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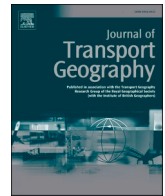
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Digital lifestyles and mobility dynamics: Temporal and platform heterogeneity in vehicle travel

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ABSTRACT

Working from home (WFH) and e-commerce are widely encouraged as practical tools to reduce congestion and environmental impacts. However, the persistence or rebound of vehicle travel following widespread digital adoption has created practical uncertainty, making it essential to understand how remote work and different e-commerce platforms reshape mobility patterns over time. This study investigates how digital lifestyles restructure regional mobility systems by examining the effect of WFH and e-commerce on residential vehicle miles traveled (VMT) across different temporal regimes. Drawing on Substitution–Complementarity Theory and Rebound Effect Theory, we conceptualize remote work and online consumption as activity-level and transaction-level mechanisms that reorganize the spatial distribution of mobility demand. Using a county-month panel constructed from Replica data, we find temporal instability and platform heterogeneity in regional digital mobility effects. County-level WFH prevalence negatively affects residential VMT in the pre-shock regime but positively affects it in the post-shock regime, consistent with a shift from substitution to rebound dynamics. E-commerce effects are platform-specific: the effect of county-level business-to-consumer (B2C) online retail activity shifts from negative to positive across regimes, whereas online-to-offline (O2O) restaurant activity negatively affects residential VMT in the post-shock regime. Interaction analyses further indicate that greater B2C intensity weakens, whereas greater O2O restaurant intensity strengthens, the positive effect of county-level WFH prevalence on residential VMT in the post-shock regime. Our findings thus urge managers to anticipate that long-term WFH may increase regional travel demand, while platform operators and logistics providers should adopt adaptive delivery and capacity strategies aligned with evolving digital mobility patterns.

1. Introduction

The rapid diffusion of digital work and consumption technologies has fundamentally reshaped the spatial organization of daily life. In the United States, the share of workers primarily working from home increased from 5.7% in 2019 to 13.8% in 2023, representing more than 22 million remote workers, while broader measures show that 35% of

employed individuals performed some work at home in 2023, reflecting the normalization of hybrid and remote work arrangements (United States Census Bureau, 2025; U.S. Bureau of Labor Statistics, 2024). At the same time, digital commerce has grown dramatically: U.S. retail e-commerce sales reached \$1.19 trillion in 2024, accounting for 16.1% of total retail sales, up from just single-digit shares a decade earlier (United States Census Bureau, 2025). These shifts indicate that both productive

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activities and consumption transactions are increasingly decoupled from traditional centralized workplaces and retail locations.

These structural changes have important implications for travel demand and regional mobility systems. The pandemic-driven expansion of remote work rapidly altered commuting patterns and substantially reduced routine commuting travel during the early stages of the COVID-19 pandemic (United States Census Bureau, 2024). However, digital lifestyles may also generate new forms of travel through residential decentralization, changes in the spatial distribution of activities, and broader shifts in regional consumption and mobility patterns. Meanwhile, despite the adoption of remote work, approximately 140 million Americans still commute regularly, and average commute times and driving rates remain substantial, highlighting the continued importance of personal vehicle travel in the mobility system (United States Census Bureau, 2024).

Rather than simply reducing travel demand, the growing integration of remote work and e-commerce may reorganize mobility across space, time, and activity types by reshaping when, where, and why travel occurs. Remote work may shift travel demand away from centralized employment hubs, while e-commerce alters how shopping activities are fulfilled and may reshape shopping-related travel demand (Balepur et al., 1998; Gould and Golob, 1997). Understanding how these digital lifestyles reshape spatial mobility patterns has therefore become critical for transportation planning, infrastructure investment, logistics network design, and regional development policy.

The objective of this study is to investigate how digital lifestyles restructure regional mobility systems by examining the effects of work-from-home (WFH) and e-commerce on residential vehicle miles traveled (VMT) across California counties. Correspondingly, we raise three research questions. First, the COVID-19 pandemic triggered an unprecedented surge in remote work, rapidly altering commuting patterns and regional travel demand. While the early expansion of remote work was accompanied by substantial reductions in commuting travel, emerging evidence indicates that post-pandemic travel has rebounded as remote work has become more widely embedded, with some regions reporting increases in discretionary and non-commute travel. Understanding how WFH affects VMT across pre- and post-COVID regimes is therefore critical for anticipating long-term regional mobility patterns, guiding transportation planning, and designing adaptive mobility and infrastructure policies. Thus, we raise our first research question: How does county-level WFH prevalence affect residential VMT across pre- and post-shock regimes?

Second, business-to-consumer (B2C) and online-to-offline (O2O) e-commerce platforms exhibit distinct consumption and logistics characteristics, which are likely to produce different effects on vehicle travel. B2C e-commerce, such as online retail purchases, often involves home delivery of goods over long distances, requires complex warehousing and last-mile logistics (Nogueira et al., 2025), and can generate complementary travel (e.g., returns, browsing trips). In contrast, O2O services, such as food delivery and online grocery services, connect online ordering with locally fulfilled goods and services. By allowing consumers to order locally fulfilled services online, O2O platforms may reduce shopping- or service-related regional travel demand while maintaining fulfillment within local physical service networks (Chen et al., 2019; Ha and Kitchen, 2020; Seo and Roh, 2025). These operational and behavioral differences suggest that the mobility effects of B2C and O2O e-commerce are both platform-specific and potentially interactive with other digital behaviors, such as working from home.

The COVID-19 pandemic created a natural “shock” that accelerated online consumption and transformed travel patterns, making it critical to understand how these e-commerce platforms affect VMT across pre- and post-shock regimes. While B2C activity may have initially reduced regional travel demand through the substitution of physical shopping, greater B2C intensity in the post-shock regime may be accompanied by complementary and rebound mobility patterns as online retail becomes more widely embedded in regional consumption systems. O2O activity,

by contrast, may continue to suppress regional travel demand by substituting short-distance shopping and service-related travel. Investigating these dynamics helps reveal how platform-specific digital consumption interacts with temporal shocks to reshape regional mobility and informs policymakers, planners, and logistics managers about the long-term travel consequences of digital shopping behaviors. Hence, we propose the second research question: How do county-level B2C and O2O e-commerce intensities affect residential VMT across the pre- and post-shock regimes?

Third, digital lifestyles reshape regional mobility through both activity-level mechanisms, such as WFH, and transaction-level mechanisms, such as e-commerce (Ridhwan et al., 2025). WFH alters the spatial and temporal distribution of regional travel demand by changing the spatial organization of work and commuting, while e-commerce shifts how shopping-related activities are spatially fulfilled through home delivery or localized service networks. These mechanisms do not operate in isolation: their effects may reinforce or offset each other, as different levels of B2C or O2O activity may amplify or mitigate the mobility effects associated with WFH. Understanding the interaction between activity- and transaction-level digital mechanisms is therefore essential for anticipating the combined impact of digital practices on VMT and for designing adaptive transportation, infrastructure, and service strategies. Thus, we propose our third research question: How do activity-level (WFH) and transaction-level (e-commerce) digital mechanisms interact in shaping regional mobility patterns?

To answer the above research questions, we collected data from Replica's mobility and spending datasets from 2019 to 2023. The empirical analysis uses a county-month panel in which WFH prevalence, e-commerce intensity, and residential VMT are measured or aggregated at the county level. By leveraging spatial variation in telework exposure and platform intensity, the analysis identifies structural relationships consistent with substitution and rebound mechanisms. The county-level analysis therefore focuses on regional mobility effects rather than behavioral changes among the same individual workers or consumers. Managers should recognize that long-term WFH adoption may increase regional travel demand, requiring firms, real estate developers, and planners to anticipate changes in the spatial distribution of work and mobility demand and adjust infrastructure, workplace policies, and service networks. Additionally, because B2C and O2O e-commerce platforms have distinct and interacting effects on regional travel demand, logistics providers and platform operators should design adaptive delivery systems, capacity planning, and service strategies that account for evolving digital consumption patterns and their combined influence on regional VMT.

The main contributions of this study lie in the following aspects. First, prior studies have documented heterogeneous mobility consequences of telecommuting across travel outcomes, telecommuting intensity, and behavioral contexts (e.g., Rezaei et al., 2025; Zhou et al., 2026). Building on this literature, our study identifies an additional temporal dimension of heterogeneity by showing that the effect of county-level WFH prevalence on residential VMT differs across pre- and post-shock regimes. Specifically, the shift from a negative to a positive county-level effect suggests that substitution effects may weaken, while complementary or rebound mechanisms may become more prominent, as remote work becomes more widely embedded in regional work and mobility patterns. Second, previous studies (e.g., Le et al., 2022; Shah et al., 2024) treated e-commerce as a homogeneous construct when examining its effects on individuals' travel behavior. Extending this literature to the regional level, our study demonstrates that B2C and O2O e-commerce have distinct effects on residential VMT and that these effects differ across pre- and post-shock regimes. This finding highlights platform architecture and fulfillment structure as important dimensions of regional mobility outcomes. Third, our study extends the conceptual discussions of telecommuting and online activities in previous research (e.g., Hill et al., 2024; Vunnavu, 2025) by providing county-level empirical evidence that WFH and different forms of e-commerce

interact in shaping regional mobility patterns.

The remainder of the paper proceeds as follows. Section 2 reviews the relevant literature, elaborates on the theoretical foundation, and develops hypotheses. Section 3 describes the data and methodology. Section 4 reports and discusses empirical results. Section 5 discusses theoretical and managerial implications. Section 6 concludes this research and proposes directions for future research.

2. Literature review and hypotheses development

This study examines how digital lifestyles reshape regional mobility patterns through the adoption of WFH and e-commerce. The research is situated at the intersection of two related streams of literature: (1) studies on digital work, online consumption, and travel behavior, and (2) studies examining substitution, complementarity, and rebound effects associated with digital technologies. Building on these streams, this section reviews the literature on telecommuting, e-commerce, and mobility, and then develops the theoretical framework that explains how activity-level mechanisms (WFH), transaction-level mechanisms (e-commerce), and temporal regime effects (pre-shock versus post-shock) jointly influence residential vehicle miles traveled (VMT). After that, we develop the hypotheses.

2.1. Literature review and theoretical background

2.1.1. Digital lifestyles and regional mobility

The rapid diffusion of digital technologies has fundamentally reshaped how individuals work, shop, and organize daily activities. In particular, WFH and e-commerce have altered the spatial and temporal structure of travel demand by enabling productive and consumption activities to occur without requiring physical presence at centralized workplaces or retail locations. The COVID-19 pandemic accelerated these trends substantially, transforming remote work and online consumption from relatively marginal practices into normalized components of everyday life (Barrero et al., 2023; Brynjolfsson et al., 2020).

These developments have important implications for regional mobility systems and VMT. Traditionally, commuting and shopping represent two major generators of routine travel demand. Digital work and digital commerce potentially substitute for these trips by allowing work activities and consumption transactions to occur remotely. However, growing evidence suggests that digital technologies do not uniformly reduce travel demand. Instead, they may reorganize mobility across space, time, and activity types by reshaping activity patterns, residential preferences, discretionary travel, and consumption behavior (Javadinasr et al., 2022; Lyons et al., 2018; Mokhtarian, 2004; Zhu and Wang, 2024).

Existing studies on telecommuting and travel behavior report mixed findings. Some studies find that telecommuting reduces VMT primarily through commute substitution (Kappler and e Silva, 2025; Obeid et al., 2024). However, other studies suggest that telecommuting may generate complementary travel through increased discretionary trips, residential relocation, or more fragmented trip patterns (Caldarola and Sorrell, 2022; Zhu and Guo, 2022). For example, teleworkers may engage in more non-work activities during the day, undertake separate errands rather than chaining them with commutes, or relocate to lower-density areas with longer travel distances (Balepur et al., 1998; Zhu and Guo, 2022). In addition, telecommuters may exhibit greater flexibility in travel timing and transportation mode choice, potentially increasing active travel and local accessibility-oriented trips (Victoriano-Habit and El-Geneidy, 2024). These findings suggest that the relationship between WFH and VMT is neither uniform nor temporally stable.

Research on e-commerce similarly demonstrates heterogeneous mobility effects. Early studies often emphasized substitution effects, arguing that online shopping reduces personal vehicle trips by replacing store visits with delivery services (Cairns, 2005; Siikavirta et al., 2003). However, subsequent research indicates that e-commerce may also

generate complementary travel through browsing trips, product returns, fragmented deliveries, expedited shipping, and increased purchase frequency (Buldeo Rai et al., 2022; Cullinane, 2009; Frick and Matthies, 2020). Importantly, these effects vary across platform types and fulfillment structures.

In this study, we distinguish between two forms of digital commerce: business-to-consumer (B2C) e-commerce and online-to-offline (O2O) e-commerce. B2C e-commerce refers to online retail platforms that deliver goods purchased digitally through centralized fulfillment and logistics systems. O2O e-commerce refers to digitally mediated access to locally fulfilled offline services, such as online restaurant ordering and grocery delivery. Although O2O literally refers to “online-to-offline,” the term reflects business models in which digital ordering interfaces are linked to localized offline fulfillment systems (Chen et al., 2019; Ha and Kitchen, 2020). Compared with B2C platforms, O2O services typically involve shorter delivery radii, localized dispatching, and faster fulfillment.

These distinctions are important because different platform architectures may reshape mobility systems in different ways. B2C systems rely on centralized warehousing and large-scale logistics networks, whereas O2O systems operate through localized delivery ecosystems embedded within neighborhood retail structures (Jamal et al., 2025; Zhang et al., 2023). As a result, digital lifestyles may influence residential mobility through multiple mechanisms operating simultaneously across work activities, shopping behavior, and household consumption patterns.

To conceptualize these relationships, this study integrates Substitution–Complementarity Theory and Rebound Effect Theory. Together, these perspectives provide a framework for understanding how digital lifestyles restructure mobility patterns across pre-shock and post-shock regimes.

2.1.2. Substitution, complementarity, and rebound mechanisms

Substitution–Complementarity Theory provides a foundational framework for understanding how digital technologies affect travel behavior (Gould and Golob, 1997; Mokhtarian, 2004). The theory proposes that information and communication technologies may either substitute for physical travel by replacing in-person activities or complement travel by generating additional trips and reorganizing activity patterns. Rather than uniformly reducing mobility, digital technologies alter how, where, and when travel demand occurs.

In the context of this study, digital lifestyles influence mobility through two related but distinct mechanisms: activity-level mechanisms and transaction-level mechanisms. Activity-level mechanisms primarily refer to WFH. Remote work substitutes for commuting by relocating work activities from centralized employment centers to residential locations. Under limited adoption conditions, this substitution mechanism can reduce VMT by eliminating routine commute trips (Kappler and e Silva, 2025; Obeid et al., 2024; Sohi et al., 2025). However, remote work may also generate complementary travel. Greater temporal flexibility can encourage discretionary trips, fragmented errands, social travel, and altered trip-chaining behavior (Caldarola and Sorrell, 2022; Kappler and e Silva, 2025; Wöhner, 2022; Zhu and Guo, 2022). In addition, sustained remote work may facilitate residential relocation toward lower-density areas, potentially increasing travel distances for non-work activities (Cairns, 2005; Salon et al., 2021).

Transaction-level mechanisms primarily refer to e-commerce. Online consumption substitutes for physical shopping trips by allowing consumers to purchase goods and services digitally (Cairns, 2005; Siikavirta et al., 2003; Wygonik and Goodchild, 2012). However, e-commerce may also generate complementary mobility through fragmented orders, high return rates, expedited shipping, and omnichannel behaviors such as showrooming or click-and-collect (Buldeo Rai et al., 2022; Cullinane, 2009; Frick and Matthies, 2020; Jaller and Pahwa, 2020). Unlike WFH, where complementarity arises primarily through behavioral flexibility, e-commerce complementarity often stems from changes in

shopping behavior, purchasing frequency, and intensified consumption patterns.

Importantly, substitution and complementarity mechanisms differ across B2C and O2O platforms. B2C e-commerce typically relies on centralized fulfillment networks, large-scale warehousing, and long-distance logistics coordination (Jamal et al., 2025; Nogueira et al., 2025). Although these systems may initially reduce consumer shopping trips, widespread adoption may intensify consumption frequency, fragmented purchasing behavior, and discretionary travel associated with digitally enabled consumption patterns over time. By contrast, O2O platforms operate through hyperlocal fulfillment systems with shorter delivery distances and geographically concentrated dispatching (Jamal et al., 2025; Tao et al., 2021; Zhang et al., 2023). Consequently, O2O services may maintain stronger substitution effects because localized delivery routes replace short consumer trips more directly.

While Substitution–Complementarity Theory explains how digital activities reorganize travel demand, Rebound Effect Theory helps explain why efficiency gains do not necessarily produce long-term reductions in VMT (Chan and Gillingham, 2015; Sonnberger and Gross, 2018). Rebound effects occur when reduced temporal, monetary, or psychological costs associated with efficiency improvements stimulate additional consumption or mobility.

Applied to WFH, eliminating commute trips reduces the constraints associated with daily travel, potentially encouraging additional discretionary mobility (Bouzaghane et al., 2024; Fatmi et al., 2021; Obeid et al., 2024; Zhu and Guo, 2022). Time previously allocated to commuting may instead be used for errands, leisure activities, social trips, or localized travel throughout the day (Bouzaghane et al., 2024; Fatmi et al., 2021; Obeid et al., 2024). Moreover, commuting often enables efficient trip chaining. When commuting declines, activities previously combined into a single trip chain may become spatially fragmented into multiple separate trips (Zhu and Guo, 2022). Although telecommuting may also support active travel and local accessibility-oriented behavior in some contexts (Victoriano-Habit and El-Geneidy, 2024), widespread and sustained adoption may simultaneously facilitate residential decentralization and more dispersed activity patterns. Consequently, the aggregate relationship between WFH and VMT may evolve over time.

Rebound mechanisms may also emerge in e-commerce systems as digital commerce becomes increasingly embedded in everyday consumption. Over time, online retail platforms have reduced transaction costs, expanded fulfillment options, shortened delivery times, simplified return processes, and more closely integrated online and offline shopping channels. For example, major retailers such as Amazon now offer same-day or next-day delivery, provide numerous drop-off locations for returns, and allow customers to return products without repackaging in many cases. These innovations increase convenience and lower the effort required to make purchases, encouraging more frequent transactions, smaller order sizes, and higher levels of consumption (Buldeo Rai et al., 2022; Cullinane, 2009; Jaller and Pahwa, 2020; Wagner et al., 2023). As consumers become more accustomed to platform-based shopping ecosystems, purchasing behavior may become less consolidated and more transaction-intensive. These rebound effects may be particularly pronounced in B2C systems that emphasize large-scale fulfillment and high transaction volume. In contrast, O2O systems may exhibit more spatially constrained rebound effects because their operations remain localized and geographically bounded.

Together, Substitution–Complementarity Theory and Rebound Effect Theory suggest that digital lifestyles influence mobility through dynamic and potentially unstable mechanisms. Importantly, the balance between substitution and rebound may change as digital practices shift from marginal adoption to widespread social embedding.

2.1.3. Temporal regimes and the structural embedding of digital practices

The COVID-19 pandemic created a major structural disruption that accelerated adoption of remote work and online consumption at

unprecedented scale. This transition provides an opportunity to distinguish between pre-shock and post-shock mobility regimes.

In pre-shock regimes, WFH and e-commerce adoption remained relatively limited and selective. Under these conditions, substitution effects are more likely to dominate because digital practices primarily replace existing commute and shopping trips without fundamentally restructuring broader activity systems. Residential locations, urban structures, and daily routines remain largely organized around traditional workplace-centered mobility patterns (Deng and Zhang, 2024; Mokhtarian, 2004; Paché, 2001). Consequently, digital activities may reduce VMT primarily through direct trip substitution.

In post-shock regimes, however, digital practices become more structurally embedded within everyday life. Remote work evolves from a marginal arrangement into a sustained organizational model (Barrero et al., 2023; Bick et al., 2023; Silver, 2023), while online shopping becomes integrated into routine consumption behavior. Under these conditions, rebound and complementarity mechanisms may intensify over time through behavioral adaptation, residential decentralization, fragmented activity patterns, and evolving consumption practices.

Importantly, these structural changes may not affect all digital platforms equally. B2C and O2O systems rely on distinct spatial and logistical architectures, implying that their mobility effects may diverge as adoption scales increase. Similarly, digital work and digital consumption may interact rather than operate independently. WFH reshapes activity spaces and temporal flexibility, while e-commerce alters how consumption activities are fulfilled (Javadinasr et al., 2022; Rezapour Fardin et al., 2026; Shah et al., 2024). Their combined effects may therefore either reinforce or offset changes in regional mobility patterns.

This integrated framework suggests that the relationship between digital lifestyles and VMT depends on three interrelated dimensions: (1) whether digital substitution occurs at the activity level or transaction level, (2) whether rebound and complementarity mechanisms emerge through activity-level or transaction-level pathways, and (3) whether digital practices operate under limited adoption or structurally embedded post-shock conditions. Building on this framework, the next section develops hypotheses regarding the temporal, platform-specific, and interaction effects of WFH and e-commerce on residential VMT.

2.2. Hypothesis development

2.2.1. Work-from-home and vehicle miles traveled

Substitution–Complementarity Theory suggests that WFH alters mobility primarily through activity-level substitution mechanisms by reducing or eliminating commute-related travel (Nayak and Pandit, 2023; Silver, 2023). In pre-shock regimes, telework adoption remained relatively limited and selective, and broader mobility systems continued to be organized around centralized workplaces and conventional commuting patterns (Bick et al., 2023; Chen et al., 2023). Under these conditions, substitution effects are expected to dominate because remote work primarily replaces routine commute trips without fundamentally restructuring residential locations or daily activity systems.

Previous studies report mixed evidence regarding the relationship between telecommuting and travel behavior (Caldarola and Sorrell, 2022; Zhu and Guo, 2022). For example, Caldarola and Sorrell (2022) found a positive association between WFH and VMT, whereas Balepur et al. (1998), Obeid et al. (2024), and Wöhner (2022) found a negative relationship. In the pre-shock regime, however, WFH is more likely to reduce residential VMT for several reasons. First, before the large-scale shock, telework adoption remained relatively limited and was often practiced on an occasional or partial basis rather than as a dominant work arrangement. As a result, WFH primarily served as a substitute for commuting rather than as a catalyst for broader changes in activity patterns, residential location choices, or vehicle-use behavior. Because commute trips represent a regular, recurring component of household travel (Su et al., 2021), even modest reductions in commuting

frequency can yield measurable declines in residential VMT.

Second, the rebound mechanisms that may offset reductions in commuting are likely to be weaker during the pre-shock period. When WFH prevalence remains limited, broader regional activity patterns, residential location structures, and discretionary travel demand are less likely to undergo substantial adjustment in response to remote work (Lennox, 2020). Similarly, complementary trips associated with telecommuting, such as additional errands, leisure travel, or fragmented non-work trips, are less likely to emerge at a large enough scale to outweigh the avoided commute mileage. This is especially relevant at the aggregate county level, where limited telework penetration constrains the magnitude of induced travel effects (Bick et al., 2023; Chen et al., 2023).

Third, under pre-shock conditions, transportation systems, land-use patterns, and household routines were still largely organized around conventional commuting (Meng et al., 2026). Therefore, the marginal adoption of WFH mainly reduces the need to travel between home and workplace while leaving most other travel needs relatively unchanged. In this context, the substitution effect of WFH on commuting is expected to dominate any complementary or rebound effects from discretionary activities. At the aggregate level, these mechanisms lead us to expect that counties with greater WFH prevalence will exhibit lower residential VMT in the pre-shock regime. Therefore, we propose:

H1a. In the pre-shock regime, WFH negatively affects residential VMT.

In post-shock regimes, however, remote work becomes more structurally embedded within everyday life following the rapid digital transformation associated with the COVID-19 pandemic. Rebound Effect Theory suggests that sustained telework may alter mobility patterns beyond direct commute substitution (Bouzaghane et al., 2024; Fatmi et al., 2021; Obeid et al., 2024). At the regional level, reductions in commuting constraints associated with greater WFH prevalence may be accompanied by increases in discretionary travel, more fragmented trip patterns, and localized non-work mobility (Bouzaghane et al., 2024; Fatmi et al., 2021; Obeid et al., 2024). In addition, widespread WFH adoption may facilitate residential decentralization and longer-distance travel for non-work purposes (Cairns, 2005; Salon et al., 2021; Zhu and Wang, 2024).

Although telecommuting may also increase active travel and local accessibility-oriented behavior in some contexts (Victoriano-Habit and El-Geneidy, 2024), large-scale and sustained remote work adoption may simultaneously intensify rebound dynamics at the regional level. As digital work becomes normalized, these behavioral and spatial adjustments may offset or exceed initial commute reductions. Therefore, we hypothesize:

H1b. In the post-shock regime, WFH positively affects residential VMT.

2.2.2. B2C E-commerce and vehicle miles traveled

B2C e-commerce influences mobility through transaction-level substitution mechanisms. In pre-shock regimes, online retail primarily substitutes for in-person shopping trips by allowing consumers to purchase goods digitally rather than traveling to retail stores (Deng and Zhang, 2024; Mokhtarian, 2004; Paché, 2001). Because B2C systems enable goods to be purchased remotely, greater online retail activity may reduce aggregate shopping-related travel demand and associated residential VMT.

Moreover, during the pre-shock period, online retail adoption remained relatively moderate, limiting the extent of delivery fragmentation and rebound consumption behavior (Cao et al., 2012). Under these conditions, substitution effects are expected to dominate. Therefore, we propose:

H2a. In the pre-shock regime, B2C e-commerce negatively affects residential VMT.

In post-shock regimes, however, B2C e-commerce becomes more deeply embedded within everyday consumption systems. Rebound mechanisms may emerge as reduced transaction costs and increased convenience encourage more frequent purchases, smaller order sizes, and greater consumption intensity (Buldeo Rai et al., 2022; Cullinane, 2009; Jaller and Pahwa, 2020; Wagner et al., 2023). As online retail becomes normalized, greater transaction frequency and consumption intensity may contribute to broader changes in regional activity and travel patterns over time.

In addition, widespread online retail adoption may reshape the spatial and temporal organization of shopping-related and other travel demand. Greater convenience may encourage additional out-of-home activities, recreational trips, and errands that were previously constrained by time and travel costs (Jaller and Pahwa, 2020; Obeid et al., 2024; Zaidan et al., 2025). Consequently, rebound and complementarity mechanisms may outweigh the initial shopping-trip substitution effects in post-shock regimes. Therefore, we hypothesize:

H2b. In the post-shock regime, B2C e-commerce positively affects residential VMT.

2.2.3. O2O E-commerce and vehicle miles traveled

Compared with B2C systems, O2O e-commerce operates through localized fulfillment and short-distance dispatch systems (Tao et al., 2021). O2O platforms allow consumers to access nearby offline services, such as restaurants and grocery stores, through digital ordering interfaces (Chen et al., 2019). These systems primarily substitute for short-distance shopping-related travel while relying on geographically concentrated delivery networks.

In pre-shock regimes, O2O adoption remained relatively limited and embedded within existing local retail structures (Dai and Liu, 2020; He et al., 2016). Because delivery radii are spatially constrained and routing systems are localized, O2O services may efficiently substitute for decentralized local travel demand without generating substantial logistics expansion. Therefore, substitution effects are expected to dominate. Thus, we hypothesize:

H3a. In the pre-shock regime, O2O e-commerce negatively affects residential VMT.

In post-shock regimes, O2O adoption expanded substantially. However, unlike centralized B2C systems, O2O fulfillment remains spatially bounded and locally embedded (Cai and Bao, 2025). Although transaction frequency may increase, delivery distances typically remain short and geographically concentrated (Liu et al., 2025; Tao et al., 2023). As a result, rebound effects may remain more limited relative to B2C systems. Consequently, even under widespread digital adoption, O2O platforms may continue to substitute for short-distance shopping-related travel more effectively than they generate additional regional travel demand. Therefore, we propose:

H3b. In the post-shock regime, O2O e-commerce negatively affects residential VMT.

2.2.4. Moderating role of B2C E-commerce

WFH and B2C e-commerce jointly reshape mobility through different but interconnected dimensions of digital lifestyles. WFH primarily operates through activity-level mechanisms by altering where work activities are performed and reducing the need for commute travel. In contrast, B2C e-commerce operates through transaction-level mechanisms by changing how consumers acquire goods and services through centralized online retail and delivery systems (Mokhtarian, 2004; Nogueira et al., 2025). Their interaction therefore reflects how digital work and digital consumption jointly reorganize daily activity systems and influence travel demand.

From a substitution–complementarity perspective, B2C e-commerce reduces the dependence of regional consumption activity on physical shopping travel by enabling goods to be purchased and delivered

without requiring store visits (Cao et al., 2012; Deng and Zhang, 2024). As online retail adoption increases, a growing share of consumption activities becomes detached from physical mobility. Consequently, travel outcomes become less sensitive to changes in work location because both production activities (through WFH) and consumption activities (through e-commerce) can be conducted digitally. In this sense, greater B2C adoption may weaken the extent to which changes in regional work patterns translate into changes in residential travel demand.

In pre-shock regimes, WFH reduces VMT primarily through commuting substitution. At the same time, B2C e-commerce substitutes for shopping-related travel through centralized fulfillment systems. When both digital practices are present, substitution occurs across multiple activity domains simultaneously. As a result, a larger share of shopping-related regional travel demand may already be displaced through digital channels, reducing the marginal contribution of WFH to overall travel reduction. Consequently, although WFH is expected to reduce VMT, its travel-reducing effect becomes weaker when B2C adoption is higher. Therefore, we hypothesize:

H4a. In the pre-shock regime, B2C e-commerce weakens the negative relationship between WFH and residential VMT.

The interaction may differ in post-shock regimes when remote work becomes structurally embedded and rebound mechanisms emerge. Rebound Effect Theory suggests that sustained WFH may increase VMT through greater temporal flexibility, discretionary travel, fragmented activity patterns, and residential decentralization (Bouzaghane et al., 2024; Obeid et al., 2024; Zhu and Wang, 2024). However, widespread B2C adoption may limit the extent to which these regional mobility adjustments generate additional residential VMT because a greater share of consumption activity can be fulfilled digitally without generating shopping-related vehicle travel.

Moreover, as online retail becomes integrated into everyday consumption behavior, shopping-related travel becomes increasingly decoupled from regional patterns of physical retail access (Shah et al., 2024; Wagner et al., 2023). Consequently, although WFH may create conditions that encourage rebound travel, B2C e-commerce may weaken the extent to which regional mobility changes associated with greater WFH prevalence translate into additional residential travel demand. In this way, B2C adoption dampens the positive relationship between WFH and residential VMT by absorbing a portion of consumption-related mobility through digital purchasing channels. Therefore, we propose:

H4b. In the post-shock regime, B2C e-commerce weakens the positive relationship between WFH and residential VMT.

2.2.5. Moderating role of O2O E-commerce

O2O e-commerce may interact with WFH differently from B2C platforms because it relies on localized, on-demand fulfillment systems embedded within neighborhood retail and service networks. While WFH primarily affects mobility through activity-level mechanisms by altering where daily activities are performed, O2O platforms influence mobility through transaction-level mechanisms by changing how nearby goods and services are accessed and fulfilled within regional service networks (Chen et al., 2019; Ha and Kitchen, 2020). Their interaction, therefore, reflects how home-centered work patterns and localized consumption systems jointly reshape daily activity spaces.

In pre-shock regimes, WFH reduces commuting travel by relocating work activities from centralized employment centers to residential locations. At the same time, O2O platforms substitute for short shopping and service trips by enabling consumers to obtain goods and services from nearby establishments through digital ordering systems (Dai and Liu, 2020; Tao et al., 2021). Both mechanisms encourage a concentration of activities around residential locations and reduce the need for longer-distance travel.

Importantly, O2O platforms reinforce the localized activity patterns

created by remote work. As WFH becomes more prevalent, a larger share of regional consumption activity may be fulfilled through nearby restaurants, grocery stores, and service providers rather than through travel to more distant commercial destinations (Jamal et al., 2025; Zhang et al., 2023). Consequently, O2O adoption strengthens the extent to which WFH compresses activity spaces and reduces travel demand. Therefore, we hypothesize:

H5a. In the pre-shock regime, O2O e-commerce strengthens the negative relationship between WFH and residential VMT.

In post-shock regimes, however, WFH becomes more deeply embedded in everyday life and generates rebound effects through greater temporal flexibility, altered activity organization, and increased discretionary mobility. O2O platforms may reinforce these behavioral adjustments by providing rapid and convenient access to locally fulfilled goods and services throughout the day (Jamal et al., 2025; Tao et al., 2021; Zhang et al., 2023). As a result, regions characterized by greater WFH prevalence and greater O2O activity may exhibit more temporally flexible and fragmented patterns of consumption and mobility.

Importantly, the proposed moderating effect does not imply that O2O directly increases residential VMT independently. Rather, O2O adoption may strengthen the extent to which regional mobility changes associated with greater WFH prevalence translate into residential VMT outcomes. In regions where WFH and localized O2O service ecosystems are both more prevalent, activity patterns may become more fragmented and transaction-intensive, potentially contributing to stronger rebound dynamics (Javadinasr et al., 2022; Rezapour Fardin et al., 2026). Consequently, O2O platforms may amplify the positive relationship between WFH and residential VMT in the post-shock regime. Therefore, we propose:

H5b. In the post-shock regime, O2O e-commerce strengthens the positive relationship between WFH and residential VMT.

3. Data and methods

This section describes the data sources, variable construction, and empirical strategy used to examine the structural relationships between digital lifestyles and residential VMT.

3.1. Data sources and coverage

The study draws on county-level data for California covering January 2019 through July 2024 for descriptive analysis. The regression analysis uses a county-month panel consisting of 696 pre-shock observations (2019) and 2088 post-shock observations (2021–2023), excluding the immediate disruption year of 2020.

The primary data source is Replica, a proprietary mobility and consumer spending platform that generates synthetic travel and expenditure datasets by combining anonymized mobile device location data with demographic, land-use, and public administrative records (Replica, 2025a, 2025b). Access to Replica data for this study was obtained through a paid academic research license. Unlike traditional demographic and survey datasets, such as the U.S. Census Bureau and the American Community Survey (ACS), which primarily provide socioeconomic and employment information, Replica generates high-frequency synthetic mobility estimates by integrating anonymized mobile-device location data with demographic, land-use, and public administrative records. Census and ACS datasets provide valuable information on population characteristics, but do not directly measure detailed travel behavior, trip patterns, or vehicle miles traveled at fine temporal scales. Similarly, aggregate mobility datasets such as Google Community Mobility Reports provide indicators of population movement but do not generate activity-based travel estimates, origin–destination flows, or consumer spending information. In contrast, Replica constructs synthetic populations and activity-based travel

models that enable the analysis of travel behavior, telework adoption, consumer spending, and VMT simultaneously (Replica, 2025a, 2025b). Replica data have been increasingly used in transportation and mobility research and planning applications (e.g., National Capital Region Transportation Planning Board, 2024; Ren et al., 2024).

For the present study, the unit of analysis is the county-month, rather than the individual. Replica constructs synthetic populations and generates mobility and demographic information using underlying disaggregate data, while the WFH, consumer spending, and residential VMT measures employed in our empirical analysis are analyzed as aggregate geographic measures. The use of geographically aggregated measures derived from synthetic or large-scale mobility data is consistent with recent transportation and mobility research (e.g., Hajlasz and Pei, 2024; Ren et al., 2024). For example, Ren et al. (2024) used Replica synthetic population data for large-scale regional mobility analysis in New York State, with mobility service regions specified at the county and block-group origin–destination levels. Similarly, Hajlasz and Pei (2024) used Google Community Mobility Reports to analyze population-level mobility across U.S. counties and conduct statistical analyses using county-level mobility, demographic, socioeconomic, and WFH measures. Consistent with this regional analytical approach, we aggregate and align the key measures at the county level and construct a county-month panel for the empirical analysis. Accordingly, the estimated relationships represent aggregate regional relationships and should not be interpreted as behavioral relationships among the same individuals.

Replica constructs regional activity-based travel models using anonymized smartphone location data representing approximately 10–15% of the population, which are then expanded to full synthetic populations using demographic calibration procedures (Yin et al., 2018). These models simulate daily trip generation, routing, and expenditure patterns consistent with census benchmarks and regional travel characteristics.

Several independent evaluations support the reliability of Replica's outputs. Ren et al. (2024) show that Replica's synthetic population aligns closely with Census benchmarks, with key demographic and commute attributes typically within 5–10% at the tract level. The Texas A&M Transportation Institute (2020) found that probe-based traffic estimates from vendors such as Replica are accurate for planning purposes on high-volume roads. Similarly, the National Capital Region Transportation Planning Board (2024) reported trip magnitudes comparable to those from Replica and other mobility data providers. While all large-scale mobility datasets involve sampling and modeling assumptions, these validations indicate that Replica provides consistent and policy-relevant regional mobility estimates.

Three Replica data modules are used in this study: (1) weekly trip data, (2) weekly consumer spending data, and (3) seasonal demographic and telework data. Below, we introduce each of these data modules in detail.

3.1.1. Weekly trip data

Replica's "Trends" module provides weekly origin–destination (O–D) trip tables and VMT estimates derived from activity-based simulations. These data incorporate anonymized mobile device traces, demographic information, and land-use inputs to model daily travel behavior. The weekly tables include trip origins and destinations, travel modes, and residential VMT. For this study, residential VMT is aggregated from the tract level to the county-month level. Commercial and freight VMT are excluded due to data limitations, thereby ensuring consistent interpretation of residential mobility patterns.

3.1.2. Weekly consumer spending data

Replica's economic model estimates weekly consumer expenditures by category, distinguishing between in-person and online spending. The model integrates publicly available data, including the U.S. Census Advance Monthly Retail Trade Survey, the U.S. Census Quarterly E-Commerce Report, and Bureau of Economic Analysis consumption data, with private merchant transaction datasets.

We aggregate online spending shares into three categories at the county-month level: online retail (proxy for B2C e-commerce), online restaurant spending (proxy for O2O food delivery), and online grocery spending (proxy for O2O grocery delivery). Online grocery spending is classified as an O2O activity because orders are typically fulfilled through nearby physical grocery stores and localized delivery systems rather than centralized e-commerce warehouses (Chen et al., 2019; Ha and Kitchen, 2020; Seo and Roh, 2025). Using shares rather than absolute spending helps control overall economic scale differences across counties.

3.1.3. Seasonal telework data

WFH measures are derived from Replica's seasonal demographic module, which reports the percentage of employed individuals working from home on a typical weekday. Specifically, Replica calculates the telework measure based on the share of employed individuals aged 16 years and older who work from home on a representative weekday (Thursday). As a result, the measure captures all individuals working from home on the observation day, including full-time remote workers, hybrid workers, and part-time telecommuters. Seasonal simulations are generated at the regional level and include detailed employment attributes and industry classifications. For the empirical analysis, these telework shares are assigned at the county level and combined with county-level monthly VMT and online spending measures.

For this study, telework shares are collected for fall 2019 (pre-shock regime) and fall 2021–2023 (post-shock regime). To align seasonal telework shares with monthly VMT observations, fall telework rates are applied to each month within the corresponding year. This approach captures structural shifts in telework prevalence while avoiding short-term volatility during the immediate pandemic disruption period.

3.2. Variable construction

The dependent variable, VMT per capita (VMT), is defined as monthly residential VMT per capita at the county level in California from 2019 to 2023. Residential VMT data, derived from Replica's weekly trip data, is used, while commercial VMT is excluded due to data unavailability.

The independent variables are from two categories. The first category refers to work-from-home (WFH), measured as the percentage of WFH employees at the county level in California. The WFH data is derived from Replica's seasonal trip data. In addition, the second category captures county-level online consumption intensity. Online_Retail (Online_Retail) is measured as the county-level share of retail spending conducted online and serves as the B2C measure. Online_Restaurant (Online_Restaurant) and Online_Grocery (Online_Grocery) are measured as the county-level shares of restaurant and grocery spending conducted online and serve as O2O measures. Data for online and in-store consumer spending is sourced from Replica's weekly consumer spending data.

To control for county-level demographic and socioeconomic conditions (Kattiyapornpong and Miller, 2009), we include population density (Population), measured in thousands of people per square mile, and county-level median family income (Income). We use median family income rather than mean income because it is less sensitive to extreme values and income outliers and is commonly used as an indicator of regional socioeconomic conditions in travel-behavior and telecommuting research (Javadinasr et al., 2022; Shah et al., 2024; Zhu and Wang, 2024). Although previous studies have shown that higher-income individuals are more likely to engage in telecommuting because higher-paying occupations tend to be more teleworkable (Mohammadi et al., 2023; Sweet and Scott, 2026), detailed county-level distributions of income categories were not consistently available in the Replica dataset. Consequently, median family income is included as a control variable to capture broader socioeconomic conditions that may influence travel behavior, telecommuting adoption, and digital consumption patterns. In

addition, we incorporate county-fixed and time-fixed effects to account for potential confounding from heterogeneity across counties and over time, respectively. Table 1 summarizes the descriptions of the key variables above and presents their descriptive statistics.

4. Empirical analysis

This section presents descriptive trends and econometric empirical results to evaluate the structural relationships between digital lifestyles and residential VMT across regimes. We first summarize aggregate shifts in mobility and digital adoption, and then assess the hypotheses using fixed-effects and instrumental-variable models.

4.1. Descriptive evidence of structural regime shifts

4.1.1. Vehicle miles traveled

Table 2 summarizes monthly residential VMT in California between 2019 and 2024. In 2019, average monthly VMT reached approximately 849 million miles. During 2020, VMT declined sharply to 736 million miles, reflecting widespread restrictions and mobility disruptions. By 2021, VMT rebounded to nearly 98% of pre-shock levels, and by 2024 had returned to 99.4% of 2019 levels. These aggregate trends indicate that while total mobility recovered, the composition and drivers of travel may have changed. The near-return of aggregate VMT suggests that substitution effects associated with digital adoption may have been offset by rebound dynamics, consistent with the regime-based framework developed in Section 2.

4.1.2. Work-from-home adoption

Fig. 1 reports the percentage of employees working from home during the fall seasons across years. WFH increased from 4.3% in fall 2019 to 21.7% in fall 2021, before stabilizing around 18–21% in 2022–2023. This persistent elevation of telework adoption relative to pre-shock levels indicates a structural embedding of remote work rather than a temporary disruption. Such normalization provides empirical variation for examining whether activity-level substitution evolves into rebound-driven mobility under sustained digital work regimes.

Table 1
Summary statistics of key variables used in the study.

Variable	Description (unit)	Mean	Std. Dev.	Min	Max
VMT	Vehicle miles traveled per capita (mile)	27.221	8.117	9.900	66.900
WFH	Percentage of work-from-home employees (%)	18.1	5.6	7.2	35.4
Online_Retail	Percentage of online retail spending over total retail spending (%)	17.0	8.3	0.2	86.0
Online_Grocery	Percentage of online grocery spending over total grocery spending (%)	2.5	1.3	0.4	9.8
Online_Restaurant	Percentage of online restaurant spending over total restaurant spending (%)	11.5	5.8	1.2	48.7
Population	Population density (1000 people per square mile)	0.692	2.415	0.002	18.558
Income	Family median income (\$ million)	0.078	0.024	0.041	0.160

Note: Summary statistics of the variables are based on the county-level panel covering 2019 and 2021–2023. The year 2020 is excluded from the analysis because it represents the immediate pandemic-disruption period, and comparable seasonal telework estimates are not available from Replica for 2020.

Table 2
Monthly residential VMTs average and trend in California.

Year	Monthly VMT average	% of 2019 monthly VMT
2019	849,269,179	
2020	736,964,844	86.8%
2021	833,448,927	98.1%
2022	805,801,365	94.9%
2023	812,414,299	95.7%
2024 YTD July	844,134,632	99.4%

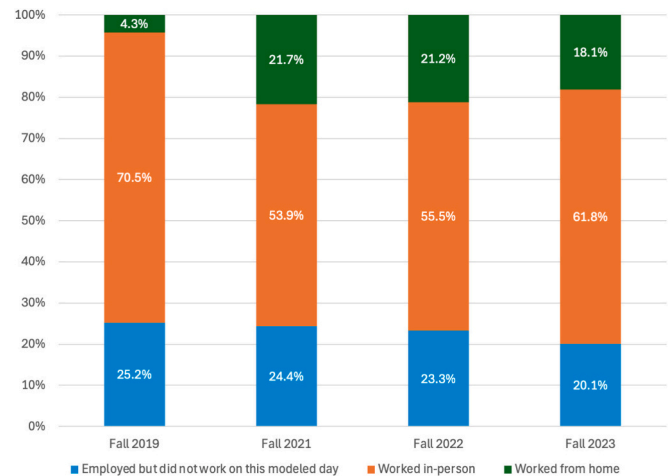


Fig. 1. Trend of work patterns in California.

Note: Replica does not provide seasonal telework estimates for 2020 because of the substantial mobility disruptions associated with the onset of the COVID-19 pandemic. Consequently, WFH shares are reported for 2019 and 2021–2023 only.

4.1.3. E-commerce adoption

Table 3 reports online spending shares. Retail online spending rose from 12.5% in 2019 to approximately 18–20% after 2020. Online grocery and restaurant spending also increased and remained above pre-shock levels. Importantly, B2C retail exhibits larger structural shifts than O2O categories. This divergence supports the platform heterogeneity argument and motivates empirical examination of differential mobility effects.

4.2. Fixed-effects regression results

To test the hypotheses, we estimate county-level fixed-effects models separately for pre-shock (2019) and post-shock (2021–2023) regimes. The unit of observation in all regression models is the county-month. Specifically, the WFH, online spending, VMT, and control variables are measured or aggregated at the county level and aligned by month to construct the panel used in the regression analysis. Thus, the models estimate relationships among aggregate county-level measures rather

Table 3
Percentages of online and in-person spending in California.

Year	Retail		Grocery		Restaurant	
	In-person	Online	In-person	Online	In-person	Online
2019	87.5%	12.5%	99.2%	0.8%	88.8%	11.2%
2020	81.1%	18.9%	97.8%	2.2%	85.7%	14.3%
2021	82.4%	17.6%	97.0%	3.0%	87.0%	13.0%
2022	81.8%	18.2%	97.4%	2.6%	88.1%	11.9%
2023	80.3%	19.7%	97.0%	3.0%	87.2%	12.8%
2024 YTD July	80.4%	19.6%	96.9%	3.1%	87.6%	12.4%

than relationships among individual-level records. As shown in Eq. (1), county fixed effects control for time-invariant spatial characteristics, while year fixed effects absorb common macro-level shocks.

$$VMT_{it} = \beta_0 + \beta_1 WFH_{it} + \beta_2 Online_Retail_{it} + \beta_3 Online_Grocery_{it} + \beta_4 Online_Restaurant_{it} + \beta_5 Population_{it} + \beta_6 Income_{it} + \mu_i + \tau_t + \varepsilon_{it}, \quad (1)$$

where i denotes the county in California; t represents the month in the years 2019, 2021, 2022, and 2023; μ_i captures the fixed effects specific to each county; τ_t captures the fixed effects specific to each year; and ε_{it} represents the error term.

In addition, Eq. (2) presents the econometric model to investigate the moderating effects of county-level online spending intensity on the WFH effect on VMT.

$$VMT_{it} = \beta_0 + \beta_1 WFH_{it} + \beta_2 Online_Retail_{it} + \beta_3 Online_Grocery_{it} + \beta_4 Online_Restaurant_{it} + \beta_5 WFH_{it} \times Online_Retail_{it} + \beta_6 WFH_{it} \times Online_Grocery_{it} + \beta_7 WFH_{it} \times Online_Restaurant_{it} + \beta_8 Population_{it} + \beta_9 Income_{it} + \mu_i + \tau_t + \varepsilon_{it}, \quad (2)$$

where the notation is the same as in Eq. (1).

To determine the appropriate panel specification, we assess whether unobserved county-specific factors are correlated with the regressors. For the pre-shock period (2019), we conduct a standard Hausman test comparing fixed-effects (FE) and random-effects (RE) estimates. The test yields a chi-square statistic of 11.67 ($p = 0.009$), rejecting the null hypothesis that differences in coefficients are not systematic. This result indicates that the RE estimator is inconsistent and supports the use of county fixed effects for the pre-shock analysis.

For the post-shock panel (2021–2023), the classical Hausman test is not well-defined in our setting because it includes time-fixed effects and clustered standard errors. We therefore implement a robust auxiliary-regression approach using a correlated random effects (CRE) framework (i.e., testing whether regressors are correlated with county effects by including unit-level means). The joint test strongly rejects the null that regressors are uncorrelated with county-specific effects ($F = 93.62$, $p < 0.001$), again indicating that RE assumptions are violated. Accordingly, all post-shock analyses adopt FE specifications with county fixed effects (and year fixed effects where applicable) to account for time-invariant regional heterogeneity in travel behavior. Table 4 reports the resulting FE estimates for the pre- and post-shock regimes.

4.2.1. Effect of WFH on VMT

From Table 4, we can find that in the pre-shock regime, county-level WFH significantly and negatively affects VMT ($\beta_1 = -2054$, $p < 0.01$), supporting H1a. This finding aligns with substitution mechanisms in which remote work displaces commute-related travel.

In the post-shock regime, however, county-level WFH prevalence significantly and positively affects VMT ($\beta_1 = 15.44$, $p < 0.01$), supporting H1b. This reversal suggests that once telework becomes spatially embedded, rebound dynamics may dominate substitution effects at the regional level. Specifically, counties with greater sustained WFH prevalence exhibit higher residential VMT, consistent with aggregate regional mobility patterns that may reflect increased discretionary travel, changes in trip organization, and greater spatial dispersion of activities. These findings provide empirical evidence of temporal instability in the effect of WFH on regional mobility patterns.

4.2.2. Effect of B2C E-commerce on VMT

The results of Table 4 suggest that in the pre-shock regime, county-level online retail (B2C) significantly and negatively affects residential VMT ($\beta_2 = -13.62$, $p < 0.01$), supporting H2a. At the aggregate level, this negative effect is consistent with a substitution mechanism whereby

Table 4
Regression results.

	Model 1 Pre-shock	Model 2 Pre-shock	Model 3 Post-shock	Model 4 Post-shock
Variables	DV=VMT	DV=VMT	DV=VMT	DV=VMT
WFH	−2017*** (130.3)	−2054*** (135.5)	8.88*** (3.34)	15.44*** (5.53)
Online_Retail	−10.29*** (2.11)	−13.62*** (3.77)	−3.00* (1.69)	20.92*** (4.59)
Online_Grocery	3.908 (20.66)	3.736 (38.57)	−11.92 (8.621)	13.46 (29.42)
Online_Restaurant	−0.92 (1.49)	−2.97 (3.10)	−1.82 (2.17)	−31.41*** (6.52)
WFH × Online_Retail		48.68 (46.11)		−111.2*** (20.26)
WFH × Online_Grocery		−38.32 (439.3)		−149.3 (148.8)
WFH × Online_Restaurant		43.47 (61.38)		156.0*** (33.44)
Population	−3.85*** (0.48)	−3.83*** (0.48)	0.032 (3.28)	−1.47 (3.32)
Income	299.1*** (38.86)	305.1*** (39.68)	−150.4*** (45.15)	−160.8*** (44.75)
County-fixed effect	Included	Included	Included	Included
Year_2019	Omitted	Omitted		
Year_2022			0.901** (0.410)	1.047** (0.410)
Year_2023			1.990*** (0.629)	2.214*** (0.623)
Constant	90.11*** (3.75)	91.40*** (3.94)	34.74*** (9.24)	37.15*** (9.22)
N	696	696	2088	2088
R ²	0.967	0.967	0.88	0.88

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

greater online retail activity at the county level corresponds to reduced travel demand associated with physical shopping.

However, in the post-shock regime, county-level B2C e-commerce significantly and positively affects residential VMT ($\beta_2 = 20.92$, $p < 0.01$), supporting H2b. This shift suggests that, as B2C platforms become more widely embedded, complementarity and rebound effects may become more prominent at the regional level. The positive effect is consistent with aggregate mobility patterns that may reflect greater consumption intensity, more frequent transactions and returns, and broader changes in regional activity patterns. These results underscore that the effect of B2C e-commerce on regional mobility evolves as digital consumption becomes more widely embedded.

4.2.3. Effect of O2O E-commerce on VMT

The results of Table 4 suggest that county-level O2O e-commerce does not significantly affect residential VMT, as the effects of both online grocery spending ($\beta_3 = 3.91$, $p = 0.85$) and online restaurant spending ($\beta_4 = -0.92$, $p = 0.54$) are statistically insignificant. Therefore, H3a is not supported.

However, in the post-shock regime, county-level online restaurant spending significantly negatively affects VMT ($\beta_4 = -31.41$, $p < 0.01$), consistent with H3b. At the aggregate level, this negative effect is consistent with a substitution mechanism in which greater prevalence of online restaurant spending within a county is associated with lower regional residential travel demand. Unlike B2C e-commerce, O2O services may therefore maintain stronger substitution effects as digital consumption becomes more structurally embedded. The localized nature of O2O fulfillment may contribute to this regional pattern by replacing some locally oriented travel demand while limiting the rebound dynamics associated with more centralized B2C fulfillment systems. County-level online grocery spending, however, does not exhibit a statistically significant effect on residential VMT in either regime, indicating heterogeneity in the mobility effects of different O2O categories.

4.2.4. The moderating effects of B2C and O2O

From Table 4, we can find the moderating role of B2C ($\beta_5 = 48.68$, $p = 0.29$) and O2O ($\beta_6 = -38.32$, $p = 0.93$; $\beta_7 = 43.47$, $p = 0.48$) is not significant during the pre-shock regime. Thus, neither of H4a nor H5a is supported. However, interaction models reveal differential moderation effects in the post-shock regime. In detail, the interaction between WFH and B2C is negative and significant ($\beta_5 = -111.2$, $p < 0.01$), indicating that B2C adoption weakens the positive WFH-VMT relationship, consistent with mitigation through transaction-level substitution, supporting H4b. At the aggregate level, this moderating effect is consistent with a transaction-level substitution mechanism in which greater B2C activity mitigates the regional mobility effects associated with higher WFH prevalence.

In contrast, the interaction between WFH and O2O restaurant spending is positive and significant ($\beta_7 = 156.0$, $p < 0.01$), supporting H5b. This result indicates that greater O2O restaurant spending strengthens the positive effect of WFH on residential VMT at the county level. The observed pattern is consistent with stronger rebound dynamics in regions characterized by both greater WFH prevalence and greater O2O restaurant activity. Overall, these findings support the integrated framework by demonstrating that activity-level and transaction-level digital mechanisms interact differently across platform types in shaping regional mobility patterns.

4.2.5. Control variables

For control variables, the results of Table 4 suggest that county-level population density negatively affects residential VMT in the pre-shock regime ($\beta_8 = -3.85$, $p < 0.01$) but loses significance post-shock ($\beta_8 = 0.03$, $p = 0.99$), suggesting that the effect of regional density on residential VMT becomes less evident in the post-shock regime. County-level median income shifts from a positive to a negative effect across regimes. Because income is measured at the county level and serves primarily as a control variable, these coefficients should not be interpreted as direct evidence regarding individual telecommuting propensity. Previous studies have shown that higher-income individuals are more likely to work remotely because higher-paying occupations tend to be more teleworkable (Mohammadi et al., 2023; Sweet and Scott, 2026). However, our county-level income measure captures broader regional socioeconomic conditions rather than the income or telecommuting behavior of particular individuals. At the aggregate level, county income may reflect multiple regional characteristics, including residential location patterns, vehicle ownership, travel demand, and digital technology adoption. Consequently, the estimated income coefficients likely reflect multiple county-level socioeconomic influences rather than a single individual-level behavioral mechanism.

4.3. Robustness check: Instrumental variables strategy

Although fixed-effects models control for time-invariant county characteristics and common-year shocks, concerns remain about potential endogeneity in county-level WFH prevalence. Reverse causality may arise if counties experiencing lower residential travel demand are more likely to exhibit greater prevalence of remote work. Additionally, unobserved county-level factors, such as labor market composition, digital infrastructure, or residential selection, may jointly affect both telework intensity and VMT (Zhu, 2012; Zhu and Wang, 2024).

These concerns are particularly salient in the post-shock regime, when WFH becomes widespread and persistent across regions. In contrast, pre-shock telework adoption was limited and exhibited minimal within-county variation, making instrumental variables estimation infeasible for that period. Accordingly, we implement an instrumental variables (IV) strategy as a robustness check for the post-shock regime.

4.3.1. The IV model

Consistent with the fixed-effects analysis, the unit of observation in the IV models is the county-month. All variables entering the IV analysis

are measured or constructed at the county level and aligned within the county-month panel; thus, the IV models estimate effects among aggregate county-level measures rather than relationships among individual-level records.

In detail, we employ a shift-share (Bartik) instrument (Bartik, 1991; Borusyak et al., 2022; Goldsmith-Pinkham et al., 2020), which leverages cross-county variation in pre-pandemic industry composition interacted with national changes in telework prevalence. The instrument is defined as:

$$TeleworkExposure_{it} = \sum_k (IndustryShare_{ik,2019} \times NationalWFH_{kt}), \quad (3)$$

where $IndustryShare_{ik,2019}$ denotes the share of employed residents in county i working in industry k in 2019, measured using the American Community Survey (ACS), and $NationalWFH_{kt}$ represents the national prevalence of telework in the year t for industry k , measured using nationally reported telework statistics.

Industries classified as teleworkable, following Dingel and Neiman (2020), include information, finance and insurance, professional and technical services, management, education, and public administration. National telework rates are drawn from ACS estimates, which show a sharp increase from approximately 5.7% in 2019 to 17.9% in 2021, followed by stabilization at elevated levels. This national time-series variation provides the exogenous “shock” component of the instrument. The identifying assumption is that county-level pre-pandemic industry composition affects post-shock residential VMT primarily through its effect on county-level telework prevalence, rather than through independent mobility trends.

To assess the robustness of the post-shock effects to potential endogeneity in WFH, we estimate a 2SLS model using the county-month panel. In this framework, county-level WFH prevalence and its interactions with county-level e-commerce variables are treated as endogenous, while a shift-share (Bartik) instrument based on pre-pandemic industry composition and national telework trends provides exogenous variation. In detail, in the first stage, county-level WFH prevalence is regressed on the instrument and controls:

$$WFH_{it} = \pi_0 + \pi_1 TeleworkExposure_{it} + \pi_2 Online_Retail_{it} + \pi_3 Online_Grocery_{it} + \pi_4 Online_Restaurant_{it} + \pi_5 Population_{it} + \pi_6 Income_{it} + \mu_i + \tau_t + u_{it}, \quad (4)$$

where $TeleworkExposure_{it}$ denotes the shift-share instrument capturing county-level exposure to national changes in telework adoption; μ_i represents county fixed effects; and τ_t denotes year fixed effects. Because interaction terms between WFH and e-commerce variables are also potentially endogenous, we instrument each interaction using the product of the Bartik instrument and the corresponding county-level e-commerce variable. That is,

$$WFH_{it} \times Online_Retail_{it} = \theta_0 + \theta_1 Online_Retail_{it} + \theta_2 Online_Grocery_{it} + \theta_3 Online_Restaurant_{it} + \theta_4 (TeleworkExposure_{it} \times Online_Retail_{it}) + \theta_5 Population_{it} + \theta_6 Income_{it} + \mu_i + \tau_t + u_{it}, \quad (5)$$

$$WFH_{it} \times Online_Grocery_{it} = \theta_0 + \theta_1 Online_Retail_{it} + \theta_2 Online_Grocery_{it} + \theta_3 Online_Restaurant_{it} + \theta_4 (TeleworkExposure_{it} \times Online_Grocery_{it}) + \theta_5 Population_{it} + \theta_6 Income_{it} + \mu_i + \tau_t + u_{it}, \quad (6)$$

$$WFH_{it} \times Online_Restaurant_{it} = \theta_0 + \theta_1 Online_Retail_{it} + \theta_2 Online_Grocery_{it} + \theta_3 Online_Restaurant_{it} + \theta_4 (TeleworkExposure_{it} \times Online_Restaurant_{it}) + \theta_5 Population_{it} + \theta_6 Income_{it} + \mu_i + \tau_t + u_{it}, \quad (7)$$

with analogous first-stage equations specified for the interactions between WFH and county-level online restaurant activity and between WFH and county-level online grocery activity.

In the second stage, county-level residential VMT is regressed on the predicted values:

$$\begin{aligned} VMT_{it} = & \beta_0 + \beta_1 \widehat{WFH}_{it} + \beta_2 \widehat{OnlineRetail}_{it} + \beta_3 \widehat{OnlineGrocery}_{it} \\ & + \beta_4 \widehat{OnlineRestaurant}_{it} + \beta_5 \widehat{WFH}_{it} \times \widehat{OnlineRetail}_{it} \\ & + \beta_6 \widehat{WFH}_{it} \times \widehat{OnlineGrocery}_{it} + \beta_7 \widehat{WFH}_{it} \times \widehat{OnlineRestaurant}_{it} \\ & + \beta_8 \widehat{Population}_{it} + \beta_9 \widehat{Income}_{it} + \mu_i + \tau_t + \varepsilon_{it}, \end{aligned} \quad (8)$$

where $\widehat{WFH}_{it}$ and the interaction terms with hats denote the predicted values from the first-stage regressions. As in the fixed-effects models, μ_i and τ_t control for time-invariant county characteristics and common year-specific shocks, respectively. Accordingly, the resulting IV estimates represent effects at the aggregate county level and should not be interpreted as effects of WFH or e-commerce on the travel behavior of the same individuals.

4.3.2. First-stage and second-stage results

The results in Table 5 show that the excluded instruments are jointly significant predictors of the endogenous variables in the post-shock regime. The first-stage F-statistics range from 22.06 to 60.39 across the four endogenous regressors, with all tests statistically significant at the 1% level. These results provide evidence that the excluded instruments have sufficient explanatory power for the endogenous regressors and support the relevance condition required for the IV strategy.

In addition, from Table 5, we can find the second-stage estimates. The coefficient on instrumented county-level WFH prevalence remains positive and statistically significant ($\beta = 60.53$, $p < 0.05$), consistent with the fixed-effects results. Although the magnitude exceeds the baseline FE estimate, the larger IV estimate may reflect differences arising from measurement error or endogeneity in observed WFH prevalence, as well as the variation in WFH identified by the instrument (Zhu, 2012). The interaction terms retain their direction and statistical

significance, reinforcing the platform-specific moderating effects on regional mobility patterns identified in the baseline models.

Taken together, the consistency between FE and IV estimates suggests that the observed post-shock county-level effects of WFH and its interactions with e-commerce on residential VMT are unlikely to be driven solely by reverse causality. These estimates should be interpreted at the aggregate county level and do not establish how WFH, e-commerce, and travel behavior jointly change for the same individuals. Moreover, as with all shift-share designs, interpretation relies on the exclusion assumption, and results should be understood as robustness evidence rather than definitive causal estimates.

5. Theoretical and managerial implications

This study contributes to understanding how digital lifestyles reshape regional mobility systems. Rather than treating WFH and e-commerce as uniform or static influences on travel demand, the findings suggest that digital practices operate through temporally contingent and platform-specific mechanisms at the regional level. The results highlight the importance of incorporating structural regime shifts, platform heterogeneity, and interaction effects into theories of digital mobility.

5.1. Theoretical implications

This study offers important extensions to substitution-complementarity and rebound theories (Mokhtarian, 2004; Sonnberger and Gross, 2018) and to the literature on telecommuting and e-commerce (e.g., Shah et al., 2024; Vunnava, 2025) in the following ways.

First, this study reveals the temporal instability in the regional mobility effects associated with activity-level digital mechanisms. The shift from a negative to a positive effect of county-level WFH prevalence on residential VMT across regimes suggests that substitution effects may weaken as digital work becomes embedded in regional work and mobility patterns. This finding extends prior work on telecommuting (e.g., Rezaei et al., 2025; Zhou et al., 2026) by showing that telecommuting does not have a uniform impact on regional mobility, demonstrating that remote work cannot be conceptualized as a uniformly travel-reducing practice. Instead, its mobility implications depend on the

Table 5
IV model results.

Variables	First stage				Second-stage
	Model 5 DV=WFH	Model 6 DV = WFH×Online_Retail	Model 7 DV = WFH×Online_Restaurant	Model 8 DV = WFH×Online_Grocery	Model 9 DV=VMT
$\widehat{WFH}$					60.53** (25.52)
TeleworkExposure	−3.24*** (0.27)				
Online_Retail	0.01 (0.01)	0.16*** (0.01)	−0.01*** (0.01)	−0.01 (0.001)	44.76*** (12.09)
Online_Grocery	0.31*** (0.06)	0.04*** (0.01)	0.04*** (0.01)	0.19*** (0.01)	123.5 (119.9)
Online_Restaurant	−0.08*** (0.01)	−0.03*** (0.01)	0.16*** (0.01)	−0.01*** (0.01)	−87.77*** (31.48)
TeleworkExposure×Online_Retail		0.56*** (0.09)			−216.0*** (57.94)
TeleworkExposure×Online_Grocery				0.08 (0.07)	−840.0 (625.8)
TeleworkExposure×Online_Restaurant			0.140** (0.0619)		477.2*** (176.4)
Population	−0.12*** (0.02)	−0.06*** (0.01)	−0.03*** (0.01)	−0.01*** (0.01)	3.644 (6.515)
Income	6.49*** (0.26)	1.119*** (0.0649)	0.645*** (0.0376)	0.11*** (0.01)	−465.5*** (96.40)
County dummy	Included	Included	Included	Included	Included
Time dummy	Included	Included	Included	Included	Included
Constant	0.19*** (0.06)	0.02 (0.01)	0.01 (0.01)	0.01*** (0.01)	54.89*** (11.91)
N	2088	2088	2088	2088	2088
R ²	0.897	0.960	0.962	0.969	0.863

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

broader structural context in which it operates. The results support a dynamic interpretation of the Substitution–Complementarity and Rebound frameworks, emphasizing that digital practices may yield distinct regional mobility outcomes across regimes.

Second, the analysis advances the theorization of platform heterogeneity in digital consumption. By distinguishing between B2C and O2O e-commerce models, the study shows that platform architecture conditions regional mobility outcomes. While B2C activity transitions from substitution-dominated to rebound-associated patterns, O2O platforms exhibit more stable substitution effects in the post-shock regime. These findings challenge treating “e-commerce” as a homogeneous construct in previous studies (e.g., [Nogueira et al., 2025](#); [Vunnava, 2025](#)) and suggest that logistical structure and fulfillment geography play critical roles in shaping regional travel demand. Platform design, spatial scale, and delivery configuration emerge as theoretically relevant dimensions in digital mobility research.

Third, the results underscore the importance of interactions among digital practices. The moderating roles of B2C and O2O platforms in the WFH–VMT relationship indicate that activity-level and transaction-level mechanisms interact in shaping regional mobility patterns rather than operating independently. This extends earlier conceptual discussions of telecommuting and online activities (e.g., [Hill et al., 2024](#); [Vunnava, 2025](#)) by providing county-level empirical evidence that patterns of digital work and digital consumption jointly shape regional mobility outcomes. Importantly, these aggregate interaction effects do not imply that the same individuals who work from home also change their online consumption and travel behavior. Rather, they demonstrate that the regional mobility effect of WFH varies systematically with county-level patterns of digital consumption. The findings suggest that future theoretical models should explicitly account for interdependencies among digital practices at multiple levels of analysis.

Fourth, the analysis highlights the effects of regional demographic and spatial conditioning. Population density and income exhibit regime-dependent effects on residential VMT at the county level, indicating that digital mobility effects are embedded within broader socioeconomic contexts. These patterns suggest that digital transformation may reconfigure mobility differently across regions with varying urban form and socioeconomic composition. Theoretical models of digital lifestyles and mobility should therefore incorporate contextual moderators rather than assuming uniform mobility responses across space.

Taken together, the findings suggest that digital transformation restructures regional mobility systems in complex and context-dependent ways. Rather than focusing solely on whether digital practices reduce travel, theoretical attention should shift toward understanding how they redistribute and reconfigure mobility demand across regions, temporal regimes, and platform types. The county-level evidence presented in this study identifies these broader regional patterns, while the individual-level behavioral mechanisms underlying them remain an important direction for future research.

5.2. Managerial implications

The findings of this study have three important managerial and planning implications. First, the regime-dependent effect of county-level WFH prevalence on residential VMT suggests that managers and planners should not assume that widespread remote work will produce uniform or permanent reductions in regional travel demand. In the pre-shock regime, greater county-level WFH prevalence reduces residential VMT, consistent with the travel-reducing potential of commute substitution. In the post-shock regime, however, greater WFH prevalence increases residential VMT at the county level. This reversal suggests that the regional mobility implications of remote work may evolve as WFH becomes more widely embedded across regions. For employers, real estate developers, and regional planners, these findings highlight the need to consider longer-term changes in regional distribution of work, residential activity, and travel demand when designing hybrid work

arrangements, locating workplaces, and planning transportation infrastructure. Rather than treating WFH as a static travel-demand reduction strategy, managers and planners should anticipate that its effects on regional mobility may change as work and residential patterns evolve.

Second, the platform-specific effects of county-level e-commerce intensity on residential VMT suggest that digital retail and service platforms should not be treated as having homogeneous mobility implications. The effect of county-level B2C online retail spending on residential VMT shifts from negative in the pre-shock regime to positive in the post-shock regime. At the aggregate level, this pattern is consistent with the possibility that the initial substitution of shopping-related travel demand may weaken as online retail becomes more deeply embedded in consumption systems and complementary or rebound mechanisms emerge. In contrast, county-level online restaurant spending has a significant negative effect on residential VMT in the post-shock regime, while online grocery spending does not exhibit a consistent significant effect. These differences suggest that platform architecture, fulfillment structure, and consumption context should be considered when firms and transportation planners evaluate the mobility implications of digital commerce. Retailers and platform operators should therefore avoid assuming that expanding online transactions will necessarily reduce regional vehicle travel and should instead consider how different digital service models may generate different regional mobility outcomes as digital consumption evolves.

Third, the interaction results demonstrate that the effect of county-level WFH prevalence on residential VMT varies with the type and intensity of online consumption within a county. In the post-shock regime, greater county-level B2C online spending intensity weakens the positive effect of WFH prevalence on residential VMT, whereas greater online restaurant spending intensity strengthens this positive effect. These findings indicate that digital work and digital consumption should not be considered independently when evaluating regional mobility outcomes. Importantly, because the empirical analysis is conducted at the county-month level, these interaction effects do not establish that the same remote workers changed their online purchasing or travel behavior. Rather, they indicate that the regional mobility effect of WFH varies systematically with county-level patterns of different forms of digital consumption. For employers, platform operators, commercial developers, and transportation planners, this finding highlights the value of coordinating decisions concerning workplace location, digital service provision, land use, and transportation infrastructure in light of these interacting regional patterns. More broadly, policymakers should avoid assuming that digitalization will automatically reduce travel demand and should instead adopt adaptive mobility strategies that account for temporal changes, platform heterogeneity, and the interacting regional effects of digital work and consumption.

6. Conclusion

Governments, transportation planners, and employers have increasingly promoted WFH and e-commerce as practical solutions to reduce traffic congestion, infrastructure pressure, and environmental impacts, based on the assumption that digital activities substitute for physical travel. However, many regions have observed that traffic levels have rebounded or even increased after the widespread adoption of remote work and online consumption, creating uncertainty about whether digital lifestyles will ultimately reduce vehicle travel. Understanding how WFH and different types of e-commerce reshape mobility patterns over time is, therefore, critical for helping policymakers, firms, and infrastructure planners make informed decisions about remote work policies, digital platform development, and transportation investment.

This study examined the effects of WFH and platform-based e-commerce on residential VMT across distinct structural regimes at the county level. Rather than assuming that digital practices uniformly reduce travel demand, the findings indicate that their mobility implications are temporally contingent, platform-specific, and spatially

differentiated. Our findings document a regime-dependent effect of county-level WFH prevalence on residential VMT. In the pre-shock regime, greater WFH reduces residential VMT, consistent with commute substitution at the regional level. In the post-shock regime, when remote work becomes structurally embedded, the effect becomes positive, indicating that counties with greater WFH prevalence experience higher residential VMT. This reversal is consistent with the emergence of rebound dynamics that may reflect changes in discretionary travel, activity organization, and the spatial distribution of travel demand at the regional level. These results demonstrate that the regional mobility effects of digital work evolve as digital practices become more widely embedded.

E-commerce exhibits similarly differentiated regional mobility effects. The effect of county-level B2C online retail activity on residential VMT shifts from negative in the pre-shock regime to positive in the post-shock regime, a pattern consistent with a transition from substitution-dominated to rebound dynamics as digital consumption becomes more widely embedded. In contrast, O2O platforms maintain more stable substitution effects, particularly for online restaurant spending in the post-shock regime, consistent with their localized fulfillment structure. Interaction analyses further show that digital work and digital consumption jointly shape regional mobility outcomes: greater B2C intensity weakens, whereas greater O2O restaurant intensity strengthens, the positive effect of county-level WFH prevalence on residential VMT in the post-shock regime. By demonstrating that digital lifestyles generate regime-dependent and platform-specific effects on regional mobility, this study highlights the need for dynamic, spatially sensitive planning frameworks that can adapt to ongoing technological transformation.

Several limitations provide opportunities for further research. First, the empirical analysis is conducted at the county-month level. The WFH, online spending, and residential VMT measures are analyzed as aggregate geographic measures and are not directly linked for the same individuals. Consequently, although the study estimates the effects of WFH and e-commerce at the aggregate county level, these estimates cannot establish how WFH, online shopping, and travel behavior jointly change for the same individual or household. Future research using directly linked person- or household-level data could test whether the behavioral mechanisms proposed in this study also hold at the individual level. Second, the Replica telework measure identifies whether individuals work from home on a representative weekday, but does not provide information on telework frequency. Future research could examine whether the mobility effects associated with different levels of telework prevalence, including full-time, hybrid, and occasional telework arrangements, differ systematically. Third, the analysis uses county-level median family income as a control variable and therefore does not capture within-county income heterogeneity. Previous studies suggest that telecommuting adoption, digital consumption behavior, and travel patterns may differ substantially across income groups because higher-income occupations are often more teleworkable and may exhibit different mobility preferences (Mohammadi et al., 2023; Sweet and Scott, 2026). Future research should incorporate more disaggregated socioeconomic data to examine whether the relationships among WFH, e-commerce, and VMT vary across income categories. Fourth, this study focuses on residential VMT and does not incorporate freight or commercial travel. Given that platform-based commerce reshapes logistics networks, future research should examine how household travel interacts with freight VMT to evaluate net system-level mobility impacts. Lastly, the analysis is confined to California, a large and automobile-oriented state with high digital adoption rates. Replicating this framework in regions with different urban forms, transit systems, and regulatory contexts would help assess the generalizability of the regime-dependent and platform-specific patterns identified here.

CRedit authorship contribution statement

Jian-yu Ke: Writing – review & editing, Writing – original draft,

Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xun Xu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fynnwin Prager:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tianjun Lu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Parveen Chhetri:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jose N. Martinez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.

Data availability

The authors do not have permission to share data.

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