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Discussion Paper

Impacts of Ride-Hailing on Energy and the Environment

A Systematic Review

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Key Points

Ride-hailing has expanded substantially around the globe over the last decade and is likely to be an integral part of future transportation systems. Through a systematic review of the literature concerning the energy and environmental impacts of ride-hailing, we have identified a dichotomy between empirical findings and theoretical projections.

- Theoretical studies offer an optimistic outlook, suggesting significant potential for ride-hailing to enhance public transit usage, decrease reliance on private vehicles, and, with the adoption of strategies such as increased electrification and ride-pooling, substantially reduce emissions and overall energy consumption.
- Contrastingly, empirical studies largely demonstrate that ride-hailing has contributed to increased congestion, vehicle miles traveled (VMT), and emissions, often exacerbating urban traffic conditions and air pollution. This is partly due to behaviors such as deadheading, where ride-hailing vehicles travel empty between passenger pick-ups.
- Both theoretical and empirical studies converge on the point that electrification holds promise for reducing ride-hailing emissions. However, the optimistic assumptions of theoretical models often do not hold up when confronted with actual consumer preferences and behavior, highlighting a critical gap between engineered estimates and observed outcomes.
- The reality of consumer behavior, including a marked reluctance towards ride-sharing and the uncertain impacts of automation on ride-hailing usage, challenges these optimistic projections.
- This discrepancy underscores the need for future research to bridge the divide between the theoretical potential and real-world impacts of ride-hailing, with a focus on understanding and influencing consumer behavior towards more sustainable practices and evaluating the long-term implications of emerging technologies such as automation. Addressing these areas will be crucial for aligning ride-hailing services with environmental sustainability goals.

1. Introduction

Ride-hailing has become a major mode of transit in many countries over the last decade, as new companies have entered the market and ridership has grown. Uber, which started in 2009, is now present in 10,000 cities worldwide (Uber 2020). Ola, founded in India in 2010, is available in over 200 cities (Ola n.d.). DiDi Chuxing, which launched in China in 2012, now serves over 550 million riders in 16 countries (Kene-Okafor 2021).

However, limited evidence exists on the impact of ride-hailing on energy use and the environment, and the studies that do exist are mixed. For example, while some studies have shown that ride-hailing has replaced the public transportation market share to a certain extent (Graehler, Mucci, and Erhardt 2019), others have shown that ride-hailing has increased public transit use in certain contexts (Hall, Palsson, and Price 2018; Berrebi and Watkins 2020) due to it helping to solve the "last mile" problem (Huang et al. 2021). Ride-hailing could also impact energy use and emissions due to changes in ridership patterns, increased accessibility, changes in vehicle miles traveled (VMT), and changes in vehicle ownership. Hence, the impacts of ride-hailing on gasoline consumption are not obvious.

As ridership continues to increase globally and policy frameworks are developed for new transportation systems, it will be more important than ever to understand the impacts of ride-hailing. For example, fleets are expected to eventually become autonomous and driverless, substantially lowering per mile costs (Gurumurthy, Kockelman, and Simoni 2019). This could increase accessibility, ridership, and VMT, thereby increasing emissions. On the other hand, fleet electrification and pooling (i.e., sharing a ride with one or more passengers with different pick-up and destination locations) could reduce emissions.

This study performs a systematic review of the existing literature on the environmental and energy impacts of ride-hailing. The goal is to better understand both the current state of ride-hailing as well as how the future of ride-hailing may evolve. Using the systematic review methodology, we provide a comprehensive review of the relevant literature while minimizing bias in the selection of studies to be reviewed (Haddaway et al. 2015), and we synthesize the evidence.

2. Methodology

Our primary research question is:

- What are the energy and environmental impacts of ride-hailing?

Our secondary research question is:

- How will electrification, sharing (pooling), and automation affect the energy and environmental impacts of ride-hailing?

To answer these research questions, we employ the "systematic review" methodology (Haddaway et al. 2015; Petticrew and Roberts 2008). By systematically searching the literature and applying precise criteria to determine inclusion of sources in the review, this methodology reduces unintentional bias (e.g., excessive citations of oneself or those in one's network) and reduces the likelihood of omitting relevant studies relative to traditional literature reviews (Haddaway et al. 2015).

We applied our search to two broadly used scientific literature databases: Web of Science[1] and Scopus. To search for relevant grey literature, we also performed a "secondary" search in Scopus to capture sources such as working papers or conference presentations that may not be fully indexed, and applied our search to WorldCat Dissertations to find relevant dissertations. First, we identified search terms to find sources relevant to our primary research question. Our search terms, which we developed iteratively, included "ride hailing" or a synonym for "ride hailing" (e.g., "ride sourcing," "ride sharing") or a ride-hailing company (e.g., "Lyft," "Uber," "DiDi Chuxing"), plus an environmental or energy impact (e.g., "gasoline consumption," "energy efficiency," "vehicle miles traveled," "public transport," "emissions"). These impacts could be direct (e.g., changes in air pollution) or indirect (e.g., decrease use of public transportation). We combined synonyms and various spellings of these terms using Booleans. Our full search strings can be found in the Appendix of this paper.

We searched titles, abstracts, and keywords of sources on the three databases using the search string. We further restricted the search to only include sources starting in 2008, just prior to the advent of ride-hailing (e.g., Uber started in 2009). Table 1 summarizes the number of results identified through our search.

Table 1. Summary of search results.

	Number of Results
Academic Literature	0
Scopus	3,090
Web of Science Core Collection	2,013
Grey Literature[2]	
Scopus Secondary	691
WorldCat Dissertations	24
Total	5,818
Duplicates	1,690
Total Excluding Duplicates	**4,128**

Source: Web of Science Core Collection, Scopus, WorldCat Dissertations.

We followed the methodological guidelines of Kohl et al. (2018a, 2018b) and used their free online platform, CADIMA, to automatically detect duplicate citations, perform the screening, and document the entire process. We developed the following inclusion criteria for screening the results to determine which ones to include in the review:

1. Refers to a quantitative analysis of a ride-hailing market.[3]

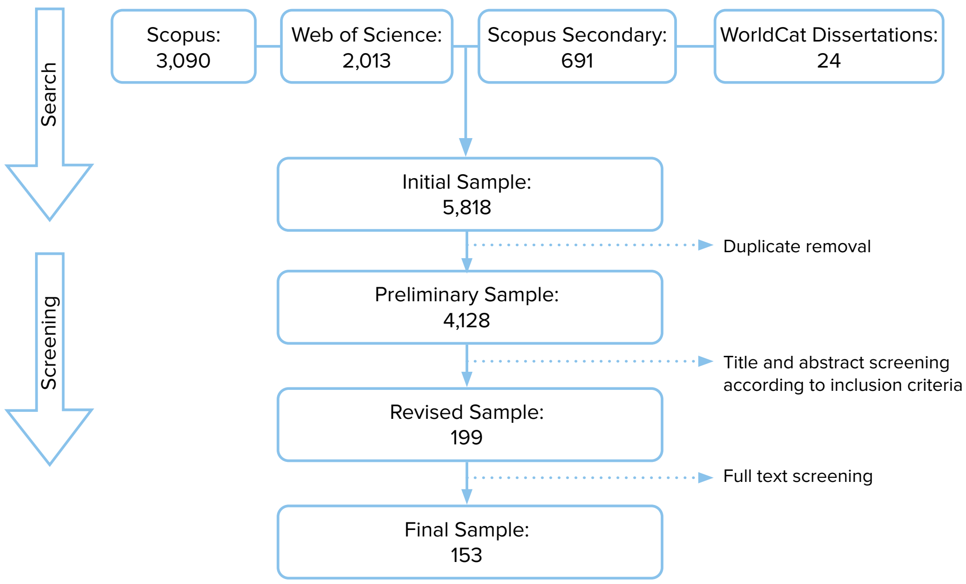
2. Refers specifically to an environmental or energy use-related effect of ride-hailing

3. Contains primary research results.

4. Is accessible at the time of review (e.g., may not be because it is behind a paywall or is not published).

Figure 1 depicts the search and screening process as well as the number of sources identified to include in the literature review.

Figure 1. Search and screening process.

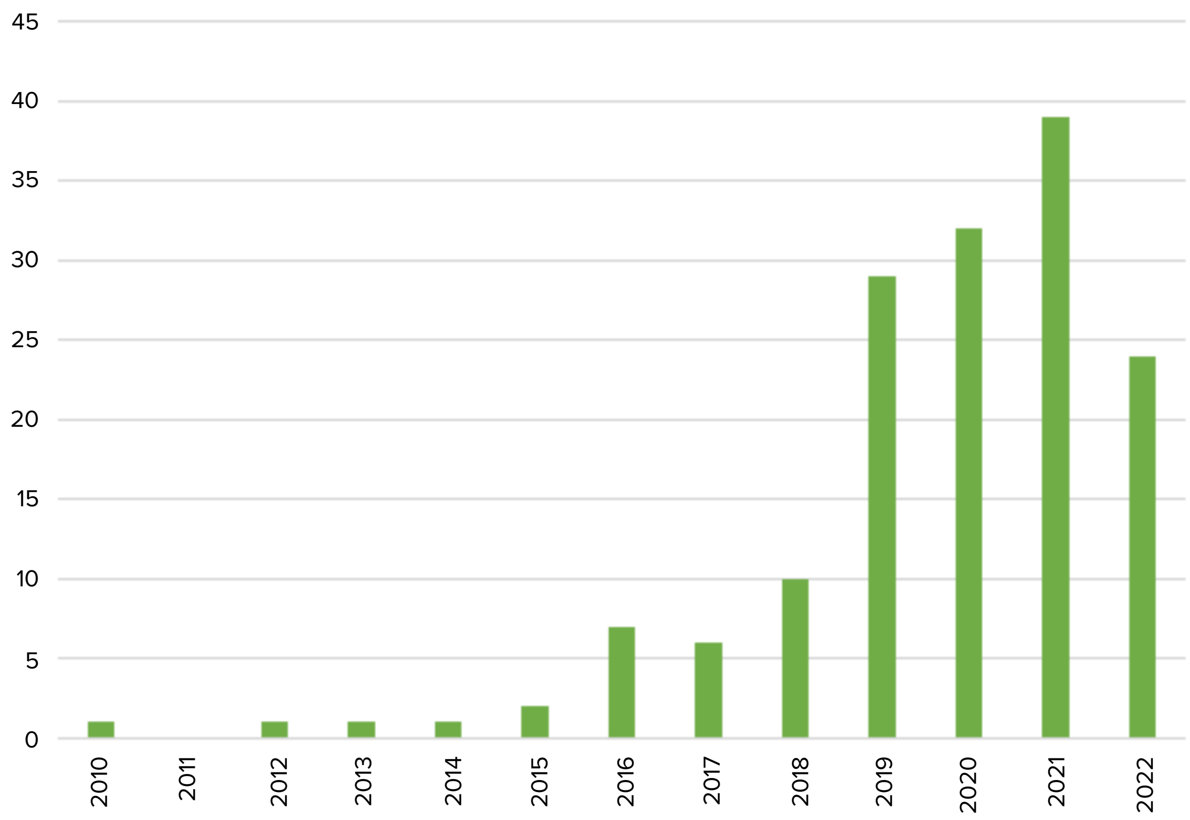


Source: Authors.

3. Results and Discussion

Of the 153 studies identified and selected for inclusion in the review, the vast majority of them were published in the last four years, with very few published prior to 2016. Figure 2 shows the number of sources included by year of study.

Figure 2. Number of sources by year of study.



Source: Authors.

A clear delineation presented itself in the papers reviewed. Eighty-nine are empirical in nature, examining observed impacts (whether direct or indirect) on the environment or energy use. The remaining 64 are theoretical in nature. In other words, just over half of the literature looks at actual or observed impacts of ride-hailing, while just under half explores the potential impact of ride-hailing. Below, we summarize and compare the various methodologies in the reviewed studies. Then, we discuss the findings of the reviewed studies, with the discussion organized around the research questions and topical themes.

3.1 Summary of Methodologies in Reviewed Studies

3.1.1 Theoretical Methodologies

The 64 theoretical papers use a diverse set of methods. The most common methods are simulation and optimization. Some rely on machine learning models, principle-agent models, and/or structural economic models. While some quality comparisons of empirical methods (discussed below) can be made based on identification strategies and sample sizes, quality comparisons across the theoretical studies are challenging if not impossible.

3.1.2 Empirical Methodologies

Causal Empirical Studies & Impacts of TNC Entry

A total of 39% (35) of the empirical papers examining impacts of ride-hailing utilize causal identification methods, with most analyzing the entry of a transportation network company (TNC), such as Uber or DiDi Chuxing, into a market. Of these, the majority (22) utilize a (often staggered) difference-in-difference (DiD) identification strategy. Generally speaking, these are the higher quality empirical studies, given that they are well powered and that they control for other factors and use methods for causal identification. In contrast, most other empirical papers (with the exception of those utilizing choice experiments) involve associational or correlational analysis as opposed to causal analysis.

Surveys and Stated Preference Studies

Just under one third of the empirical papers (25) utilize survey and stated preference methodologies, with 10 employing choice experiments. Stated preference methods allow for quantitative analysis when revealed preference data do not exist or are hard to collect, and choice experiments allow for clean causal identification. However, survey and stated preference methods can be subject to hypothetical bias (Johnston et al. 2017). Ten of the stated preference studies utilize choice experiments. In most of these, respondents choose their preferred mode of travel (e.g., ride-hailing, private car, transit), where the cost, travel time, and other attributes of the modes vary. The data is usually analyzed by estimating a mixed logit or random parameter logit model. While sample sizes are generally moderate, with 10 studies' sample sizes being between 1,000 and 2,000, only five studies have sample sizes larger than 2,000. Ten studies have sample sizes of 1,000 or less, three of which have sample sizes of 500 or less. These studies are generally not as robust as the causal studies above due to hypothetical bias and limited sample sizes, but are more reliable than associational studies.

Other/Associational Empirical Studies

The remaining third of empirical papers (29) do not leverage ride-hailing entry or other events for causal identification, instead providing associational or correlational results. These studies utilize various sources of data, including ridership, GPS trajectory, and national household survey datasets, to investigate the impacts of ride-hailing. Because they are not causal studies, care must be taken with the interpretation of results.

3.2 Energy and Environmental Impacts of Ride-Hailing

Here we address the primary research question: What are the energy and environmental impacts of ride-hailing? As discussed in Section 2, ride-hailing has several potential intermediate impacts that could in turn influence energy use and environmental outcomes. We divide these into two themes: (1.) impacts on modal choice, public transit, and vehicle ownership, and (2.) impacts on VMT, deadheading, traffic congestion, and emissions. Within each theme, we first discuss related results from the theoretical literature (predicted impacts) and then related results from the empirical literature (actual, observed impacts).

3.2.1 Impacts on Modal Choice, Public Transit, and Vehicle Ownership

Ride-hailing offers another modal choice of transit, which could impact usership of public transit and/or ownership of private vehicles, with opposing implications for gasoline usage and environmental outcomes. If riders move away from public transit and substitute it for ride-hailing more and more, transportation emissions are likely to increase. However, ride-hailing could also solve the "last mile" problem, connecting more users to public transit. Therefore, ride-hailing could be a substitute for public transit. If riders move away from private vehicle ownership, the associated change in transportation-related emissions would depend on ride-hailing usage (i.e., how many miles are ridden and what fraction of those are pooled), but life-cycle emissions from private vehicle ownership would likely decrease.

3.2.1.i Theoretical Studies

Theoretical studies show great potential for ride-hailing, under certain assumptions and with optimization, and a large fraction of private vehicles and private vehicle trips could be replaced by ride-hailing and/or public transit. Deshmukh (2018) combines agent-based and travel demand models to simulate various scenarios. They find that by 2050, under an "improved" ride-sharing scenario, the U.S. national vehicle stock would decline by 1%.

Alemi and Rodier (2017) combine MATSim data on commuting time and distance in the San Francisco area with data on ride-hailing and public transportation travel times from Google and BART. They use a dynamic assignment model to identify that 31% of private vehicle commutes could be replaced by a combination of ride-hailing and BART at a lower "generalized cost" that includes both travel time and monetary costs. They estimate that this could avoid over half a million VMT. Ke, Zhu, Yang, and He (2021) use an analytical model with a numerical case study to examine the relationship between public transit and ride-hailing. They find that the ride-hailing fleet size is an important determinant of whether the relationship is complementary or substitutive.

3.2.1.ii Empirical Studies

Public Transit

Nine papers use a DiD methodology to examine the impact of TNC entry on public transit (Ward et al. 2021; Scholl et al. 2022; Li, Chen, Yu, and Zhang 2022; Pan and Qiu 2018; Babar and Burtch 2020; Dhanorkar and Burtch 2022; Lee, Animesh, and Ramaprasad 2018; Hall, Palsson, and Price 2018; Shi, Li, and Xia 2021), essentially assessing how transit ridership changed between the location where it entered versus a location it did not enter (before versus, after entry).

Overall, evidence is mixed. Ward et al. (2021) find no significant impact of Uber and Lyft entry on transit use in U.S. cities. Similarly, Scholl et al. (2022) find no significant impact of Uber's entry on Colombian urban transit ridership. Li, Chen, Yu, and Zhang (2022) find no significant impact of Uber's entry on the transit ridership in U.S. cities, but they do find that Uber's entry increased bus ridership in sprawling urban areas yet decreased it in compact urban areas.

Pan and Qiu (2018), on the other hand, estimate a significant decline in bus ridership after the entry of Uber into U.S. cities. Similarly, Babar and Burtch (2020) find a 1.3% decrease in bus ridership, albeit a 3% increase in rail ridership, following Uber's entry. Dhanorkar and Burtch (2022) also find evidence of Uber substituting for public transportation in California, though they find it may complement public transit for carpooling users. In a similar vein, Lee, Animesh, and Ramaprasad (2018) find that after market entry in U.S. urban areas, Uber reduced transit ridership by 2%-4% in the following four months, although they also find that Uber's entry led to a 1%-2% increase in ridership by people who used to drive private cars. Grahn et al. (2021) utilize Uber and Lyft price surge events in Pittsburg, Pennsylvania, as "treatments" that increase fares. They compare bus ridership changes immediately following price surges to other times of day in order to determine the increase in bus boardings that result from higher ride-hailing costs. They assume that the treatment effect does not impact travelers not making decisions between the two modes, and they control for community events that might affect demand for both modes by controlling for local and network traffic speeds. They find a substitutionary effect for buses and ride-hailing in four of 10 locations, and they find that the relationship varies by time of day.

Hall, Palsson, and Price (2018), however, find the entry of Uber increases U.S. urban public bus and rail ridership by 5% after two years. Shi, Li, and Xia (2021) find entry of DiDi Chuxing in Chinese cities reduces bus ridership but increases passenger rail ridership.

Several papers find heterogeneity of impacts, with Ward et al. (2021) finding reductions in transit ridership in higher income areas with more childless households, and Hall, Palsson, and Price (2018) find that the increase in ridership is larger in bigger cities, smaller bus transit agencies, and larger rail agencies. Pan and Qiu (2018) find the drop in bus ridership is smaller in areas with an older population and larger in areas with higher rates of disability.

Seven additional studies use alternative empirical approaches to evaluate the impact of TNC entry on public transit (Pan and Qiu 2022; Diao, Kong, and Zhao 2021; Ngo, Götschi, and Clark 2021; Nelson and Sadowsky 2019; Malalgoda and Lim 2019; Erhardt et al. 2022; Zheng 2019). Pan and Qiu (2022) utilize causal estimators to improve upon the standard DiD methodology that does not account for time-varying unobserved cofounders. Their results suggest Uber's entry into U.S. cities resulted in a 7%-8% decrease in bus trips. Diao, Kong, and Zhao (2021) uses fixed effect panel regression models to investigate the impact of Uber and Lyft's entry into U.S. cities. They find that entry decreased public transit ridership by 8.9%.

Ngo, Götschi, and Clark (2021) use a natural experiment of the temporary ban on Uber service in Eugene, Oregon, to estimate the impact of Uber on bus ridership. They find that, relative to control cities and when Uber was banned, bus ridership was 5.4% lower when Uber was active.

Nelson and Sadowsky (2019) use a staggered event study to examine the impact of a first TNC (usually Uber) and then a second TNC (usually Lyft) in U.S. urban areas, finding that the first entry increased public transit use on average, but that this effect mostly dissipated after the second entry, and that while ride-hailing may more likely have been used for last mile travel initially, the prevalence of ride-hailing and the decrease in price after the second entry likely led ride-hailing to be a substitute for transit.

Malalgoda and Lim (2019) estimate a fixed effect regression model to find that Uber and Lyft entry increased rail transit ridership in US cities by 7%-22% in 2015 to 2017 (relative to 2007-2009), but that it did not significantly impact bus ridership. Erhardt et al. (2022) estimate a similar model, comparing bus and rail ridership in the San Francisco Bay area in 2010 (when ride-hailing was negligible) to 2015 (after ride-hailing became common). While they find that TNCs caused a 10% decrease in bus ridership, they do not find any significant impacts on light rail ridership.

Zheng (2019) employs a regression discontinuity research design, leveraging Uber's introduction to New York City in 2011 and subsequent suspension of new vehicle license issuance in 2018. The author estimates that Uber's entry to New York City increased public transit trips by 3%.

Studies utilizing choice experiments generally find greater disutility associated with transit than ride-hailing, and find that while ride-hailing can be a complement to public transit, it is often more of a substitute to public transit. Zhang et al. (2022) find that when ride-hailing is absent in Beijing, private vehicle, public transport, and taxi ridership increase by 17%, 10%, and 10%, respectively. Oviedo, Granada, and Perez-Jaramillo (2020) estimate reallocation of modal choice upon the introduction of ride-hailing in Bogotá, Columbia, finding roughly one-third of public transit trips shift to ride-hailing. Half of these are complementary and half of them are substitutionary. The authors find that the introduction of ride-hailing increases VKT by one- to 14-fold. Dong (2020a) finds that in Philadelphia, PA, waiting for transit is 4-5 times costlier to respondents than waiting for ride-hailing. Longer walking times to and from transit also decreases the probability of choosing transit, with each additional minute reducing odds by 6%-7%. A modest reduction in transit wait time (15%) is almost five times more impactful than a large fare reduction (40%) in increasing respondents' odds of choosing transit. Dong, Guerra, and Daziano (2022) find that ride-hailing substitutes transit more than complements it in Philadelphia, that ride-hailing allows customers to delay or forgo purchasing a private vehicle, and that the cost of waiting for transit is around three times higher than waiting for a ride-hailing vehicle. Unlike the above studies, Khaloei et al. (2021) find that in the U.S., the total share of transit is not very sensitive to the introduction of ride-hailing, even as ride-hailing cost decreases, which suggests limited competition between the two modes.

Thirteen papers survey ride-hailing users, either online or in person, and they directly enquire about alternative travel modes. Tang et al. (2020) and Yang et al. (2022) survey frequent DiDi Chuxing users in China, asking which mode they would choose if ride-hailing was unavailable. Tang et al. (2020) finds that more than 35% would take a taxi and 37% would take public transit, and over 6% would not purchase a private vehicle if ride-hailing services were permanently available. Yang et al. (2022) (which limit their study area to Chengdu) find that over half would choose public transit and 27% would choose a taxi. A face-to-face survey in Chengdu, China, found the highest proportion of respondents would have used public transit followed by a taxi if ride-hailing was not available (Shi et al. 2021). The authors also found that ride-hailing increased the frequency of trips by almost 17%. Yi and Yan (2020) combine DiDi Chuxing ridership data from across China with a survey of riders (co-designed by DiDi Chuxing), and they find that roughly a third of riders would have otherwise take a taxi while a third would take a public bus. A similar study using DiDi Chuxing ridership data combined with survey data from Beijing finds that 50% of respondents would use the subway or a bus while 29% would use a taxi or a private car if ride-hailing was unavailable (Yu et al. 2017).

Similar studies focusing on Brazil (de Souza Silva, de Andrade, and Maia 2018) and Ghana (Acheampong et al. 2020) both find that around half of riders would choose a taxi while about a third would choose public transit if ride-hailing was not available. Furthermore, though 70% of the respondents in de Souza Silva, de Andrade, and Maia (2018) declared that they would be interested in pooling, over a fifth said they would never use UberPool, and over a fifth said that they would never share a trip with an unknown passenger. An intercept survey in Boston showed that 41% of riders would otherwise use public transit and 40% would use a private vehicle (Gehrke, Felix, and Reardon 2019). Surveys at major California airports showed that in 2015, 21% and 30% of travelers who used ride-hailing to get to the San Francisco and Oakland airports, respectively, would have used shared transit (mostly BART) if ride-hailing was not an option (Hermawan and Regan 2018). An intercept survey in Santiago de Chile also finds that ride-hailing replaces public transit (37%) and taxis (39%) the most, with 11 riders substituting public transit for every one rider who combines it with transit (Tirachini and del Río 2019).

The remaining studies are associational. Wang, Moudon, and Shen (2022) use panel data regression analysis to estimate the relationship between modes of transportation using three waves of a transit survey in Seattle, WA, including travel logs. They find that ride-hailing appears to be a substitute for private vehicle use, but not for public transit.

Two studies use the Transportation Tomorrow Survey (TTS) from Toronto with similar methodologies as the NHTS papers. Young, Allen, and Farber (2020) analyze the 2016 TTS data and find that a third of ride-hailing trips of 15 minutes or less in duration have public transit alternatives of a similar duration, but that a quarter of ride-hailing trips would take at least a half hour longer by transit. Loa, Rahman, and Habib (2021) combine the 2016 to 2018 TTS data with ride-hailing trip data, and they find a positive association between ride-hailing and public transit. Li, Shalaby, and Habib (2022) estimate panel regression models on detailed ride-hailing trip data from Toronto from 2016 to 2018, finding a positive association between ride-hailing trips and subway ridership and a negative correlation between these trips and surface transit ridership (i.e., bus and streetcar).

Ma, Yu, and Xue (2018) combine DiDi Chuxing trip data for the Beijing-Tianjin-Hebei area with survey data in which respondents indicate their alternative modes of transport to conduct a lifecycle analysis. They find that while ride-hailing does not lead to an increase in travel demand, riders in Beijing and Tianjin substitute away from the subway and bus, respectively. Kong, Zhang, and Zhao (2020) combine DiDi Chuxing data from Chengdu, China, with Baidu Map and Google Distance data to identify that 33% of the DiDi Chuxing trips could potentially be substitutes for public transit.

Vehicle Ownership

Six papers use a DiD strategy to investigate the impact of TNC entry on vehicle ownership (Ward et al. 2019, 2021; Zhong, Lin, and Yang 2020; Widita and Diwangkari 2022; Wadud and Namala 2022; Paundra et al. 2020). Ride-hailing could decrease vehicle ownership if drivers substitute away from private vehicles. Indeed, Ward et al. (2019) estimate a 3% decrease in U.S. state-level per-capita vehicle registrations following the entry of Uber and Lyft. However, in a subsequent city-level analysis, Ward et al. (2021) estimate a 0.7% increase in vehicle registrations in urban U.S. areas following the entry of Uber and Lyft, with a larger increase in vehicle ownership in “car-dependent” cities. This is likely due to potential drivers purchasing vehicles. Despite the apparent advantages of ride-hailing drivers using more fuel-efficient vehicles, the authors find no significant impact of entry on fuel economy.

Zhong, Lin, and Yang (2020) find that the entry of Uber and DiDi Chuxing led to decreased ownership of private vehicles in Chinese cities. Specifically, private car ownership declined 11.5% and 4.2% the first and second years after entry, respectively. They also estimate a larger effect in Eastern than in Western cities. Similarly, Widita and Diwangkari (2022) find that the entry of Gojek and Grab, two ride-hailing companies, into Indonesian cities resulted in a 1.1% decline in per capita vehicle ownership. Wadud and Namala (2022), meanwhile, find that Ola and Uber have jointly reduced vehicle ownership in various Indian cities by 7.7% since their introduction.

Paundra et al. (2020) investigate the entrance of Gojek, Grab, and Uber on province-level Indonesian vehicle registrations. The analysis distinguishes between motorcycle sharing and car sharing. The authors find that the entrance of motorcycle ride-hailing led to a decrease in vehicle registrations, likely because drivers already had their own vehicles. However, the entrance of car ride-hailing services led to an increase in vehicle registrations as prospective drivers invested in new cars.

Two studies use alternative methodologies. Diao, Kong, and Zhao (2021) find no significant impacts of TNC entry on vehicle ownership in the U.S., while Naidu et al. (2019) perform regression analysis, examining the relationship between GDP and vehicle sales in India before and after the introduction of Ola, finding a weaker relationship in the second period.

Summary

A few patterns emerge. In the causal studies, ride-hailing appears to be a substitute for some riders, especially bus riders, but a complement for other riders. In particular, ride-hailing seems to solve the “last mile” problem for some commuters, making public transit, particularly rail, more accessible and convenient. The studies using choice experiments and surveys find evidence of ride-hailing sometimes complementing but more often being a substitute for public transit, with 37%-50% of riders across numerous countries reporting that they would have taken transit if ride-hailing were not available.

The associational studies, on the other hand, find more evidence on the complementarity between ride-hailing and public transit (particularly subway ridership). This could, however, be due to selection in which the people who already ride public transit are more likely to also ride-hail. Overall, there is no clear net impact of ride-hailing on public transit usage, and the net impact is likely to vary across regions and types of riders.

As for private vehicle ownership, results for the U.S. are mixed. There does not appear to be a clear reduction in private vehicle ownership as a result of ride-hailing. There is more evidence for substantial reductions in private vehicles in China and Indonesia. However, the entry of ride-hailing in some cases increases vehicle registrations from prospective drivers.

3.2.2 Impacts on VMT, Traffic Congestion, Deadheading, and Emissions

If ride-hailing leads to an increase in vehicles on the road or miles traveled, there could be substantial energy and environmental implications. Ride-hailing can impact vehicle miles traveled (VMT) both through an extensive margin (more users, such as those substituting away from public transit) and an intensive margin (for example, riders take more trips due to convenience). Furthermore, ride-hailing vehicles drive miles without passengers, whether the driver is driving between a drop-off and a new pickup or else cruising and waiting for the next ride to be ordered. This is known as “deadheading.” All of these possibilities could impact traffic congestion and emissions of air pollutants and greenhouse gases.

3.2.2.i Theoretical Studies

Theoretical studies demonstrate the great promise of ride-hailing for reducing deadheading, VMT, and, ultimately, emissions. Wang et al. (2020) perform an optimization with a deep learning neural network to minimize deadheading. Simulations with DiDi Chuxing data from Chengdu, China, show that the system can reduce the picking-up distance by 7.5%. Similarly, Kontou, Garikapati, and Hou (2020) use a machine learning model combined with RideAustin and DiDi Chuxing data from Chengdu to show that deadheading can be reduced by 53%-82%.

Tikoudis et al. (2021) use calibrated discrete choice model preference parameters from a choice experiment about transportation modes in 29 OECD countries to simulate “synthetic trips” through 2050. They find that, with substantial policy support, CO_2 emissions will be 6% lower on average due to ride-hailing with pooling, but they do find geographic variation. In a life-cycle analysis, Kawaguchi et al. (2019) find that full-scale ride-hailing reduces CO_2 emissions by just over 30%, and also reduces copper usage due to the higher utilization resulting in up to 70% fewer vehicles being produced.

A couple of theoretical studies show more nuanced results. Huang (2020) develops a simple theoretical model showing that different combinations of ride-hailing prices and price elasticities could lead to either decreases or increases in congestion. Benjaafar et al. (2022) model vehicle ownership under two different ride-hailing models, peer-to-peer and business-to-customer services, using a game theoretic approach. They find that the introduction of ride-sharing can decrease vehicle ownership but may also increase traffic. They also identify conditions under which both ownership and traffic could increase.

Ward, Michalek, and Samaras (2021) perform Monte Carlo simulations based on publicly available ride-hailing data from several U.S. cities to evaluate the impact of replacing private vehicle travel with ride-hailing systems. They find that local air pollutants would decrease by 50%-60% due to a decline in "cold starts" and to the ride-hailing fleet being composed of newer, lower emitting vehicles. However, they also find that deadheading would lead to an increase in VMT, resulting in a 20% increase in fuel consumption and CO_2 emissions.

3.2.2.ii Empirical Studies

Traffic Congestion and VMT

Nine papers use a DiD strategy to investigate the impact of TNC entry on traffic congestion (Li, Chen, Yu, and Zhang 2022; Dhanorkar and Burtch 2022; Lee, Animesh, and Ramaprasad 2018; Hall, Palsson, and Price 2018; Tarduno 2021; Choi 2017; Li, Yu, and Zhang 2017; Fageda 2021; Agarwal, Mani, and Telang 2023). While substitution from transit to ride-hailing and a general increase in demand due to the convenience of ride-hailing could lead to increased congestion, decreased private vehicle usage, pooling, and operational efficiencies versus taxis (i.e., matching algorithms reducing cruising time searching for passengers) could decrease congestion.

Hall, Palsson, and Price (2018) find that while commuting time for transit riders decreased after Uber's entry into U.S. urban areas, commuting time for private vehicle drivers increased. They interpret this as evidence of an increase in congestion. Lee, Animesh, and Ramaprasad (2018) find that traffic increased upon Uber's entry, particularly in more urban areas – with nearly a 5-minute increase to a 20-minute ride, and with a 10% increase in baseline transit ridership. Tarduno (2021) finds that Uber and Lyft increase traffic in Austin, Texas, decreasing daytime traffic speeds by about 2.3%. Dhanorkar and Burtch (2022) explore differences in congestion impacts in California by weekday versus weekend: they find that Uber's entry increases congestion more on weekends, particularly in higher population density areas and on interior (versus highway) roads, and they find that Uber's entry decreased weekday congestion in areas with low population density but increased weekday congestion in more densely populated areas. Choi (2017) finds the entry of Uber and Lyft into U.S. urban areas caused a 1% increase in travel delay times, with a larger increase for "large" metropolitan areas with populations greater than 1 million.

Li, Yu, and Zhang (2017) find that Uber's entry into U.S. cities did not significantly affect travel time in general, but it did decrease travel time in peak directions during peak periods. However, Li, Chen, Yu, and Zhang (2022) find that the entry of Uber significantly increased traffic in compact U.S. cities but decreased traffic (marginally significantly) in sprawling urban areas. This is a result of ride-hailing substituting for transit in denser urban areas but solving the last mile problem in less dense areas.

The majority of the empirical evidence above points to an increase in traffic congestion in the U.S. following the entries of Uber and Lyft. However, the one study on Europe comes to the opposite conclusion. Fageda (2021) investigates Uber's entry into European cities from 2008 to 2016, finding that this entry reduced congestion by an average of 3.5%, with the effects only being statistically significant in denser cities, and, furthermore, that the reduction in congestion is greater in cities that did not impose strong regulatory restrictions, such as quantitative restrictions, to Uber and other ride-hailing firms.

Taking advantage of various periods of the unavailability of ride-hailing in three Indian cities during the Uber and Ola driver strikes, Agarwal, Mani, and Telang (2023) use real-time traffic and route trajectory data from Google Maps to find that in the absence of ride-hailing, travel times fell by 10%-14% in the most congested areas and during the most congested times. The authors provide suggestive evidence that the reductions were caused by reduced deadheading and a switch to public transit.

Five studies use alternative empirical approaches (Diao, Kong, and Zhao 2021; Zheng 2019; Dong 2020b; Erhardt et al. 2019; Choi, Guhathakurta, and Pande 2022), and the findings are consistent with those above. Zheng (2019) finds that Uber's entry into New York City decreased the average travel speed by 0.13 mpg while not affecting traffic volume. Diao, Kong, and Zhao (2021) find that the entry of Uber and Lyft into U.S. cities increased congestion, increasing travel time and congested hours by 0.9% and 4.5%, respectively, on average. Dong (2020b) compares in-vehicle wait time data from taxi trips to Philadelphia, Pennsylvania, before and after the entry of Uber and Lyft, and finds increases in weekday wait times, particularly during morning commute hours. Erhardt et al. (2019) estimate a fixed effects panel regression comparing San Francisco traffic in 2016 to 2010, when ride-hailing was negligible, using the city's own traffic demand model to produce a counterfactual for 2016 assuming no ride-hailing, finding that ride-hailing caused half of the 13% increase in VMT and a third of the 30% and 62% increases in vehicle hours traveled as well as vehicle hours of delay, respectively, between these two years. Furthermore, average travel speeds over the timeframe decreased by 13% versus 4% in the counterfactual scenario with no ride-hailing.

Choi, Guhathakurta, and Pande (2022) compare VMT for Atlanta, Georgia, before TNC entry (2012) to after TNC entry (2018) using the empirical Bayes approach for constructing counterfactual VMT for 2018, assuming no ride-hailing. Their counterfactual combines cross-sectional analysis for regional peers with time-series analysis based on Atlanta. They find that ride-hailing led to an increase in VMT, with TNCs contributing an additional 0.6% to average annual VMT growth. This is consistent with the increase in U.S. congestion found by the above studies.

Several associational papers utilize the 2017 U.S. National Household Travel Survey (NHTS) data to identify correlations between transit behavior, mostly using regression analysis or binary choice models and controlling for other socio-demographic variables and built environment characteristics. Wang, Shi, and Chen (2021) find that regular and active ride-hailing users own fewer vehicles than occasional users. Zou and Cirillo (2021) find ride-hailing users are less likely to be primary drivers of a car and that ride-hailing does not have a significant impact on annual VMT. Wu and MacKenzie (2021) find that among households with vehicles, frequent ride-hailing users tend to have lower annual VMT, but among households without a vehicle or respondents without a driver's license, greater ride-hailing use is associated with higher VMT. They estimate that ride-hailing increased net national daily VMT by 7.8 million. Sabouri, Brewer, and Ewing (2020) use machine learning methods in an attempt to capture non-linearities, and they find a negative correlation between ride-hailing usage and private vehicle ownership. They also find a negative correlation between vehicle ownership and the number of years Uber has operated in a country.

Roy et al. (2020) use Uber and Lyft Application Programming Interface data with a travel demand model to decompose contributors to worsening congestion in San Francisco between 2010 and 2016. They find that ride-hailing was the biggest contributor, relative to road and transit network changes as well as population and employment growth, and that ride-hailing accounted for 47% of the increase in VMT.

Gao et al. (2022) perform regression analysis on the DiDi Chuxing trip-level data from Chengdu, China, to investigate the impact of subway proximity from ride origin and destination on trip VKT and emissions. They find that closer proximity is associated with lower VKT and CO_2 emissions.

Due to the lack of causal identification in the associational studies, their results are best interpreted in the context of understanding which types of households are more likely to use ride-hailing and in which built environments.

Deadheading

Most of the empirical evidence points to deadheading being a significant source of ride-hailing VMT and emissions. One of the authors from Henao and Marshall (2019) collected primary data by driving for Lyft and Uber in Denver, Colorado. In addition to collecting data about the trips and deadheading/occupancy rates, a survey was administered to riders, including questions about modal choices if ride-hailing was not available. Using this data, the authors estimate that deadheading miles accounted for more than 40% of VMT, and that ride-hailing led to 83% more VMT than would have been driven if ride-hailing was unavailable. Bekka, Louvet, and Adoue (2020) surveyed Uber riders in Paris, France. They estimate changes in VMT due to changes in private vehicle ownership resulting from ride-hailing usage (not factoring in deadheading or other modal substitutions). They estimate that less than 5% of riders gave up their private vehicle in the past four years as a result of Uber service. Netting this change with the associated miles generated by ride-hailing, the authors estimate a net impact of a -0.6% to 0.9% change in city-wide VKT. Tirachini and Gomez-Lobo (2020) similarly interview Uber users in Santiago, Chile. Around 40% and 30% of riders would have taken a taxi or public transportation, respectively, if ride-hailing was not available. The authors use the survey data to parameterize a modal transportation choice model. Simulations show that each ride-hailing trip is associated with an average increase of 1.7km (netting out VKT changes from all modes), and that the probability of ride-hailing reducing VKT is zero.

The remaining deadheading-related studies are associational. Bansal et al. (2021) calculate deadheading emissions based on detailed trip data from RideAustin. They find deadheading accounted for 59% of VMT and emissions by the ride-hailing fleet from June 2016 to July 2017. Wenzel et al. (2019) perform a similar analysis on this data, finding that driver commutes and deadheading account for 45% of ride-hailing VMT. Tengilimoglu and Wadud (2022) also examine deadheading from a subset of the RideAustin data, focusing on the 200 drivers with the highest number of trips and examining heterogeneity and uncertainty in driver behavior. They estimate that deadheading ranges from 28.4% to 55.7% of VMT. These three studies consistently find that deadheading in this context accounts for close to, if not more than, half of the miles driven in ride-hailing vehicles.

Schaller (2021) combines published estimates from a variety of sources as well as Uber and Lyft surveys across several U.S. cities in order to estimate the impact of ride-sharing on VMT from 2014 to 2020. Back-of-the-envelope calculations incorporate average estimates of pooling rates, modal shifts, and deadhead miles to find that total VMT during this time was roughly double what it would have been without ride-hailing, based on average rates of self-reported secondary mode choice.

Sun and Ertz (2021) input actual traffic data for residents in Toronto and Beijing into a "bottom-up" life cycle analysis. They find that the decrease in 2016 greenhouse gas emissions relative to 2011 was mostly a result of car sharing as opposed to ride-hailing, and that ride-hailing increased emissions over this period in Beijing, mostly due to deadheading, which accounted for 30% of vehicle lifecycle emissions.

Sui et al. (2019) combine taxi trajectory data with DiDi Chuxing trajectory from Chengdu, China, and they order data in order to compare fuel consumption and emissions. They find that taxi trips have longer idle distance and shorter delivery distance, and that DiDi Chuxing drivers tend to park more and deadhead less than taxis. This results in fuel consumption and local air pollution from taxi trips to be 1.3 to 1.5 times greater than those of DiDi Chuxing trips.

Chen et al. (2021) use DiDi Chuxing GPS records from Chengdu, China, to estimate the share of the distance driven without passengers. They find that deadheading accounts for up to 45% of miles and decreases when demand is high.

Emissions

Al Balawi et al. (2020) employ a DiD on UberX entry using EPA measured air pollutants. They find that UberX's entry into U.S. cities led to an increase in local air pollution – specifically, 2% and 18% increases in maximum nitrous oxide and volatile organic compounds, respectively. Barnes, Guo, and Borgo (2020) find that the entry of DiDi Chuxing into China led to a short-term decrease in PM2.5 pollution in the early months, but that after three months, pollution increased above pre-entry levels as the number of ride-hailing vehicles and trips rose.

Kitchel (2017) uses state-level fuel consumption data from the Energy Information Administration and a DiD approach to find that the entry of Uber into U.S. urban areas reduced excess fuel consumption by 4.6% between 2004 and 2014, though this effect is only marginally significant.

Other empirical research has shown that existing ride-hailing systems are associated with increased air pollution. Qian et al. (2020) develop a data crawler to collect high-frequency trajectory data in New York City from Uber's API, allowing the authors to convert the trajectories to space-time paths and separate stationary from moving activities, identifying stop-and-go traffic states. Using this data as a measure of actual traffic states, Qian et al. (2020) compare traffic conditions between 2017 and 2019, finding that the average daily speeds decreased more than 22% over this time period, and that the deteriorated traffic conditions also caused a 21g increase in gasoline consumption per kilometer as well as a 1g, 0.15g, and 0.04g increase in carbon monoxide, hydrocarbon, and nitrogen oxide emissions per kilometer, respectively. However, Qian et al. (2020) do not control for other factors that might also have been changing and impacting traffic in the city during this time period.

Wang et al. (2022) utilize a spatial econometric model to estimate the impact of DiDi Chuxing ride orders on various air pollutants in Shenzhen, China, finding that an increase in orders was associated with an increase in measured air pollutants, but that pollution has decreased following government regulations restricting ride-hailing. Wang et al. (2021) use cross-sectional data from different cities in China in 2017 to estimate the impact of ride-hailing on haze utilizing a generalized spatial two-stage least squares model, and they find that lower levels of ride-hailing are associated with decreases in haze, but that as the ride-hailing markets grow, they lead to higher levels of haze. However, external validity is limited here given that the study relies on annual level pollution and ride-hailing measures and does not exploit variation across time nor fully account for other differences across location.

In a life cycle analysis, Carranza et al. (2016) calculate CO_2 emissions for ride-hailing versus private car ownership under various assumptions, and they find that if riders do not own private cars and rely solely on high fuel economy ride-hailing vehicles, emissions would be significantly reduced, whereas emissions are highest when riders spilt travel between a private vehicle and an Uber. This study has several major limitations, though, including assuming perfect substitutability between ride-hailing and private vehicle ownership.

Summary

Most of the causal empirical research on the U.S. finds that ride-hailing increases traffic congestion and travel times, lowers average speeds, and increases VMT. More limited evidence suggests ride-hailing causes an increase in congestion in India but a decrease in Europe. Empirical studies also suggest deadheading leads to significant increases in VMT as a result of ride-hailing. As ride-hailing increases the number of vehicles on the road and the miles driven in these vehicles, studies have demonstrated actual, causal increases in measured air pollution as a result of ride-hailing.

3.3 Interactions with Electrification, Pooling, and Automation

Here, we address the secondary research question: How will electrification, sharing (pooling), and automation affect the energy and environmental impacts of ride-hailing? Electrification and automation are two trends that, while not specific to ride-hailing, could have significant implications for the energy and environmental impacts of ride-hailing. Pooling, or ride-sharing, on the other hand, is one avenue to mitigate VMT and congestion impacts of ride-hailing.

3.3.1 Ride-Hailing and Electrification

Eight theoretical papers focus on the electrification of ride-hailing fleets. This research suggests that the electrification of ride-hailing fleets is feasible, and that it could significantly reduce $C0_2$ emissions.

Three of these papers assess the potential for electrifying the ride-hailing fleet, with findings suggesting electric vehicles (EVs) could satisfy the majority of miles in a cost-competitive manner. Taiebat, Stolper, and Xu (2022) use 2019 U.S. Lyft driving data to find that daily travel needs for 86% of drivers can be met by a fully charged EV with at least 250 miles of range, and that such a vehicle would generally be cost competitive given annual mileage. Combining Uber and Lyft data from New York City and San Francisco with agent-based simulations, Bauer et al. (2019) show that EVs can provide the same level of ride-hailing service with only three to four 50kW chargers per square mile. Tu et al. (2019) perform a similar analysis using GPS trajectories of DiDi Chuxing drivers in Beijing. They find a 200-km range EV would satisfy the needs of more than half of the drivers, assuming that slower home charging is fully available. With widely available level-2 charging, such a vehicle would suffice for 91% of drivers and 80% of ride-hailing distance traveled.

Two of the other papers focus on the EV charging scheduling (Zhang et al. 2020; Iacobucci, Bruno, and Schmöcker 2021). An agent-based model is used in Zhang et al. (2020) to simulate driving, parking, and charging behaviors in the San Francisco Bay area, with a hybrid algorithm is then used for the site and size-charging stations to meet charging demand, and, based on the existing California grid and the daily load profile, the authors estimate electrification could reduce CO_2 emissions by more than 75% in this setting. Iacobucci, Bruno, and Schmöcker (2021) develop an approach to optimize ride-hailing fleet smart charging in an environment with dynamic electricity prices, and their optimization-simulation approach leads not only to 50% lower charging costs but also about 20% lower CO_2 emissions.

Li, Li, and Jenn (2022) simulate a shared autonomous electric vehicle fleet, comparing various adoption levels, occupancy rates, and charging strategies, finding that in California, this fleet would be about five times less carbon intensive per mile relative to ICEVs. Bruchon, Michalek, and Azevedo (2021) optimize the ride-hailing fleet composition across internal combustion engine, hybrid, and electric vehicles, satisfying demand and minimizing cost. In the majority of future scenarios, hybrids and EVs satisfy the majority of miles, with conventional vehicles used mostly during peak demand periods, and Bruchon, Michalek, and Azevedo (2021) find that this could lead to a 10% and 22% reduction in air pollution externalities such as local pollutants and greenhouse gas (or GHG) emissions, respectively.

In a life-cycle analysis, Gawron et al. (2019) find that an electrified and autonomous ride-hailing fleet could reduce energy use and GHG emissions by upwards of 60%, with most of the reductions coming from electrification.

Another empirical paper assesses be emissions reductions potential of electrification of ride-hailing. Jenn (2020) combines Uber and Lyft ridership data from California with data from household surveys to find that switching from an internal combustion engine vehicle to an electric vehicle is associated with three times more emissions reductions for ride-hailing versus private vehicles, mostly due to the higher utilization factor of the former. In this case, the empirical findings support the theoretical findings that electrification of ride-hailing fleets holds great promise for greenhouse gas emissions reductions.

3.3.2 Ride-Hailing and Pooling

3.3.2.i Theoretical Studies

Almost 60% (37) of the theoretical papers examine the potential impacts of pooling. These papers, summarized in Table 2, are overwhelmingly positive in terms of energy and environmental impacts. Methods include designing vehicle dispatch systems, optimization, and algorithms to match riders for pooling. Simulations show pooling can reduce VMT by 4%-57%, reduce fuel consumption by 7%-21%, and reduce vehicles in use by 30%-60%, thereby reducing traffic by 37%-50% and reducing both local air pollution and CO_2 emissions by around 10%. Many studies show these effects can be achieved with only minimal to moderate increases in waiting and trip times and/or while maintaining or improving passenger fares and/or driver profit.

Table 2. Energy/environmental impacts of pooling.

Paper	Method	Location	Energy/Environmental Impact of Pooling
[106]	Design an autonomous taxi ride-sharing system (using a directed network) for commuting	Theoretical	Ride-sharing reduces fuel consumption by 21% relative to regular taxi service
[107]	Assume optimal 20% ride sharing participation rate, applied transport model VISUM	Milan, Italy	Reduce VKT by 3.8%
[108]	Optimization using Genetic Algorithm, objective function is shortest route	Dalian, China	Reduce empty-load rate from 35% to 8%
[109]	Routing optimization of ride-sharing taxis, minimize operation cost and maximize passenger satisfaction, simulated annealing algorithm	Theoretical	Reduce VMT by 19%
[110]	Use taxi data, match riders	Beijing, China	Reduce VMT by 33%
[111]	Propose dynamic taxi-sharing system based on Intelligent Transportation Systems.	Theoretical	System saves time and fuel compared to existing solutions.
[112]	Use license plate recognition data, match riders	Langfang, China	With 100% ride-sharing and car-sharing, one SAV could replace 3.8 private vehicles and reduce VKT by about 15%.
[113]	Deep learning model using GPS travel records	Tokyo, Japan	Reduce VKT by almost 27%
[114]	Propose ride-sharing framework using weighted graph coloring optimization	New York City, NY, USA	Reduce vehicles in use by over 60%
[115]	Use call description records and social network data, match riders	Madrid and Barcelona, Spain and New York City and Los Angeles, USA	Reduce number of cars in city by up to 31%
[116]	Graph-based approach for trip matching.	New York	Reduce CO_2 emissions by 12.4-15.5% with shared trip discounted tariff of $0.15-0.10/minute
[117]	Optimal ride-sharing problem solved using clustering method	Lyon and Paris, France	Reduce VMT by 25% to 36%
[118]	Shareability networks applied to survey of trips	Santiago de Chile, Chile	Reduce VMT by 50% or more
[119]	Late acceptance metaheuristic optimization	Theoretical	Reduce VMT by 34%
[120]	Algorithm to miminize fleet fuel consumption	Ann Arbor, MI, USA	Reduce fuel consumption by 7%, pooling is a major contributor
[121]	Clustering-based request matching and route planning algorithm	New York City, USA and Beijing, China	Reduce VMT by up to 50%
[122]	Propose dynamic ride pooling method	San Francisco, New York City,and Los Angeles, USA	Nearly 50% of rides can be pooled, which would reduce fuel consumption by 15% and total vehicle count by 30%
[123]	Propose commute trip-sharing problem to maximize ride sharing, solved with route-enumeration and branch-and-price algorithms	Ann Arbor, MI, USA	Reduce vehicle use and VMT by up to 57% and 46%, respectively
[124]	Use taxi data, match riders	Kuwait	Reduce local air pollution by nearly 10%
[125]	Use DiDi data, match riders. Objective is to maximize VKT reduction.	Haikou, China	Pooling reduce VKT by 8.21% compared to standard ride-hailing
[126]	Aggregate traffic flow model to compare the equilibrium states of a ride-hailing market with pooling to one without	Theoretical	Identify scenarios in which both the time cost to the riders and traffic congestion decrease with pooling
[127]	Travel demand model, use census and survey data, match trips	Prague, Czech Republic	Reduce VMT by 40%
[128]	Full-stack transportation simulation using an insertion-based algorithm	Berlin	Reduce VKT by 15-20%
[129] and [130]	Integrated transportation and land-use model, incorporating feedback such as modal changes, route and distance changes, and relocating further from urban centers	Paris, France	While pooling reduces VMT, VMT reductions are 30% less due to rebound effects. Assuming average vehicle occupancy of 1.5, they find that CO_2 emissions are reduced by about 11%, versus 33% not accounting for the rebound effect.
[131]	Formulate NP-hard route calculation and solve with various algorithms	Shenzhen, China	Reduce VMT by 33%
[132]	Propose improvements over dynamic ride-sharing (DRS) using existing model, including recommending locations, transfers, and cooperation with other transportation systems	Shanghai	Reduce VMT by 44% relative to DRS
[133]	Centralized and decentralized optimization algorithms to match passengers and drivers	Sioux Falls, SD, USA	Multi-passenger rides reduce VKT more than single-passenger rides
[134]	Propose algorithms for passenger transfer with pooling	Theoretical	Passenger transfer can reduce travel distance by 30%
[135]	Nonlinear bipartite matching problem	Theoretical	Reduce vehicle traffic by 50%
[136]	Mobile-cloud architecture-based system that enables real-time ride-sharing	Sunway City, Malaysia	2-10% ride-sharing can reduce fuel consumption by 4-16%
[137]	Use student residential addresses and course schedules, match riders	Ontario, Canada	Reduce total trips by 30%
[138]	Genetic Algorithm to assign taxis and match riders	Tehran, Iran	Reduce taxi vehicles by 69%
[139]	Propose cluster-based algorithm to dispatch vehicles to serve passengers, using similarity of passengers' demand	Theoretical	Reduce total travel distance
[140]	Propose large-scale ride-sharing solved by capacitated clustering and location-allocation problems	Shanghai, China	Reduces number of vehicles and oil use by 96% and 92% compared with no ride-sharing
[141]	Integer programming model to maximize greenhouse gas savings for dynamic ride-sharing system	Atlanta, GA, USA	1-3% participation reduces daily CO_2 emissions and VMT by 0.025-0.115 million Kg and 0.06-0.28 million miles, respectively
[142]	Use mobile phone data, match trips	Boston, MA, USA	Some scenarios show modest increases in VMT (1.8%) and congestion (7%), other scenarios show large potential decreases (11.5% in VMT and 37% in congestion)

Sources: Provided in Table 2 above.

3.3.2.ii Empirical Studies

Empirical studies show that price differentials can induce more riders to share, and they also show the promise of pooling in terms of reduced emissions. Abkarian, Hegde, and Mahmassani (2023) leverage a change in taxation in Chicago in early 2020 that effectively made solo ride-hailing more expensive and shared ride-hailing less expensive. Using an interrupted time series methodology, the authors find that this effective $1.75 price difference led to a 27% increase in the count of shared trips and a 12% decrease in the count of private trips. Li et al. (2021) estimate CO_2 and local air pollutant emissions factors for solo trips versus shared ride-hailing trips based on GPS trajectory data of DiDi Chuxing trips in Chengdu, China. They find pooling reduces emissions by around 30%. Liu et al. (2021) analyze DiDi Chuxing trip data from pooled rides in Chengdu, and they estimate counterfactual travel distances, assuming that the rides were not pooled. Accounting for detour distance, Liu et al. (2021) also find that almost 91% of pooled rides reduce distance traveled, and they calculate associate emissions reductions.

Zheng, Chen, and Chen (2019) and Chen et al. (2021) survey recent ride-hailing users in Hangzhou, China and combine the results with DiDi Chuxing ridership data, with a focus on pooling (i.e., users of DiDi Chuxing Hitch and DiDi Chuxing Express). Zheng, Chen, and Chen (2019) find that pooling reduced the number of vehicles on the road by an amount equivalent to 2.6% of the vehicle ownership in the city. Chen et al. (2021) quantify VKT changes resulting from pooling, finding that while pooling reduces ride-hailing VKT, if users switch from public transit, it could still increase VKT. Chen et al. (2021) also find a net decrease in VKT, though it is small, since 37% of riders would have otherwise used public transit.

Nevertheless, empirical studies also show that riders prefer not to pool and that actual pooling rates are quite low. Using choice experiments, Asgari, Jin, and Corkery (2018), Kang et al. (2021), Lazarus et al. (2021), and Lavieri and Bhat (2019) examine the choice between private versus pooled ride-hailing trips in the U.S., as does Alonso-González et al. (2021) in the Netherlands. All find that riders prefer private rides. Asgari, Jin, and Corkery (2018) also find that public transit users are more open to pooled rides. Kang et al. (2021), Lazarus et al. (2021), and Lavieri and Bhat (2019) find that a higher pooling discount is needed for leisure versus commuting trips. Lazarus et al. (2021) also find that riders are least likely to pool when starting a trip from home. Lavieri and Bhat (2019) and Alonso-González et al. (2021) conclude that the disutility of pooling stems more from the additional time associated with it than sharing per se.

Young, Farber, and Palm (2020) examine ride-hailing data from 2016 to 2017 in Toronto (including all providers) in an associational analysis, and find that for 15% of the trips for which riders selected the pooled option (e.g., UberPool), only 52% of these riders were actually matched with an additional rider along their route. Young, Farber, and Palm (2020) find that longer trips and those during higher demand times increase the probability of matching.

Li et al. (2019) create an algorithm to identify pooled trips using data from DiDi Chuxing in Chengdu, China, from November 2016, and they find that pooling rates are low, at 6%-7%, and are associated with a 10-minute delay and 1.5km detour on average. Tu et al. (2019) build on the data and methods from Li et al. (2019) to examine the gap between actual and potential pooling, finding that while 7.85% of trips were pooled, a ride-splitting trip identification algorithm based on a shareability network suggests that 90.69% of the rides could have been pooled. Tu et al. (2019) estimate that observed cost savings from pooling are only 1.22%, with an average time delay of just under 10 minutes. Under their optimized algorithm, cost savings could exceed 18%, with an average delay of just under 5 minutes.

Overall, empirical evidence shows that the number of riders choosing the pool is quite low in both places studied (Toronto and China) and that actual cost savings are low despite travel delays of around 10 minutes. Two studies in China show pooling reduced vehicles on the road slightly, but that the reduction on VMT from pooling was small since over a third of pooled riders substituted from public transit (Li et al. 2019; Tu et al. 2019). This research also reveals inefficiencies in current matching algorithms.

3.3.3 Ride-Hailing and Automation

Nine theoretical papers focus on shared autonomous vehicles (SAVs). SAVs can be operated more efficiently and at a lower cost per mile (no labor costs for paying driver). Overtoom et al. (2020) simulate traffic in The Hague, Netherlands, finding that while the autonomous abilities of SAVs could reduce congestion, curbside stops lead to a net increase in congestion due to bottlenecks and deadheading.

Six studies use agent-based models and simulations. Gurumurthy, Kockelman, and Simoni (2019) determine that SAVs would increase VMT in Austin, TX, by 4.5%, despite average vehicle occupancy of nearly 1.5. Levin et al. (2017) propose a more realistic method for implementing SAVs in existing traffic simulation models, finding that without pooling, the introduction of SAV ride-hailing could increase congestion. Yan, Kockelman, and Gurumurthy (2020) explore how SAVs could satisfy trip demand in the Minneapolis-Saint Paul region, finding that without pooling, VMT would increase by 13%, but with pooling, VMT would fall by 17%. Gurumurthy and Kockelman (2022) find increasing pick-up and drop-off spacing for SAVs could increase average occupancy by up to 20% and decrease VMT by up to 27%. Javanshour, Dia, and Duncan (2019) simulate an autonomous mobility-on-demand system in Melbourne, Australia, showing that while the current fleet could be reduced by 84% to meet existing travel demand, VKT would increase by 29% under a pooled ride-hailing system. Oh et al. (2020) use a similar model for Singapore and find that VKT in 2030 would be 13% higher, with "moderate" adoption of autonomous mobility on demand, and 32% higher with "high" adoption – in large part due to deadheading.

Agent-based simulations of a ride-hailing market in Hangzhou, China, however, show that introducing a small share of autonomous vehicles into a ride-hailing market can reduce not only average rider waiting times but also reduce exhaust emissions and VKT by 12.3% (Yao et al. 2020). Zhu et al. (2016) proposes public vehicles (PVs), autonomous and possibly electric high occupancy vehicles, and to develop a system model, which, combined with traffic flow simulations, show that PVs could reduce total travel distance by 34% relative to a conventional vehicle system and 14% relative to UberPool.

One empirical study, Khaloei et al. (2021), utilizes a choice experiment to investigate autonomous vehicles (AVs), or driverless vehicles, which can substantially lower ride-hailing costs, finding a larger increase in ride-hailing share when the ride-hailing vehicles are autonomous, and, thus, an associated decrease in transit, although the respondents exhibited a strong preference for private rather than pooled rides.

Overall, the research is mixed on the impacts of the automation on ride-hailing VMT. Lower per-mile costs could increase VMT while automation technology could reduce congestion. The research also suggests a crucial interaction between automation and pooling. Autonomous technology could facilitate pooling, and pooling can mitigate or reverse potential VMT increases. Some of the studies also indicate that there is scope for improvements in programming.

4. Conclusion

We have performed a systematic review of the literature on the energy and environmental impacts of ride-hailing. Of the studies included in our review, just over half are empirical papers that estimate actual impacts, while the rest explore future or potential impacts.

Table 3 shows this review's research question and distills the literature's answers to these questions. In terms of the first research question, theoretical studies have optimistic findings overall, showing that ride-hailing has the potential to increase public transit, decrease private vehicle ownership, reduce VMT and congestion, and, ultimately, reduce emissions, thereby decreasing energy use and improving environmental outcomes. In contrast, the empirical studies are decidedly more pessimistic, showing ride-hailing has increased congestion and travel times in many cases, and that is also leads to higher VMT (in part due to deadheading), which increases emissions and air pollution.

In terms of the second research question, the theoretical studies are again more optimistic about pooling and automation, showing how both (especially pooling) could lead to lower VMT and emissions. However, the (limited) empirical studies show that riders do not want to pool and that automation could increase ride-hailing usage without increasing pooling. The theoretical and empirical studies agree only on electrification, which could substantially reduce ride-hailing emissions.

Table 3. Summary of results.

	Theoretical Studies	**Empirical Studies**
What are the energy and environmental impacts of ride-hailing? (Primary research question)		
Impacts on Modal choice, public transit, and vehicle ownership	A large fraction of private vehicles and private vehicle trips could be replaced by ride-hailing and/or public transit.	Higher quality studies (causal and survey-based) show ride-hailing is more often a substitute than a complement to public transportation, through evidence is mixed. There is evidence of a decrease in private vehicles in Asia but not necessarily in the U.S.
Impacts on VMT, traffic congestion, deadheading, and emissions	Ride-hailing has significant potential for reducing deadheading, VMT, and therefore emissions.	Ride-hailing increases traffic congestion and travel times, lowers average speeds, and increases VMT (partially due to deadheading), thereby increasing emissions and air pollution.
How will electrification, sharing (pooling), and automation affect energy and environmental impacts of ride-hailing? (Secondary research question)		
Ride-hailing and electrification	Electrification of ride-hailing fleets is feasible and could significantly reduce CO_2 emissions.	Electrification of ride-hailing vehicles reduces emissions more than electrification of private vehicles.
Ride-hailing and pooling	Pooling has the potential to reduce VMT by 4-57%, reduce fuel consumption by 7-21%, reduce vehicles in use by 30-60%, thereby reducing traffic by 37-50% and reducing both local air pollution and CO_2 emissions by around 10%.	Riders prefer not to pool, and actual pooling rates are quite low.
Ride-hailing and automation	Lower per mile costs could increase VMT while automation technology could reduce congestion. Autonomous technology could facilitate pooling, and pooling can mitigate or reverse potential VMT increases. There is scope for improvements in programming.	Autonomous vehicles could increase ride-hailing and decrease public transit use. Potential riders show a strong preference for private rather than pooled rides.

Source: Authors.

The disconnect between the empirical and theoretical research on the energy and environmental impacts of ride-hailing is likely caused by the overly optimistic assumptions of the theoretical models. For example, many assume that all of the trips that could be replaced by ride-hailing would be replaced, or that all of the riders who could feasibly share a ride would do so. Such optimal assumptions not being realized, given actual consumer preferences and behavior, are one of the elements that drive the gap between "engineering estimates" and observed performance (e.g., of energy efficiency programs (Christensen et al. 2021)). For example, one of the theoretical papers (Ward, Michalek, and Samaras 2021) estimates that replacing private vehicle travel in six U.S. cities with ride-hailing would decrease local air pollution by 50%-60% due to a reduction in "cold starts" and more fuel-efficient vehicles. However, two empirical papers (Al Balawi et al. 2020; Qian et al. 2020) find that TNC entry in various U.S. cities increased local air pollution by as much as 18%. The theoretical papers pointing to the substantial potential benefits of pooling do not factor in consumer behavior, such as the fact that many riders are quite reluctant or even unwilling to share rides. This suggests that optimistic future projections of ride-hailing should be taken with a grain of salt by practitioners and policymakers alike.

Ride-hailing has in many cases increased VMT, congestion, and emissions. Ride-hailing has the potential to decrease energy use and emissions, with pooling and electrification being the key drivers of reductions. The impact of automation leads to future uncertainty.

We suggest two major themes for future research. First, as test beds for automation arise, it will be important to assess the impact of the automation of ride-hailing systems, particularly factoring in consumer behavioral responses. Second, future research should seek to identify why current pooling rates are so much lower than many studies suggest would be optimal, and it should also develop policies that incentivize consumer behavior to better align with engineers and planners' goals.

Endnotes

[1] Technically, Web of Science is a platform for accessing other databases. We searched their "Core Collection" of databases.

[2] While our grey literature searches cover conference abstracts and working papers, they do not cover all types of grey literature, such as newsletters and government documents.

[3] A market as a group of buyers and sellers – in this case, riders and drivers – interacting. We use this broad term to essentially include any use or test case of ride-hailing, including both real and simulated ride-hailing markets.

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Appendix

Search Strings:
Scopus:

TITLE-ABS-KEY((“ride hail*” OR ride-hail* OR ridehail* OR “ride shar*” OR ride-shar* OR rideshare* OR UberPool OR “ride split*” OR ridesplit* OR “ride sourc*” OR ride-sourc* OR ridesourc* OR TNC OR “transportation network companies” OR Uber OR Lyft OR Didi OR Ola OR Gojek) AND (“gasoline consum*” OR “gas consum*” OR “fuel consump*” OR “fuel demand” OR “oil consum*” OR “oil demand” OR “energy use” OR “energy demand” OR “energy consum*” OR “fuel economy” OR “energy efficien*” OR “fuel efficien*” OR pool* OR VMT OR “vehicle miles travel*” OR VKT OR “vehicle kilometers travel*” OR “vehicle use” OR “travel demand” OR “vehicle own*” OR “car own” OR “vehicle stock” OR “car stock” OR congest* OR traffic OR transit OR “public transport*” OR bus OR subway OR “mode shift*” OR “last mile” OR environment OR emission* OR CO2 OR GHG OR “air pollut*”)) AND PUBYEAR > 2007

A Scopus Secondary document (searched for using same string as above) “is a document that has been extracted from a Scopus document reference list but is not available directly in the Scopus database since it is not indexed by Scopus.” Results include conference proceedings, government, business, and industry reports.

Web of Science Core Collection:

Search String (“topic” search includes titles, abstracts, and keywords):

(“ride hail*” OR ride-hail* OR ridehail* OR “ride shar*” OR ride-shar* OR rideshare* OR UberPool OR “ride split*” OR ridesplit* OR “ride sourc*” OR ride-sourc* OR ridesourc* OR TNC OR “transportation network companies” OR Uber OR Lyft OR DiDi Chuxing OR Ola OR Gojek)

AND

(“gasoline consum*” OR “gas consum*” OR “fuel consump*” OR “fuel demand” OR “oil consum*” OR “oil demand” OR “energy use” OR “energy demand” OR “energy consum*” OR “fuel economy” OR “energy efficien*” OR “fuel efficien*” OR pool* OR VMT OR “vehicle miles travel*” OR VKT OR “vehicle kilometers travel*” OR “vehicle use” OR “travel demand” OR “vehicle own*” OR “car own” OR “vehicle stock” OR “car stock” OR congest* OR traffic OR transit OR “public transport*” OR bus OR subway OR “mode shift*” OR “last mile” OR environment OR emission* OR CO2 OR GHG OR “air pollut*”)

With Date Range: 2008-01-01 to 2023-12-31

WorldCat Dissertations and Theses subject (su:) (8) and title (ti:) (16) searches

((su: ride and su: hail*) OR su: ride-hail* OR su: ridehail* OR (su: ride and su: shar*) OR su: ride-shar* OR su: rideshare* OR su: UberPool OR (su: ride and su: split*) OR su: ridesplit* OR (su: ride and su: sourc*) OR su: ride-sourc* OR su: ridesourc* OR su: TNC OR ((su: transportation and su: network and su: companies) OR su: Uber) OR su: Lyft OR su: DiDi Chuxing OR su: Ola OR su: Gojek) AND ((su: gasoline and su: consum*) OR (su: gas and su: consum*) OR (su: fuel and su: consump*) OR (su: fuel and su: demand) OR (su: oil and su: consum*) OR (su: oil and su: demand) OR (su: energy and su: use) OR (su: energy and su: demand) OR (su: energy and su: consum*) OR (su: fuel and su: economy) OR (su: energy and su: efficien*) OR (su: fuel and su: efficien*) OR su: pool* OR su: VMT OR ((su: vehicle and su: miles and su: travel*) OR su: VKT) OR ((su: vehicle and su: kilometers and su: travel*) OR (su: vehicle and su: use) OR (su: travel and su: demand) OR (su: vehicle and su: own*) OR (su: car and su: own) OR (su: vehicle and su: stock) OR (su: car and su: stock) OR su: congest*) OR su: traffic OR su: transit OR (su: public and su: transport*) OR su: bus OR su: subway OR (su: mode and su: shift*) OR (su: last and su: mile) OR su: environment OR su: emission* OR su: CO2 OR su: GHG OR (su: air and su: pollut*)) not mt: juv and yr: 2008-2023 and la= “eng” and ((dt= “bks”) or (dt= “ser”) or (dt= “art”)) and mt: deg.

((ti: ride and (ti: ti and ti: hail*)) OR ti: ride-hail* OR ti: ridehail* OR (ti: ride and ti: shar*) OR ti: ride-shar* OR ti: rideshare* OR ti: UberPool OR (ti: ride and ti: split*) OR ti: ridesplit* OR (ti: ride and ti: sourc*) OR ti: ride-sourc* OR ti: ridesourc* OR ti: TNC OR ((ti: transportation and ti: network and ti: companies) OR ti: Uber) OR ti: Lyft OR ti: DiDi Chuxing OR ti: Ola OR ti: Gojek) AND ((ti: gasoline and ti: consum*) OR (ti: gas and ti: consum*) OR (ti: fuel and ti: consump*) OR (ti: fuel and ti: demand) OR (ti: oil and ti: consum*) OR (ti: oil and ti: demand) OR (ti: energy and ti: use) OR (ti: energy and ti: demand) OR (ti: energy and ti: consum*) OR (ti: fuel and ti: economy) OR (ti: energy and ti: efficien*) OR (ti: fuel and ti: efficien*) OR ti: pool* OR ti: VMT OR ((ti: vehicle and ti: miles and ti: travel*) OR ti: VKT) OR ((ti: vehicle and ti: kilometers and ti: travel*) OR (ti: vehicle and ti: use) OR (ti: travel and ti: demand) OR (ti: vehicle and ti: own*) OR (ti: car and ti: own) OR (ti: vehicle and ti: stock) OR (ti: car and ti: stock) OR ti: congest*) OR ti: traffic OR ti: transit OR (ti: public and ti: transport*) OR ti: bus OR ti: subway OR (ti: mode and ti: shift*) OR (ti: last and ti: mile) OR ti: environment OR ti: emission* OR ti: CO2 OR ti: GHG OR (ti: air and ti: pollut*)) not mt: juv and yr: 2008-2023 and la= “eng” and ((dt= “bks”) or (dt= “ser”) or (dt= “art”)) and mt: deg.

About the Authors

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Rubal Dua, a Research Fellow at KAPSARC, is actively engaged in exploring emerging challenges and priorities in sectors that critically influence transportation and infrastructure, viewed through the lens of energy economics, policy, and sustainability. He holds a Ph.D. from KAUST, Saudi Arabia, an M.Sc. from the University of Pennsylvania, USA and a B.Tech. from the Indian Institute of Technology (IIT), Roorkee.

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About the Project

Promoting the adoption of energy-efficient vehicles has become a key policy imperative in both developed and developing countries. Understanding the impacts of various factors on adoption rates forms the backbone of KAPSARC's efforts in the light-duty vehicle demand field. These factors include (i.) consumer-related factors – demographics, behavioral, and psychographics; (ii.) regulatory factors – policies, incentives, rebates, and perks; and (iii.) geotemporal factors – weather, infrastructure, and network effects. Our team is currently developing models at different levels: microlevel models using large-scale data comprising new car buyers' profiles, and macrolevel models using aggregated adoption data to understand and project the effects of various factors affecting the adoption rate of energy-efficient vehicles.

KAPSARC

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