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Transportation and the Environment in Developing Countries

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Abstract

In urban areas around the world, increasing motorization and growing travel demand make the urban transportation sector an ever-greater contributor to local air pollution and greenhouse gas emissions. The situation is particularly acute in developing countries, where growing metropolitan regions suffer some of the world's highest levels of air pollution. Policies that seek to develop and manage this transportation sector—both to meet rising demand linked to economic growth and to safeguard the environment and human health—have had strikingly different results, with some inadvertently exacerbating the traffic and pollution they seek to mitigate. This review summarizes findings in the recent literature on the impacts of a host of urban transportation policies used in both developed- and developing-country settings. The article identifies research challenges and future areas of study regarding transportation policies, which can have important, long-lasting impacts on urban life and global climate change.

1. INTRODUCTION

Air pollution and climate change represent serious threats to human health. In 2016, air pollution was responsible for approximately 7 million deaths from various life-shortening diseases, including heart disease, lung cancer, and stroke, according to the World Health Organization (WHO).[1] The public health and economics literatures have established that air pollution increases mortality, especially among the most vulnerable groups, including infants and older adults, and that it leads to large morbidity costs.[2] Climate change is expected to cause far-reaching and sweeping economic and societal changes that are likely to affect agriculture, biodiversity, economic growth, geopolitics, human health, and world peace.[3]

Many developing countries, especially rapidly growing countries, are experiencing pressing environmental challenges as a result of the dramatic increase in fossil fuel consumption to meet the need for consumption and production, limited access to clean technologies, and the lack of stringent and well-enforced environmental regulations. The populations in these countries are particularly vulnerable to adverse environmental conditions because of the lack of effective government interventions and the costs of and limits on options available to individuals to prevent or mitigate the effects of pollution.

Figure 1*a* depicts the level of fine particulate matter ($PM_{2.5}$) across the globe, illustrating that concentrations tend to be higher in low- and middle-income countries. The United States and Japan were historically the world's major contributors of carbon dioxide (CO_2) emissions. **Figure 1*b*** shows that over the past two decades, emissions from developing countries such as China and India surged to catch up. In 2006, China surpassed the United States to become the world's largest emitter of CO_2.

Rapid urbanization in developing countries presents both challenges and opportunities in addressing environmental challenges (Kahn 2006). The world's urban population increased from less than 1.4 billion (or 36%) in 1960 to nearly 4.2 billion (or 55%) in 2018. By 2050, over two-thirds of the world's population are projected to live in urban areas, and the rural to urban migration during this process will mostly occur in developing countries. On the one hand, the high concentration of people and activities in cities could lead to severe traffic congestion and exacerbate air pollution, especially with the rise in vehicle ownership in emerging economies. On the other hand, cities have the potential to organize economic activities spatially to reduce energy consumption and environmental impacts and to better take advantage of the economies of scale in public transit. Understanding the role of transportation in addressing urban environmental challenges has important implications for policy design to foster the emergence of green cities.

The transportation sector, which relies heavily on fossil fuels, is a major source of air pollution and greenhouse gas (GHG) emissions. The WHO estimates that road transport contributes 30% of particulate emissions in European cities and up to 50% in member countries of the Organisation for Economic Co-Operation and Development (OECD) (Carter 2019). According to the US Environmental Protection Agency (EPA), the transportation sector is responsible for about 10% of $PM_{2.5}$, more than 55% of nitrogen oxide (NOx), and about 10% of volatile organic compound (VOC) emissions in the United States.

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[1] WHO Global Ambient Air Quality Database: **https://www.who.int/airpollution/data/cities/en/**.

[2] Studies on the mortality impact of air pollution include Chay & Greenstone (2003), Currie & Neidell (2005), Currie & Walker (2011), Knittel et al. (2016), and Deryugina et al. (2019). Studies on morbidity costs include Moretti & Neidell (2011), Deschênes et al. (2017), Barwick et al. (2019), and Williams & Phaneuf (2019).

[3] Recent papers on the impacts of climate change include Nordhaus (2006) and Dell et al. (2012) on economic growth; Mendelsohn et al. (1994), Schlenker et al. (2005), Deschênes & Greenstone (2007), and Burke & Emerick (2016) on agriculture; Deschênes & Moretti (2009), Deschênes & Greenstone (2011), and Barreca et al. (2016) on mortality; and Miguel et al. (2004), Hsiang et al. (2011), and Jia (2014) on social conflict.

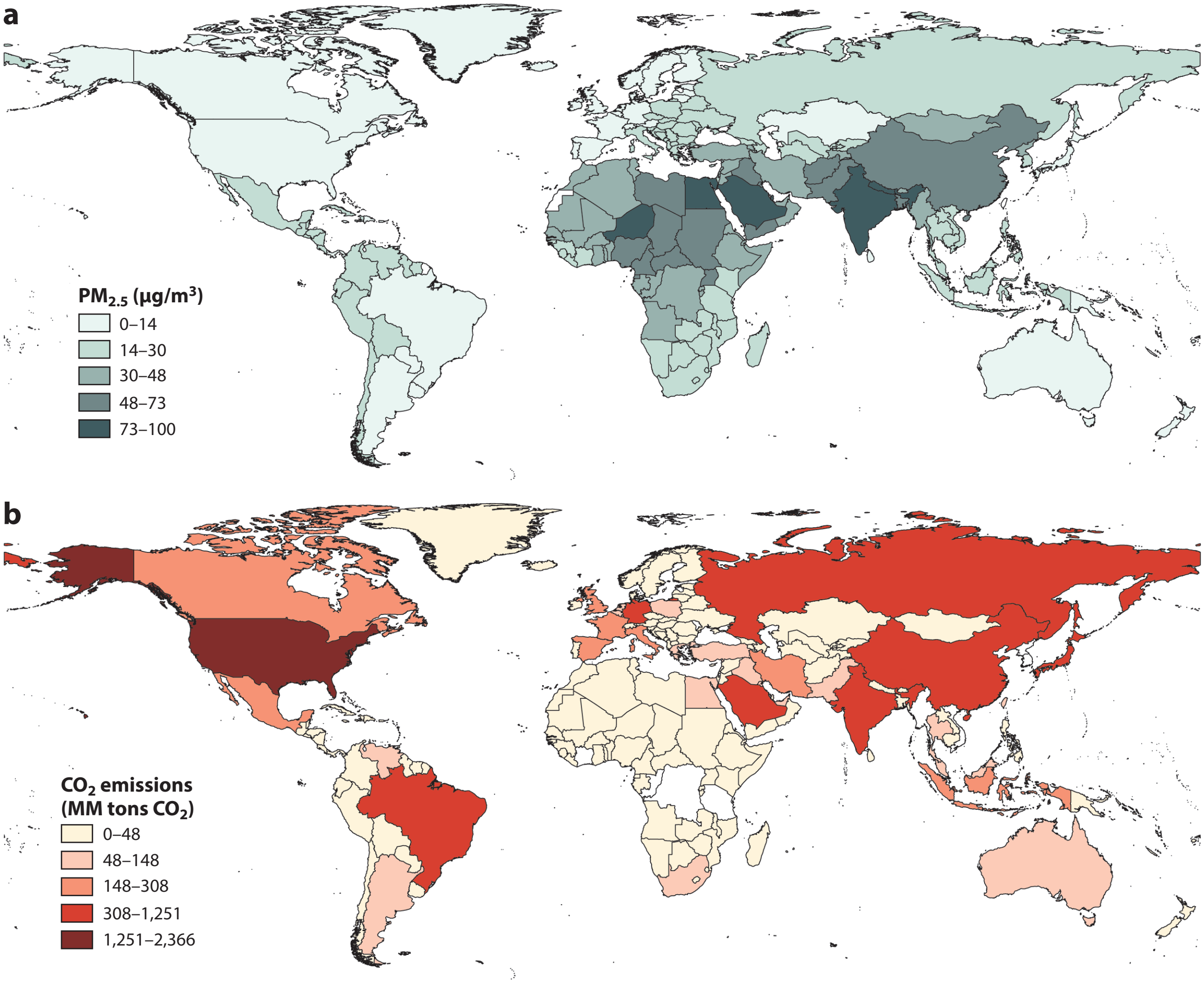

Figure 1

Fine particulate matter (PM$_{2.5}$) and greenhouse gas emissions by country. (*a*) PM$_{2.5}$ concentration in 2017. (*b*) Average CO$_2$ emissions between 2005 and 2016. Reconstructed based on data from the World Bank (**https://data.worldbank.org/indicator/EN.ATM.PM25.MC.M3**) and the US Energy Information Administration (**https://www.eia.gov/international/data/world**).

Because of the rapid rise in private vehicle ownership and travel demand, as well as the relatively low fuel efficiency in developing countries, the transportation sector plays an increasingly significant role in local air quality. **Figure 2** shows the increase in new passenger vehicle registrations in selected countries from 2005 to 2017. Among developed countries, new vehicle sales were stable or declined slightly during this period. By contrast, China and India experienced dramatic increases in vehicle ownership, with total new passenger vehicles in China increasing fivefold. Although per capita vehicle ownership is still relatively low in developing countries, and total gasoline consumption is still far behind that in the United States (**Figure 3**), the upward trend in these countries is substantial.

As household income rises in developing countries, the need for travel and the desire for automobile ownership grow, and willingness to pay for a cleaner environment increases as well.

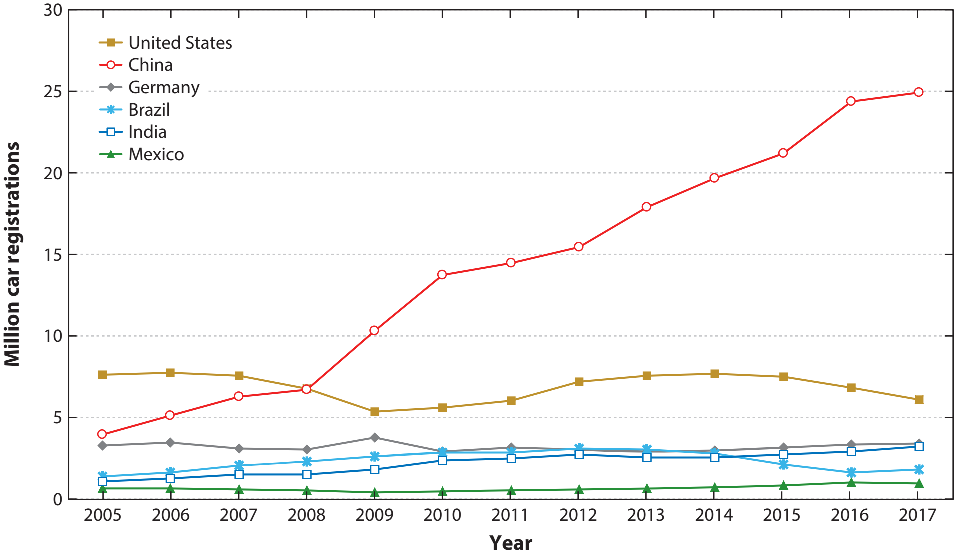

Figure 2

New passenger car registrations by country and changes from 2005 to 2017 using data from the International Organization of Motor Vehicle Manufacturers (**http://www.oica.net**).

In order to strike a balance between these competing incentives, policy makers need to recognize that (*a*) automobile usage generates several types of externalities (including pollution, congestion, noise, accidents, and road damage) that need to be addressed by policy interventions (Parry et al. 2007), and (*b*) automobiles and transportation infrastructure are durable goods. Short-term decisions on vehicle purchase and transportation network design can have far-reaching implications

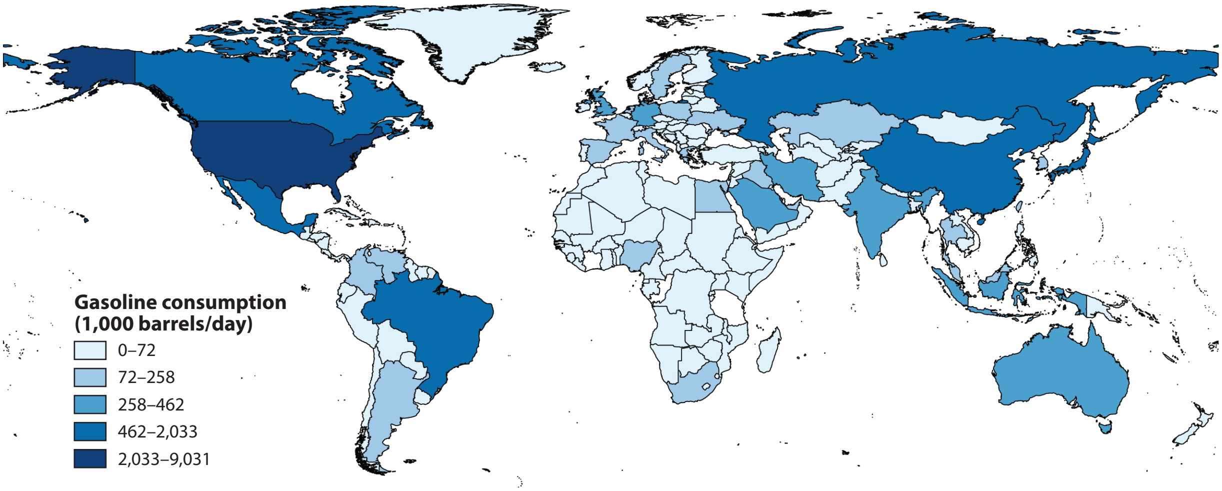

Figure 3

The global distribution of gasoline consumption between 2005 and 2016. Data from the US Energy Information Administration (**https://www.eia.gov/international/data/world**).

for emissions trajectory for decades to come. Government policies need to be forward looking and take long-run household behavioral responses into account.

A suite of policy tools has been used to reduce urban air pollution from automobiles. These tools include demand- and supply-side policies that aim to encourage travel mode shifts, reduce emission intensity levels via fuel-economy and emission standards, and promote alternative fuels or zero-emission technologies. These policies can also be distinguished as command-and-control or market-based instruments. This article reviews recent research on each of these policy tools, with a focus on their application in developing countries. It discusses the cost-effectiveness of each policy in addressing the pollution challenge, giving special attention to the empirical challenges in identifying the causal impacts of policies.[4]

2. POLICIES TO PROMOTE MODAL SHIFTS

2.1. Expansion of Public Transit

Faced with increasing air pollution and traffic congestion, local governments use the expansion of road and public transit networks as the first line of defense. In Beijing, the government invested more than $67 billion in transportation infrastructure between 2007 and 2015, greatly expanding the public transit network by adding 14 new subway lines and more than 200 bus routes (3,300 new buses).[5] Similar expansions are happening in India, Mexico, and many other emerging economies.[6] Although it requires massive funding, this type of investment can also stimulate economic activities and facilitate trade (Redding & Turner 2015).

With the goal of reducing traffic-related air pollution and traffic congestion, supply-side policies such as expanding the public transit network can create two countervailing forces on air quality. Improving the public transit network can divert commuters from driving private vehicles to public transport (Mohring 1972). This traffic diversion effect (the Mohring effect) could potentially reduce traffic congestion and vehicle emissions. However, improving transportation infrastructure (by increasing road capacity or enhancing public transit) can reduce the cost of travel and driving, resulting in an increase in travel demand and driving (Vickrey 1969) and leading to more pollution. Duranton & Turner (2011) find that traffic volume increased as a result of the expansion of highway capacity in US cities between 1983 and 2003. Although the expansion of road capacity can initially reduce traffic congestion and air pollution, it increases travel demand in the long run, eroding the initial improvement in traffic conditions.

Given the high cost of transportation infrastructure and potential countervailing forces at play, empirically estimating the impact of supply-side policies on air quality is important. The central challenge lies in finding exogenous variation in public transit infrastructure, which could be confounded with other unobserved factors. For example, urban planners may situate public transit (such as the subway) in areas where population and economic activities are projected to grow. In this case, air quality in those areas may have deteriorated in the counterfactual scenario of no expansion of public transit. The issue of endogenous location could bias the true impact of subway expansion in the empirical analysis.

To tackle the identification challenge, researchers have used the regression discontinuity (RD)-in-time, difference-in-differences (DID), and event study (ES) approaches, which rely on different

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[4] Because the choice of travel modes is also tied to housing and job location choices, smart urban planning can play an important role in curbing car-related emissions by reducing travel distances or eliminating the need to travel altogether. This review does not examine the cost-effectiveness of urban policies. Section 5 briefly discusses actions that can help improve system-wide efficiency, such as ridesharing and autonomous driving.
[5] See the Beijing Transport Annual Report (**http://www.bjtrc.org.cn/List/index/cid/7.html**).
[6] See India Brand Equity Found. (2020), Oxford Bus. Group (2015).

identification assumptions. The key assumption behind the RD-in-time and ES approaches is that no unobservables exhibit discrete changes at the time of treatment (e.g., subway opening), so as not to confound the impact of the treatment.[7] The key identification assumption behind DID is the parallel trend assumption; i.e., unobservables do not affect the treatment and control groups differently in the absence of the treatment.

Chen & Whalley (2012) estimate the effects of opening one subway line in Taipei on air pollution based on the RD-in-time framework. They find that opening the subway line reduced carbon monoxide (CO) emissions by 5–15%. Employing an approach similar to that used by Chen & Whalley (2012), Goel & Gupta (2017) use the RD-in-time method to examine the impact of the Delhi Metro expansion on air quality. They find a 34% localized reduction in CO in the short run. Using an ES design, Gendron-Carrier et al. (2018) examine 43 cities across the world that opened new subway systems between 2000 and 2014. They find that particulate concentrations dropped by 4% on average following the opening of a new subway system. Zheng et al. (2019) use the DID method to estimate the impacts of the opening of the first subway line in Changsha, China. They find an 18% reduction in CO in areas close to subway stations.

A strategy to deal with the endogenous location concern of the public transit is the instrumental variable (IV) method. The instrument should provide variation that affects location choices but is exogenous to contemporaneous shocks to air pollution and other outcome variables. Baum-Snow (2007) uses planned routes (many of which were not built) as the IV for US highways to examine the trend of suburbanization, and Faber (2014) constructs a hypothetical highway system in China based on historical planning maps using a minimum spanning tree (MST) approach to examine trade integration and industrialization. Li et al. (2019) follow a similar strategy to examine the impact of Beijing's subway system, using the original planning routes as the IV.

An additional empirical challenge in this literature is accounting for the spillover effect of the transportation network. Local changes in road or subway networks could have a system-wide impact, making it difficult to find a valid control group in the DID framework. Li et al. (2019) employ a continuous measure of subway network density as the key regressor to estimate the citywide effect. The network density varies across space within a city and over time for a given location as a result of the expansion of the subway network. A new subway line would more sharply increase network density in adjacent areas than in areas that are farther away. Using the predetermined planning map as an IV, the authors estimate the effect of subway expansion on air pollution for the rapid build-out of 14 subway lines in Beijing from 2008 to 2016. They contrast the estimates based on this approach with those from a distance-based DID approach. The DID approach focuses on the local effect and provides a larger estimate; the network density approach allows for the spillover effect across the whole network and relies on the assumption that the impact diminishes over distance.

Several other studies examine the impact of expanding bus and railway services on air quality or traffic congestion. Anas & Timilsina (2009) use a simulation model to study the lock-in effects of transportation infrastructure in Beijing. They find that increasing bus services in the city center would reduce overall CO_2 emissions and that expanding suburban roads would increase them. Lalive et al. (2013) and Bel & Holst (2018) show that increasing rail services in Germany and expanding bus rapid transit (BRT) services in Mexico City reduced emissions of pollutants such

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[7] The RD-in-time method uses time as the running variable and assumes that the impact of unobservables on air quality can be captured by flexible functions of the time trend. The identification relies mainly on time-series variation, different from the traditional RD in cross-sectional settings. The RD-in-time, in essence, is the same as the event study method, which explicitly uses pre- and post-event data for identification. Hausman & Rapson (2018) discuss the pitfalls and recommendations for addressing them when applying the RD-in-time method.

as CO, NOx, and $PM_{2.5}$. Three studies—by da Silva et al. (2012) in Brazil, Anderson (2014) in Los Angeles, and Bauernschuster et al. (2017) in Germany—take advantage of exogenous variations in public transit supply created by strikes of public transit workers to show that decreased public transit use led to more air pollution and traffic congestion.

Although improving transportation infrastructure is necessary to address traffic congestion and promote economic activities, it is unlikely to be a cost-effective way to improve environmental quality. Findings from the literature suggest that expanding subways has at best a modest effect on reducing air pollution in the short run and that these effects may erode over time as travelers adjust their travel behavior. Beaudoin & Lin-Lawell (2017) and Rivers et al. (2020) find no evidence of air quality improvement from the expansion of public transit. In fact, Beaudoin and Lin-Lawell find that the increase in US public transit supply between 1991 and 2011 led to a small deterioration in overall air quality, especially for NO_2 and PM_{10}. Li et al. (2019) estimate that the benefit from pollution reduction generated by the rapid subway expansion in Beijing represents only a small fraction of the overall construction and operating costs; the benefit from congestion relief is much larger and of the same order of magnitude as the costs.

2.2. Restrictions on Driving and Vehicle Purchase

Governments can use a variety of demand-side policies to incentivize commuters to change their travel behavior (e.g., switching from driving to public transit or driving less during congested hours). This subsection discusses command-and-control approaches (Subsection 2.3 discusses market-based policies).

The command-and-control approach has been widely adopted, especially in developing countries. This approach includes driving and vehicle-purchasing restrictions. The driving restriction (or road space rationing) policy was first introduced in Athens, Greece in 1982; Santiago, Chile was the second city to adopt it in 1986. In 1989, Mexico City started perhaps the longest-running and best-known license plate–based driving restriction policy. Based on the last digit of the vehicle's license plate, the policy restricts about 20% of vehicles from driving on each workday. In 2008, Beijing's municipal government adopted the driving restriction policy to prepare for the 2008 Olympic Games. Initially, the government adopted an even-day/odd-day policy, whereby a vehicle could be driven only on an odd or even day, based on its license plate. After the Olympics, the restriction was relaxed so that the license plate–based ban applied on only one designated weekday, a policy also used in Mexico City. In recent years, Paris, Rome, Milan, Oslo, and New Delhi imposed temporary driving restrictions to address congestion and air pollution. Many German cities implemented low emission zone policies, which ban high-polluting vehicles from driving in certain areas (Wolff 2014).[8]

Several studies examine the impact of these policies on traffic congestion and the environment. Like the literature on supply-side policies, these studies commonly adopt quasi-experimental strategies, such as the RD-in-time, DID, and ES methods, using identification from both spatial and temporal variations. The empirical findings are mixed, highlighting the importance of understanding competing forces and consumer responses in policy design.

Using the RD-in-time method, Davis (2008) finds that the driving restriction led to worse air quality in Mexico City because the policy incentivized drivers to circumvent the restriction by purchasing a second vehicle, which tended to be older and dirtier. In contrast, the evidence on the environmental impact of Beijing's driving restriction policy has been largely positive. Using both RD-in-time and DID methods, Viard & Fu (2015) show that the every-other-day driving

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[8] See Wolff & Perry (2010) for a review of low emission zone policies in European cities.

restrictions in Beijing led to a 19% reduction in air pollution and that the one-day-a-week restrictions led to a 7% reduction. Zhong et al. (2017) confirm that the driving restriction policy in Beijing reduced both traffic congestion and air pollution and, as a result, emergency room visits also declined.[9]

The difference in the environmental outcomes of the license plate–based driving restriction between Mexico City and Beijing suggests that an effective policy design needs to pay attention to the broad operating environment, which affects consumer responses to the policy and, ultimately, the effectiveness of the policy. In response to the driving restriction policy, commuters in Beijing have mainly resorted to public transit instead of the purchase of a second vehicle to meet their travel demand (Xu et al. 2015). There are two important institutional differences between Mexico City and Beijing. First, as previously discussed, Beijing has been investing heavily in improving the public transit system since 2007. The expansion of public transit, including subway and buses, provides residents alternative travel modes. Second, the Beijing municipal government adopted two policies that limited households' ability to purchase a second vehicle. At the time of the driving restriction policy, the Beijing government also implemented a policy to restrict sales and registrations of used vehicles from other cities that did not meet Beijing's tailpipe emission standards. In addition, Beijing implemented a quota system on vehicle purchases from 2011 that limited households' ability to purchase a second (new or used) vehicle. The theoretical model developed by Zhang et al. (2017) highlights the uncertainty of the effects on air quality that result from license plate–based driving restrictions. They show both theoretically and empirically that the same policy could lead to different outcomes depending on the substitution among travel modes, the purchase of second vehicles, and atmospheric chemistry, which could result in differential impacts across pollutants.

Another command-and-control policy to curb the growth in travel demand is a vehicle quota system. In 1990 Singapore adopted such a policy, allocating licenses (known as certificates of entitlement, COEs) through a monthly auction system. The cap is defined over different categories of vehicles based on engine power. The COE price ran as high as SGD 50,000 (about US$35,000) for large passenger vehicles. In 1994 Shanghai started an auction system to allocate limited vehicle licenses; it switched to an online system with a reservation price in 2008. The monthly cap has been about 10,000 units. The number of bidders per month is about 150,000 to 200,000; the average winning bid was about CNY 90,000 (about $14,000) in recent years.

In 2011, the Beijing municipal government implemented a vehicle quota policy to reduce air pollution and traffic congestion. It uses a lottery system to allocate limited vehicle licenses. The lottery was initially held monthly; since 2014, it has been held every second month. The quota was reduced over time, and the odds of winning decreased substantially.[10] Five other cities in China now have vehicle quota systems based on various allocation mechanisms: Guiyang and Guangzhou adopted license lotteries in July 2011 and August 2012, respectively; Tianjin, Hangzhou, and Shenzhen started to implement a hybrid system in January, March, and December 2014, respectively.

Li (2018) uses a structural econometric model to compare the allocative efficiency and environmental outcomes of auction and lottery systems. The analysis suggests that the lottery system leads to a large welfare loss from misallocation, although it has an advantage over an auction in

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[9] These results are consistent with the findings of Chen et al. (2013), who examine short-term environmental measures, including the driving restriction policy and other policies the Chinese government adopted in preparing for the 2008 Olympic Games. They find a positive but temporary impact of the measures on air quality.

[10] The odds of winning the license plate lottery in Beijing decreased from 1:10 in early 2011 to nearly 1:2,000 in 2018 because the cap tightened, and the pool of lottery participants increased dramatically.

terms of reducing externalities such as air pollution from automobile usage.[11] The environmental impacts of the purchase restriction policy warrant future research. The short-run impact is likely small; hence, given that the first-order effect of the policy is on the flow rather than the vehicle stock, the short-term impact is hard to empirically detect. The long-run impact could be more significant, but it is harder to identify because there is more room for confounding factors to be at play in a longer time horizon.

2.3. Congestion Pricing

The command-and-control approaches that restrict driving or vehicle ownership are not the first-best policies to address environmental and congestion externalities; such policies can lead to unintended consequences (Davis 2008). Market-based policies have gained more traction from policy makers in recent years. This subsection discusses congestion pricing as a market-based policy tool to affect travel behaviors such as travel time, distance, frequency, and modes.

Congestion pricing was first proposed by Vickrey (1959), who recognized congestion as a classic externality and identified the mispricing of transport resources as its root cause. To maximize the efficiency gain, congestion pricing can be designed to allow charges to vary by location and time based on the spatial and temporal variation of the congestion externality. To address distributional concerns and further promote the use of public transit, the revenue raised can be used to improve access to and the quality of public transit.

Singapore adopted the first congestion pricing scheme in 1975. Some European cities have adopted area-based congestion pricing (London in 2003, Stockholm in 2006, Milan in 2008, Gothenburg in 2013). In the United States, several area-based schemes were proposed but failed to be implemented over the years. New York state's 2019 budget proposes congestion pricing on vehicles that enter Manhattan below 60th Street. If adopted, New York City would become the first US city to use congestion pricing.[12] Real-time congestion pricing is now technically feasible. Singapore is slated to become the first city to use a GPS-based system in 2020. The more flexible congestion charges raise privacy concerns, however, as they rely on collecting commuters' travel information (Parry et al. 2007).[13]

Several studies examine the effectiveness of congestion pricing designs. They include Olszewski & Xie (2005) (Singapore), Beevers & Carslaw (2005) (London), Simeonova et al. (2018) (Stockholm), and Gibson & Carnovale (2015) (Milan). These studies find that the schemes reduce congestion by approximately 10–30% and provide significant environmental benefits for the priced area.[14] (For a review of studies on the impacts of existing congestion pricing schemes, see Anas & Lindsey 2011.[15])

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[11] Chin & Smith (1997), Koh (2003), Chen & Zhao (2013), and Xiao et al. (2017) have examined the impact of the quota policy on vehicle purchases and consumer welfare in Singapore and China.

[12] Several dozen high-occupancy toll (HOT) lanes with variable or dynamic tolls are operating or planned in the United States. For example, the express lanes on Interstate 66 near Washington, DC charge single-occupancy vehicles a fee that fluctuates according to traffic conditions.

[13] Singapore's electronic road pricing system features about 80 entry points that record passing vehicles around the city. The charges are not based on distance traveled, and they vary only infrequently. The system is being upgraded to a GPS-based system with the ability to incorporate time-varying and location-specific charges.

[14] Drivers may respond to the charges by driving around the priced area. Such behaviors may lead to more traffic and emission outside the area, as Gibson & Carnovale (2015) suggest.

[15] Daniel & Bekka (2000), Bigazzi & Figliozzi (2013), and Fu & Gu (2017) study highway tolls and their environmental impacts. Using data from 98 Chinese cities, and both RD-in-time and DID methods, Fu & Gu (2017) show that eliminating highway tolls increases air pollution by 20% and decreases visibility by 1 km.

Congestion pricing has not been implemented in any developing country. Two recent studies attempt to study the potential benefits of adopting such a policy in these countries. Using real-time, fine-scale traffic data from Beijing, Yang et al. (2020) analyze the relationship between traffic density and speed. They estimate the optimal time-varying and location-specific congestion charges to be between CNY 0.05 and CNY 0.39 per kilometer; they conclude that the pricing scheme could help relieve peak-hour traffic congestion and lead to annual welfare gains of CNY 1.5 billion.

With a similar focus but a different method, Kreindler (2018) uses GPS data on more than 100,000 commuter trips in Bangalore, India to conduct a randomized experiment for the morning commute. He compares two congestion charge policies that impose fees for driving through certain areas during peak hours. Based on the experimental price variation, he estimates commuters' preference for scheduling flexibility relative to their value of time. He concludes that the costs of rescheduling travel to inconvenient times will almost entirely offset the benefits of the saved travel time, resulting in only a small consumer welfare gain.

3. POLICIES TO PROMOTE ALTERNATIVE FUEL VEHICLES

The past two decades have witnessed the rapid development and diffusion of alternative fuel vehicle (AFV) technologies amid heightened concern over energy security and transportation-related air pollution and GHG emissions. AFV technologies include flexible-fuel vehicles (FFVs), hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell vehicles (FCVs), and natural gas vehicles (NGVs). By reducing the consumption of gasoline and running on cleaner fuels, AFV technologies provide potential pathways to mitigate or even eliminate the environmental externalities associated with petroleum consumption.

AFV technologies face common adoption barriers in the early stage of diffusion, such as higher up-front costs, limited model choices, consumers' lack of familiarity with the new technology, and the potential undervaluation of future fuel-cost savings. To help speed the diffusion of AFVs, governments in both developed and developing countries have provided various incentives to consumers and automakers. They include both monetary and nonmonetary incentives for purchasing AFVs and mandates and regulations that require automakers to produce AFV vehicles.

This section investigates the effectiveness of various policy tools as evidenced by the findings of recent studies of AFVs. Most of the empirical studies focus on markets in developed countries, but their conclusions and policy implications could be generalized to developing countries.

3.1. Subsidies for Adoption of Alternative Fuel Vehicles

The most widely used policies to stimulate the adoption of AFVs rely on tax credits and rebates. Tax credits are usually claimed on a tax return; rebates are either provided after mailing in a proof of purchase or directly deducted upon purchasing an AFV. Governments can also implement vehicle scrappage schemes, in which buyers of energy-efficient vehicles receive rebates if they trade in their old emission-intensive vehicles (Li et al. 2013, Jacobsen & van Benthem 2015).

A large body of empirical studies estimates the effects of subsidies on consumer adoption of AFVs. The stated preference approach was especially popular during the early stage of the diffusion of alternative fuel technology because of the lack of data. A challenge of the stated preference analysis is that the hypothetical purchase environment is often different from the real world, and the choices that respondents make in a survey may not reflect their true preferences in a real vehicle purchase situation, biasing the elasticity estimates. With the increasing availability of sales data and the adoption of real policies, recent studies have used the revealed preference method by exploiting the spatial and temporal variation in market sales of AFVs and incentive policies while controlling for vehicle model characteristics and consumer demographic variables.

The effectiveness and efficiency of subsidy programs hinge on several factors. The first is the lack of additionality: the notion that incentives do not always result in additional AFV sales, because many buyers who receive the subsidy might still have purchased AFVs without it. This problem may be pronounced during the early deployment stage because early adopters of AFVs are consumers who embrace new technologies, who have the strongest environmental awareness, and who usually have higher incomes. Therefore, their purchase decisions do not heavily rely on the provision of subsidies; these people would probably have purchased AFVs without the subsidies.

Various empirical studies document the challenge of additionality. Chandra et al. (2010) argue that the HEV tax rebates offered by Canadian provinces subsidized many consumers who would have bought HEVs in any case. Beresteanu & Li (2011) find that HEV sales in the United States would still be growing rapidly, even without tax incentives. Huse & Lucinda (2014) find that a substantial share of FFV consumers in Sweden would have purchased FFVs in the absence of the cash rebates because of the vehicles' lower operational costs. Xing et al. (2019) find that federal income tax credits for purchasing plug-in electric vehicles (PEVs)[16] in the United States resulted in a 29% increase in PEV sales, but 70% of the credits went to households that would have purchased PEVs without the credits.[17]

Replacing a one-size-fits-all policy with one that targets marginal buyers who are more responsive to the subsidy and would purchase AFVs only with the subsidy could improve effectiveness. Marginal buyers are those who consider the higher up-front cost the only obstacle to the adoption of AFVs or those who view the subsidy amount as sufficient compensation for the utility loss from the other drawbacks of AFVs. Using the EV subsidy receipts data and vehicle transaction prices, Muehlegger & Rapson (2018) show that EV demand by low- and middle-income households is price elastic and that the pass-through of the subsidy is complete among these consumers. Xing et al. (2019) find that cost-effectiveness is greater for policies that eliminate or reduce subsidies for high-income households and provide more generous subsidies for low-income households. Improving the targeting of subsidy policies is an important issue and an active area of research in other energy- and poverty-reduction programs (Allcott et al. 2015, Kitagawa & Tetenov 2018).

The second important factor is the need to design a subsidy that pays attention to the heterogeneity in benefits across locations and vehicles. Although PEVs produce little or zero tailpipe emissions on the road, substantial heterogeneity of environmental impacts could exist when factoring in upstream emissions. The environmental advantage of PEVs over conventional vehicles is lower in locations where electricity is generated through fossil fuels. Holland et al. (2016) find considerable heterogeneity in the environmental benefits of PEV adoption in the United States, depending on the location. They therefore argue for a regionally differentiated PEV policy. The environmental benefit of PEVs is the largest in California, where the damage from gasoline vehicles is great, and the electric grid is relatively clean. In contrast, PEVs cause more harm than gasoline vehicles in places such as North Dakota, where electricity is generated mostly from coal. For the many developing countries that rely on coal for electricity generation, the environmental benefit of PEVs is an important empirical question.

A third factor to consider in policy design is that the environmental benefits of AFVs hinge on the amount of gasoline replaced by alternative fuels. This figure is challenging to estimate

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[16] PEVs include both battery electric vehicles (BEVs) and PHEVs.

[17] See DeShazo (2016) for a literature review on the effectiveness of US subsidy programs for PEVs.

because consumers who choose to buy AFVs may be different from others in driving demand. Consumers who purchase AFVs may have greater environmental awareness; they may thus have purchased another fuel-efficient vehicle had they not purchased an AFV. As a result, the reduction in emissions may be small (Xing et al. 2019). In addition, the ability of AFVs to reduce pollution depends on how many miles AFVs are driven and how many miles would have been driven by gasoline vehicles. Because they have a shorter range and charging is inconvenient, BEVs may not be driven as much as conventional vehicles. Davis (2019) finds that both BEVs and PHEVs are driven considerably fewer miles per year than gasoline vehicles and suggests that PEVs may therefore imply smaller environmental benefits than previously believed.

For AFVs, such as FFVs and PHEVs, that piggyback on gasoline vehicles and can run on both gasoline and alternative fuels, "fuel arbitrage" could also weaken the effectiveness of subsidies in reducing emissions. With relatively low gasoline prices, FFV and PHEV drivers are more incentivized to choose gasoline over ethanol or electricity, given the lack of ethanol and electric fueling infrastructure and the inconvenience of refueling. Huse & Lucinda (2014) estimate that CO_2 savings would fall by 14% if gasoline usage among FFV drivers increased to 50% and by 18% if such gasoline usage increased to 75%. Salvo & Huse (2013) find imperfect substitutability between gasoline and ethanol among flexible-fuel motorists in Brazil because consumers discriminate among fuel options based on characteristics other than price, including engine performance, the station-stopping cost, and the origin of the fuel. They suggest that substantial investments in consumer education on less-established alternative fuel technologies are required because consumer demand for the "incumbent" gasoline is sticky.

To summarize, when designing AFV subsidy policies, policy makers need to account for fuel-switching behaviors and alternative fuel usage. Both factors affect the effectiveness of such policies in reducing emissions. One possible solution is to adjust the AFV subsidy amount based on the frequency of alternative fuel usage when such data are available. Providing valuable fuel price information and accessible price comparison could increase the usage of alternative fuels (Salvo 2018).

3.2. Subsidies for Alternative Fueling Infrastructure

FFVs and PHEVs can be fueled at any gasoline station. The diffusion of other AFVs relies heavily on alternative fueling infrastructure, which is limited during the early deployment stage. The interdependence between the building of fueling stations and the adoption of AFVs gives rise to the chicken and egg problem: Consumers are reluctant to adopt AFVs unless there are sufficient alternative fueling stations, but governments and private companies are reluctant to build such stations when few AFVs are on the road. The installation of home charging for PEVs could reduce dependence on public fueling stations; the fueling of FCVs depends entirely on public hydrogen stations.[18]

In addition to providing subsidies to AFV buyers, many governments have been subsiding construction of AFV fueling stations. It is important to understand whether subsidizing one side of the market is more efficient than subsidizing the other side. Dimitropoulos et al. (2016) find that early adopters of PHEVs are sensitive to changes in the detour time to reach a fast-charging station. They argue that policies that expand fast-charging stations could be an effective stimulus for

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[18] FCVs are powered by hydrogen and fueled with pure hydrogen gas from hydrogen fueling stations. They can fuel in less than 10 minutes and have a driving range of about 300 miles. As of October 2019, there were only 41 hydrogen stations in the United States. The FCV market will not witness significant penetration unless the mass deployment of hydrogen stations occurs.

the early adoption of BEVs, potentially saving public spending for the stimulation of the adoption of electric vehicles.

Li et al. (2017) and Springel (2019) quantify the indirect network effects in the PEV market in the United States and Norway, respectively. Both studies find that the network effects of charging stations on PEV adoption are larger than the effects of PEV stock on investment in charging stations; they therefore suggest that subsidizing charging stations is more effective in speeding PEV diffusion at the initial rollout stage. This finding is likely driven by the fact that early adopters are less price sensitive and more concerned about whether they can conveniently refuel wherever they drive.

At the early stage of a technology deployment, the existence of multiple standards of the complementary service may lead to efficiency loss. Li (2019) finds that unifying the three incompatible standards for charging EVs in the United States would have increased consumer surplus by US$500 million between 2011 and 2015 and allowed car manufacturers to sell 20.8% more EVs.

4. FUEL STANDARDS AND EMISSIONS REGULATION

Instead of directly providing incentives to alter consumer vehicle purchase and driving behavior, governments can impose mandates and regulations on vehicle producers to reduce pollution. This section discusses the main mandates on manufacturers: fuel-economy standards, fuel-content regulations, and tailpipe emission standards.

4.1. Fuel-Economy Standards

Many countries have adopted fuel-economy standards that require vehicle manufacturers to improve fleet-wide fuel efficiency and provide a minimum level of AFVs. Nine governments, including the United States, Japan, the European Union, and China, have established fuel-economy and GHG emission standards for passenger vehicles. The standard an automaker needs to meet is usually a (sales-) weighted average of the target for each vehicle model in the automaker's fleet. Automakers who fail to meet the requirement either pay the penalty or buy regulatory credits from the market under the credit-trading regime.[19]

One argument that supports fuel-economy regulations is that consumers may undervalue fuel economy and fail to adopt fuel-saving technologies. The empirical literature has mixed evidence on the extent to which consumers discount future fuel-cost savings (Busse et al. 2013, Allcott & Wozny 2014, Sallee et al. 2016, Grigolon et al. 2018). Studies that evaluate the efficiency of fuel-economy regulations in reducing gasoline consumption consistently find that gasoline taxes can achieve the same goal at a much lower cost (Goldberg 1998, Austin & Dinan 2005, Jacobsen 2013, Anderson & Sallee 2016).

However, due to the political challenge of increasing taxes and the difficulty of quantifying the marginal social harms, the external cost of gasoline consumption in many countries around the world is not properly reflected by the gasoline tax (Parry & Small 2005). If the regulator decides to implement fuel-economy mandates, there are several lessons from the literature that are relevant for this situation in developing countries. First, with a binding fuel-economy mandate, providing additional AFV subsidy may have little impact on reducing energy consumption or GHG emissions. Fuel-economy mandates essentially increase the cost of producing vehicles that are less fuel

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[19] In addition to establishing fuel-economy mandates, some governments require that a certain share of the entire fleet each automaker sells be zero emission vehicles (ZEVs). California, for example, requires that 4.5% of vehicles produced be ZEVs in 2018 and 22% by 2025.

efficient and encourage automakers to sell more AFVs. However, when the additional AFV subsidy induces extra AFV sales, the mandate stringency is relaxed, and automakers can thus sell more gasoline vehicles and still maintain compliance. Therefore, the AFV subsidy implicitly subsidizes gas guzzlers, as it makes it easier to sell them. One possible solution is to exclude AFVs from the average fleet fuel-economy calculation so that the mandate takes only gasoline vehicles into account. Second, the fuel-economy mandates in many countries are now attribute based; the stringency of the regulation depends on the vehicle's weight or size, and larger and heavier vehicles are subject to a less-stringent requirement. However, this policy design provides an incentive for automakers to increase vehicle size, which could undermine the gains from fuel economy (Whitefoot & Skerlos 2012, Ito & Sallee 2018). Policy makers should be aware of the potential for vehicle substitution across sizes to occur when assigning fuel economy targets for different vehicle segments.

4.2. Fuel-Content Regulations and Tailpipe Emission Standards

Implementing fuel-content regulations that restrict the chemical composition of the fuel is another strategy to reduce the harmful pollutants from fuel consumption. Most developed countries enforce the European Union's Fuel Quality Directive, which requires sulfur levels <10 ppm for both gasoline and diesel vehicles. In contrast, many developing countries still set sulfur limits above the level recommended by the United Nations.

When designing these policies, regulators should be mindful of firms' responses and unintended consequences. Auffhammer & Kellogg (2011) find that the US federal gasoline content regulation, which allowed refiners flexibility in choosing a compliance mechanism, did not improve air quality because refiners lacked incentives to reduce the emission components that are most closely related to ozone formation. By contrast, the standards used in California that better target harmful components are more effective in improving air quality.

Emission control systems can be installed that reduce tailpipe emissions per gallon of fuel combusted. Tailpipe emission standards set the maximum amount (grams per mile) of targeted pollutants allowed in exhaust emissions from a fuel combustion engine. A number of countries, including the United States, Canada, Japan, members of the European Union, China, and India, have implemented this type of regulation. Tests conducted at specified intervals measure vehicle emissions, typically particulate matter (PM), NOx, CO, and hydrocarbons. Under such regulations, manufacturers may only sell vehicles that comply with standards. In the United States, the EPA manages and implements emission standards. California is allowed to implement more stringent emission standards, which are set by the California Air Resources Board (CARB).

In 2000, both China and India introduced their first emission standards, based on European regulations of that time. Since then, both countries have tightened their standards several times to address serious air pollution in urban areas. Based on the more stringent European standards (Euro 6) already imposed in the European Union, the new standards are slated to go into effect in 2020 in both China and India. The effectiveness and efficiency of these policies remain to be studied.

5. FUTURE RESEARCH AREAS

Many developing economies, especially rapidly growing ones, are facing pressing environmental challenges due to the increased use of fossil fuels for energy and the lack of effective and stringent regulations. As income rises in these countries, demand for environmental quality increases, putting pressure on governments to reevaluate their positions on economic growth and environmental quality. This article reviews recent studies on policies related to road transportation, their impacts on the environment, and the implications for developing countries.

In theory, market-based policies such as congestion pricing and credit trading have efficiency advantages over command-and-control approaches in addressing the externalities associated with transportation. Their applications have been very limited, however, especially in developing countries. Future research could shed light on the pros and cons of different policy instruments while paying attention not only to the efficiency and distributional impacts of existing policies, but also to the emerging opportunities afforded by new technologies and practices. The following questions warrant future research.

First, understanding how consumers in developing countries value fuel economy could help policy makers estimate the efficiency and effectiveness of policy tools such as gasoline taxes and fuel-economy standards to incentivize the purchase of fuel-efficient vehicles. This question is especially important for developing countries, where many vehicle buyers are first-time buyers, and information on fuel economy may not be well understood. If consumers are not well informed, or if they do not pay attention to fuel cost, they may choose vehicles that are less fuel efficient than optimal, providing a justification for government intervention through fuel-economy regulations.[20] As discussed in Section 4.1, there is no consensus on the extent to which consumers undervalue fuel economy in developed countries. Even less evidence is available on this issue in developing countries (Greene 2010). Chugh et al. (2011) find no strong evidence that consumers undervalue fuel economy in India. Comparing the vehicle consumption tax and fuel tax in China, Xiao & Ju (2014) find that increases in the fuel tax decrease total car sales but do not effectively encourage consumers to choose fuel-efficient vehicles. When choosing vehicles, consumers are more sensitive to changes in up-front costs than fuel costs. Further studies are needed to understand consumer preferences, information access, and awareness of fuel economy in developing countries.

Second, new technologies related to transportation could offer opportunities and challenges for developing countries in addressing environmental issues. Autonomous vehicles have the potential to profoundly transform the transportation sector and the economy in general (Winston & Karpilow 2019). However, a decade may pass before these vehicles comprise a significant share of the overall vehicle market. Thus, related empirical data may not be available for many years.[21] By contrast, ridesharing services are already prevalent in many parts of the world. As travel demand and vehicle ownership increase in developing countries, encouraging ridesharing could potentially help combat severe air pollution and congestion. By increasing the flexibility of travel and providing a new travel mode, ridesharing could increase consumer surplus (Cohen et al. 2016). Its impact on consumer travel behavior and the environment is not well understood. The environmental impact hinges critically on the emissions of the substituted travel modes and on total travel demand.[22]

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[20] Even when fully informed about the fuel economy of each vehicle model, consumers may not have the correct perception of the monetarized value of fuel economy, because of "MPG Illusion," in which consumers mistakenly think that fuel costs scale linearly in miles per gallon rather than gallons per mile (Larrick & Soll 2008). The estimated welfare cost of the MPG Illusion is negligible, however, and is not sufficient to justify the current fuel economy regulations (Allcott 2013). Using data from experiments that provide fuel economy information to new vehicle buyers in the United States, Allcott & Knittel (2019) find no impact of the information intervention on consumers' vehicle choices; the authors suggest that US fuel economy standards are more stringent than necessary in addressing imperfect information.

[21] Researchers would need to use projections and simulations to conduct forward-looking analysis on how autonomous vehicles would affect travel behavior, vehicle choices, housing locations, and the broad economy.

[22] If ridesharing mainly encourages carpooling and reduces private car driving, it may reduce overall on-road emissions. If the introduction of this new travel mode increases travel demand, if ridesharing replaces walking or public transit trips, or if deadheading to search for customers (out-of-service movement) accounts for a significant component of vehicle miles, ridesharing may increase on-road pollution and impose new challenges to pollution reduction in the transportation sector.

By exploiting the spatial and temporal variation of Uber entry and Uber penetration in the US market, Hall et al. (2018) estimate the impact of ridesharing on public transit ridership. They find that Uber complements public transit by solving the last-mile problem of public transit. They suggest that ridesharing could worsen pollution and congestion by increasing the number of car trips without taking the substitution between ridesharing and private vehicle driving into account. However, if ridesharing complements public transit and encourages more consumers to switch from driving private cars to using public transit for the entire trip, ridesharing may help reduce the overall on-road tailpipe emissions and congestion.

In addition, ridesharing may help mitigate air pollution and congestion through other channels. By better matching consumers and drivers, it reduces the time taxi drivers spend finding consumers. Reduced search time on the road could potentially reduce congestion and fuel consumption from the combined taxi and ridesharing market (Hahn & Metcalfe 2017). In addition, people who switch from driving private cars to ridesharing can save time and fuel wasted when finding parking spaces, a problem in more populated cities (Winston 2013). The extent to which ridesharing reduces air pollution and congestion through these channels depends on the substitutability between ridesharing and private driving and taxi riding. Understanding the full impact requires estimating consumer travel mode choice incorporating ridesharing.

Third, transportation policies could have broad social and economic impacts by changing a variety of household choices. Previous studies have shown that changes in commuting cost can affect labor participation decisions, fertility, and productivity (Duranton & Turner 2012, Black et al. 2014, Liu et al. 2018). Few studies have examined the broad impacts of transportation-related policy beyond immediate goals, especially in developing countries. Understanding household location choices and the general equilibrium impacts of transportation policies could help policy makers better understand their impacts on the environment and urban structure, as well as the distributional consequences. Transportation innovations and policies such as infrastructure expansion and congestion pricing affect the commuting cost and household location choices, as predicted by classical urban models (LeRoy & Sonstelie 1983). The spatial pattern of household locations in turn affects travel choices (travel mode and distance) and the environment. To examine these questions, researchers can employ equilibrium sorting models that incorporate consumer heterogeneity and allow for general equilibrium feedback between economic agents and the environment (Epple & Sieg 1999, Sieg et al. 2004, Kuminoff et al. 2013). These types of models can shed light on the interactions between transportation policies and housing markets and provide a unified framework with which to analyze and compare the effectiveness of different transportation policies to address the environment, traffic congestion, and social welfare.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

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