure to pollution. In the aggregate, the tax has a social impact through reductions in congestion and pollution, and revenue generation, which can offset the individuals' higher cost but can also distribute benefits more widely to both non-users and users. These societal benefits are dependent on process equity which influences how governments implement road charges (Ricord et al., 2023).

Road charges are regressive in the absence of exemptions or subsidies. Lower-income users must pay proportionally more of their income to use the charged roads in exchange for shorter travel time on many priced facilities. Evaluating the magnitude of road charges' impact is challenging because data on travel behavior are rarely attached to individual characteristics. Studies using surveys and simulations are better able to address this data gap and find that not only is the financial burden greater for lower-income users, but they are also the users who account for much of the elasticity (i.e., they reduce their driving on the priced roads more than higher income users) (West & Björesson, 2020; Mishra et al, 2013). Given that lower-income people already drive far less, the implication is that they sacrifice essential trips they can no longer afford (Levinson, 2010).

In addition to income-tested pricing, transit is the most direct contributor to a more equitable road user system. Where transit is accessible, reliable, and affordable (and where revenues from road charging are used to improve service) road charging is more likely to lead to a modal shift rather than trip reduction (Björesson & Kristoffersson, 2018). This modal shift, however, may come with greater travel time. Other alternatives, such as using non-tolled roads, have similar implications for travel time. Alternate routes are not only likely to be slower, but they also increase the burden on residents along those routes who face greater congestion and worse safety (Ricord et al., 2023).

In contrast to individual welfare effects, the aggregate equity impact of road charging is more likely to be positive with some caveats. While lower-income users pay a disproportionate cost, road pricing can be progressive across income groups, meaning that higher-income people pay more into the system than lower-income people. Partly, this is because lower-income people drive less, but the geographic distribution of users also factors in. Cordon charging applies to central business districts where most workers are higher wage, lower-income workers can rely on transit and car-dependent lower-wage workers benefit from lower overall congestion to travel outside the cordon (Herzog, 2023). Lower-income workers are also less likely to travel at peak hours and pay the highest rates where variable rates are in use (Cortright, 2017). Furthermore, where road charging leads to significant reductions in pollution, users and non-users benefit.

Decisions about the use of revenues are more variable and can significantly alter equity impacts for individuals. Where governments invest revenues in transit, the greater availability and affordability of transit can offset the higher cost of driving. However, in the absence of such investments or income-based discounts, inequities persist (West & Björesson, 2018). Other strategies for using revenues have focused on redistribution to communities most affected by the congestion and pollution that pricing aims to reduce (King et al., 2007). This is particularly important where spillovers are likely to arise. For instance, where drivers can avoid tolls through the use of alternative roads, the increased traffic on these roads requires more frequent maintenance (the cost of which would fall on the affected communities), but also a greater risk of accidents (Baumgarten & Middelkamp, 2015).

Lastly, people are likely to factor changes in the cost of driving when making choices about where to live (Andani, 2021). This effect on residential mobility can have downstream consequences. If road pricing alters the cost of living in a neighborhood sufficiently, it can make some locations more attractive, increasing the risk of gentrification and rapid housing cost increases (Herzog, 2023).

Synergy

Investment in improving public transit is the primary strategy to increase the effect of road charging. Agarwal and Mo Koo (2016) and Björesson and Kristoffersson (2018) found a large cross elasticity of public transit with an uptake of 12% in bus ridership in Singapore and an increase of 20% in transit in Stockholm. The case of Gothenburg shows that while traffic volume still declined after the implementation of a cordon, the decline was not as large.

Tolls and cordon-based charging can significantly affect land use. The charges effectively increase the cost of travel, usually commuting. This cost can be substantial and, under the right conditions, push people to make different decisions about where to live and prioritize locations within the tolled area (Andani et al., 2021; Zhong et al., 2015). Increasing the supply of homes within a cordon or tolled area can, therefore, decrease VMT. Increasing the supply of housing inside a cordon, which usually surrounds the area with the highest land values, may be difficult and many people and employers may decide to locate outside the cordon (Anas and Hiramatsu, 2013).

Network-wide tolling or distance-based charging for heavy-duty vehicles is often paired with policies to decrease emissions (such as subsidizing replacing older trucks with cleaner models). Increasing the weight limit trucks can carry and increased efficiency in routing contribute to the decrease in VMT, but these carry some safety risks and other considerations for road network maintenance. Investments in rail, like transit, should further reduce heavy-duty vehicle VMT. However, lack of investment and challenges to addressing first/last mile issues for freight have led to little empirical evidence of the magnitude.

Confidence

Evidence Quality

The quality of research on road charging is generally high thanks to the built-in measure of traffic flow of tolls and cordons. The studies in Tables 1 through 3 use before-and-after analysis to estimate the direct impact of the road charge. Cordon charging is an impactful policy that requires years of planning and deliberation. The sensitive nature of the policy means that considerable attention goes to measuring the impact.

The high quality of the data, however, is limited to the charging point (toll or cordon). The complexity of road charging's downstream effect creates a number of gaps in research. For example, there are few estimates of the total effect of road charging on regional traffic or VMT. Herzog (2023) developed a model for estimating the impact of the London cordon charge on regional traffic volume and found a small decrease. While the estimation of tolls' effect is reliable, it says little about the potential increase of congestion on alternative roads. Matas and Raymond (2003) find that congestion on alternative roads does increase, but not as much as the decreased congestion on the tolled segment.

Caveats

While there is a high degree of confidence that cordon charging and tolls reduce congestion, there is a lack of evidence to link road charging with a region-wide reduction VMT and, by extension, greenhouse gas emissions. The lack of evidence is primarily tied to the paucity of data available for before-and-after studies. The availability of alternative routes and also alternative destinations for non-commute trips means that people may drive the same amount (if not more in cases where the alternative is longer) than they were before the road charge was implemented, pushing VMT up. However, studies of cordon pricing emphasize the significant modal shift toward transit which would decrease VMT.

Where the balance falls is unclear and would depend on contextual factors. The urban spatial structure (what share of the population lives in areas that would require them to cross a toll), the spatial distribution of employment and services, socioeconomic segregation, and the availability of transit and other subsidized mobility options can amplify or undermine the effect of road charging (Garcia-López et al., 2022; Zhong et al., 2015).

Technical & Background Information

Study Selection

Study selection is largely constrained by the number of available road charging projects available for analysis. There are many tolls in the United States and globally, but relatively few make their data available to researchers (Bain, 2017). There are only five cordon charging programs in the world: Singapore, London, Milan, Stockholm, and Gothenburg, and the number of countries that levy a distance-based fee on trucks is also small.

The literature on tolls spans many decades and approaches (see methodological considerations below). We selected studies based on real-world data from tolls and that controlled for the many potential effects on traffic volume over several years, including employment, population, vehicle registration, local and national gross domestic product, fuel prices, transit availability and fares, and alternative route availability. In addition, we prioritized studies that used panel data analysis to estimate short- and long-run elasticity.

Most tolls have been in place for many decades and are small in scale, preventing a systematic evaluation of their initial impact on traffic flow (Lehe & Devunri, 2022). In contrast, cordon charging programs are relatively recent (with the exception of Singapore) and the large projects involved a great deal of tracking from before their implementation. This made it possible for researchers to evaluate the initial impact of cordon charging and, with later changes in prices, the subsequent change in elasticity. Where possible we selected studies that included and differentiated both the initial impact and subsequent changes. For these studies, researchers establish a baseline cost of commuting into the cordoned area to estimate the elasticity of adding a cordon charge.

Methodological Considerations

Two main methodological considerations are relevant in summarizing the literature on road charges. The first set of issues deals with the temporality of road charges. Most included studies aim to assess the initial impact of road charging and the long-term effects. The initial impact is a time of learning and adaptation. Users take time to learn of alternative modes of transportation that can substitute for the charged trip, alternative free routes, or different locations that offer the same amenities, all of which can depress the elasticity. There is no clear definition for the length of this initial period of adaptation and few studies attempt to establish a timeline or standard (Lehe, 2022).

The longer-term effect usually refers to how traffic flow has changed several months or years after the initial implementation and with respect to the non-charged flow. However, in the absence of a change in the charge, these estimates tend to be significantly larger because users have had time to adapt their behavior (Kweun, 2017). This can make comparison across estimates challenging. The magnitude of estimates can vary based on the time elapsed between price changes, which in many cases means the charge becomes relatively cheaper because of general price inflation. In cases where prices are fixed for a long time, and especially if there is a general growth in congestion, users may become less sensitive to the charge. Therefore, long-term estimates need to be carefully gauged when comparing across locations both for context (how often were prices adjusted) and for methodology (how do the researchers define the 'long-term effect'?).

The second methodological consideration is the choice of analytical approach, including those that aim to address the temporality of road charge impacts on traffic volume. There are five main methods for estimating the elasticity of traffic volume with respect to road charges. Before-and-after evaluations simply compare traffic volume before and after the implementation of road charging, using the elasticity formula. Static estimations use statistical models to examine how changes in road charging affect traffic volume based on the contemporary conditions. In contrast to static estimation, dynamic panel data analysis accounts for the nature of change to pre-existing conditions by including a traffic volume lagged by one (or more) time period as an explanatory variable. The inclusion of this lagged variable allows for a more systematic (meaning with an explicit definition of the short- and long-term) estimation of the effects of road charging. The fourth method is to use a discrete choice model. These estimates are based on a survey of either stated preference (the user was asked for their preferred choice in regard to the charge) or revealed preference (the user was observed in their choice in regard to the charge). The discrete choice models, because they are based on surveys, have a different interpretation of elasticity as the percent change in the probability of choosing to use the tolled road as opposed to the free alternative. The last method uses a static or dynamic analysis but is based on simulated data rather than observed data from a toll or cordon. The data are usually simulated from a regional travel demand model and the researchers calibrate the model to estimate the effect of adding to the travel cost in the form of a charge.

Of these five methods, we focused on studies using static and dynamic panel analysis. Before and after comparisons lack the ability to control for the multiple relevant variables that change along with the road charge (e.g., employment levels and gas prices). Discrete models reflect attitudes toward road charges and, while useful to gain insights into how attitudes change with socioeconomic background for example, do not have a direct relationship to the effect on total traffic volume. Lastly, simulations also have the benefit of including information on the users' socioeconomic background but are based on a set of assumptions and parameters that may not reflect the implementation of a road charge.

References

Agarwal, Sumit, and Kang Mo Koo. 2016. Impact of Electronic Road Pricing (ERP) Changes on Transport Modal Choice. *Regional Science and Urban Economics* 60 (September): 1–11. https://doi.org/10.1016/j.regsciurbeco.2016.05.003.

Ait Bihi Ouali, Laila, Davis Musuuga, and Daniel J. Graham. 2021. Quantifying Responses to Changes in the Jurisdiction of a Congestion Charge: A Study of the London Western Extension. Edited by Hironori Kato. *PLOS ONE* 16 (7): e0253881. https://doi.org/10.1371/journal.pone.0253881.

Anas, Alex and Tomoru Hiramatsu. 2013. The economics of cordon tolling: General equilibrium and welfare analysis. *Economics of Transportation* 2 (1): 18–37. https://doi.org/10.1016/j.ecotra.2012.08.002

Andani, I Gusti Ayu, Lissy La Paix Puello, and Karst Geurs. 2021. Modelling Effects of Changes in Travel Time and Costs of Toll Road Usage on Choices for Residential Location, Route and Travel Mode across Population Segments in the Jakarta-Bandung Region, Indonesia. *Transportation Research Part A: Policy and Practice* 145 (March): 81–102. https://doi.org/10.1016/j.tra.2020.12.012.

Bain, Robert. 2017. Toll Road Pricing: Demand Elasticity and Affordability – a State-of-the-Practice Scan. RBConsult.

Bari, Muhammad Ehsanul, Mark W. Burris, and Chao Huang. 2015. The Impact of a Toll Reduction for Truck Traffic Using SH 130. *Case Studies on Transport Policy* 3 (2): 222–28. https://doi.org/10.1016/j.cstp.2015.04.002.

Baumgarten, Patrick, and Jens Middelkamp. 2015. On Interurban Road Pricing Schemes and the Impacts of Traffic Diversion on Road Safety in Germany: Empirical Findings and Implications.

Börjesson, Maria. 2018. Long-Term Effects of the Swedish Congestion Charges. Discussion Paper ITF Roundtable 170. Paris, France: International Transport Forum.

Börjesson, Maria, and Ida Kristoffersson. 2018. The Swedish Congestion Charges: Ten Years On. *Transportation Research Part A: Policy and Practice* 107 (January): 35–51. https://doi.org/10.1016/j.tra.2017.11.001.

Broaddus, Andrea, and Carsten Gertz. 2008. Tolling Heavy Goods Vehicles: Overview of European Practice and Lessons from German Experience. *Transportation Research Record: Journal of the Transportation Research Board* 2066 (1): 106–13. https://doi.org/10.3141/2066-12.

Cavallaro, Federico, Federico Giaretta, and Silvio Nocera. 2018. The Potential of Road Pricing Schemes to Reduce Carbon Emissions. *Transport Policy* 67 (September): 85–92. https://doi.org/10.1016/j.tranpol.2017.03.006.

Cortright, J. (2017), Why peak period road pricing is fair. StreetsBlogUSA https://usa.streetsblog.org/2017/09/29/why-peak-period-road-pricing-is-fair/ .

Croci, Edoardo. 2016. Urban Road Pricing: A Comparative Study on the Experiences of London, Stockholm and Milan. *Transportation Research Procedia* 14: 253–62. https://doi.org/10.1016/j.trpro.2016.05.062.

Jong, Gerard de, Arno Schroten, Huib van Essen, Matthijs Otten, and Pietro Bucci. 2010. Price Sensitivity of European Road Freight Transport – towards a Better Understanding of Existing Results. Report 9012–1. Significance and CE Delft.

Gibson, Matthew, and Maria Carnovale. 2015. The Effects of Road Pricing on Driver Behavior and Air Pollution. *Journal of Urban Economics* 89 (September): 62–73. https://doi.org/10.1016/j.jue.2015.06.005.

Gomez, Juan, and José Manuel Vassallo. 2015. Evolution over Time of Heavy Vehicle Volume in Toll Roads: A Dynamic Panel Data to Identify Key Explanatory Variables in Spain. *Transportation Research Part A: Policy and Practice* 74 (April): 282–97. https://doi.org/10.1016/j.tra.2015.02.017.

Gomez, Juan, and José Manuel Vassallo. 2020. Has Heavy Vehicle Tolling in Europe Been Effective in Reducing Road Freight Transport and Promoting Modal Shift? *Transportation* 47 (2): 865–92. https://doi.org/10.1007/s11116-018-9922-3.

Gomez, Juan, José Manuel Vassallo, and Israel Herraiz. 2016. Explaining Light Vehicle Demand Evolution in Interurban Toll Roads: A Dynamic Panel Data Analysis in Spain. *Transportation* 43 (4): 677–703. https://doi.org/10.1007/s11116-015-9612-3.

Herzog, Ian. 2023. The City-Wide Effects of Tolling Downtown Drivers: Evidence from London's Congestion Charge. Preprint. SSRN. https://doi.org/10.2139/ssrn.4404817.

Huang, Chao, and Mark W. Burris. 2015. The Short-Run Impact of Gas Prices Fluctuations on Toll Road Use. *Case Studies on Transport Policy* 3 (2): 137–50. https://doi.org/10.1016/j.cstp.2014.12.005.

Kweun, Jeong Yun. 2017. Essays on Travel Demand for Toll Roads. George Mason University.

Lehe, Lewis J., and Saipraneeth Devunuri. 2022. Large Elasticity at Introduction. *Research in Transportation Economics* 95 (November): 101116. https://doi.org/10.1016/j.retrec.2021.101116.

Levinson, David. 2010. Equity Effects of Road Pricing: A Review. *Transport Reviews* 30 (1): 33–57. https://doi.org/10.1080/01441640903189304.

Luk, James. 1999. Electronic Road Pricing in Singapore. *Road and Transport Research* 8 (4): 29–40.

Matas, Anna, and José-Luis Raymond. 2003. Demand Elasticity on Tolled Motorways. *Journal of Transportation and Statistics* 6 (2/3): 92-108.

Martin, Leslie A, and Sam Thornton. 2017. n.d. Can Road Charges Alleviate Congestion? Available at SSRN: https://ssrn.com/abstract=3055428 or http://dx.doi.org/10.2139/ssrn.3055428

Miquel-Àngel Garcia-López, Ilias Pasidis, Elisabet Viladecans-Marsal, Erratum to: Congestion in highways when tolls and railroads matter: evidence from European cities, *Journal of Economic Geography*, Volume 22, Issue 5, September 2022, Page 961, https://doi.org/10.1093/jeg/lbab036

Mishra, Sabyasachee, Timothy F. Welch, and Arnab Chakraborty. 2014. Experiment in Megaregional Road Pricing Using Advanced Commuter Behavior Analysis. *Journal of Urban Planning and Development* 140 (1): 04013007. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000175.

Odeck, James, and Svein Bråthen. 2008. Travel Demand Elasticities and Users Attitudes: A Case Study of Norwegian Toll Projects. *Transportation Research Part A: Policy and Practice* 42 (1): 77–94. https://doi.org/10.1016/j.tra.2007.06.013.

Odeck, J. (2019). Estimating and predicting the operational costs of road tolls: An econometric assessment using panel data. *Transportation Research Part A: Policy and Practice*, *130*, 466–478. https://doi.org/10.1016/j.tra.2019.09.047

Olszewski, Piotr S. 2007. Singapore Motorisation Restraint and Its Implications on Travel Behaviour and Urban Sustainability. *Transportation* 34 (3): 319. https://doi.org/10.1007/s11116-007-9115-y.

Plotnick, R., J. Romich, and J. Thacker. 2009. The impacts of tolling on low-income persons in the Puget Sound region. Olympia, Washington. https://depts.washington.edu/trac/bulkdisk/pdf/721.1.pdf

Ricord, S., Kitali, A., and Wang, Y., 2023. Toll Programs and Tolling Equity: Current Best Practices. Available at SSRN: https://ssrn.com/abstract=4608858 or http://dx.doi.org/10.2139/ssrn.4608858

West, Jens, and Maria Börjesson. 2020. The Gothenburg Congestion Charges: Cost–Benefit Analysis and Distribution Effects. *Transportation* 47 (1): 145–74. https://doi.org/10.1007/s11116-017-9853-4.

Zhong, S., Wang, S., Jiang, Y., Yu, B., & Zhang, W. (2015). Distinguishing the land use effects of road pricing based on the urban form attributes. *Transportation Research Part A: Policy and Practice*, *74*, 44–58. https://doi.org/10.1016/j.tra.2015.02.009