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TOD effects on travel behavior: A synthesis of evidence from cross-sectional and longitudinal studies

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Abstract: The impacts of transit-oriented development (TOD) on travel behavior have been extensively studied, with a predominant focus on cross-sectional analyses that provide a static evaluation at a specific point in time by comparing TODs and non-TODs. Longitudinal assessments that capture changes in behavior over time remain relatively uncommon, and the literature tends to overlook differences in evaluating TOD effects across cross-sectional and longitudinal analyses. Additionally, the role of trip purpose as a significant but unexplored variable influencing the degree of TOD effects is often disregarded. To address these gaps, this systematic review examines 48 quantitative studies, comparing the effects of TOD on travel behavior from cross-sectional and longitudinal perspectives, restructuring indicators of effects into transit use, non-motorized travel, vehicle dependence, and vehicle ownership, and differentiating the effects by trip purpose. A metric has been introduced to quantitatively assess the impact of TOD on travel behavior. The pooled results indicate that private vehicle usage remains high in TOD areas, particularly for non-commuting trips, and that the longitudinal effects of TOD are limited and potentially influenced by individual travel attitudes, residential self-selection, and long-term travel habit change. Furthermore, the methodological differences between cross-sectional and longitudinal studies may lead to divergent conclusions regarding the effects of TOD on travel behavior. Our analysis sheds light on the importance of carefully selecting an appropriate method for a given research question to maximize the accuracy and relevance of the findings. Combining TOD and shared mobility can create a more efficient multi-model transport network that meets the diverse needs of city residents and improves accessibility for all. Overall, this review provides new insights into the impacts of TOD on travel behavior and supports the potential for a paradigm shift toward multimodal transport through the integration of TOD and shared mobility.

Keywords: Transit-oriented development, travel behavior, self-selection, cross-sectional analyses, longitudinal analyses

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1 Introduction

Addressing the negative consequences of urban sprawl and fulfilling the demands for mobility are commonly recognized as key concerns among both scholars and practitioners engaged in the field of urban planning. One prevailing planning strategy has been transit-oriented development (TOD). TOD is a dense development model where mixed communities are built around transit nodes to reduce dependence on private vehicles and to increase the use of sustainable transport modes by providing walking and cycling-friendly built environments (Cervero, 1993; Dittmar & Ohland, 2004; Nasri & Zhang, 2014). TOD has emerged as a widely accepted transport planning approach over the past two decades, which has been credited with generating diverse environmental, social, health, and economic benefits. TOD achieves these outcomes by reducing automobile dependence, enhancing transit ridership, promoting active transport, fostering regional polycentricity, mitigating urban sprawl, and stimulating local economic development (Arrington & Cervero, 2008; Bao et al., 2023; Liu et al., 2021; Xiao et al., 2021; Yang, 2018).

A considerable body of literature has extensively examined the impacts of TOD on travel behavior, investigating various dimensions such as public transport ridership (Dill, 2008), walking and cycling use (McKibbin, 2011), automobile dependence (Faghri & Venigalla, 2013), and vehicle ownership (Pongprasert & Kubota, 2017). The majority of empirical investigations suggest that there is a correlation between TOD and travel behavior. Studies have found that TOD residents exhibit a greater propensity to utilize sustainable modes of transport such as public transit and active transport and tend to drive less frequently than those residing in conventional low-density suburban areas (Lund et al., 2004) or compared to citywide averages (Cervero, 1993). Despite the observed preference for sustainable transport modes among TOD residents, car dependency persists for specific types of trips. While prior research has established that travel behavior is shaped by the purpose of trips, existing literature on the effects of TODs on travel behavior tends to focus primarily on commuting trips (Renne, 2005), and in some cases disregards the role of trip purpose altogether (Kamruzzaman et al., 2013).

The extant literature on examining the impacts of TOD employs two main approaches: cross-sectional (Kamruzzaman, Shatu et al. 2015; Nasri & Zhang, 2014; Tian et al., 2017), and longitudinal studies (Cervero & Day, 2008; Lund et al., 2004; Renne, 2005). Cross-sectional analyses compare selected travel behaviors of residents living in TODs with those living outside of TODs at a specific point in time. In longitudinal studies, the effects of TOD are typically assessed by observing changes in the travel behavior of TOD residents over a period of time or by examining their modal shift before and after moving to a TOD or opening of transit service. While cross-sectional studies are more prevalent in the literature, longitudinal studies are comparatively scarce. Moreover, inconsistencies have been observed in the results obtained from the two analytical approaches. However, prior literature has not adequately distinguished between these methodological approaches, nor has it fully explored their implications for examining the effects of TOD.

Despite the extensive body of research on the effects of TOD on travel behavior, the literature reveals a noticeable gap in systematic analyses focusing specifically on TOD interventions. While several prior reviews have examined the broader impact of built environments and rail transit on travel behavior (Ewing & Cervero, 2010; Wang & Zhou, 2017; Wang et al., 2023), these lack a concentrated focus on TODs. Moreover, existing reviews, such as the one by Ibraeva et al. (2020), offer a comprehensive overview of research findings on the influence of TOD on travel behavior, yet their review lacks an analytical approach that combines both cross-sectional and longitudinal perspectives. Additionally, existing studies often neglect to consider the role of trip purpose in shaping travel behavior within TOD contexts.

In light of these gaps, this study has two primary objectives. Firstly, it aims to systematically restructure the documented effects of TOD by examining distinct analytical approaches, including cross-sectional and longitudinal studies, in order to establish a more in-depth and comprehensive comprehension of the impact of TOD on travel behavior. These two streams of analyses provide static and dynamic perspectives of the TOD effects, enabling insights into the spatial and temporal effects on travel behavior. Secondly, it conducts a thorough investigation into the role of trip purposes in shaping travel behavior within TOD contexts by differentiating between commuting and non-commuting purposes. This review's contribution lies in providing a more insightful and accurate understanding of the TOD-travel behavior relationship by disaggregating results by trip purpose and analytical method. This understanding can inform urban planners and transport policy makers in devising more effective and targeted strategies to promote sustainable travel behavior in the long run.

This study is structured into several sections. In Section 2, the literature selection process and the definition of TOD used in this review are presented. Section 3 presents the effects of TOD, featuring both cross-sectional and longitudinal analyses. Section 4 scrutinizes the travel mode choices of TOD residents, categorizing them by different trip purposes. The discussion in Section 5 covers the limitations of TOD effects, potential reasons for inconsistencies in the literature, and suggestions for improving TOD implementation. The final section offers insights into research gaps and opportunities.

2 Methods

2.1 Literature selection criteria

We used the Web of Science database to collect journal articles, conference proceedings, and dissertations published from 1990 to 2021 for this literature review, focusing on the data, variables and empirical results of each study. We employed a set of search terms in the Title, Keywords, or Abstract fields to identify relevant literature. The search query was as follows: (AB=("transit-oriented development" OR "TOD" OR "transit-oriented development")) AND ALL=("travel behavior" OR "travel behavior" OR "travel pattern" OR "mode choice" OR "mode share" OR "transit" OR "public transport" OR "ridership" OR "auto" OR "car" OR "vehicle" OR "ownership" OR "impact" OR "effect" OR "benefit" OR "walk" OR "walking" OR "cycle" OR "cycling" OR "bike" OR "bicycle" OR "non-auto" OR "non-motorized" OR "non-motorized"). Additionally, we restricted the subject area to focus on "Transportation" and "Urban Studies." The search resulted in 432 publications generated from the Web of Science database.

In the paper selection process, we followed a three-step sequence as outlined in Figure 1. Initially, we excluded publications in languages other than English and articles that did not pertain to the relationship between TOD and travel behavior. Secondly, we focused solely on the study providing quantitative outcomes employing either cross-sectional or longitudinal analyses. In the third step, we deployed a combination of backward and forward snowballing techniques to identify additional relevant studies. Specifically, backwards snowballing involved reviewing the references of initially selected papers to find more studies meeting our criteria. Forward snowballing entailed examining papers that cited our initial selections to uncover more contemporary research. This snowballing approach was chosen for its effectiveness in systematically identifying studies that might have been overlooked in conventional database searches. Through this technique, we were able to incorporate an additional 20 papers into our review. After a rigorous screening process, a total of 48 studies were chosen that met our inclusion criteria. These selected studies not only reflect the current state of research in the field but also provide valuable insights into the relationship between transit-oriented development and travel behavior, thereby contributing to a more comprehensive understanding of the subject.

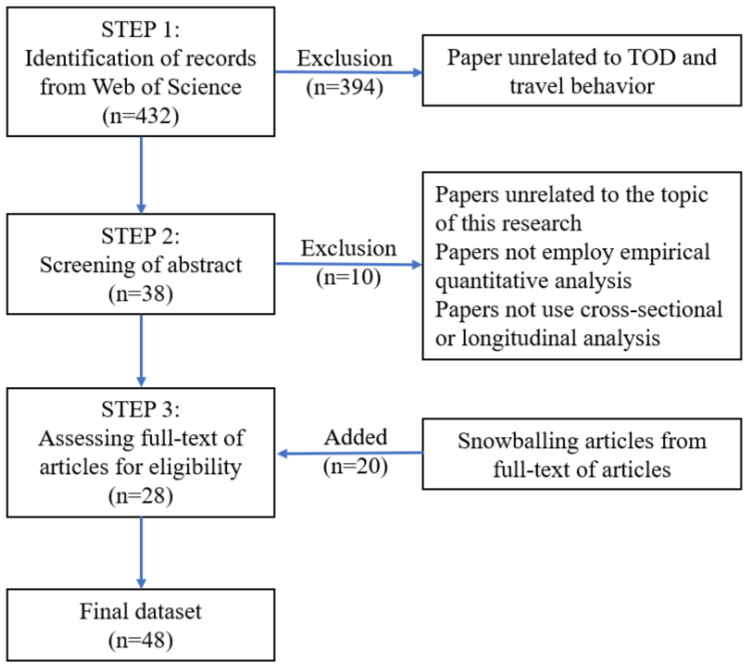


Figure 1. Literature selection process

2.2 Scope of literature analysis

The concept of TOD was codified by an American architect Peter Calthorpe, one of the advocates of New Urbanism, in his book *The Next American Metropolis* published in 1993. Calthorpe (1993) defined TOD as “a mixed-use community within an average 2,000-foot (or 10-minute) walking distance of a transit stop and core commercial area.” TODs aim to reduce reliance on private vehicles and promote the use of public transport, walking and cycling through integrating land use with high-quality transit infrastructure, which typically has moderate to high density developments around transit nodes with walkable and mixed-use communities.

Although the exact definition of TOD may vary across different studies, this review includes all study sites that were self-defined as TODs by each study. The table in the appendix offers supplementary details about each of the reviewed studies, such as the transit modes available in the TOD areas, the boundaries of the study area, the year when transit service began, the year when data collection took place and socio-economic data. These factors could potentially impact the association between TOD and travel behavior, but the limited availability of information prevented a thorough analysis to determine the exact impact of these factors on the research outcomes. For instance, most studies do not distinguish between the individual type of transit and its associated TOD effects when more than one transit service is present in the study area.

Several studies recognized the potential impact of the time lag between when a TOD was developed and when the analysis was conducted due to changes in traffic patterns or demographics over time (Houston et al., 2015; Loo et al., 2010; Pan et al., 2017).

However, it was challenging to obtain detailed information on when and how public transport systems were established in the study areas where previous research was conducted. Identifying the precise timeline for the commencement and completion of a particular TOD also poses difficulties, because TODs can include a mix of old, new, and renewed developments (Renne, 2005).

Defining the TOD boundary is an important factor that may vary depending on the specific characteristics of the local context and site (Lund et al., 2006). The reviewed studies commonly define the TOD boundary as the area within a walking distance ranging from 0.25 mile (about 0.4km) to 1 mile (about 1.6km) or a 10- to 15-minute walk time from the transit station. Some studies also used a combination of factors, including density, land use diversity, pedestrian-friendly design, adjacency to transit, and transit service quality, to define the TOD boundary.

3 Effects of TOD on travel behavior

Many studies have been undertaken to reveal the interrelationship between TOD and travel behavior. The following sections provide a synthesis of cross-sectional and longitudinal analyses of TOD effects in the literature that examine the travel behavior differences between TODs and non-TODs, and the behavioral shifts over time of TOD residents, respectively.

3.1 Cross-sectional analyses

Substantial research efforts have been devoted to studying the effects of TOD by comparing the degree to which travel behavior differs between TODs and non-TODs. Studies have explored TOD effects in four main categories: transit mode share; non-motorized mode share; vehicle mode share; and vehicle ownership. Table 1 compares the travel behavior indicators of TOD residents with non-TOD counterparts. The ratio indicates the quantitative behavior value of TOD residents relative to non-TOD residents. For example, a positive ratio in “Public transport” would mean that the transit usage rate among TOD residents is higher, by a multiple of the number, than the transit usage rate among non-TOD residents. The different trip purposes, i.e., commuting, non-commuting, and both commuting and non-commuting trips, are presented separately in each sub-column. Green shading implies the effects are encouraging trends in sustainable transport, whereas red implies the opposite. Lighter colors correspond to weaker effects, darker shades to stronger effects, and yellow depicts statistically insignificant effects.

3.1.1 Transit use

If all parties agree on one aspect of TOD that brings benefits for society as a whole, it is the increase in public transport use (Calthorpe, 1993). The literature consistently shows, by comparing TODs with non-TODs or a citywide average, that TOD brings benefits in increasing public transport use. For commuting trips, TOD residents had higher transit mode shares than non-TOD neighborhoods, ranging from 1.7 times higher in Shanghai (Chen et al., 2017) to 6 times higher in California (Cervero, 2004). Compared to the citywide average, the transit mode share in TODs was found to be from 1.3 times higher than non-TODs in Toronto (Higgins & Kanaroglou, 2016) to up to 7 times higher in the San Francisco Bay area (Cervero, 1993, 1994). One exception is Nasri and Zhang (2014), which reported that the commuting mode shared by transit, walking and bicycle was lower in Baltimore TODs than in their counterparts (20.82% vs. 25.23%). This study reported that the lack of fast and reliable public transport services for long-distance commuters might have been a contributing factor to these results.

Table 1. Comparison of travel behavior between TOD and non-TOD groups

Location (Source)	Transit type	Public transport			Non-motorized			Private vehicle			Vehicle ownership
		C	NC	All	C	NC	All	C	NC	All	
Bay Area, US (Cervero, 1993, 1994)	HR&LR	+7.0						-0.8			-0.9
Portland, US (Switzer, 2002)	LR	+3.7									
10 US regions, US (Cervero, 2004)	HR&LR	+6.0			+3.0						-0.5
California, US (Lund et al., 2004; Lund et al., 2006)	HR&LR	+4.9						-0.8			
12 US regions, US (Renne, 2005)	HR&LR	+2.4			+3.5						-0.6
Portland, US (Dill, 2005)	LR&Bus	+1.9			+3.2			-0.6			
California, US (Cervero, 2007)	HR&LR	+3.9									
4 US regions, US (Arrington & Cervero, 2008)	HR&LR	+3.5						-0.5			-0.5
Portland, US (Dill, 2008)	LR	+2.5									
San Francisco, US (Renne, 2009)	HR	+2.5			+8.6						
Brisbane, Australia (Muley et al., 2012)	Bus			+3.5			+3.7			-0.4	-0.7
New Jersey, US (Chatman, 2013)	HR&LR							-0.7	-0.7		-0.7
Brisbane, Australia (Kamruzzaman et al., 2013)	HR			+4.2						-0.8	
Washington DC, US (Faghri & Venigalla, 2013)	HR									-0.3	
Washington DC, US (Nasri & Zhang, 2014)	HR	+2.1	+2.9	+2.6	+2.1	+2.9	+2.6	-0.7	-0.8	-0.7	-0.6
Baltimore, US (Nasri & Zhang, 2014)	HR	-0.8	+1.5	+1.2	-0.8	+1.5	+1.2	0	-0.9	-0.9	-0.7
Washington DC, US (Zamir et al., 2014)	HR			+2.4			+1.9			-0.8	-0.8
Baltimore, US (Zamir et al., 2014)	HR			+2.5			+2.7			-0.8	-0.8
Brisbane, Australia (Shatu & Kamruzzaman, 2014)	Bus			+1.1			+1.4			-0.9	
Brisbane, Australia (Kamruzzaman, Baker et al., 2015)	HR&Bus	+1.5			1			-0.7			
Los Angeles, US (Houston et al., 2015)	HR&LR			+2.2			+1.2			-0.6	-0.7
New Jersey, US (Noland & DiPetrillo, 2015)	H&L	+2.5			+3.2			+1.2			
Toronto, Canada (Higgins & Kanaroglou, 2016)	HR	+1.3			+4.0						
Shanghai, China (Shen et al., 2016)	HR	+4.4									1
5 US regions, US (Ewing et al., 2017)	HR&LR									-0.5	
Bangkok, Thailand (Pongprasert & Kubota, 2017)	HR										+1.1
Seattle, US (Tian et al., 2017)	Bus			+3.3			+1.9			-0.6	
Shanghai, China (Chen et al., 2017)	HR	+1.7	+1.9		+1.7	+1.7		-0.5	-0.3		-0.5
8 US regions, US (Park et al., 2018)	HR&LR			+1.9			+2.5			-0.3	
Delhi, India (Kumar et al., 2018)	HR	+1.4						-0.8			-0.5
Portland, US (Ewing et al.,2019)	LR			+3.6			+2.4			-0.5	
Atlanta, US (Choi & Guhathakurta, 2020)	HR				+1.9	+1.2					
Dallas, US (Hamidi er al., 2020)	LR			+2.5			+18.2			-0.83	

Note: "C" denotes commuting trip; "NC" denotes non-commuting trip; "All" denotes all trip purposes; "HR" denotes heavy rail; "LR" denotes light rail; Blank denotes unassessed.

For non-commuting trips, the transit mode share for TOD was from 1.5 times higher in Baltimore TODs (Nasri & Zhang, 2014) to 2.9 times higher in Washington DC (Nasri & Zhang, 2014b) than for non-TODs or the citywide average. For all trip purposes combined, the transit mode share in Brisbane TODs was from 1.1 times higher than in non-TODs (Shatu & Kamruzzaman, 2014) to 4.2 times higher than in non-TODs (Kamruzzaman et al., 2013).

Comparing the difference in mode by trip purpose, for regular commuting trips, the difference in transit mode share between TOD and non-TOD ranges from 16.7% to 60.6%. For non-commuting trips, the difference in transit mode share was relatively marginal at between 1% and 8.2%. When these commuting and non-commuting trip purposes are examined in combination, the difference in transit mode share was between 13% and 35.7%. The analysis results confirm what is known from a wide range of travel data: the type of trip has an important influence in choosing a means of transport.

3.1.2 Non-motorized travel

Reportedly, residents of TOD areas are more likely to walk or cycle compared to those who live farther away from transit stations or the citywide average. Table 1 shows that, for commuting trips, TOD residents had higher non-motorized mode shares, ranging from 1.7 times higher than non-TODs in Shanghai (Chen et al., 2017) to 8.6 times higher in San Francisco, (Renne, 2009). The differences in mode shares were found to be 1.2–2.9 times higher for non-commuting trips and 1.2–18.2 times higher for all trip purposes. This gap for commuting trips is relatively greater than for non-commuting trips. As well as walking and cycling serving as the main travel modes on their own, walking and cycling are also an important access mode to transit stations. A study in California found that TOD significantly increased the likelihood of transit commuters walking or cycling to access transit stations, accounting for up to 85% of access modes to transit for commuting (Cervero, 2007).

However, other research highlighted different results. In Baltimore, the share of commuting trips made by transit or non-motorized modes for TOD residents was slightly lower than the share for non-TOD residents (20.82% vs. 25.23%). The authors suggested this reflected the lack of inter-city transit connections in Baltimore which meant commuters opted for driving (Nasri & Zhang, 2014). There are no cycling trips reported by Muley et al. (2012) in Brisbane TODs, where the limited cycling connections at a remote destination, heavy traffic, and the hilly terrain are postulated to be possible obstacles. Kamruzzaman, Baker et al. (2015) found no difference between TODs and traditional neighborhoods in Brisbane in the mode share of non-motorized modes for commuting, and the authors suggested attitudes towards cycling and walking may contribute to the result.

3.1.3 Vehicle dependence

Most studies report that TOD residents are less vehicle dependent than their non-TOD neighbors. In general, TOD residents have a vehicle mode share that is 0.3 to 0.9 times lower than non-TOD residents. Nasri and Zhang (2014) reported that people living in TODs had 38% and 21% fewer household Vehicle Miles Travelled (VMT) for all trip types in Washington DC and Baltimore, respectively, compared to their non-TOD counterparts with similar land use patterns. Park et al. (2008) found that TOD residents in eight regions of the US generated 41% less VMT compared to those who live farther afield. In five US cities, TODs created significantly less demand for driving than surrounding suburbs, and the vehicle trip generation rates were found to be about one-third to two-thirds of rates predicted in the Institute of Transportation Engineers (ITE) Trip Generation Manual (Ewing et al., 2017).

The literature provides additional evidence about the effects of TOD on vehicle dependence by the purpose of the trip. When compared to traditional neighborhoods, the percentage of commuting by private vehicles in TODs was found to be lower in Shanghai (Chen et al., 2017) with only 0.5 times as many people, in New Jersey (Chatman, 2013) with a range of 0.53 to 0.94 times (average at 0.7), and in California (Lund et al., 2004; Lund et al., 2006) with 0.8 times. In 17 TODs in four US metropolitan areas, the actual vehicle trip rates were 44% less than the estimated values by ITE (Arrington & Cervero, 2008). For non-commuting purposes, the vehicle mode share in TODs was found to be from 0.3 times lower in Shanghai (Chen et al., 2017) to 0.9 times lower in Baltimore (Nasri & Zhang, 2014). For all trip purposes, it was from 0.3 times lower in Washington, DC (Faghri & Venigalla, 2013) and 8 US regions (Park et al., 2018) to 0.9 times lower in Baltimore (Nasri & Zhang, 2014) and Brisbane (Kamruzzaman, Baker et al., 2015). However, Pongprasert and Kubota (2017) found a contrary outcome in Bangkok where vehicle use in the Bangkok TOD area is still high, and the limited transit system and difficulty in accessing transit stations may result in high vehicle dependence.

3.1.4 Vehicle ownership

A body of literature examining the effect of TOD on vehicle ownership has produced inconsistent findings. Studies show that TOD residents have vehicle ownership of 0.5 times (that is, half) the ownership of non-TOD counterparts in ten US regions (Cervero, 2004) and four US regions (Arrington & Cervero, 2008) to 0.9 times in the Bay Area (Cervero, 1993, 1994). Some studies have shown different results. Pan et al. (2017) revealed that a transit-oriented neighborhood in Shanghai, served by three railway stations and 26 bus stops, had higher vehicle ownership than its neighboring communities although its transit mode share was the highest in the region. The authors suggested that the high vehicle ownership was likely due to the lack of access to trains, poor transit service quality, and ample parking spaces for residents. Additionally, Loo et al. (2010) found in Hong Kong TODs that neighborhoods with higher average vehicle ownership tend to use public transport more often than the neighborhoods with lower vehicle ownership. TOD neighborhoods are likely to use their vehicles for different purposes such as short pick-up and drop-off trips to transit stations. Shen et al. (2016) showed that in Shanghai proximity to a transit station has an insignificant correlation with vehicle ownership, while socioeconomic factors are rather important predictors. Moreover, Pongprasert and Kubota (2017) demonstrated that people in Bangkok still owned private vehicles even if they lived near a transit station, and their vehicle ownership rates were higher than the citywide average (77 vs. 72 cars per 100 people). Thailand’s building regulations do not limit car parking spaces in residential and office buildings, and real estate developers can freely provide parking spaces to attract buyers.

3.2 Longitudinal analyses

A relatively small number of longitudinal studies in the literature have examined the modal shift of TOD residents over time. Although cross-sectional analyses are suitable and satisfactory for steady state comparisons, they are not able to explain transient behavior change (Kitamura, 1990). Cross-sectional studies consistently report higher transit use and lower vehicle dependence amongst TOD residents, but these benefits accrue only when TOD influences travel behavior and individuals who previously drove switch to non-auto modes. However, the mode shifts over time seem relatively insignificant from existing longitudinal evaluations.

Table 2. Longitudinal comparison of travel behavior of TOD residents

Location (Source)	Transit Type	Method		Public transport						Non-motorized						Private vehicle						Vehicle ownership	
		Type	Period	C		NC		All		C		NC		All		C		NC		All			
				RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI
Bay Area, US (Cervero,1993, 1994)	HR&LR	CS	1990-1993	+1.2%	+1.07																		
California, US (Lund et al., 2004: Lund et al. 2006)	HR&LR	CS	1992-2003	+1.8%	+1.07			+0.9%	+1.04	-1.0%	-0.74			-1.2%	-0.74	-0.5%	-0.99			+1.1%	+1.02		-0.92
12 US regions, US (Renne, 2005)	HR&LR	CS	1970-2000	+1.6%	+1.11					-6.2%	-0.63											+	
Toronto, Canada (Crowley et al., 2009)	HR	CS	1986-2001					+6.0%	+1.86											-5.0%	-0.85		0.84
San Francisco, US (Renne, 2009)	HR	CS	1970-2000	+10.2%	+1.74					-4.1%	-0.9												
Brisbane, Australia (Kamruzzaman et al., 2013)	HR	CS	2009-2011																			-0.2%	
Portland, US (Ewing & Hamidi, 2014)	LR	CS	1994-2011 B&A Transit						+18.5						-0.32						-0.93		
Perth, Australia (Olaru & Curtis, 2015)	HR	CS	2006-2009 B&A Transit					+4.7%	+1.91					+4.1%	+1.33					-8.9%	-0.89		
Porto, Portugal (Ibraeva et al., 2021)	LR	CS	2001-2011 B&A Transit														-						
Perth, Australia (Griffiths & Curtis, 2017)	HR	CS	2010-2015	+2.2%	+1.08					+19.2%	+2.83					-18.7%	-0.68						
California, US (Cervero, 2007)	HR&LR	PS	2003 B&A Reloc														-0.71 VMT						
Brisbane, Australia (Kamruzzaman, Shatu et al., 2015)	N/A	PS	2009-2011	+2.2%	+1.04					-0.8%	-0.99					+0.5%	+1.01						
7 North American regions (Langlois et al., 2015)	HR&LR	PS	2013 B&A Reloc	-1.3%	-0.96	-1.4%	-0.89	-1.3%	-0.92	-3.3%	-0.82	+4.9%	+1.13	+3.9%	+1.11	+4.7%	+1.11	-3.5%	-0.93	-2.6%	-0.95		
Seattle, US (Huang et al., 2017)	LR	PS	2008-2010 B&A Transit											+6.0%	+1.3								
Portland, US (Switzer, 2002)	LR	RS	2002 B&A Reloc	+15.0%	+1.48	+12.0%	+1.6			-3.0%	-0.77	+1.0%	+1.05			-12.0%	-0.79	-13.0%	-0.78				
California, US (Lund et al., 2004)	HR&LR	RS	2003 B&A Reloc	+1.8%						-3.5%						+1.7%							
Portland, US (Dill, 2005)	LR & B	RS	2005													-25.8%						-17.0%	

Location (Source)	**Transit Type**	**Method**		**Public transport**						**Non-motorized**						**Private vehicle**						**Vehicle ownership**	
		Type	Period	C		NC		All		C		NC		All		C		NC		All			
				RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI
Shanghai, China (Cervero & Day, 2008)	HR	RS	2006 B&A Reloc	+4.6%						+0.6%						+6.6%							
Portland, US (Dill, 2008)	LR	RS	2005 B&A Reloc	+15.0%				+64.0%						+51.0%						-61.0%		-11.0%	

Note: "C" denotes commuting trip; "NC" denotes non-commuting trip; "All" denotes all trip purposes; "RT" denotes rate; "RI" denotes ratio; "HR" denotes heavy rail; "LR" denotes light rail; "CS" denotes cohort survey; "PS" denotes panel survey; "RS" denotes retrospective survey; "B&A Transit" denotes before and after commencement of transit service; "B&A Reloc" denotes before and after relocating to TOD; Blank denotes Unassessed.

Longitudinal study enables one to make observations over an extended period of time. There are three types of longitudinal surveys including cohort, panel, and retrospective surveys in the literature. Cohort surveys identify some categories of people that are of interest and then regularly survey the people who fall into that category. The same people do not necessarily participate from year to year, but all participants must meet the categorical criteria fulfilling the researcher's primary interest. In this study, common cohorts could be the residents living in TOD at the time of data collection. This type of study does not take into account the behavior of new movers to TOD and/or leavers from TOD. In a panel survey, the same people participate in the survey each time it is administered. Panel surveys repeatedly collect data from TOD residents to track their travel patterns and behavior change over a period of time and to examine if TOD can influence its residents to change their behavior. In a retrospective survey, participants are asked to report their mode shift after relocating to TOD. By collecting respondents' past travel behaviors, researchers are able to gather longitudinal-like data without the time-consuming process of conducting a longitudinal survey. However, the reliability of this approach may be subject to recall bias, as participants' recollections of past behaviors may not be entirely accurate.

Table 2 demonstrates the changes of TOD residents in transit use, non-motorized travel and vehicle dependence. In a cohort survey, the "Rate" column indicates the change in mode share. In the case of panel survey and retrospective survey, "Rate" indicates the percentage of residents who have changed their mode choice after moving to TODs. For vehicle ownership, the "Rate" indicates the percentage of residents who have either increased or decreased their vehicle ownership. The "Ratio" column shows the data of a later year relative to the prior year, where positive values represent the increase in mode share, while negative values represent the reduction in mode share. The purposes of trips are presented separately in each sub-column. Green shading implies the encouraging trends in sustainable transport, whereas red implies the opposite. Lighter colors correspond to weaker effects, darker shades to stronger effects, and yellow depicts neutral.

3.2.1 Transit use

The literature generally shows that TOD residents increased their transit use over time, but the magnitude of the increase appears to be moderate, especially in cohort surveys and panel surveys. The transit mode share for commuting trips increased by between 1.2% in the Bay Area (Cervero, 1993, 1994) and 2.2% in Brisbane (Kamruzzaman, Shatu et al., 2015) and Perth (Griffiths & Curtis, 2017), while the rate is even lower at 0.9% in California when non-commuting trips are included (Lund et al., 2004). Renne (2005) made the first attempt to track long-term trends in commuting travel and vehicle ownership in 103 TOD precincts across the US from 1970 to 2000. This study found that over the 30-year period, the transit mode share for commuting trips amongst TOD residents increased by 1.6% (from 15.1% in 1970 to 16.7% in 2000), whereas it decreased by 11.9% (from 19% in 1970 to 7.1% in 2000) in surrounding areas. However, Langlois et al., (2015) observed that the percentage of respondents who used public transport remained relatively unchanged compared to their pre-TOD location in seven North American regions.

Although some studies have reported increases for a time period, the authors considered these increases to be modest (Kamruzzaman, Shatu et al., 2015; Lund et al., 2004). Nevertheless, the results are relatively significant in the studies that examine the travel mode changes using retrospective surveys. The results showed that TOD residents are more likely to use public transport than in their previous residence where the percentages of respondents range from 1.8% in California (Lund et al., 2004) to 15% in Portland (Dill, 2008). According to Dill (2008), 19% of TOD commuters switched from non-transit modes including car, walking and biking, to transit as their primary mode, and 4% did the opposite, for a net change of about 15% of commuters. However, 71% of respondents continued their non-transit commuting modes.

3.2.2 Non-motorized travel

Only limited information has been captured about longitudinal non-motorized travel patterns. The observed changes are diverse in three survey approaches. For commuting trip purposes, a drastic change over time was observed by Griffiths and Curtis (2017) in Perth, Australia, where the rates of walking and cycling of TOD residents increased from 10.5% in 2010 to 29.7% in 2016. However, the slight decrease in walking and cycling mode shares were reported by most rest of the studies. According to Renne (2005), while the share of walking and cycling to work has been declining nationally in the US, the degree of decline was less significant in TODs. Cities with the biggest increases in transit use also had the smallest decreases in walking and cycling. In the retrospective survey, Lund et al. (2004) found that 1.3% of respondents changed from private vehicles to walking or cycling after moving to TOD, while 4.8% showed the opposite trend.

The effects appear to be relatively positive if non-commuting trips are considered. In seven North American regions, Langlois et al., (2015) reported that TODs exerted a significant influence on the selection of active modes for accessing amenities such as gyms, service providers, restaurants, and entertainment, which may have been accessed by auto before. A study by Huang et al. (2017) found that while overall walking decreased from before to after the opening of light rail in Seattle, there was an increase in the proportion of overall walking around station areas, which suggests TODs are attracting walking traffic. Dill (2008) reported a relatively stronger change that 51% of respondents in Portland walk more often and longer distances after moving to TOD, but the study did not reveal how many respondents made the reverse shift or continued using their previous mode.

3.2.3 Vehicle dependence

On vehicle dependence, the literature shows that the effects vary over different studies. The mode share changed from an 18.7% decrease in Perth (Griffiths & Curtis, 2017) to a 4.7% increase in seven North American regions (Langlois et al., 2015) in cohort survey and panel survey. There appears to be a distinctive shift away from vehicles in Perth as presented by Griffiths and Curtis (2017). The vehicle mode share for commuting declined from 57.9% in 2010 to 39.2% in 2016, and 82% of TOD residents agreed that their vehicle use had declined since relocating to TODs, compared with

54.9% of TOD residents in the previous year. Cervero et al. (2007) also found that TOD residents reduced their vehicle travel, and the average VMT plummeted some 42% after residents relocated to TODs in California. However, Ewing and Hamidi (2014) reported a slower increase in VMT after the opening of the light rail, which is probably attributable to increased incomes and urban sprawl. In a retrospective survey, as reported by Dill (2005), 29.2% of TOD commuters switched from a private vehicle to transit, walking or cycling. Only 3.4% shifted from a non-auto mode to a private vehicle. The remainder either remained in a private vehicle (39.7%) or other modes. However, Cervero and Day (2008) reported that 8.6% of TOD residents changed their commute mode from non-vehicle to vehicle, with nearly 15% of respondents still using their vehicles, while an increase in the opposite direction from vehicle to non-vehicle was relatively rare at less than 2% of respondents.

Lund et al. (2004) suggested that the pattern of mode switch after moving to TOD is rather complex. Their study demonstrated that vehicle mode share decreased for commuting trips while it increased for all trip purposes, which implied a possible increase in non-commuting trips by private vehicles. On the contrary, Langlois et al. (2015) found that the number of respondents who commuted to work by vehicle grew when they moved to a TOD, whereas the number of respondents who drove to access amenities decreased. Furthermore, Kamruzzaman, Shatu et al. (2015) held the view that behavior changes in vehicle mode share are rather a slow process in Brisbane. A minor increase of 0.5% (from 43.7% in 2009 to 44.2%) in mode change towards vehicles was observed in the respondents.

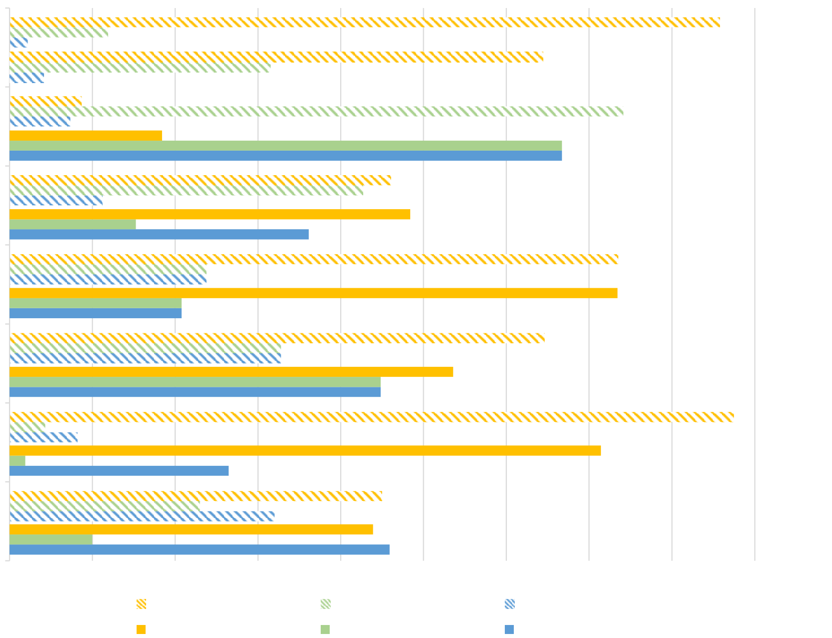
3.2.4 Vehicle ownership

The long-term effects of TOD in inducing a change in vehicle ownership seem to be modest in the literature. In California TODs vehicle ownership per household slightly dropped from 1.2 in 1992 to 1.1 in 2003 (Lund et al., 2004). In a TOD project of Merrick, Portland, only 8% of the residents owned no vehicle, and 73.3% of residents kept their vehicles after relocating to their current TOD residence. Only 17% of households responded that they disposed of a vehicle because of the neighborhood characteristics. A subsequent study by Dill (2008) in Oregon showed similar results, with 76% of respondents indicating that moving to a TOD had no effect on vehicle ownership, while 13% reduced their vehicles, and 2% increased their vehicles. As shown in Kamruzzaman et al. (2013)'s study in Brisbane investigating the change in vehicle availability between 2009 and 2011 in TOD, the majority of participants (92.7%) reported no change in their vehicle availability, while 3.5% reported an increase and 3.7% reported a decrease. On the contrary, Renne (2005) reported the percentage of car-less TOD households decreased over 20 years, from 20.5% to 14.1%, while the percentage appeared to be lower compared to region-wide data, 8.5% in 1980 and 7.5% in 2000.

4 Travel mode choice by trip purpose in TOD

The significance of trip purpose in determining travel mode choice is well-documented in existing literature, although studies specifically focusing on TOD areas are relatively sparse. Analysis of the literature reveals distinct mode share patterns for work-related and non-work-related trips among TOD residents. This trend is proven by the data presented in Figure 2, which delineates the travel mode choices of TOD residents for both commuting and non-commuting trips. The chart employs various colors and fills patterns to distinguish between different modes and trip purposes: blue, green, and yellow denote the mode shares of public transport, non-motorized modes and private vehicles, respectively. Solid fills denote commuting trips, while diagonal stripes are indicative of non-commuting trips. It should be noted that some studies aggregate the data of public transport and non-motorized modes, denoted as "PT&NM" in the chart, sharing the same percentage values. An exceptional study is made by Laham & Noland (2017), which exclusively focuses on non-work trip patterns of TOD residents and provides a segmented analysis for specific non-work trip purposes such as restaurant-coffee shops, and food-groceries.

As shown in Figure 2, in most of the locations, public transport is more frequently used for commuting trips. The most pronounced disparities between the use of public transport for commuting and non-commuting trips are seen in California (Lund et al., 2004; Lund et al. 2006) and seven North American regions (Langlois et al., 2015). In these cases, the mode share of public transport for commuting exceeds that for non-commuting by a factor greater than three. Similarly, Arrington and Cervero (2008) reported that transit mode shares in TOD areas can range from 5% to nearly 50% for commuting trips, but typically plummet to between 2% and 20% for non-commuting trips. In terms of non-motorized mode, it appears to be preferentially used for non-commuting trips. This trend is most evident in the seven North American regions (Langlois et al., 2015), where non-motorized modes are utilized nearly 2.8 times more frequently for non-commuting activities than commuting. Although the use of private vehicles varies across locations for different trip purposes, the data generally reveals a higher propensity for their use in non-commuting trips. Notably, in New Jersey (Laham & Noland, 2017), less than 4% of trips to restaurants-coffee shops or food-grocery stores are made via public transport, while over 60% are undertaken using private vehicles. Furthermore, while the mode share of private vehicles commonly exceeds that of public transport, the disparity is considerably widened in non-commuting trips. For instance, in California (Lund et al., 2004; Lund et al., 2006), the mode share of private vehicles is approximately 2.7 times greater than that of public transport during commuting (71.6% vs. 26.5%), while this disparity increases to a notable 10.7 times (87.5% vs. 8.2%) for non-commuting trips.



Note: “C” denotes commuting trip; “NC” denotes non “ ” “ ”
groceries; “PT&NM” denotes public transport and non

Figure 2. TOD residents’ travel mode choice in commuting and non-commuting trips

Disparities become apparent when examining the modal choices across specific non-work trip purposes. According to Laham and Noland (2017), there is a higher tendency for using private vehicles for food-grocery shopping as opposed to restaurants-coffee shops. Conversely, non-motorized modes are more prominently utilized for the latter. One possible explanation could be the logistical requirements of shopping trips, such as the need to carry goods and the presence of additional family members, which render public transport and non-motorized modes less appealing (Chatman, 2013; Nasri & Zhang, 2014). This observation is confirmed by additional studies, including Langlois et al. (2015), who reported a higher mode share of private vehicles for trips to shopping streets or malls (56.32%) compared to trips to cafes, bars, or restaurants (43.48%). The mode share for non-motorized transport stood at 27.62% and 47.61% for the respective trip types, with public transport consistently recording the lowest share. Likewise, in California (Lund et al., 2004; Lund et al., 2006), non-motorized modes emerged as the second most significant choice for shopping (8%) and meals or snacks (4.6%), following behind private vehicles. In a similar vein, Chen et al. (2017) noted an exceptionally high percentage of non-motorized mode use among TOD residents in Shanghai. The mean travel time for non-work trips was significantly shorter than for work trips (14 mins vs. 30.6 mins), suggesting that these destinations are easily accessible by walking or cycling for TOD residents. Therefore, it can be inferred that, with the exception of shopping trips, non-motorized modes have substantially replaced private vehicles for non-work-related activities. This trend aligns with the hypothesis that TODs possess the potential to foster walking and cycling by fulfilling non-work needs within proximal distances to TOD housing (Chatman, 2005; Chen et al., 2017; Laham & Noland, 2017; Lund et al., 2004; Lund et al., 2006).

In summary, while there has been appreciable progress towards auto-independent for commuting trips, a high proportion of residents in TOD continue to rely on private vehicles for non-commuting activities. On a positive note, TOD has been effective in encouraging the use of non-motorized transport modes, particularly for accessing non-work amenities. These findings support the idea that TODs are effectively creating walkable, mixed-use communities, and that residents are making good use of this enhanced local accessibility. However, it should be highlighted that the available data on the travel mode choices of TOD residents across different trip purposes is limited, which may constrain the comprehensiveness of this analysis.

5 Discussions

Overall, there is consensus that TODs encourage the use of public transport and non-motorized modes and discourage vehicle ownership and use. Inconsistencies observed in the effects of TOD on travel behavior, as reported in both cross-sectional and longitudinal analyses, can be attributed to differences in cultural norms, demographics, land use policies, and transport infrastructure that are specific to different regional contexts. These factors have been previously recognized and discussed in the literature. Nevertheless, the literature also suggests that the TOD effects might not be as strong as expected in some cases when disaggregating the study results by trip purposes, and by analytical approaches.

Drawing upon the empirical evidence presented in Tables 1 and 2, Tables 3 and 4 below enumerate the frequency distributions of various trends across distinct modes of transport and trip purposes. To provide a quantitative representation of the impact exerted by TOD, it is introduced a metric termed “Intensity.” This metric is computed using the following formula:

$$Intensity = \frac{1}{n}\sum_{i=1}^{n} |Ratio_i - 1|$$

Where n denotes the total count of ratios, while $Ratio_i$ refers to the specific ratio at the i-th position within the data set. The objective of the Intensity metric is to calculate the absolute value of the deviation of each ratio from the unitary value (1), and then to average these absolute deviations. This resultant average serves as a quantifiable index for evaluating the relative influence of TOD. In the first column of Table 3, the term “higher” signifies that the value corresponding to TOD residents surpasses that of non-TOD residents, while the term “lower” denotes the converse situation. Similarly, in the first column of Table 4, the term “increase” indicates a rise in the mode share among TOD residents, whereas “decrease” signifies a decline. It should be noted that the dataset purposefully omits specific ratios—namely, the non-motorized ratio of 18.2 as cited in Hamidi et al., (2020) in Table 1, and the public transport ratio of 18.5 as detailed in Ewing and Hamidi (2014) in Table 2. The rationale behind these omissions is to mitigate the potential skewing effects these exceptionally high values could have on the overall analysis, thereby maintaining the integrity of the results.

Table 3. Intensity of TOD effects from cross-sectional analyses

	Public transport			Non-motorized			Private vehicle			Vehicle ownership
	C	NC	All	C	NC	All	C	NC	All	
Frequency for higher	17	3	12	8	4	10	1	0	0	1
Frequency for lower	1	0	0	2	0	0	9	4	14	13
Intensity for higher	2.13	1.10	1.58	2.47	0.83	1.15	0.20	0	0	0.10
Intensity for lower	0.20	0	0	0.20	0	0	0.32	0.33	0.36	0.35
Intensity for overall difference	2.02	1.10	1.58	2.24	0.83	1.15	0.31	0.33	0.36	0.33

Note: "C" denotes commuting trip; "NC" denotes non-commuting trip; "All" denotes all trip purposes.

Table 4. Intensity of TOD effects from longitudinal analyses

	Public transport						Non-motorized						Private vehicle						Vehicle ownership	
	C		NC		All		C		NC		All		C		NC		All			
	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI	RT	RI
Frequency for increase	10	7	1	1	4	4	2	1	2	2	4	2	4	2	0	0	1	1	1	0
Frequency for decrease	1	1	1	1	1	1	7	6	0	0	1	3	4	5	2	2	4	4	3	2
Intensity for increase	-	0.23	-	0.60	-	0.60	-	1.83	-	0.09	-	0.25	-	0.06	-	0	-	0.02	-	0
Intensity for decrease	-	0.04	-	0.11	-	0.08	-	0.19	-	0	-	0.47	-	0.21	-	0.15	-	0.1	-	0.12
Intensity for overall change	-	0.20	-	0.36	-	0.47	-	0.43	-	0.09	-	0.34	-	0.16	-	0.15	-	0.08	-	0.12

Note: "C" denotes commuting trip; "NC" denotes non-commuting trip; "All" denotes all trip purposes; "RT" denotes rate; "RI" denotes ratio; "-" denotes unavailable data.

5.1 Commuting trips versus non-commuting trips

The influence of trip purposes on travel behavior has received considerable attention in the literature. While TODs appear to differentially impact mode choices for commuting and non-commuting trips, the evidence presents some variations across cross-sectional and longitudinal studies. In a cross-sectional context, the majority of studies reveal a consistent pattern: TOD residents are more likely to use public transport and non-motorized modes, and less likely to use private vehicles, compared to their non-TOD counterparts, as elaborated in Section 3.1. Regarding the ratio that quantifies the behavior of TOD residents relative to non-TOD residents, the data suggests greater intensity in commuting modes compared to non-commuting modes, while the intensity is moderately consistent for vehicle dependence. This implies that TOD exerts a more pronounced influence on mode choice for commuting-related mode choices. Such observations align with previous research, supporting the hypothesis that TOD has a greater impact on travel behavior for work trips compared to non-work trips (Song et al., 2012). Additionally, the data indicate that the average mean intensity for public transport and non-motorized modes is over fourfold higher than that for private vehicle usage and vehicle ownership. This suggests that the influence of TOD is markedly more pronounced in encouraging the use of public transport and non-motorized modes than in reducing vehicle dependence.

Longitudinal analyses generally indicate an increase in transit use among TOD residents for both commuting and non-commuting trips. Conversely, the use of private vehicles shows a slight overall reduction with variances in both commuting and non-commuting trips. Non-motorized modes, however, present a more complex picture: while their use declines for commuting trips, there is an increase for non-commuting trips. This trend is likely attributable to the growing role that non-motorized modes play in facilitating access to short-distance, non-work-related amenities, as discussed in Section 4 (Chen et al., 2017). One notable exception is shopping trips, where sustainable transport modes are less likely to be adopted post-relocation to a TOD (Langlois et al., 2015). When examining the intensity of change over time, the TOD impact varies by trip purpose and mode. Consistent with cross-sectional analyses, TOD seems to have a more prominent effect on commuting modes than non-commuting for non-motorized modes and private vehicles. However, the effect of TOD is more pronounced for transit use in non-commuting trips. Despite this, the share of public transport in non-commuting trips remains significantly lower than that of private vehicles and even underperforms its share in commuting trips (see Figure 2). This suggests untapped potential for increasing transit use for non-commuting purposes, underscoring the need for long-term strategic planning. Furthermore, in alignment with cross-sectional observations, the data indicate that the average mean intensity for public transport and non-motorized modes is more than twice that for private vehicle usage and vehicle ownership.

In summary, this study confirms that the influence of TOD on travel behavior is contingent on the type of trip—commuting or non-commuting—and the mode of transport. Cross-sectional data predominantly indicate that TOD residents are more inclined to use public transport and non-motorized modes for commuting trips, thereby having a more pronounced impact on work-related travel. Longitudinal data, however, paint a more complex picture. While there is an encouraging trend toward increased public transport use and a decline in vehicle dependence among TOD residents, these changes are not consistent across different trip purposes. Notably, despite TOD's greater impact on non-commuting trips, public transport still lags behind its share in commuting trips and is dominated by private vehicle usage. It appears that many TOD residents tend to use public transport for commuting trips, use non-motorized modes and private vehicles for non-commuting trips. This suggests that transit commuters residing in TODs still retain their vehicles for non-commuting trips, although they are not completely reliant on private vehicles, while incrementally adopting non-motorized modes for access to non-work amenities. These findings suggest that while TODs have been somewhat successful in shifting travel behavior, there is room for improvement, especially for non-commuting trips. The consistently higher intensity of TOD effects in public transport and non-motorized modes, as opposed to private vehicle usage and vehicle ownership, further underscores the notion that TODs are more effective in promoting sustainable travel modes—public transport and non-motorized mode—than they are in reducing vehicle dependency.

For remedial strategies, it is crucial to consider activity-specific factors that may influence modal choices (Jiang & Mondschein, 2019). Short-term interventions should aim for immediate impact by targeting shifts in commuting behaviors, while long-term strategies ought to focus on inducing sustainable changes in non-commuting travel patterns. The successful promotion of non-motorized modes for non-commuting trips could serve as a blueprint for encouraging transit use. This is especially applicable given the empirical evidence highlighting the role of mixed-use development, high residential and retail densities, and small block sizes in promoting public transport for short-distance, non-work trips (Arrington & Cervero, 2008; Cervero & Day, 2008; Lund et al., 2004; Nasri & Zhang, 2014). Future TOD planning is advised to continue enhancing transit services during non-peak hours and diversifying amenities by incorporating pedestrian- and cycle-friendly infrastructure around transit stations to promote both public transport and non-motorized travel, while concurrently reducing vehicle dependency. Specific focus should be given to understanding travel behavior associated with shopping and other consumer activities to identify factors for promoting alternative transport modes over private Additional attention should also be devoted to enhancing first-mile and last-mile connectivity from transit stations to workplaces through non-motorized modes. These targeted measures would not only build upon the existing successes of TOD but also address the gaps identified in this study, thereby making TODs more effective in fostering sustainable travel behaviors.

5.2 Cross-sectional analyses versus longitudinal analyses: Self-selection and transient behavioral change

In assessing the degrees of travel behavior change, Tables 3 and 4 offer comparative insights by presenting both the frequency and intensity of TOD effects on diverse travel modes and trip purposes through cross-sectional and longitudinal lenses. The results are generally consistent in confirming that TOD residents are more likely to use public transport and non-motorized modes and drive less than residents of non-TOD areas. In contrast, longitudinal analyses yield more varied and sometimes adverse results, particularly regarding the adoption of non-motorized modes and vehicle dependence. The disparities between these two methodological approaches are particularly obvious when examining the intensity of TOD effects. Cross-sectional analyses consistently show a more marked impact across all variables. This contrast is especially noticeable in the use of public transport and non-motorized modes, where cross-sectional data show intensities approximately 4.6 and 6.6 times higher than those in longitudinal studies, respectively. Although less pronounced, the effects on private vehicle use and vehicle ownership are also more evident in the cross-sectional analyses, being around 2.6 and 2.8 times higher than in longitudinal analyses. These variations suggest that temporal factors may significantly influence the effectiveness of TOD initiatives in shaping travel behaviors.

The discrepancies between findings from cross-sectional and longitudinal analyses suggest that travel behavior change is a slow process. For example, existing literature highlights that although residents exhibited a shift in travel modes upon relocating to a TOD, most of them continued using their previous travel modes (Cervero & Day, 2008; Dill, 2008; Kamruzzaman, Shatu et al., 2015; Langlois et al., 2015). Additionally, Lund et al. (2006) revealed that while transit usage did not notably increase between 1992 and 2003, the residents who lived in a TOD area for more than five years were 10% more likely to use transit for any trip purpose than those who lived there for less than five years. Studies also indicate that residents near older TODs are more inclined to frequent transit use and exhibit lower VMT as opposed to those near newly established TODs (Houston et al., 2015; Loo et al., 2010; Pan et al., 2017). This is supported by research suggesting that the built environment associated with new TODs may take an extended period to fully mature and influence travel behavior (Loukaitou-Sideris, 2010). Given that travel behavior, particularly for routine trips such as commuting, is habitual and not easily or quickly changed, and is influenced by personal, environmental, and policy factors (Ibraeva et al., 2021; van Wee & Witlox, 2021). The slow pace of this behavioral shift offers a plausible explanation for the more prominent effects observed in cross-sectional analyses as compared to longitudinal studies.

The finding has also triggered debates about the role of residential self-selection in travel behavior. People who have a preference for a particular mode of transport tend to choose residential locations conducive to such preferences (Laham & Noland, 2017). Many studies confirmed that residents with favorable attitudes towards sustainable travel behavior are more inclined to reside in TOD (Cao et al., 2009; Cervero, 2007; Cervero &

Arrington, 2008; Chatman, 2009; Kamruzzaman et al., 2013; Li & Zhao, 2017; Lund et al., 2004; Mokhtarian & Cao, 2008), resulting in higher transit use and non-motorized modes and lower reliance on private vehicles. These studies suggest that personal attitudes toward travel could account for between 21-40% of the observed TOD effects on individual travel behaviors (Cervero, 2007; Cervero & Duncan, 2008; Nasri et al., 2020; Zhou & Zolnik, 2013). However, this view is not universally held. Some studies, which have sought to control for self-selection bias by directly querying participants on their residential choice motives, argue that the impact of self-selection on travel behavior is relatively minimal and that the influence of TOD remains significant (Cao et al., 2009; Chen et al., 2017; Nasri et al., 2020). Other studies also highlighted that the influence of attitudes could be limited because it can be adaptable and responsive to the changes in the built environment (Brown & Werner, 2008; Chatman, 2009; Ibraeva et al., 2021; van de Coevering et al., 201;). With regard to trip purpose, research suggests that while transit access is a significant factor in residential location choice for work-related commuting, its influence is more limited when it comes to non-work activities (Ben-Akiva & Bowman, 1998; Chatman, 2005).

Travel behavior change is a complex and multifaceted phenomenon, influenced by a range of factors, necessitating future research to further explore the impact of residential self-selection and travel attitudes on travel behavior outcomes. Urban planning interventions, such as TOD, should not be viewed as panaceas for stimulating travel behavior change (Olaru & Curtis, 2015). Policymakers and urban planners need to consider not only enhancing the physical built environment, but also devising policy interventions to change people's attitudes, perceptions, and residential self-selection. A long-term approach that leverages a variety of tactics and interventions is warranted to support residents' attitudinal shift towards a more sustainable travel mode. This holistic strategy would require a confluence of infrastructural, educational, and behavioral interventions to truly effect a sustainable shift in travel modes.

5.3 Contextual factors in TODs

TODs are integrated within local transport and socio-economic systems. This section first explores the role of different transit types in shaping TOD impacts, as demonstrated in Table 5 and Table 6. These tables quantify the intensity of TOD effects by transit type through cross-sectional and longitudinal analyses. The second column of the tables, representing the number of reviewed research studies for each transit type, serves as an indicator of the findings' robustness. However, it is worth noting that some transit types have limited cases; therefore, the analysis will be conducted with special consideration given to the number of cases for each type.

The data from cross-sectional analyses and commuting trips reveal higher intensities, supporting earlier findings of stronger TOD effects. TODs featuring both heavy and light rail services exhibit the most significant impact on transport modes. This is supported by studies such as those conducted in the Bay Area (Cervero, 1993, 1994) and across eight US regions (Park et al., 2018), which show substantial effects on transit use and vehicle dependence. TODs with heavy rail also exhibit a considerable degree of impact, as evidenced by studies such as research in San Francisco (Renne, 2009), which reported the highest ratio of non-motorized mode. Although the number of studies focusing on light rail and bus services is limited, some have reported noteworthy impacts. This suggests that effective transit systems should offer a diverse range of transport modes to maximize benefits. Moreover, the longitudinal data show that TODs with only heavy rail or light rail also have a considerable impact, such studies in Perth (Griffiths & Curtis, 2017) and Portland (Dill, 2008; Ewing & Hamidi, 2014). However, the lowest intensity is observed in TODs featuring both heavy and light rail, contrasting with the cross-sectional findings. This discrepancy underscores the influence of various contextual factors over the long term.

Table 5. Intensity of TOD effects from cross-sectional analyses broken down by transit type

Transit type	No. of cases	Mode of transport				Trip purpose		
		Public transport	Non-motorized	Private vehicle	Vehicle ownership	Commuting trip	Non-commuting trip	All trip purposes
HR	13	1.98	2.04	0.28	0.28	1.55	0.72	0.95
LR	4	2.08	1.40	0.34	-	2.10	-	1.17
Bus	3	1.63	1.33	0.37	0.30	-	-	1.11
HR & LR	11	2.81	1.68	0.38	0.35	2.08	0.30	0.71
HR & Bus	1	0.50	0.00	0.30	0.30	0.27	-	-
LR & Bus	1	0.90	2.20	0.40	-	1.17	-	-

Note: "HR" denotes heavy rail; "LR" denotes light rail; "-" denotes unavailable data.

Table 6. Intensity of TOD effects from longitudinal analyses broken down by transit type

Transit type	No. of cases	Mode of transport				Trip purpose		
		Public transport	Non-motorized	Private vehicle	Vehicle ownership	Commuting trip	Non-commuting trip	All trip purposes
HR	6	0.53	0.57	0.15	0.16	0.39	-	0.48
LR	4	0.54	0.37	0.14	-	0.31	0.29	0.34
HR & LR	5	0.08	0.26	0.13	0.08	0.16	0.10	0.09

Note: "HR" denotes heavy rail; "LR" denotes light rail; "-" denotes unavailable data.

Given that TOD impact intensity is also shaped by other contextual factors, further analyses consider variables such as study design, timing, transit infrastructure, and socio-economic data, detailed in the Appendix. Despite these considerations, no clear pattern emerges. This could be attributed to varying sample sizes, differing scopes of studies, or the lack of sufficient data available at the time when the corresponding research was conducted. Some insights can still be gleaned from the data. For instance, studies predominantly from developed countries, where heavy rail systems have been well-established and operational for extended periods, often come with robust socio-economic indicators. These factors collectively contribute to the reporting of more pronounced TOD effects.

5.4 Analytical approaches

The effects of TOD are normally measured by utilizing a cross-sectional or longitudinal approach and the choice of methods could affect the validity of the findings. Cross-sectional studies are prevalent in the field of TOD research. However, this approach has limitations, especially in tracking long-term behavioral changes and accounting for residential relocation. Furthermore, cross-sectional studies often struggle to isolate the effects of TOD from confounding variables like travel attitudes and residential self-selection (Cervero, 2007; Dill, 2008; Nasri & Zhang, 2014). Consequently, they may not be the most effective method for establishing causal relationships between TOD and changes in travel behavior.

On the other hand, longitudinal studies provide a more insightful analysis by incorporating a temporal dimension. This allows for the observation of evolving travel behaviors over extended periods, offering a richer context for understanding the impact of TODs. Given that individuals may require time to adjust their travel preferences and modes in response to new living conditions (Ibraeva et al., 2021), longitudinal studies prove advantageous. They are particularly effective in controlling for variables like residential self-selection (Cao et al., 2009; Wang & Lin, 2019), thereby strengthening the validity of causal inferences between TODs and travel behavior changes (Ewing & Hamidi, 2014). Our review identifies three specific types of longitudinal research—cohort surveys, panel surveys, and retrospective surveys—each contributing unique advantages and limitations to the study of TOD effects.

A cohort survey is the mostly adopted method of collecting data from a group of people who live in TOD to examine how their travel behavior has changed over the years at an aggregated level. Some cohort surveys encompass repeated cross-sectional data by conducting multiple data collections in the same areas, such as TOD vs. non-TOD or a regional level. However, cohort surveys can be affected by demographic changes in the sample population over time since it does not consider people moving in and out of TOD, which can suffer from attrition or loss of survey participants and thus affect the findings. As indicated in the previous section, cohort surveys can hardly control self-selection bias since TOD can attract specific types of households who demand higher levels of transit accessibility and take full advantage of transit (Cervero et al., 2002).

Panel surveys and retrospective surveys provide means to analyze changes in travel behavior over an extended period of time, while also controlling for the potential biases from factors such as residential self-selection and personal preferences (Handy et al., 2005; Mokhtarian & Cao, 2008; Olaru & Curtis, 2015). A panel survey follows the same group of people over time to track changes in their travel behaviors by conducting multiple data collections, while a retrospective survey asks participants to recall their past behaviors. Although a retrospective survey is effective in garnering behavior changes where past data collection is not feasible, recall bias is a major concern because participants may have difficulty accurately recalling their past behaviors or may be influenced by their current attitudes. This could explain why the impacts in retrospective surveys seem to be stronger than other approaches, because it is difficult to verify the accuracy of the data compared to panel surveys, as the past behaviors being reported cannot be directly observed.

Numerous studies utilize panel surveys or retrospective surveys to investigate changes in travel behavior, specifically modal shifts, that occur before and after individuals relocate to TOD areas. However, many of these surveys often do not consider whether the respondents' previous residences were also located in TOD or transit-accessible areas. The absence of data regarding respondents' prior residential environments and a myriad of factors, such as changes in family composition or employment status, influencing travel behavior presents a challenge in drawing conclusions about whether it was the built environment of TOD that led to changes in travel behavior. It appears that selecting an appropriate analytical approach is crucial to fully capture the TOD effect and to improve the validity, reliability, efficiency, and generalizability of the findings.

In summary, we propose several methodological recommendations for future research aimed at accurately assessing the real impact of TOD on travel behavior. Firstly, to mitigate self-selection bias, a comprehensive approach involving longitudinal analyses is advisable. Specifically, panel surveys that track the same group of individuals over time through multiple data collections are the most effective. Secondly, it is crucial to supplement these studies with profile surveys. These should inquire about individuals' travel preferences as well as the socio-demographic profiles of their households to track any changes in travel attitudes, family composition, or employment status. Thirdly, researchers should take into account whether the respondents' previous residences were located in TOD or transit-accessible areas. Fourthly, employing repeated cross-sectional data with well-defined control groups, such as comparing TOD residents with non-TOD residents, is advisable to isolate the treatment effect from other temporal variables. Lastly, considering that behavioral change in travel habits may be a slow process, it is recommended that future studies conduct data collection across different periods. These could range from the short-term (2 to 3 years) to medium-term (5 to 8 years), and long-term (10 years or more). This multi-temporal approach would offer a continuous and more insightful understanding of the influence of TOD on travel behavior.

5.5 Integrating shared mobility to enhance the TOD effect

TOD aims to trigger a mode shift from private vehicles to public transport and active transport. However, the findings from this review show that TOD residents who own vehicles may still prioritize their vehicles in many situations. As previously outlined, the impact of TOD is more pronounced on commuting trips than on non-commuting journeys. Additionally, the highest effects of TOD are observed in public transport usage, followed by non-motorized modes and lastly, vehicle dependence. These findings suggest that more efforts are needed to target non-commuting trips and reduce private vehicle use. Given these limitations, the integration of TOD with burgeoning shared mobility services offers a viable solution to the current challenges of TOD. Shared mobility allows short-term access to shared transport modes including vehicles, bicycles or scooters according to the user's needs and convenience without ownership (Jiao et al., 2020). Shared mobility also aims to encourage sustainable mobility and disincentivize vehicle ownership and use. The integration of TOD with well-established shared mobility services appears to be a viable option to overcome the current challenges of TOD.

Fixed public transport services may not fully satisfy the diverse travel needs of TOD residents. Shared mobility can partially replace the role of a private vehicle for non-commuting trips by taking advantage of the flexibility of shared mobility. Some empirical evidence suggests that auto-centric shared mobility, such as car sharing, is more popular for non-commuting trips than commutes (Cervero, 2003; Cervero & Tsai, 2004; Cervero et al., 2007; Clewlow, 2016; Jiao et al., 2020). For short-distance trips (1–2 km), bike or scooter sharing could become an effective replacement for private vehicles due to economic competitiveness and parking convenience (Liao & Correia, 2022; Ou et al., 2023; Smith & Schwieterman, 2018). Moreover, shared mobility can expand the transit catchment area as a first and last mile (FMLM) facilitator by providing access to and from public transport, a role previously provided by private vehicles (Martin & Shaheen, 2014; Shaheen et al., 2013).

TOD should not be viewed simply as a way to increase the demand for transit services by placing more residents within the station or stop catchment area. Rather, it is most effective as an approach that uses the accessibility provided by key nodes on integrated public transport systems to create centers that reduce reliance on vehicles (Chia & Lee, 2020; Mees, 2014). Integrating the merits of TOD and shared mobility can upscale the multimodal mobility service to address the diverse transport needs in cities with complex transport supply and land-use characteristics (DeMaio, 2009). The multimodal shared transport system is often represented by MaaS (Mobility as a Service), which offers alternatives to solely relying on public transport or private vehicles (Parkes et al., 2013; Li et al., 2018). Multimodal shared mobility as part of the high-quality transit and high-density, mixed-use development principles of TOD could be an important approach to further improve the effects and benefits of TODs in addressing private vehicle dependence and eventually reducing vehicle ownership.

6 Conclusions

In the context of an emerging literature that examines travel behavior, this research is, to the best knowledge of the authors, the first endeavor examining the effects of TOD on travel behavior from a perspective through cross-sectional and longitudinal analyses. From the literature, TOD is often considered as an ideal approach to encourage the use of more sustainable transport and consequently to increase public transport use and reduce vehicle dependence. However, studies also show that some TODs have not achieved their full potential. As evidence reveals, travel mode choice is complicated in virtually all real-world environments, and private vehicles are retained for TOD residents' non-commuting trips. The effects of TOD on long-term travel behavioral change appear to be minimal which implies individuals' modal shift over time is a slow process, and self-selection bias may partially counterbalance the effects of TOD. Furthermore, this research highlights that the methodological approach—whether cross-sectional or longitudinal—can significantly influence the interpretation of TOD's effects on travel behavior. This underlines the importance of methodological rigor and the need to carefully match the research method with the specific question at hand to accurately capture and understand the multifaceted impacts of TOD.

Effective TOD planning strategies must navigate the complex travel behavior influenced by a wide array of factors. Short-term interventions should target immediate shifts in commuting behavior, while long-term strategies should aim to induce sustainable changes in non-commuting travel patterns, leveraging empirical evidence that underscores the role of the built environment in promoting public transport and non-motorized travel. A thorough consideration of activity-specific factors that influence modal choices, especially for non-commuting trips, is crucial. Moreover, the success of TOD extends beyond the physical environment, it also relies on shifting travel attitudes and steering public perception towards embracing alternative, more sustainable transport modes. Policymakers and mobility service providers need to strategically employ both incentives and disincentives to nudge public preferences away from private vehicles towards more sustainable options like public transport, active transport, and shared mobility, thereby aligning urban mobility with the overarching goals of sustainability and enhanced quality of urban life.

The findings from this review suggest that TOD calls for a modal shift from a single mode, where only transit matters, and towards a multimodal travel pattern with the aid of shared mobility. Shared mobility seems to be a suitable option to fill service gaps in TODs where existing public transport services are largely focused on high-speed, mass transport. Shared mobility can predominantly serve as first and last mile travel options connecting public transport for shorter commuting trips, for non-commuting trips and encouraging active transport that replaces private vehicles. TODs could coexist with shared mobility to underpin genuine multimodal travel that involves transferring between different travel modes at TOD and encourage better use of non-vehicle modes of transport. Supporting policies and infrastructure that promote shared mobility, such as creating recognition in shared mobility as a merit good, and providing designated cycling paths, dedicated parking spaces and affordable parking pricing, could help transition it from a niche to a mainstream transport mode and further embrace multimodal travel patterns.

In light of the above research studies, there are still several gaps in the studies of TOD. First, many studies have examined the effects of TOD on commuting trips solely or have disregarded the trip purpose when analyzing its effectiveness. Future studies should explore how trip purposes affect travel behavior to enhance the understanding of behavioral change. Second, further investigation is warranted to examine travel behavior in trip chains that combine multiple trip purposes and destinations within a single trip, as this may also affect mode choice. Third, a longer time span of research could capture longitudinal changes in all types of factors to robustly infer the cause-and-effect relationships. Fourth, future studies could investigate the empirical evidence of both TOD and shared mobility in a combined study to provide a more in-depth analysis and offer additional insights not provided here. Fifth, future studies could investigate and expand the scope of review to include variables like trip frequency and travel distance to provide a more comprehensive understanding of the topic. Furthermore, many studies show that place-specific factors are important in influencing travel behavior. To glean more insights into the shifts in travel behavior triggered by key developments, such as the introduction of new public transport services or residential projects, a broader and more variety of case studies is essential. Additionally, the definition of TOD boundaries is crucial for effectively assessing TOD impacts. Future research should undertake a thorough exploration of TOD boundaries, considering local context, and providing strategic guidelines for their implementation in a variety of urban environments. Undertaking such analyses can provide insight into how different societal, economic, and cultural contexts may influence travel patterns. This, in turn, will aid in pinpointing the most effective strategies to encourage sustainable and efficient modes of transport.

Appendix

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