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The effects of ridesourcing services on vehicle ownership: The case of Great Britain

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ABSTRACT

Understanding the impacts of ridesourcing on various transport externalities is an active research area. However, research on relatively long-term impacts such as vehicle ownership is limited and mostly focused on certain geographies. This is the first study that empirically examines the impacts of ridesourcing on vehicle ownership in Great Britain. We used vehicle licensing data for local authority districts from 2001 to 2019. We exploit the heterogeneity in entry dates of ridesourcing and employ the difference-in-differences method. We found that the impacts of the ridesourcing on vehicle numbers are heterogeneous across Great Britain. While the changes in vehicle numbers attributable to ridesourcing availability are not statistically significant in metropolitan districts and urban areas, we find 2.2% and 1.1% reductions in London and rural areas respectively. Our results contribute to future research on the broader impacts of ridesourcing and can inform research and policy efforts in this area, notably regarding decarbonisation.

1. Introduction

Ridesourcing is a mobility service provided by Transport Network Companies (TNCs) that matches riders and drivers through a smartphone application that enables passengers to reach real-time information about their rides and to make online payments (Fu, 2020). The use of dynamic matching algorithms through the internet and smartphone technology is the distinctive characteristic of ridesourcing from traditional hailing services (Rayle et al., 2016). The advancements in information and communication technologies helped create an appropriate environment for the rapid growth of ridesourcing services (Alemi et al., 2018; Bansal et al., 2020; Oviedo et al., 2020; Yu and Peng, 2019). Uber started providing the service first in 2010 and has provided over 7 billion rides in 69 countries worldwide as of the end of 2019 (Uber Technologies Inc., 2020).

Travel patterns have also started to change with the rapid rise of ridesourcing services over the past decade. A growing literature

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Abbreviations: TNC, Transport Network Company; GB, Great Britain; NHTS, National Household Travel Survey; UK, United Kingdom; PHV, Private Hire Vehicle; LAD, Local Authority District; FoI, Freedon of Information; DfT, Department for Transport; GDHI, Gross Disposable Household Income; LEZ, Low-emission Zone; DiD, Difference-in-differences; DK, Driscoll-Kraay; VMT, Vehicle Miles Travelled.

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has investigated different aspects of this mobility technology. One major part of the literature discusses the ridesourcing users' profiles and ridesourcing trip characteristics, while another part focuses on the implications of ridesourcing from different aspects including the impacts on travel behaviour, environment, traffic and transport systems. Research shows mixed findings on the impacts of ridesourcing. Some studies point out the advantages of lower waiting time (Rayle et al., 2016), not being exposed to the stress and time loss of driving, and lower cost and congestion especially when the ride is shared (Etminani-Ghasrodashti and Hamidi, 2019), and effective first- and last-mile connection to public transit (Ghaffar et al., 2020; Habib, 2019). On the other hand, increased congestion due to lower vehicle occupancy, increased vehicle miles travelled due to empty running (deadheading) and induced trips (Etminani-Ghasrodashti and Hamidi, 2019; Ghaffar et al., 2020; Habib, 2019; Tengilimoglu and Wadud, 2022; Wu and MacKenzie, 2021), and competing with public transit and active modes (Ghaffar et al., 2020; Habib, 2019) are discussed as the key adverse impacts of ridesourcing. Given that the net impacts of ridesourcing services depend primarily on the modes they substitute, understanding how existing modes have been affected is an important step to understanding the broader impacts.

The relatively short-term effects on mode choice are substantially addressed in the literature (e.g. Clewlow and Mishra, 2017; Hampshire et al., 2017; Rayle et al., 2016). However, the long-term effects such as the change in vehicle ownership in the presence of ridesourcing services are yet to be fully revealed. Especially, Uber and Lyft, which are among the largest ridesourcing companies, have stated one of their goals is to reduce car ownership by providing a convenient and reliable alternative to private cars (Hawkins, 2018; Shontell, 2015). However, to what extent this goal is realised is uncertain. Given the significant impact of vehicle ownership on mode choice and travel behaviour (Scheiner and Holz-Rau, 2007; Simma and Axhausen, 2001; Van Acker and Witlox, 2010), investigating the change in vehicle ownership is a good starting point when examining the broader impacts of ridesourcing. This is because reducing the number of vehicles they own or have access to inevitably encourages people to reconsider their mobility options and hence their travel behaviour (Bekka et al., 2020).

To date, most of the studies that examine how vehicle ownership has changed in the presence of ridesourcing have relied on surveys (e.g. Bekka et al., 2020; Hampshire et al., 2017; Yang et al., 2022; Zheng et al., 2019), but few studies have used vehicle licensing or registration data (e.g. Gong, Greenwood and Song, 2017; Guo, Li and Zeng, 2019; Ward et al., 2019, 2021; Wadud, 2020). Also, the vast majority of these studies focused on the US and China, and none from Great Britain (GB) which is very different from the US and China in terms of vehicle ownership and transport infrastructure. Also, GB is more representative of Europe, an important market for ridesourcing companies,[1] although smaller than the US and China.

This research aims to fill this gap by modelling the impacts of ridesourcing on vehicle ownership in GB based on official vehicle licensing statistics data. Also, compared with the other studies in the literature, this study covers a longer period (from 2001 to 2019). Furthermore, in our study, we considered the heterogeneous effects of ridesourcing in different areas, since a single estimation for the entire country may not represent the actual effect in different areas with distinct built-environment, socioeconomic and demographic characteristics. As such, we examined the effect in rural local authority districts, urban local authority districts, metropolitan districts and London boroughs.

The rest of the paper is organised as follows. Section 2 presents the literature review on the impacts of ridesourcing on vehicle ownership. Section 3 covers the ridesourcing operations and regulations in GB briefly. In Section 4, the design of this research including the description of the study area and data is covered. In Section 5, the modelling approach is explained. Section 6 covers the empirical results of the case study conducted in GB. Section 7 presents the discussion of the results. Finally, Section 8 draws conclusions.

2. Literature review

It has been argued that ridesourcing services offer an opportunity to replace ownership-based consumption with access-based consumption (Paundra et al., 2020). By providing an affordable, convenient and comfortable alternative to existing transport modes, ridesourcing services facilitate people to rethink car ownership. Given that app-based ridesourcing services have only been available for about a decade, the actual long-term impacts are only now beginning to emerge. Therefore, there exists limited but growing literature regarding the impacts of ridesourcing on vehicle ownership. Related research in the early stages of ridesourcing has mainly relied on surveys and found no substantial change in vehicle ownership status (Rayle et al., 2016, 2014). Since ridesourcing services were mostly used occasionally to fill the mobility gap rather than as the main mode for routine or frequent trips, only a few people attributed the change in their vehicle ownership decisions to ridesourcing services (Feigon and Murphy, 2018). Hampshire et al. (2017) investigated the travel behaviour of ridesourcing users after Uber and Lyft ceased their services in Austin which provides evidence of the revealed preference of ridesourcing users in the absence of ridesourcing services. In this study, about 9 % of prior Uber and Lyft users reported purchasing a car, and 40 % started using their cars more because of the ridesourcing service disruption (Hampshire et al., 2017).

A substantial part of the related literature used the 2017 NHTS dataset to examine whether and how ridesourcing changed household vehicle ownership in the US. Studies using NHTS dataset consistently found a negative association between ridesourcing use frequency and the number of household vehicles (Blumenberg et al., 2021; Sabouri et al., 2020; Wang et al., 2021; Wu and MacKenzie, 2021). However, the direction of the relationship between vehicle ownership and ridesourcing usage, i.e. whether households with no or fewer vehicles use ridesourcing more frequently or ridesourcing causes a reduction in the number of household vehicles, is

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[1] Europe, Middle East and Africa region generated more than 15% of Uber's revenues in 2019 (Uber Technologies Inc., 2020).

inconclusive in these studies because the cross-sectional nature of the dataset does not allow to reveal a causal relationship (Sabouri et al., 2020).

A limited number of studies have used vehicle registration data at the aggregate level to model the relationship between ridesourcing and vehicle ownership in the US. Vehicle registration data shows a decrease in vehicle registration numbers at the state level (Ward et al., 2021, 2019). However, when disaggregating the data to the urban area level, a 0.7 % increase was found in vehicle registrations in urban areas (Ward et al., 2021). Also, it was found that ridesourcing has heterogeneous effects across areas with different levels of urbanity (Ward et al., 2021). Finally, Diao et al. (2021) found that ridesourcing has only had a significant and negative effect on vehicle ownership in metropolitan areas with good public transit services, which may also suggest complementarity between ridesourcing and public transit.

In China, findings on the impacts of ridesourcing on vehicle ownership are mixed. On the one hand, the availability of ridesourcing services encourages people to reconsider their vehicle purchase plans. Participants of stated preference studies in China expressed reluctance to purchase a car when ridesourcing services exist (Tang et al., 2020; Yang et al., 2022; Zheng et al., 2019). Using vehicle registration data, Zhong et al. (2020) consistently found a negative association between ridesourcing service availability and vehicle ownership in urban areas in China. On the other hand, the possibility of extra income from the excess capacity may encourage people to keep their existing cars or purchase new ones and can lead to an increase in new vehicle purchases as seen in China (Gong et al., 2017). Contradictory to people's stated intentions, vehicle registration numbers show about a 9 % increase in the number of vehicles in China (Guo et al., 2020). Supporting this, 10 % of survey participants with no vehicle purchase plans expressed their intention to purchase a car to serve as ridesourcing drivers in Hangzhou, China (Zheng et al., 2019).

In most places, multiple ridesourcing platforms, including global and local companies, operate simultaneously, which inevitably causes competition between them. Guo et al. (2019) revealed the booster effect of competition between different ridesourcing companies on the number of vehicles in China. They found that new vehicle registrations increased due to platform competition in the presence of two different ridesourcing companies. Ridesourcing companies offer different incentives and promotions to service suppliers and riders to improve or at least maintain their shares in the market despite intense competition. These incentives and promotions are discussed as one of the main drivers of increasing vehicle numbers in China (Guo et al., 2018). Offering promotions or incentives to drivers by ridesourcing platforms to expand their driver pools is indeed a common practice worldwide. For example, Uber has partnered with two car dealers to offer discounts on new car purchases (Brandom, 2013) and flexible leasing options (Lutz, 2016). Similarly, DiDi funded car-leasing companies in China to help procure new vehicles to expand its fleet (Si, 2018).

The existing literature overwhelmingly focuses on the US and China, while other geographies have only recently started receiving attention. Among them, in Paris, it was found that although ridesourcing does not play a significant role in abandoning a household car, along with other factors it facilitates a reduction in car ownership (Bekka et al., 2020). In Dhaka-Bangladesh, using vehicle registration data, it was found that motorcycle-hailing services caused about a 7.5 % increase in motorcycle numbers (Wadud, 2020). In Indonesia, while motorcycle-based ridesourcing services caused a decrease in motorcycle numbers, after the introduction of car-based ridesourcing services car numbers increased because of the insufficient number of cars to provide car-based ridesourcing services (Paundra et al., 2020). Lastly, in large cities in India, a 7.7 % slowing of growth in vehicle ownership was attributed to the introduction of ridesourcing services (Wadud and Namala, 2022).

Overall, the evidence on the effects of ridesourcing services on vehicle numbers is in both directions. On the one hand, the convenience, comfort, affordable fares and reliability of ridesourcing services may attract people to use ridesourcing and replace their cars, especially in those urban areas where car use is inconvenient and public transit services are good. In such areas, people may complement their journeys by public transit with ridesourcing and use them as a practical first/last mile connector as part of multimodal travel patterns and enjoy exclusive rides without being exposed to driving stress. On the other hand, in rural areas, ridesourcing services do not operate much because of the low passenger volume which can cause longer waiting times, less efficient services and hence loss of earnings. Therefore, from the riders' point of view, in areas where public transit services are scarce and viable alternatives to the private car are lacking, ridesourcing services are less likely to change vehicle ownership. However, it is also possible that car purchases could increase especially when the ridesourcing companies offer special incentives and promotions on new vehicle purchases to new ridesourcing drivers. In addition to the ease of car purchase provided by ridesourcing companies, the possibility of making extra income by working as a ridesourcing driver may encourage car purchases.

It is clear from the review that the impacts of ridesourcing on vehicle ownership are highly location-specific possibly due to differences in the market characteristics, regulations and industry policies. As in the cases of the US and China, researchers found different effects even in the same geography which may stem from the differences in data sources, analysis period and aggregation levels which points out the need for further investigation. Also, the survey-based and cross-sectional nature of the datasets used in most of the literature studies constrain them from investigating the actual causal relationship between ridesourcing services and changes in vehicle numbers. We contribute to the existing literature by empirically investigating the causal relationship between ridesourcing services and vehicle ownership in GB, where there is a lack of research regarding the impacts of ridesourcing.

3. Ridesourcing in Great Britain

In this study, we focused on the case of GB (England, Wales and Scotland), instead of the United Kingdom because of the lack of data for Northern Ireland. GB is a developed economy where the growth of car use has substantially ceased after reaching its peak in 2002 (Stapleton et al., 2017). As in most developed countries (Metz, 2013), in the UK, travel demand stabilised and even slightly decreased during the study period (Department for Transport, 2020a).

Uber is the first ridesourcing company in GB that started its operation in 2012 in London (Uber, 2017) and grew rapidly both in

London and the rest of GB. Less than a decade after its introduction, Uber has reached 1 billion rides (Uber, 2021). In GB's ridesourcing market, in addition to large global ridesourcing companies such as Uber, Ola and, more recently, Bolt, many local private hire vehicle (PHV) companies, such as Addison Lee in London or Amber Cars in Leeds, have also adopted app-based hailing, primarily after the entry of Uber.

However, the introduction of ridesourcing services into the GB market where the taxi and private hire trades are highly regulated has been the subject of debate. As each local council is free to set its own standards in addition to national minimum standards which are generally low, licensing standards show differences between local authorities. This may cause a substantial increase in the number of PHVs in some local authorities that have lower licensing standards because although local authorities outside London[2] can limit the number of taxis operating within their borders, they are unable to impose limits on the number of PHVs (Department for Transport, 2020b). Although there is no definitive figure available to present solely the number of ridesourcing vehicles, Fig. 1 presents the total number of licensed PHVs in England and Wales. From the figure, it can be clearly observed that there is a noticeable increase in PHV numbers which were more stable before the introduction of ridesourcing services which may suggest that this increase in PHV numbers is potentially caused by the introduction of ridesourcing services. It can be also observed from the figure that about one-third of PHVs are in London which also points out the intense PHV operations in London.

The key question is whether this increase in PHV numbers is offset by overall car ownership or not. While few studies investigate different aspects of ridesourcing in the UK context such as the implications of ridesourcing on road accidents in GB (Kirk et al., 2020) or policy implications in London (Mohamed et al., 2019), there are no studies available that investigate the impacts of ridesourcing on vehicle ownership. Therefore, investigating how these innovative mobility services have affected this relatively stable, mature and highly regulated mobility market would contribute to the existing knowledge.

Before proceeding further, it is worth mentioning the ridesourcing regulations, specifically regulations regarding cross-border operations (i.e. ridesourcing operations happening across licensing authority boundaries) as they play an important role in our research design. In GB, ridesourcing has been regulated as PHVs and subjected to certain requirements and restrictions which are set by the local councils (Linton and Bray, 2017).[3] Until the change in the taxi and PHV licensing regulation[4] after the report of the Law Commission in 2014, the operation area of ridesourcing vehicles was limited within the boundaries of the licencing authority (Butcher, 2016). However, in the report, it was argued that this limitation hinders the expansion of the business and becomes difficult for police to control (Law Commission, 2014). Therefore, to allow ridesourcing services to expand across GB, cross-border operation was allowed as long as the operator, vehicle, and driver were properly licensed by the same licensing authority (Triple Licence Rule). After this change in the regulation, any ridesourcing vehicle that meets the Triple Licence Rule was allowed to accept ride requests out of the borders of their licensing authorities. Triple Licence Rule has the potential to affect specifically the LADs in which the ridesourcing services were officially introduced after the regulation change, as ridesourcing services may already be available before the official introduction date. Therefore, it is important to consider the effect of regulation change when investigating the effect of ridesourcing services on any outcome in the GB context.

4. Research design

4.1. Study area

Our analysis covers 387 local authority districts (LADs) in GB (333 in England including 24 county councils, 36 metropolitan districts, 59 unitary authorities, 181 districts, 32 London boroughs and the City of London,[5] 32 in Scotland, 22 in Wales) over 19 years from 2001 to 2019 (Office for National Statistics, 2019). We excluded the county councils to avoid double counting because they are composed of districts and cover the same region as the district councils.

In this study, we only considered Uber, Ola and Bolt, the biggest global ridesourcing companies dominating the GB market. Although different local ridesourcing companies are available across GB, most of these local companies are the former traditional taxi or PHV companies that have adopted the app-based hailing operation, particularly after the introduction of the large TNCs. Since our primary interest is the "first" entry into a LAD, we only examined the availability of these companies and launch dates.

We collected the launch dates data from three sources: 1) existing literature, 2) the British Newspaper Archive and 3) local authorities through Freedom of Information (FoI) Law requests (the complete list of TNCs' launch dates can be found in Table SI1 in Supplementary Information (SI) 1). We started with the official ridesourcing launch date information presented in Kirk et al. (2020) which is based on Uber's official entry announcements in the Newsroom section of their website.[6] In addition, we scanned the local newspapers in the British Newspapers Archive database for ridesourcing entry announcements.[7] Lastly, we made FoI requests to LADs.

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[2] In London, TfL is unable to impose limit on the number of both taxis or PHVs (Department for Transport, 2020b).

[3] Different than others, in London, taxi and PHVs are licensed by Transport for London (TfL), rather than borough councils.

[4] In Great Britain, "black cabs" or "hackney carriages" are referred as "taxis", while ridesourcing is classified under PHVs which also cover minicabs and other chauffeured hire vehicles including minibuses, limousines, luxury cars etc. Although both "taxis" and "PHVs" are licensed to carry passengers, they are considered as two separate categories and are subject to different restrictions and regulations.

[5] City of London is the historic centre of London city. Greater London consists of City of London and 32 other boroughs.

[6] https://www.uber.com/en-GB/newsroom/.

[7] The following search terms were used to scan the newspaper archive: Uber, Ola, Bolt, ridesourcing, ride-hailing, ride-sharing, transport network companies, private hire vehicles. Also, results were limited to the period of 2010–2019.

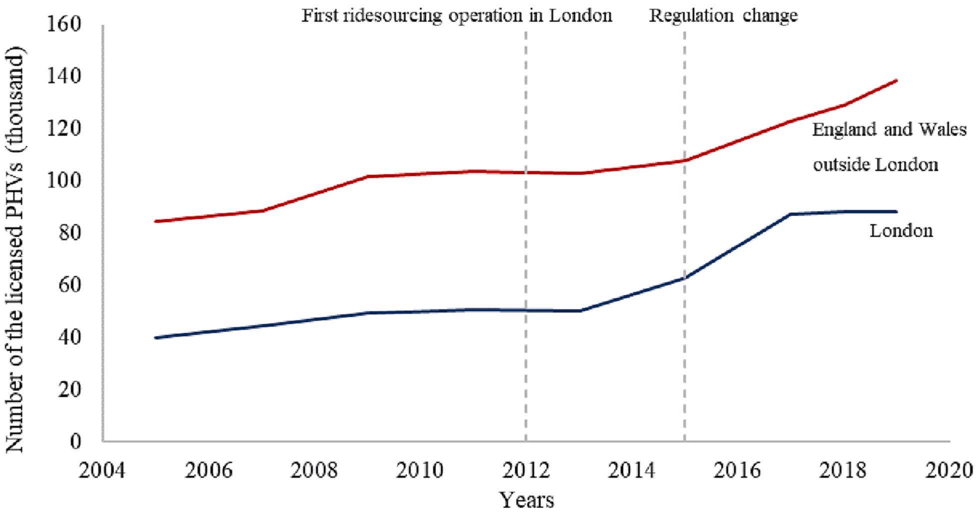

Fig. 1. Evolution of the number of PHVs in England and Wales (Department for Transport, 2019a) [*Note: Until 2017, taxi and PHV licensing statistics were released biennially.*].

The Triple Licence Rule has challenged the determination of the launch date of ridesourcing in LADs that do not grant a ridesourcing licence because these LADs have not held information about ridesourcing operations. For example, although a substantial number of local authorities reported no operation within their boundaries, when we check the smartphone applications of Uber and Ola, we could request a ride in the given local authority district. As a result of the findings from the sources mentioned above and smartphone application checks, we couldn't find evidence that shows the availability of ridesourcing services in 13 LADs. Therefore, we consider that ridesourcing services are not available in these LADs. Finally, in our models, we relied on the LADs with known ridesourcing launch dates (110 LADs) and 13 LADs without ridesourcing services, shown together with ridesourcing start years and background information in Fig. 2. We excluded the City of London and the Isles of Scilly[8] from our analysis because they have a very small residential population. We also excluded Trafford, Stockport, Solihull, Bristol, Cheshire West and Chester and Renfrewshire because of the discrepancies in vehicle numbers (see Fig. SI 1 in SI 2 for the evolution of vehicle numbers in the study area). Finally, we ended up with 115 LADs. It is worth noting that although these cover about one-third of all LADs and 10 % of the total area of GB, they cover around half of GB's population.

4.2. Variables and data

4.2.1. Dependent variable

The dependent variable in our analysis is the number of vehicles per 1000 people. We used Vehicle Licensing Statistics (data table VEH0105)[9] prepared by the UK Department of Transport (DfT). This dataset contains the number of vehicles registered in LADs and does not separate private cars and PHVs. It is worth noting that taxi numbers are not included in the number of private vehicles and are considered under different categories in the dataset.

4.2.2. Predictor

The main variable of interest in our econometric models is the ridesourcing dummy that indicates the availability of ridesourcing services in a given year in a local authority. The ridesourcing dummy is created using the ridesourcing availability and start dates mentioned in the previous section.

4.2.3. Control variables

Vehicle ownership depends on many different factors including the built environment, and socioeconomic and demographic characteristics (Scheiner and Holz-Rau, 2007; Van Acker and Witlox, 2010). As such, when investigating the effect of the ridesourcing introduction on vehicle ownership, these factors should be considered. The control variables we included are vehicle price index[10] (Office for National Statistics, 2021a), gross disposable household income (GDHI) (Office for National Statistics, 2021b), population density (Office for National Statistics, 2020), number of buses per 1000 people (Department for Transport, 2021), metro, light rail or

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[8] The Isles of Scilly is among 13 LADs without ridesourcing services. Therefore, after excluding the Isles of Scilly from the analysis, we continue with 12 LADs without ridesourcing services.

[9] Vehicle licensing statistics for the period of 2009–2019 are available on https://www.gov.uk/government/collections/vehicles-statistics. For data of earlier years, we made request to DfT via e-mail.

[10] Vehicle price index varies at country level over time, not at the local authority level.

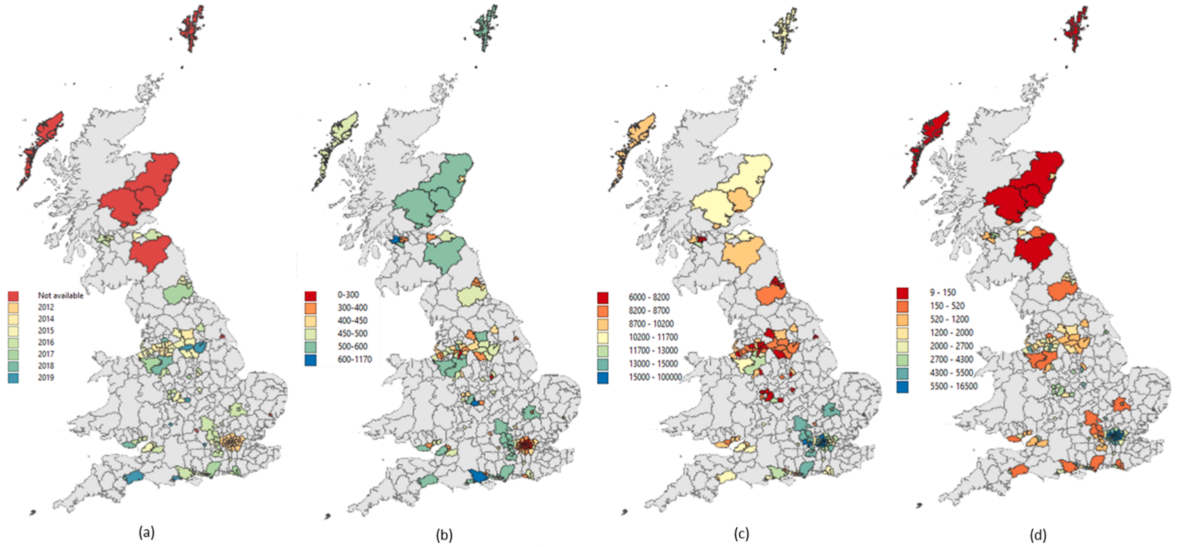

Fig. 2. Background information about the study area. (a) Official ridesourcing entry dates (b) the number of vehicles per 1000 people in 2019, (c) real GDHI per capita in 2019, (d) population density (number of people per km^2) in 2019.

tram availability. We also included a dummy variable for low-emission zone (LEZ) availability. LEZ is a defined area where access by some polluting vehicles (mostly diesel vehicles) is restricted to improve air quality. LEZ availability is expected to negatively affect the marginal private vehicle users who are occasional users and reluctant to replace their old cars after disposing of them with new ones. Fuel prices were also included in the model. However, fuel prices are only available for the whole UK and not for the smaller areas. Therefore, using the number of diesel vehicles and petrol vehicles (Department for Transport, 2021) and diesel and petrol prices (Department for Business Energy and Industrial Strategy, 2022) weighted average fuel prices over time were calculated for each LAD. All price variables in our dataset are in real terms.

5. Methods

Difference-in-differences (DiD) method is generally applied in similar studies. This method seeks to establish the effects of interventions on the outcomes of interest. By ruling out the possible impacts of other factors on outcomes under consideration, this method can be used to establish the causality between intervention and outcomes (Gertler et al., 2016). We followed the fixed-effects regression specifications presented below:

$$Y_{it} = \alpha_i + \theta t + \sum_j \delta_j X_{jit} + \gamma Z_{it} + \varepsilon_{it} \tag{1a}$$

$$Y_{it} = \alpha_i + \beta_t + \sum_j \delta_j X_{jit} + \gamma Z_{it} + \varepsilon_{it} \tag{1b}$$

where y_{it} is the dependent variable (vehicle numbers per 1000 people in logarithm) for LAD i and year t. Z_{it} is the ridesourcing dummy which indicates the availability of ridesourcing services in LAD i in year t (1 if ridesourcing is available in LAD i in year t, 0 otherwise). X_{jit} is the jth control variable for LAD i and year t with corresponding coefficient δ. α_i and β_t are LAD- and yearly-fixed effects and t is the general time trend with the respective coefficient of θ. Lastly, ε_{it} is the unobserved error term.

In addition to the average effect, we also examined the heterogeneous effect in different areas. As such, we included interaction terms with dummy variables for each group (rural LADs, urban LADs, metropolitan districts and London boroughs),[11][12] to reflect the area-group effects. In area-group effects models, we followed the specifications below:

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[11] Rural areas are defined as physical settlements with less than 10,000 population, while all other areas are considered urban (Bibby and Brindley, 2014). However, although metropolitan districts (e.g. Birmingham, Leeds, Manchester, Greater London Area) are also considered as urban LADs, we separated metropolitan districts from other urban LADs as they represent a larger and more complex structure with urban areas, conurbations, agglomerations and surrounding area that is economically and socially integrated when compared with the non-metropolitan urban LADs. We further separated London from metropolitan districts because of the economic, demographic and administrative differences that potentially affect the outcome and included London boroughs in our analysis rather than Greater London Area as a whole.

[12] Rural LADs are taken as reference group and hence interaction term for this group is not included in the equation.

$$Y_{it} = \alpha_i + \theta t + \sum_k \tau_k V_{ki} t + \sum_j \delta_j X_{jit} + \gamma Z_{it} + \sum_k \vartheta_k Z_{it} V_{ki} + \varepsilon_{it} \tag{2a}$$

$$Y_{it} = \alpha_i + \beta_t + \sum_k \rho_{kt} V_{ki} + \sum_j \delta_j X_{jit} + \gamma Z_{it} + \sum_k \vartheta_k Z_{it} V_{ki} + \varepsilon_{it} \tag{2b}$$

$$Y_{it} = \alpha_i + \alpha_i t + \sum_j \delta_j X_{jit} + \gamma Z_{it} + \sum_k \vartheta_k Z_{it} V_{ki} + \varepsilon_{it} \tag{2c}$$

where V_{ki} is the dummy variable that represents the *kth* group to which LAD i belongs. γ represents the effect in the reference group, while ϑ_k is the interaction coefficient and shows how the effect differs in the *kth* group compared with the reference group. Now, θ represents the linear time trend for the reference group and τ_k is the interaction coefficient that shows the difference in time trends between groups. Similarly, β_t represents year-fixed effects for the reference group and ρ_{kt} shows the difference in year-fixed effects between the reference group and the *kth* group. Lastly, $\alpha_i t$ represents the LAD-specific time trend.

We exploit the staggered introduction dates of ridesourcing services in LADs to construct our models.[13] In our case, ridesourcing started first in London and was followed by the metropolitan districts and large urban areas.[14] The decision of ridesourcing companies whether and when to enter into the LADs in GB may potentially be strategic, as they seem to enter densely populated areas with relatively low vehicle ownership earlier which may raise endogeneity issues. However, entry decisions of large TNCs, including the ones that we consider in our research, are described as "*more opportunistic than strategic*" (Ward et al., 2019). This is also supported by the responses of many local authorities to our FoI requests stating the operation of these TNCs is based on the demand in the respective LAD. Further, the event study presented in SI 4.1 finds statistically insignificant effects before the entry of ridesourcing services suggesting there is no anticipatory effect and the entry of ridesourcing services into a LAD is exogenous. Also, by including interaction terms for these 4 groups in area-group effects models, we control for the potential differences between groups that may affect the outcome of interest and reduce the bias that may result from this.

It is possible to violate the fundamental OLS assumptions due to the nature of our panel dataset with observations from 115 LADs over 19 years. Therefore, we tested our models against heteroscedasticity, serial correlation and cross-sectional correlation and test results indeed show the residuals violate these fundamental OLS assumptions. Ignoring the violation of these assumptions in the panel data estimations results in biased statistical inference (Hoechle, 2007). To ascertain correct inferences, we used the Driscoll–Kraay (DK) estimator (Driscoll and Kraay, 1998) to calculate appropriate standard errors of the estimates. The DK estimator builds on Newey and West's (1987) popular heteroscedasticity and serial correlation consistent covariance matrix estimator, the DK estimator produces heteroscedasticity, serial correlation and cross-sectional correlation robust standard errors (Baltagi, 2005; Driscoll and Kraay, 1998). Using the nonparametric technique for standard error estimation, it performs well for panels with large cross-sectional dimensions and reasonable time dimensions (Driscoll and Kraay, 1998). Hoechle (2007) also suggests the use of Driscoll-Kray estimators when there is cross-sectional correlation in such dataset, which is our case, too.

Additionally, we conducted a series of robustness checks to test the stability of our baseline model estimates by applying some of the methods recommended by Neumayer and Plumper (2017). These checks include alternative model specifications with alternative ridesourcing variables, placebo test and Jackknife test. Details and results of robustness tests are explained in SI 4.

6. Results

6.1. Baseline models

In Table 1, the results of the difference-in-differences models that estimate the effect of ridesourcing on vehicle numbers per 1000 people in LADs are summarised. In these models, we take the official entry date of ridesourcing services as the start dates of ridesourcing in respective LAD. It is worth noting that we tested the potential lagged effect of ridesourcing entry using the 1-year-lagged ridesourcing variable[15] as the variable of interest. However, no-lag models perform better in terms of goodness-of-fit statistics, hence we select no-lag models as main models and 1-year-lagged models as alternative models.[16]

Model 1a and Model 1b, which follow specifications 1a and 1b presented in the previous section respectively, assume a homogeneous response across all LADs and present the average effect across GB. In Model 1a, all the control variables that were mentioned in previous sections are included and the effect of time is represented by adding the general time trend into the model. In Model 1b, yearly-fixed effects represent the effect of time instead of the time trend. Vehicle price index and fuel price variables are excluded because of multicollinearity with the yearly-fixed effects.

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[13] To interpret the effect as causal, the comparison groups should meet the parallel trends assumption which requires similar trends in outcome variable of comparison groups before the intervention takes place. A visual inspection of figures included in the supplementary material shows that neither individual LADs (see Figure SI 1 in SI 2) nor the LAD groups that are classified based on the ridesourcing introduction dates (see Figure SI 2 in SI 3) show clear evidence for violation of parallel trends.

[14] See Figure SI 3 in SI 3.

[15] We also tested for 2 years-lagged effect. However, as these models performed marginally poorer than no-lag and and 1 year-lag models in terms of goodness-of-fit statistics, we have not presented the results of 2 years-lag models here for brevity.

[16] Alternative models with 1 year-lagged ridesourcing variable are further discussed in SI 4.2. Alternative model specifications.

Table 1
Estimation results for baseline models.

Dependent variable: Vehicle number per 1000 people (ln)	Model 1a		Model 1b		Model 2a		Model 2b		Model 2c	
	Estimate	Std. err.	Estimate	Std. err.	Estimate	Std. err.	Estimate	Std. err.	Estimate	Std. err.
Ridesourcing dummy	−0.008	0.009	−0.008	0.007	−0.013***	0.004	0.004	0.003	−0.011*	0.006
Ridesourcing dummy × Urban LADs dummy					0.016**	0.007	0.001	0.004	0.007	0.005
Ridesourcing dummy × Metropolitan districts dummy					0.021**	0.008	−0.020***	0.004	0.018*	0.010
Ridesourcing dummy × London dummy					−0.003	0.010	−0.038***	0.006	−0.011	0.007
Real GDHI per capita (ln)	0.494***	0.145	0.229	0.149	0.404***	0.130	0.528***	0.177	−0.126	0.075
Real GDHI per capita square (ln)	−0.028***	0.008	−0.024**	0.009	−0.023**	0.008	−0.037***	0.011	0.008**	0.004
Vehicle price index (ln)	−0.393***	0.069			−0.300***	0.104			−0.245***	0.077
Real fuel price (ln)	−0.339***	0.062			−0.345***	0.083			−0.060	0.053
Real fuel price square (ln)	0.043***	0.009			0.041***	0.012			0.003	0.006
Population density (ln)	−0.924***	0.053	−0.917***	0.038	−0.777***	0.030	−0.864***	0.039	−0.799***	0.067
Bus number per 1000 people (ln)	0.005	0.005	0.007	0.005	0.005	0.004	0.006	0.005	0.009*	0.005
Rail transport availability	−0.008	0.018	−0.015	0.017	−0.021	0.015	−0.024	0.016	0.007	0.013
LEZ	−0.067***	0.022	−0.057***	0.017	−0.007	0.006	−0.115***	0.005	−0.010*	0.005
Constant	13.041***	0.411	12.569***	0.506	11.946***	0.567	10.549***	0.776	13.617***	0.548
Model specification										
LAD-fixed effect	Yes		Yes		Yes		Yes		Yes	
General time trend	Yes									
General year fixed effect			Yes							
Group-specific time trend					Yes					
Group-specific year fixed effect							Yes			
LAD-specific time trend									Yes	
Model fit statistics										
Adjusted R^2	0.575		0.611		0.624		0.668		0.862	
AIC	−8370.6		−8533.7		−8622.2		−8770.3		−10825.3	
BIC	−8308.0		−8391.5		−8525.5		−8320.8		−10751.4	
Observations	2185		2185		2185		2185		2185	
Total effect (estimated through the linear combination of ridesourcing variable and interaction terms with group dummies)										
Effect in rural LADs	–		–		−0.013***	0.004	0.004	0.003	−0.011*	0.006
Effect in urban LADs	–		–		0.004	0.004	0.005	0.003	−0.004	0.003
Effect in metropolitan districts	–		–		0.008	0.006	−0.016***	0.003	0.008	0.009
Effect in London	–		–		−0.016*	0.009	−0.034***	0.004	−0.022***	0.003

Statistically significant *** at 99%, ** at 95%, * at 90%.

Models 2a-2c are the area-group effects models that include interaction terms of ridesourcing variable and area-group dummies. These models differ from each other in terms of the way the effect of time is represented which is presented in Table 1 and follow specifications 2a, 2b and 2c respectively. Taking rural LADs as the reference group, the interaction terms represent whether and how different the effect of ridesourcing services on vehicle ownership in urban LADs, metropolitan districts and London boroughs is compared to the rural LADs. Net effects in each group of LADs are obtained by the linear combination of the interaction terms and the reference area-group's coefficient, and the results are presented at the bottom rows of the table. As mentioned before, we only report heteroscedasticity, serial correlation and cross-correlation robust Driscoll-Kraay estimators and associated standard errors.

Both average effect models (1a and 1b) suggest that there has been no statistically significant change in vehicle ownership compared to the baseline in GB as a result of the introduction of ridesourcing services. The area-group effects models revealed that our average effect models overlook the variations across groups. Among area-group effects models, Model 2c performs better in terms of goodness of fit statistics (Adjusted R^2, AIC and BIC). Therefore, we select Model 2c as the preferred model which represents area-group effects and models the effect of time using LAD-specific time trend. Our results suggest that ridesourcing availability caused a 2.2 % and 1.1 % decrease in London boroughs and rural LADs respectively, while no statistically significant effect is observed in other groups.

Most control variables are in line with the findings from the related literature. Fuel price and vehicle price index variables are found to be statistically significant and negatively related to vehicle numbers, which is expected as the cost of vehicle ownership increases, a reduction is intuitively expected in vehicle numbers., A negative relationship between vehicle numbers and population density is in line with the literature. As expected, the availability of low-emission zones in LADs negatively affects the vehicle numbers in these regions. Only the association between vehicle ownership and bus numbers per 1000 people was against the expectations, as one may expect a decrease in vehicle ownership as public transit services improve. However, keeping in mind the differences between the two countries in many ways (developed vs developing, built environment and geography, policy and regulations, etc.), the same effect of bus numbers was observed in China (Gong et al., 2017), indicating bus number may have picked up the effects of a correlated factor.

6.2. Alternative models with the effect of the regulation change

As was mentioned, after the regulation change in 2015 ridesourcing services have been free to operate beyond the borders of the licensing authority. This means that ridesourcing services may be available before the official introduction date in the LADs where ridesourcing services have officially been introduced after the 2015 regulation change which results in the change in the variable of interest that is based on the first start date of ridesourcing services in the respective LAD. In alternative models presented in Table 2, it was thus assumed that ridesourcing services have become available in every LAD after the regulation change in 2015 except for the 12 LADs where ridesourcing was not available during the study period. Therefore, the ridesourcing start year was assumed as 2015 for LADs where ridesourcing officially started after 2015.

Table 2 presents the results of these alternative models that implement the effect of the regulation change. Model 3 and Model 4 follow the same specifications as Model 1b and Model 2c respectively. Concentrating on the area-group effects model, Model 4, we find similar effects in London boroughs, metropolitan districts and rural LADs for this model as in Model 2c, but results for urban areas are different. Despite having a marginally higher model fit compared to Model 2c, we believe Model 4 is less reliable as it is highly unlikely that in all LADs ridesourcing services were available in 2015; even where available, the service would likely be unreliable to bring about substantial changes. As such our discussions in the next section focus on the findings from Model 2c, our preferred model.

7. Discussion of results

Our difference-in-differences model finds no statistically significant change in vehicle ownership in GB on average, while area-group effects models suggest heterogeneity in the effects of ridesourcing on vehicle ownership across GB. Also, the results of alternative model specifications with lagged ridesourcing variables suggest that the effects of ridesourcing services are likely immediate and comparable in magnitude (confidence intervals overlap) with the baseline models with no lag.

Our preferred baseline model (Model 2c) finds a statistically significant 2.2 % reduction in vehicle ownership in London that can be attributed to the introduction of ridesourcing services there. This reduction is qualitatively supported by other model specifications, too. The direction of the effect in London can be explained by other findings in the literature. According to more than half of the car owners in London, car ownership is not convenient but is a burden for them because of the high cost of ownership, driving stress, parking and car-use restrictions (Kamargianni et al., 2018). They also stated their intentions to use alternative mobility options instead of private cars if ridesourcing and public transit services can be effectively integrated. The availability of ridesourcing in the presence of a good public transit network, higher accessibility of various key services, regulations and restrictions that make driving less convenient may encourage people to give up their cars in London. Fig. 1 shows that the number of PHVs has increased in London since

Table 2
Estimation results for alternative models with the effect of the regulation change.

Dependent variable: Vehicle number per 1000 people (ln)	Model 3		Model 4	
	Estimate	Std. err.	Estimate	Std. err.
Ridesourcing dummy	−0.009	0.008	−0.021***	0.006
Ridesourcing dummy × Urban LADs dummy			0.008	0.005
Ridesourcing dummy × Metropolitan districts dummy			0.024***	0.004
Ridesourcing dummy × London dummy			−0.001	0.005
Real GDHI per capita (ln)	0.229	0.149	−0.117	0.073
Real GDHI per capita square (ln)	−0.025**	(0.009	0.008**	0.004
Vehicle price index (ln)			−0.228**	0.082
Real fuel price (ln)			−0.082**	0.033
Real fuel price square (ln)			0.004	0.003
Population density (ln)	−0.916***	0.040	−0.781***	0.049
Bus number per 1000 people (ln)	0.007	0.005	0.008*	0.004
Rail transport availability	−0.016	0.017	0.011	0.015
LEZ	−0.057***	0.017	−0.007	0.005
Constant	12.572***	0.504	13.382***	0.483
Model specification				
LAD-fixed effect	Yes		Yes	
General year fixed effect	Yes			
LAD-specific time trend			Yes	
Model fit statistics				
Adjusted R^2	0.611		0.863	
AIC	−8533.2		−10843.6	
BIC	−8391.0		−10769.6	
Observations	2185		2185	
Total effect (estimated through the linear combination of ridesourcing variable and interaction terms with group dummies)				
Effect in rural LADs	–		−0.021***	0.006
Effect in urban LADs	–		−0.013***	0.002
Effect in metropolitan districts	–		0.003	0.005
Effect in London	–		−0.022***	0.002

Statistically significant *** at 99%, ** at 95%, * at 90%.

2012, clearly a result of the introduction of ridesourcing services. However, our results on total ownership (which includes PHVs) suggest that this increase in number is more than offset by the drop in private vehicle ownership.

For urban areas, the findings are consistent across all three baseline models (2a-2c), while for metropolitan districts the different models disagree. Our preferred model (2c) shows no statistically significant effects on ownership in either urban or metropolitan areas. One potential explanation for this may be related to the length of time that ridesourcing has been available. As ridesourcing has been introduced in these LADs much later than in London, we may not be able to observe a change in these areas yet. Also, the lower frequency and quality of public transit services and accessibility and less deterrent regulations or restrictions to private vehicle use compared to London may result in a statistically insignificant change in these LADs.

The preferred model specification (2c) shows a potential reduction of 1.1 % in vehicle ownership in rural LADs, but the statistical evidence for this is quite weak, only at a 90 % confidence level and not consistent across the three model specifications. Given rural areas had ridesourcing services appear much later than London and other urban areas, the potential reduction in ownership is intriguing. An explanation for the results in rural LADs is likely related to the proportion of households with multiple cars in rural regions because, in the presence of alternative mobility options, people are likely to replace their second car more easily (Wadud and Mattioli, 2021). In 2019, more than 50 % of households in rural areas had two or more cars, this rate is 31 % on average in urban areas (Department for Transport, 2020c). This also explains the statistically insignificant results in urban LADs and metropolitan districts where the number of carless and single-car households is more than that in the rural LADs. These findings are consistent with the findings in the US, where vehicle registration decreases in rural states, but does not change in urban states (Ward et al., 2019).

Clearly, London is at the opposite end of the spectrum, with much lower car ownership, but the city also has an extensive public transport network, which still encourages car shedding in the presence of ridesourcing. In addition to public transit services, an improved environment for walking and cycling may also contribute to a reduction in vehicle numbers in London. Especially, significant investment in cycling infrastructure such as bike-sharing scheme and cycle superhighway and quietway constructions has increased cycling (Li et al., 2018). However, these infrastructure improvements are concentrated in inner boroughs where vehicle ownership is already low (Tait et al., 2022) and mostly encourage cycling for commute trips which have been often made by public transit (Department for Transport, 2019b). Therefore, it is unlikely that the increase in cycling in London had led to significant changes in vehicle ownership.

Our results are opposite to those in the urban areas of the US where vehicle registrations increased after the introduction of ridesourcing services (Ward et al., 2021). There may be several reasons behind different outcomes that are based on the differences in built environment characteristics, transportation systems and regulations between these countries. Compared to the US, GB has diverse land use with generally smaller size dense cities with their own multifunctional centres, including different land-use types (e.g. residential, industrial, commercial, recreational etc.). Together with better public transit services in terms of variations, quality and quantity and more advanced infrastructure for active modes, GB's relatively less car-centric structure with shorter trip distances enables multimodal travel patterns which can be complemented by ridesourcing. Also, private vehicle use restrictions (e.g. low emission zone, ultra-low emission zone, congestion charge in London), parking restrictions and increasing cost of car ownership have potentially caused people to shift from car ownership to car access on an as-needed basis. Additionally and perhaps more importantly, differences in regulations that ridesourcing services are exposed to may result in different outcomes. As explained before, ridesourcing services in GB are regulated as PHVs and expected to meet certain standards and licensing requirements. In contrast, US ridesourcing licensing is much more flexible[17] which allows anyone to buy a car and serve as a ridesourcing vehicle without bothering high standards for licensing (Moran et al., 2017). Therefore, when compared to the US, GB's less car-centric structure, more advanced public transit services and stricter regulations may facilitate a more favourable change in vehicle ownership level after ridesourcing services.

Although early studies find an increase in new car sales in China (Gong et al., 2017; Guo et al., 2019, 2018), more recent findings reveal the heterogeneous effects across different areas and the direction of these effects is consistent with our findings (Guo et al., 2020; Zhong et al., 2020). In the short-run, the introduction of ridesourcing has increased vehicle car purchases in China which potentially is the result of incentives that ridesourcing companies offer (Si, 2018) and the car ownership regulations that limit new car registrations except for ridesourcing vehicles in large cities (Wadud and Namala, 2022). In the long-term, however, similar to the GB case, inconvenient and restricted car use (e.g. limited park spaces, increasing driving durations because of the congestion, inter-city car use limitations) together with less car-centric city structure seem to facilitate a reduction in car ownership in large and more developed cities (Guo et al., 2020; Zhong et al., 2020).

8. Conclusion

In this study, we present empirical evidence of the impacts of ridesourcing in LADs on the number of licensed vehicles per 1000 people in GB. We use vehicle licensing statistics released by the government which places our study among the limited number of studies in the related literature that use aggregate vehicle ownership statistics.

We find no statistically significant effect of ridesourcing services on ownership when all of GB is considered as a whole. However, our models with area-group effects capture heterogeneous effects across the study area – especially a clear reduction in ownership is observed in London. Findings from other countries also support this heterogeneity and suggest that ridesourcing services can help

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[17] In the US, 36 out of 44 states in which ridesourcing services were available as of 2017, have required TNC permit, while only 6 states have required a license for the ridesourcing driver or operator (Moran et al., 2017).

reduce vehicle ownership in specific cases, e.g. in large and more developed cities (Guo et al., 2020; Zhong et al., 2020) where there are good alternative transport modes that can be complemented by ridesourcing services. This heterogeneity is useful for policymaking, especially in the context of net-zero emissions goals. Instead of assuming a homogeneous response to such innovations in the transportation systems, authorities need to consider managing them on a case-by-case as our study reveals the location-specific nature of the effects of ridesourcing.

Our results together with the findings from the literature also highlight the importance of urban and transport system planning. We find that ridesourcing services cause a reduction in vehicle ownership when it is supported by built environment characteristics and good public transit services. This implies that when the necessary actions are taken to make cities less car-centric considering the 5D's of the built environment (Ewing and Cervero, 2010), authorities may utilize the proposed benefits of ridesourcing services to tackle the increasing vehicle numbers in cities and related problems. In the short-term, improving public transit networks and services may be an effective step as there is evidence that ridesourcing services help reduce car ownership in large and developed cities where there are viable alternatives to private cars (Guo et al., 2020; Zhong et al., 2020). Therefore, public transport improvements in urban LADs and metropolitan districts can bring about an additional reduction in vehicle ownership in the presence of ridesourcing services.

Given the total vehicle ownership (including private cars and PHVs) has reduced and PHV numbers have likely gone up (Fig. 1), most likely the actual ownership of *private* cars has further reduced- especially in London. Likewise, in urban LADs and metropolitan districts where there was no statistically significant change in vehicle ownership, it might be possible that *private* car ownership may actually have gone down. This possibly implies that our estimates are capturing the lower bound of the reduction in private car ownership in GB, as our dependent variable is the total vehicle ownership including both private cars and PHVs. However, it is important to note that even a reduction in vehicle ownership may not necessarily imply a reduction in negative traffic and environment-related externalities, as found by Ward et al. (2019). There is evidence in the literature that ridesourcing services add extra VMT to the system mostly because of the deadheading (Henao and Marshall, 2018; Tengilimoglu and Wadud, 2022) or induced travel demand (Rayle et al., 2016). In our case, assuming that PHVs are used much more intensively than private cars, although the total vehicle ownership is stable or even decreased when the decrease in VMT from a decreasing number of private cars is more than offset by the increase in VMT from an increasing number of more intensively used PHVs then an increase in VMT and related externalities like emission could be expected. However, it is also possible that old vehicles may be replaced with more efficient and newer vehicles as the participation policy of ridesourcing companies often limits the age of vehicles in their fleets which may result in more vehicles but reduced emissions (Ward et al., 2019). Preventing excessive increase in the number of ridesourcing vehicles and excess VMT generation with the proper regulatory system,[18] reducing excess VMT with efficient curb space management practices (Tengilimoglu and Wadud, 2022), supporting electrification of ridesourcing vehicles, implementation of ridesourcing into the public transit system as an effective first-last mile connector and facilitating shared use of these services (Marsden et al., 2019) may be some of the actions that can be considered when planning effective and environmentally sustainable ridesourcing operations.

In the long term, our results may have implications for autonomous vehicles, too. The shared use of autonomous vehicles for ridesourcing services is discussed as the primary deployment mode of autonomous vehicles. It is expected to accelerate the reduction of vehicle ownership specifically in dense urban areas (Litman, 2020), and our results for London support this hypothesis. Also, as on-demand autonomous ridesourcing services are expected to reduce the total cost of use, a further reduction in vehicle ownership is likely in a future with autonomous vehicles, especially in urban areas, as shown by Wadud and Mattioli (2021).

Given the clear demonstration that the effects of ridesourcing services are location specific, our results for GB may not be directly translated to other countries. However, evidence from diverse countries is further needed so that these findings can be associated with different urban, population, socio-economic and transport services and infrastructure provisions in order to draw more robust conclusions.

CRediT authorship contribution statement

Pinar Bilgin: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization. **Giulio Mattioli:** Supervision, Writing – review & editing. **Malcolm Morgan:** Supervision, Writing – review & editing. **Zia Wadud:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[18] An example is the attempt of the NYC authorities to limit the empty cruising time of ridesourcing vehicles. However, it was rejected by the court and was never implemented (Hawkins, 2019).

Appendix A. Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.trd.2023.103674.

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