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Transit-oriented development: A review of research achievements and challenges

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ABSTRACT

Among the attempts made worldwide to foster urban and transport sustainability, transit-oriented development (TOD) certainly is one of the most successful. Since the TOD concept appeared in the late 1980s, it has received increasing attention from researchers and practitioners as a way to merge together transport engineering and planning, land-use planning, and urban design for providing comprehensive solutions to contemporary urban problems. This attention has notably led to the publication of over 300 articles explicitly concerned with TOD in Web of Science journals, as well as to many implementations of the concept, some already completed and others underway (as, for example, the Grand Paris Project in France and Moscow Central Circle in Russia). Essentially, TOD can be described as land-use and transport planning that makes sustainable transport modes convenient and desirable, and that maximizes the efficiency of transport services by concentrating urban development around transit stations. However, as TOD projects started to be implemented worldwide, it became evident that their outcomes could be quite diverse, revealing that in practice the results of a project would depend on a wide variety of factors, trends and complex interrelations between them. In this article, we aim to provide a comprehensive, systematic and up-to-date review of TOD research achievements and challenges. We start by presenting the TOD concept, framing it in the theory of urban planning, and by describing the different typologies of TOD proposed in the literature. Then, we review the vast research dedicated to the study of TOD effects, distinguishing impacts on travel behavior, real-estate prices, residential location, urban form, and community life. The next subject we look at is TOD planning, focusing separately on policy issues and decision-support tools. In the final part of the article, based on the analysis of previous literature, we identify the main gaps and challenges that TOD research needs to address in the future.

1. Introduction

Achieving sustainable development is one of the major goals of urban policies. Since transport is an essential part of cities' activity, many attempts have been made to foster the use of sustainable transport modes, including (public) transit, which have not been entirely successful. In this context, exploring transit-oriented development (TOD) appears to be promising: even though several of its principles had been applied in the early post-war years in Denmark and Sweden, the very idea of TOD only became conceptualized in the late 1980 s, making it a relatively new notion in urban planning. Inspired by classic concepts like the Garden City and the Linear City, TOD proposes to organize settlements around transit nodes as centers of urban life and in a certain way reverse our cities back to transit after the post-war decline (for example, in the United States the number of unlinked trips by bus and surface rail decreased by 3–9 times in the years 1946–1974, remaining steadily low after that; see APTA, 2018). Facilitating access to

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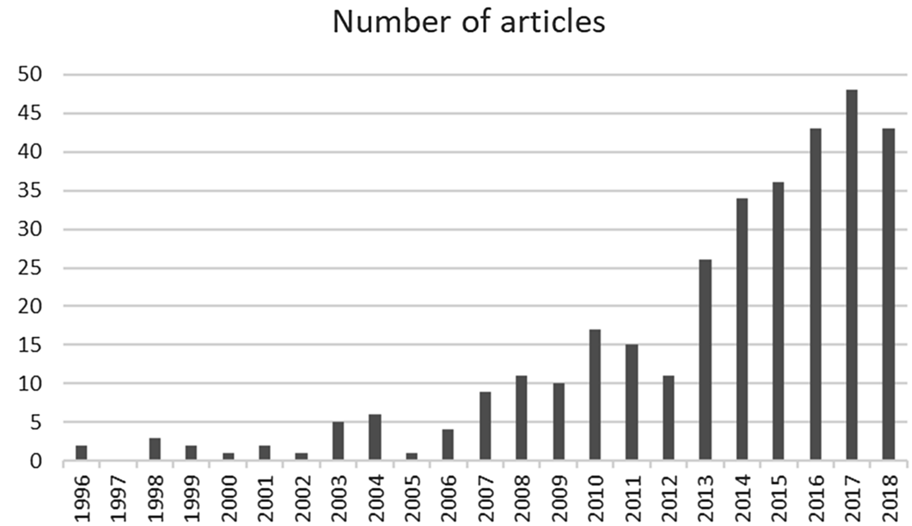

Fig. 1. Number of articles on TOD registered in the Web of Science.

sustainable transport and transit stations, densification of immediate station areas and diversification of the functional composition of these areas appear to be critical elements of the successful implementation of a TOD project. However, as TOD projects started to surge around the world, it became evident that their performance depends on a wide variety of factors such as the socio-economic level of a neighborhood, habits and long-established preferences of residents, and regional accessibility conditions. Therefore, TOD performance reflects the complex and multi-faceted nature of contemporary urban agglomerations, providing a challenging field of research. In the context of increasing levels of urbanization worldwide and major infrastructure investments like the Grand Paris Project in France or the Moscow Central Circle in Russia, this is a highly relevant topic.

Since the 1990s, accompanying the emergence of TOD projects worldwide, the number of journal articles dedicated to this subject has been progressively growing (Fig. 1). Analyzing the 330 articles registered in the Web of Science until the end of 2018 (using the search phrase “transit-oriented development” and considering only the journal categories “transportation”, “urban studies”, “transportation science and technology”, “development studies” and “regional urban planning”), it is evident that the vast majority of research on the subject of TOD originates from the USA, in particular from the University Systems of California, Minnesota, and Texas. In Europe, TOD research is mostly present in Dutch universities, especially in the University of Amsterdam and in the Delft University of Technology. In addition to this, there is also a growing interest in TOD in the Asia-Pacific region, notably in Beijing University and in the Universities of Hong Kong, Melbourne, and Queensland. Overall, it is clear that, despite the unquestionable preponderance of the USA on this matter, TOD-related studies are becoming internationally widespread.

In parallel to the interest that researchers have devoted to TOD, influential organizations such as the U.S. Federal Transit Administration (particularly through the Transit Cooperative Research Program) and the World Bank have dedicated a significant attention to the concept and are contributing to its dissemination by making available information on the effects of its application and by supporting its implementation in practice both financially and through the publication of planning manuals and toolkits (see, e.g., Global Platform for Sustainable Cities, 2018; Salat and Ollivier (2017); Suzuki et al., 2013; TCRP, 2002, 2004, 2008).

In this context, we found opportune to perform a comprehensive, systematic and up-to-date review of TOD research achievements and challenges. Despite several articles offer related reviews (Ewing and Cervero, 2001; Hess and Lombardi, 2004; Ewing and Cervero, 2011), they tend to be more specific than we are with respect to thematic and/or geographic scope, and do not cover the considerable efforts developed to explore TOD in recent years.

Two essential directions are pursued in this article. First, we present and discuss what we believe to be the main research results achieved since the TOD concept was introduced. For this, we have performed an in-depth analysis of the literature focused explicitly on TOD and listed on the main bibliographic databases (Web of Science, Scopus, and Google Scholar), providing special attention to the most impactful articles according to the total and the annual average number of citations they received so far. Second, based on the opinions of the many authors who have written on the subject and on our own analysis, we try to identify the main gaps in the literature, as well as the ensuing research challenges (and opportunities).

The remainder of the article is structured in five sections. The first of these sections focuses on the definition(s) of the TOD concept, on its connections with previous urban planning concepts, and on its best-known early implementations. Then, we look into the efforts that have been made to establish TOD typologies capturing the main dimensions of the concept. The next section deals with the existing knowledge on TOD effects considering five different (but not completely independent) domains: travel behavior, real-estate prices, residential location, urban form, and community life. This is followed by the identification of policy issues raised by TOD planning and a discussion of advanced tools specifically designed to support planning decisions. Our views on TOD research gaps, challenges and opportunities appear afterward. The last section briefly concludes the article.

2. TOD concept(s)

In the 1980s, observing the shortcomings of suburban gridlock and car-oriented developments, urban planners and researchers started to look for alternatives, getting inspired by traditional neighborhood design, new urbanism ("planning and development approach based on the principles of… walkable blocks and streets, housing and shopping in close proximity, and accessible public spaces"; see CNU, 2019) and successful developments around transit stations. As noted by Cervero and Kockelman (1997), the main objectives of the research agenda at that time were: reduction of motorized trips and especially solo-driving; shortening of motorized trip length; and increase of non-motorized trips like cycling and walking.

The concept of TOD was then introduced by architect and urban planner Peter Calthorpe, who, in his book *The Next American Metropolis*, urged for planning for pedestrians and transit, "not to eliminate the car, but to balance it" (Calthorpe, 1993). His ideas were closely associated with the notion of "pedestrian pocket" (a neighborhood layout which facilitates walking trips, offering a variety of available routes and shortening travel times for pedestrians) introduced a few years earlier. In that book, Calthorpe specifically defined TOD as a "mixed-use community within average 2000-foot [AN: 600 m] walking distance of a transit stop and core commercial area. TODs mix residential, retail, office, open space, and public uses in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot, or car". Major commercial and employment areas should be located in close proximity to a station ("primary area"), and nearby public space should ensure neighborhood vitality. A residential zone should be developed in the remaining area, with densities gradually decreasing (yet remaining in the range of 25–62 units per hectare, depending on the surroundings). Additionally, a "secondary area" related to TOD might appear at the maximum distance of 1.6 km from the core zone, where low-density housing, vast park areas, schools and other facilities for local community could be placed. The street network of this outer area should secure easy, fast and direct access to the core, especially by bicycle, and provide park-and-ride lots. By contrast to the secondary area, which could have larger building blocks and lots, constructions in the primary area should ideally occupy less surface, thus allowing for higher street connectivity. Having a variety of available routes, users are expected to choose local streets for their short displacements, instead of using arterial axes. The initial version of the concept focused mostly on neighborhood organization, yet later the importance of TOD on a larger regional scale was emphasized, mixing issues of local neighborhood arrangement with more ambitious public transport strategies.

The idea of TOD was clearly inspired by previous urban planning concepts, notably the Garden City. In his famous Three Magnets Diagram, Ebenezer Howard attempted to reconcile rural countryside and a city by proposing town-country features, mixing the environmental quality and comfort of a rural area with the opportunities and income levels of a city (Howard, 1902; Hall and Tewdwr-Jones, 2011). Similarly, TOD is an effort to infuse a suburb with elements of a city core, supposedly making an area less busy, congested and chaotic than the downtown, yet still vivid and functional. Furthermore, both concepts promote dense, compact and walking-scale settlements. However, there are certain differences between the two concepts with regard to the spatial arrangement of a settlement. Firstly, the location of major employment sites in the Garden City is at the edge of the agglomeration while in TOD employment is concentrated in the central area. Such difference stems from the fact that, when the Garden City concept was proposed, a large number of people was working for heavy industries, which should be isolated from residential areas. Currently, the tertiary sector has assumed primary importance, whereas heavy industries almost disappeared in many cities of the developed world and their location is not considered in TOD. Secondly, life in the Garden City was organized around the main square (which also hosted health, administration and cultural venues) with radial boulevards originating from it, while the center of TOD is a transit station, revealing the major importance ascribed to the transport infrastructure.

Interestingly, the idea of organizing urban settlements adjacent to transport infrastructure remits to another planning concept: the Linear City, elaborated by Arturo Soria y Mata in a series of articles published in 1882. Acknowledging transport as a major challenge for urban planning, Soria y Mata suggested arranging urban settlements along a public transport corridor, tramway or railway, thus achieving a linear form of urbanization instead of the traditional radiocentric city layout (Boileau, 1959; Hall and Tewdwr-Jones, 2011). Rectangular shaped buildings had to guarantee comfortable circulation with easy access to the central avenue. On a wider scale, the Linear City would serve as a link between two larger cities, complementing a transport corridor and concentrating urban growth next to it, what clearly resonates with the TOD concept.

As industrialization and first systems of mass transit were expanding in traditional compact cities, cars were still unaffordable to the majority of people. Public transport service was essential for the community, and linear urbanization patterns along tramways or railways were introduced in many cities: Ciudad Lineal in Madrid, streetcar suburbs in the USA, Stalingrad, and Magnitogorsk in the Soviet Union, etc. In contrast, later on, with the proliferation of private cars, scattered forms of settlement became fairly widespread since the 1960 s. Functional segregation was common for these settlements, creating residential neighborhoods and retail or business centers as clusters, interconnected by roads.

Notwithstanding, several cities managed to partially divert from these trends despite the prevailing diffusion of car-oriented developments elsewhere. For example, in Copenhagen, urban growth concentrated mostly along rail corridors in the absence of better alternatives for commuting as massive motorization had not occurred yet. In these circumstances, locating new settlements in proximity to a rail line was considered a very suitable solution (Knowles, 2012). In Stockholm, rail-based urbanization was facilitated and supported by the city council, which managed to acquire land around the city, giving authorities the freedom to decide upon the organization of new satellite towns (Cervero, 1995). In both cases, functional mix was incorporated in the plans: in Copenhagen, businesses were allowed to settle at a maximum distance of one kilometer away from rail stations, and stations received park-and-ride facilities; in Stockholm's new towns, the number of companies had to be proportional to the number of residents and, at the same time, main points of attraction like shopping centers have been located near rail stations. Furthermore, an influential study by Newman and Kenworthy (1996) identified several cities which have been successful at directing their development towards public transport. Overall, the initiatives which allowed for a reduction in car use involved the implementation of parking restrictions (in cities such as Freiburg, Toronto and Zurich), the expansion of the public transport network (Freiburg, Portland, Toronto, Vancouver and Zurich), the limitation of land available for development (Freiburg and Portland), and the revitalization and infill of the inner city (Portland, Toronto and Vancouver). TOD precursors also emerged in a few Asian and South American cities. In Singapore, integrated land-use and transport planning ("Concept Plan") aided to relocate residents from the overpopulated city center to master-planned new towns, and later a "Constellation Plan" aimed at relocating commercial establishments (Richmond, 2008). In Tokyo, private transport companies developed rail-adjacent lands in the outer areas, placing commercial and entertainment facilities at terminal stations, thus obtaining passenger flows in non-working days (Chorus, 2009). In Curitiba, the development of linear TOD was pioneered by the introduction of an integrated transit network and the concentration of densities along the BRT lines (Lindau et al., 2010). Eventually, these sporadic examples of coordinated land-use and transport policies served as empirical evidence for the shaping of TOD principles.

To sum up, broadly, the concept of TOD may be defined as "careful coordination of urban structure around the public transport network" (Hickman and Hall, 2008). More detailed definitions introduce soft modes: "TOD can be described as land-use and transportation planning that makes cycling, walking, and transit use convenient and desirable, and that maximizes the efficiency of existing public transit services by focusing development around public stations, stops, and exchanges" (Thomas and Bertolini, 2017). In contrast to these definitions, which highlight the primary importance of transit for local neighborhoods, TAD (transit-adjacent development) is defined as a development which "lacks any functional connectivity to transit, whether in terms of land-use composition, means of station access, or site design" (TCRP, 2002). Besides, some definitions highlight the regional importance of TOD, describing it as "an approach to station area projects which reaches further than single-locations, and aims at the re-centering of entire urban regions around transport by rail and away from the car" (Bertolini et al. 2012). As noted by Ewing and Cervero (2001), compact and dense developments would produce only minor effects on travel behavior if they were not properly incorporated into a wider regional transport network. Behind these theoretical considerations stands the assumption that by planning accurately and accounting for the effects of land-use and spatial organization on people's behavior and choices, one can shape travel demand.

3. TOD typologies

Various authors have attempted to classify TOD according to various features of stations and adjacent areas. Typically, the criteria for evaluation of a station area involve density, diversity, and design, the 3Ds identified by Cervero and Kockelman (1997) as the main features of a TOD. Based on indicators that reflect the relative importance of these components, the resulting typologies contribute to a better understanding of how the concept is implemented. Furthermore, they are useful to support TOD planning processes, as grouping stations allows to diagnose common problems and design targeted policies for specific station types (see Section 5).

Probably, the best-known approach leading to a TOD typology is the node-place approach (or "model"), developed by Bertolini (1996, 1999). The approach basically translates into an XY-diagram, where the Y-axis represents the accessibility of a node (the "node-index", describing the variety and frequency of transit supply) and the X-axis the characteristics of a place (the "place-index", describing the functional mix of the station area). The stations are positioned on the diagram depending on their performance on both indexes. Balanced stations with reasonable transit supply and land-use diversity around stations will appear in the middle of the diagram (with approximately 0.5 for both indexes), while stressed stations with considerable passenger flow and extremely intense use of the adjacent area will be placed near the upper right corner (where both indexes achieve the maximum value of 1). In contrast to stressed stations, around dependent stations both land use intensity and the demand for public transport are low (both indexes near 0). Finally, stations with intense urban activities and low transport supply are defined as "unsustained places" and stations with abundant transport supply but lacking diversity of uses are qualified as "unsustained nodes". Applying the node-place model to Amsterdam and Utrecht, Bertolini (1999) concluded that most stations are relatively balanced, except Amsterdam Sloterdijk (low place-index) and Amsterdam and Utrecht Central Stations (both stressed stations). Thus, the node-place approach provides a means to simultaneously evaluate the transport supply and land-use characteristics of a site, and since these two elements are fundamental for the TOD concept, various studies used it as a basis for the classification of TOD, either with or without modifications (Reusser et al., 2008; Monajem and Nosratian, 2015; Chen and Lin, 2015; Groenendijk et al. 2018).

Attempting to adjust node-place model to the TOD classification specifically, various modifications to the original model were introduced. Vale (2015), concerned with walkability and pedestrian comfort, added a pedestrian shed ratio, measured as the proportion of walkable area inside a 700-m buffer from a station. Pedestrian comfort measure represented a considerable improvement in the evaluation of the station areas as some stations qualified as "balanced" by the original model were not pedestrian-friendly, suggesting that these are more likely to be TAD than TOD.

Incorporating design characteristics in the node-place approach, Lyu et al. (2016) to incorporate design characteristics in the node-place approach. These authors suggested classifying metro stations in Beijing using a set of indicators that correspond to the three dimensions hidden behind the acronym TOD: "transit", "oriented" and (urban) "development". The "oriented" dimension included indicators like average block size, the average distance from a station to jobs/residences, and intersection density, among others. This approach allowed to group stations that lacked transit elements (like high transit frequency), "oriented" elements or development elements (like mixed uses and high density). Using this typology, Beijing metro stations were grouped into six clusters. As might be expected, stations located in the city core were highly ranked on all criteria, while distant peripheral stations did not score much, however, for the stations located in-between these two extremes, the typology managed to produce quite sophisticated results, accounting for nuances between different stations (like the degree of walkability or the diversity of station areas).

A different perspective on a TOD typology was proposed by Singh et al. (2014), who, focusing on urban agglomerations as a whole, classified TOD according to their actual TOD index and their potential TOD index. The first index is meant to assess existing TOD levels in locations already served by transit, whereas the second one aims to identify sites with already high levels of TOD (in terms of the built environment, density, etc.) but lacking the “transit” element. The approach was tested on the Arnhem Nijmegen City Region (in the Netherlands), and the authors focused on the potential TOD index, identifying appropriate sites for future TOD based on the levels of 3Ds and economic activity (number of business establishments). A grid cell of 300 × 300 m was selected as unit of analysis and potential TOD index values (from 0 to 100) were obtained using spatial multi-criteria analysis (SMCA). For the selected area, the highest value of a potential TOD index reached only 60 points, meaning that the demand for TOD in the region might not be very strong. The majority of sites with high scores were found in proximity to urban areas.

Motivated by the fact that available TOD typologies were rarely validated against station’s actual performance (in terms of ridership level, mode choice, auto ownership, etc.), Kamruzzaman et al. (2014) proposed a TOD classification and tested whether it reflected the travel behavior observed at the stations. Six indicators were used: public transport accessibility level (PTAL), net residential density, net employment density, land use mix, intersection density, and cul-de-sac density. Cluster analysis disclosed four types of station sites in Brisbane: residential TOD (high PTAL and intersection density, average land use mix), activity center TOD (high diversity level, high PTAL and net employment density), potential TOD (modest density levels, low PTAL), non-TOD areas (lacking both the transport and built environment features of a TOD). Subsequent validation of the typology confirmed higher probabilities of using transit in residential TOD. Curiously, the authors noted certain irregularity in the spatial distribution of TOD in the urban areas (some activity center TOD were located in the center but others were located in the periphery), arguing that such pattern invalidates geographical classifications based on TOD location in a city (central TOD vs suburban TOD for example).

A similar logic was adopted by Higgins and Kanaroglou (2016) who developed a TOD typology for the Toronto region and evaluated the performance of station types in terms of the modal split. Latent class analysis was applied to heavy rail, light rail, and bus rapid transit stations (existing and planned) and resulted in 10 different station types. The typology was based mostly on 3Ds criteria, but also included a destination accessibility measure accounting for employment and residential sites within a 10-min walk from stations and for the travel times between stations. As opposed to the aforementioned case of Brisbane, in Toronto, stations with high TOD levels were concentrated in the city core, while stations in the outskirts could hardly be classified as TOD. Transit appeared as the preferred mode for traveling to work in the inner urban neighborhoods, except for residents of TOD located in central commercial areas who preferred to walk. The socio-demographic structure of central TOD was found to be quite specific, largely composed of young professionals and single-member households.

A different approach was used in a recent work by Huang et al. (2018) where station typology aims to reveal different roles of TOD in order to assess the relationship between them. As argued by the authors, differences between TOD are essential in order to achieve synergistic effects which appear once places differ from each other or provide access to different goods/services but still share the same geographical market. Using latent class cluster analysis and correspondence analysis for the case of the Arnhem Nijmegen City Region, the authors based the analysis on the following variables: population density, job density, business density, land-use diversity, mixed-ness of land uses, intersection density and length of bicycle and pedestrian networks. Results provided three types of TOD: urban mixed-core, urban residential and suburban residential. Probably, only three categories were distinguished because the network was relatively small and dominated by two central stations.

4. TOD effects

A very substantial amount of research effort has already been devoted to analyze the effects of TOD. Based on a detailed assessment of the literature, we have classified this research into five areas according to the types of effects. Each type is addressed below in a separate subsection. The effects on travel behavior are the most studied (especially mode choice as could be expected, but also trip generation and parking), followed by the effects on real-estate prices in and around TOD areas. Other effects, less studied, are the ones concerning residential location (in both directions, i.e., effects of travel behavior on peoples’ choice of where to live as well as the inverse), urban form (i.e., effects on land use and on the spatial distribution and accessibility of activities) and community life. In Fig. 2, the sizes of squares are proportional to the number of articles dealing with the different types of effects. Some articles focus on more than one effect (for example, travel behavior and residential location). This is represented in Fig. 2 by arrows whose width is proportional to the number of articles addressing (at least) two types of effects.

4.1. Travel behavior effects

Amongst the articles dedicated to the effects of TOD, the ones dealing with travel behavior are certainly the most frequent. For this section, we selected articles that, besides being recurrently cited, may also complement each other, and provide an ample overview of research results on the matter. These articles are listed in Table 1. In this table, we specify the methodology adopted in each article and the case study to which it was applied (if any).

Allegedly, the quality and configuration of the surrounding built environment exerts influence on travel choices: according to Cervero and Gorham (1995), residents of a transit-oriented neighborhood commute 1.4–5.1% more by public transport than those living in a car-oriented neighborhood; and, according to Cervero and Radisch (1996), residents of traditional neighborhoods averaged 10% more leisure walking trips than residents of car-oriented suburbs. In Brisbane, the probability of using transit in non-TOD and potential TOD areas is 1.4 and 1.3 times lower compared to residential TOD, whereas walking and cycling are respectively 4 and 2.5 times less likely (Kamruzzaman et al., 2014). In central commercial areas of Toronto transit is competing with walking, as 41% of

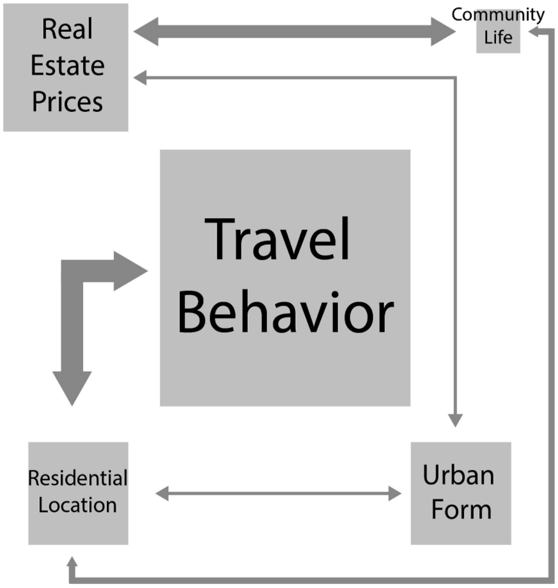

Fig. 2. Areas of study of TOD effects and their interactions.

Table 1
Selected articles on the effects of TOD on travel behavior.

Reference	Methodology	Case study
Cervero and Gorham (1995)	Descriptive statistics/OLS regression model	San Francisco, Los Angeles (USA)
Cervero (1995)	Historic overview/descriptive statistics	Stockholm Area (Sweden)
Cervero and Radisch (1996)	Comparative analysis/discrete choice modeling (binomial logit)	San Francisco (USA)
Ewing and Cervero (2001)	Literature review	n/a
Lund et al. (2004)	Descriptive statistics/comparative analysis	California (USA)
Handy et al. (2005)	OLS regression model/discrete choice modeling (ordered probit)	California (USA)
Cervero (2007)	Discrete choice modeling (nested logit)	California (USA)
Cervero and Arrington (2008)	Descriptive statistics. comparative analysis/OLS regression model	Philadelphia, Portland, Oregon, Washington, D.C., San Francisco (USA)
Cervero and Day (2008)	OLS regression model/discrete choice modeling (binomial logit)	Shanghai (China)
Laham and Noland (2017)	Instrumental variable probit model	New Jersey (USA)
Loo et al. (2010)	OLS regression model	New York City (USA), Hong Kong (China)
Chatman (2013)	OLS regression model/discrete choice modeling (logit regression)	New Jersey (USA)
Kamruzzaman et al. (2014)	Cluster analysis/OLS regression model	Brisbane (Australia)
Nasri and Zhang (2014)	Comparative analysis/multilevel mixed-effect regression	Washington, D.C., Baltimore (USA)
Higgins and Kanaroglou (2016)	Latent class method	Toronto (Canada)
Pan et al. (2017)	Spatial analysis/OLS regression model	Shanghai (China)
Ewing et al. (2017)	Descriptive statistics - comparative analysis	Denver, Los Angeles, San Francisco, Seattle, Washington, D.C. (USA)
Tian et al. (2017)	Descriptive statistics	Seattle (USA)
Park et al. (2018)	Discrete choice modeling/negative binomial model	Atlanta, Boston, Denver, Miami, Minneapolis-St. Paul, Portland, Salt Lake City, Seattle (USA)
Pongprasert and Kubota (2018)	Factor analysis/structural equation modeling	Bangkok (Thailand)

commute trips are made by foot (Higgins and Kanaroglou, 2016). Other works also point out that neighborhood characteristics may influence the modal split as well, e.g., Ewing and Cervero (2001), Handy et al. (2005), and Chatman (2013). It is believed that TOD, combining transit supply with a highly walkable built environment, may encourage more sustainable travel patterns, yet, for example, the degree to which car trips decrease with TOD varies in different studies.

One of the early attempts to analyze the effects of TOD on modal split was made by Cervero (1995). He analyzed the case study of Stockholm rail-served satellite towns, where half of all workers and a third of the residents commute by public transport (Tunnelbana). The towns showed higher levels of transit use than a typical “control” suburb also served by a rail line and with similar income levels, yet characterized by a market-led development. As a descriptive study based on aggregate data for each studied urban area, it provided a general overview of mobility patterns in these settlements, however, without trying to explain the factors influencing them.

A more detailed analysis of TOD effects on travel behavior is provided by Cervero (2007) using data from a one-day travel diary of residents of 26 TOD housing projects in California. Public transport ridership levels in neighborhoods within walking distance (800 m) from a station were compared to those in farther areas, considering heavy rail, light rail, and commuter rail. Attempting to attenuate the influence of self-selection (people's willingness to reside in locations where they can continue using their usual transport mode, transit in this case; see also Section 4.3) in travel patterns, only interviewees who did not reside in TOD before and whose workplace did not change were selected for the analysis. This group of respondents reported a 4 USD decrease in average daily commute costs and a mean increase in job accessibility of 6.5%. Among residents living at a distance between 800 m and 4.8 km of a station, the share of public transport reached only 7%, while for those living within 800 m the equivalent figure was 27% with 85% of them traveling to the station by non-motorized modes. This led the author to conclude that greater public transport patronage levels could be reached by intensifying housing supply near stations and offering accommodation for smaller households with fewer cars which tend to reside in proximity to transit. Chances of using public transport were estimated to be 41.6% higher if a person lived close to a station, other factors held constant. However, significant differences existed in terms of urban design and pedestrian comfort between the selected sites, as noted by Lund et al. (2004), and mixing station areas with rather different characteristics made the findings difficult to interpret.

A similar risk is present in another influential study by Cervero and Arrington (2008) that analyzed 17 multi-family residence projects varying considerably in densities. Selected TOD were located in proximity to either heavy rail, commuter rail or light rail in different parts of the United States, all mostly mono-functional (only 6 of the 17 projects hosted commerce or services at the ground floor). The majority of developments were 3- or 4-floor high, excluding four projects in Washington, which ranged in height from 16 to 21 floors. On average, each dwelling unit was provided with 1.16 parking spaces. Compared to the estimations made in the national guidelines, TOD areas were generating 70–90% fewer car trips per domicile in central areas and 15–25% in suburban areas. Moreover, it was found that an increase in densities was accompanied by a decrease in car trips.

While the selection of study areas in the aforementioned works was based mostly on distance to a station, a work of Nasri and Zhang (2014) comparing TOD vs. non-TOD areas in Washington D.C. and Baltimore is an interesting example of defining TOD through quantitative indicators: residential or employment density of a TOD had to be the same or higher than the metropolitan average, mixed-use level should be at least 0.30 (according to an entropy measure), and maximum distance to transit should be half-mile. It was revealed that, in terms of socioeconomics, TOD residents had smaller households, lower levels of car ownership, and higher rates of zero-car households. In Washington, the results concerning trip characteristics confirmed that people make less use of cars in TOD areas both for work and non-work trips. Yet, in Baltimore, several outcomes were quite unexpected: work trips by public transport/walking/bike turned out to be approximately 5% more in non-TOD areas, whereas the use of cars was found to be almost the same (73.61% in TOD and 73.45% in non-TOD). The authors suggested that such phenomena might be explained by the fact that many people commute to Washington from Baltimore and the public transport links are quite poor between the two cities. Estimated elasticities of vehicle miles traveled (VMT) in Washington was 37.7% lower in TOD areas than in non-TOD areas, and 20.9% lower in Baltimore, all else being equal. Considering the physical layout of selected areas, land-use parameters (residential and employment density, mixed-use) were found to negatively affect VMT levels. On the contrary, distance to CBD and street connectivity increased VMT.

These results were further confirmed in a work of Park et al. (2018), who analyzed data from eight metropolitan areas in the United States. Detailed data availability allowed to analyze origin-destination pairs and the influence of regional accessibility on travel behavior. Regional job accessibility ("the percentage of jobs that can be reached within 30 min by transit") was found to negatively affect VMT by car, at the same time increasing the probabilities of using public transport or walking. Regional compactness (predominantly compact built environment form as opposed to sprawling) was also favoring transit use and walk trips.

A comparative study by Loo et al. (2010) aimed to explore common factors that contribute to high levels of public transport in Hong Kong and New York. Data from a typical weekday rail usage for 80 stations in Hong Kong and 468 in New York were used to create a combined model (meaning that both cities were included in a single model and not considered in two separate models) for two cities with data weighting to compensate for the difference in the number of observed stations. Results showed that mixed land use was associated with transit patronage especially because it created bi-directional travel patterns. Highest levels of transit use were recorded on interchange stations and stations/lines which have been in operation since a long time ago (these are typically centrally located). Bus service connectivity that increases the catchment area of a railway station was also found important in attracting passengers. Similar results were provided by Pan et al. (2017) in a study of passenger volume in Shanghai, adding that longer trips are more likely to be made by transit due to lower travel cost and time. Employment opportunities in a 500-m buffer zone, the presence of a district commercial center, possibility of line transfer in a station, and opening year of a station were found to be statistically significant. Seemingly, Asian cities, and Shanghai in particular, are attracting much attention in the context of TOD due to high-density levels and population dynamics: as the inner city of Shanghai is gradually ceded to offices, public sector or retail, households are moving from the historical center to suburban areas that are mostly represented by single-use superblocks and poor walking environment, which potentially may increase car use.

In order to understand how a change in residential location may affect modal split, Cervero and Day (2008) analyzed the results of a survey of 900 households conducted in four neighborhoods in the outskirts of Shanghai, of which two are served by a metro line and the other two by bus service only. A large part of the respondents (46%) used to live in more central areas before moving into the neighborhoods studied, so, in general, they have experienced an increase in distance to work and lower regional accessibility ("the number of jobs accessible to a household within 1 h of network travel time, either via public transit or private automobiles"). Changes in modal split were considered only for household heads' and only in cases where the previous travel mode was a non-motorized mode or the bus. People were found to maintain the same transport mode they had used before relocation (58.8%), or switch from non-motorized modes to bus (8.2%) or from bus to metro (8.0%) (Cervero and Day, 2008). As noted by the authors, relocating population to areas served by transit allows minimizing the risk of an increase in car-ownership rates.

Residential location choice was accounted for in Laham and Noland (2017), who undertook a noteworthy attempt to estimate the influence of TOD on non-work trips to restaurants/coffee shops and food stores using survey data for several stations in New Jersey. Presuming that residents with positive attitude to public transport or recent movers to an area are likely to choose a specific residential location due to public transport availability, home tenure and attitudinal factors were introduced as instrumental variables to address potential endogeneity bias from self-selection. Proximity to a TOD was found to increase the probability of walking for non-work trips, surprisingly, even to food stores (initially, the authors hypothesized that shopping trips are more likely to be made by car than trips to restaurants/coffee shops). In contrast, higher car ownership rates decreased this probability.

Another issue related to travel behavior in TOD is parking supply. This issue was in particular addressed by Chatman (2013) in a study for New Jersey. Advocating for a more detailed approach to factors other than rail access, the author analyzed the correlations between car ownership/car use and factors like type and age of housing, parking supply, trip purpose, and demographics. The study considered 10 railway stations, and their buffer areas were intentionally increased to 3 km in an attempt to control for spatial autocorrelation as travel behavior of residents within 650 m was compared to travel behavior observed in the areas beyond walking distance to the station. Limited on- and off-street parking availability surged as the most significant predictor for a lower probability of car ownership or car commuting, whereas rail distance did not have a significant influence on car ownership rates. Car commuting was shown to decrease by 60% in station areas with limited parking supply compared to other sites. Similarly, limited parking availability was related to a 25% decrease in using a car for secondary trips. Several other factors were significant as the number of bus stops, smaller apartments, and functional mix, leading the author to conclude that simple rail proximity might not be a decisive factor in lower levels of car use, instead, it is the combination of factors that makes a difference.

Subsequent studies show that even limited parking in station areas is frequently underused. Ewing et al. (2017) analyzed this issue from a user's perspective, using data obtained from counting people on site entering or exiting the buildings and briefly interviewing them, in addition to registration of parking occupancy. TOD were defined as master-planned sites that possess multi-story buildings (density), mixed uses and a walking-friendly environment and are well conjugated with transit stations, while the approach for site selection was mostly qualitative (direct observations, interviews with stakeholders, imagery analysis). Five sites were selected, with one (Redmond, a city near Seattle) being only served by bus and the others also by rail. At peak-hour time, maximum parking occupancy in selected TOD was 84%, being worth noting that these areas already have at least two times less parking than the national guidelines prescribe. Besides, the number of car trips amounted to a maximum of 37.4% of the threshold in the national guidelines. Redmond was found to generate only 65% of the average residential parking demand and 27% of the commercial parking demand estimated in the national guidelines (Tian et al., 2017). Studied TOD areas required less parking space than the national guidelines would suggest, putting at risk site's attractiveness as an oversupply of parking might induce car trips and worsen pedestrian environment. Such risk could probably be minimized introducing demand management to enable different drivers to use the same parking lots (most sites had only dedicated parking for residents or visitors), liberating area for other amenities like green spaces or cycle lanes.

It should be noted that most studies are concerned with the travel choices of TOD residents living within approximately 800 m from the station. Station proximity is likely to be the most influential factor in mode choice. Other frequently mentioned transit-related variables include station opening year (Loo, et al. 2010; Pan et al. 2017), distance to CBD (Cervero and Arrington, 2008; Nasri and Zhang, 2014; Pan et al. 2017) and number of bus stops (Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Park et al. 2018). Most frequent sociodemographic variables are car ownership (Cervero, 2007; Cervero and Day, 2008; Nasri and Zhang, 2014) and household income (Cervero, 2007; Cervero and Day, 2008; Chatman, 2013; Park et al. 2018; Pongprasert and Kubota, 2018). The weight and importance of other TOD components, for example residential density (Cervero and Arrington, 2008; Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Pan et al. 2017), employment density (Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Pan et al. 2017) and retail (Chatman, 2013; Loo et al. 2010; Pan et al. 2017) in station areas have started to be evaluated more recently. The conclusion is that their effect on travel behavior seems to be moderate, at least for commuter trips which have been the focus of most studies. Still, when considered together with other TOD-related factors like diversity or urban design, the effect might be more visible, particularly in terms of access mode to transit. Comfortable and safe access to transit is quite important for TOD residents (Pongprasert and Kubota, 2018). Therefore, accurate selection of station areas is paramount: station areas need to adequately correspond to TOD characteristics in terms of urban design and walkability, otherwise, final results may be misleading.

4.2. Real-estate price effects

Most of the studies on this topic use hedonic price models to deconstruct the price of real estate parcels based on its characteristics, including those not directly inherent to the property itself, like the surrounding environment (Table 2). Data for these studies can be obtained both through a revealed preference approach, i.e., the analysis of empirical evidence on commercial transactions, or through a stated preference approach based on surveys aiming to measure respondents' willingness to pay for a particular good (Bartholomew and Ewing, 2011).

Overall, in theory, proximity to a station and subsequent accessibility benefits should be reflected in the price premium. However, in reality, the relationship between the two factors may not be so straightforward. For example, it is possible that the effect on property values differs depending on the type of transport infrastructure (heavy rail or light rail), property type (commercial or

Table 2
Selected articles on the effects of TOD on real-estate prices.

Reference	Methodology	Case study
Bowes and Ihlanfeldt (2001)	Hedonic price model/random-effects regression models	Atlanta (USA)
Hess and Almeida (2007)	Hedonic price model	Buffalo (USA)
Atkinson-Palombo (2010))	Hedonic price model	Phoenix (USA)
Bartholomew and Ewing (2011)	Literature review	n/a
Duncan (2011a)	Hedonic price model	San Diego (USA)
Duncan (2011b)	OLS regression model/2SLS	San Diego, Carlsbad, San Marcos (USA)
Mathur and Ferrell (2013)	Hedonic price model	San Jose (USA)
Kay et al. (2014)	Hedonic price model	New Jersey (USA)
Renne et al. (2016)	Factor analysis/multilevel regression model	USA
Xu et al.(2016)	Hedonic price model/spatial autoregressive model/spatial error model	Wuhan (China)
Yu et al. (2018)	Hedonic price model/spatial Durbin model/geographically weighted regression	Austin (USA)

residential) and neighborhood income level (Bowes and Ihlanfeldt, 2001; Hess and Almeida, 2007). Furthermore, a study in Atlanta showed that residential property values in immediate metro station areas (radius of up to 400 m) are likely to decrease in value due to congestion, noise and potential increase in crime rates, but tend to increase beyond this limit, reaching a maximum at a distance of 1.6–4.8 km, and then decrease again. Moreover, there is a price increase (4.7%) for properties located beyond the 4.8-km limit if the nearest station has a parking lot, but for houses located closer to the station it may be insignificant (Bowes and Ihlanfeldt, 2001).

The discussion concerning factors affecting house prices in station areas was supported by Kay et al. (2014) in a case study involving eight station areas in New Jersey, five of which were providing direct access to Manhattan, New York City. House prices around stations without direct access to Manhattan were decreasing with distance (properties located within 800 m of a station showed a 6.3% premium compared to those 1.6 km away) before starting to increase again at a 3.2-km distance. The authors suggest that a slight increase at a 3.2-km distance can be partially related to the presence and influence of another station. Interestingly, for stations providing direct access to Manhattan, the price premium decreased steadily with distance (properties within 800 m valued 10.6% more than those 3.2 km away). This makes clear that a price increase in station areas and its distribution may depend not only on the distance but also on the service coverage and attainable destinations. Controlling for spatial autocorrelation and other potentially important factors for property values, an additional surplus in value was discovered in high-income neighborhoods.

Similar conclusions were drawn from the evaluation of the effects of light rail transit (LRT) in Buffalo (New York), where transport improvements were introduced as part of a wider revitalization strategy for central areas. Hess and Almeida (2007) used hedonic regression models to assess variations in residential property prices in buffers of approximately 800 m around LRT stations. Two types of distance measurements were considered: network distance and straight-line distance. Residential property values were found to increase by \$0.99 every 30 m closer to the station using network distance and \$2.31 using straight-line distance, so straight-line distance was considered to be a more important factor, yet the increase in price was regarded as modest. Generally, the authors noted that a price premium was observed only in areas where access to LRT was highly valued and mostly in high-income areas located on the periphery, whereas in depressed central neighborhoods the effect of proximity to a station was limited, leading the authors to conclude that the introduction of LRT alone could hardly revitalize deprived areas.

Further exploring factors affecting property values in the vicinity of station areas, Duncan (2011a) compared condominium prices in neighborhoods with similar pedestrian amenities inside and outside of stations' catchment areas in San Diego. The author distinguished between TOD and TAD, focusing thus on the importance of neighborhood layout and pedestrian environment. It was observed that prices decreased significantly as distance to the station increased for areas with good pedestrian environment, suggesting that residents of these neighborhoods highly value proximity to transit. The price premium could reach around 11% in poor pedestrian environments near stations and more than 15% in pedestrian-friendly environments. Attempting to further evaluate station-generated price premiums, Duncan (2011b) studied their magnitude based on allowable density levels. Controlling for the bidirectional influence between zoning and property prices, it was revealed that despite higher allowable densities are negatively associated with home values, this does not apply to station areas: limiting densities in station areas is unlikely to augment prices; on the contrary, property prices in station areas with permissive zoning tend to be higher. Yet, the cross-sectional model used in both studies did not allow to understand the causal influence of the rail system.

Addressing this challenge, Mathur and Ferrell (2013) analyzed the Ohlone-Chenyoweth area in San Jose using longitudinal data for three time periods (before, during and after TOD construction), comparing the same station area under different conditions. Hedonic regression models showed that, in the pre-TOD period and during TOD construction, distance to a station was statistically insignificant for house prices, however, after TOD was implemented, it became relevant, with a 50% decrease in the distance being associated to a price premium of 3.2% within 1.6 km from a station. After TOD construction, house prices within approximately 200 m from the station increased by 11.2%.

As increases in TOD housing prices are frequently reported, concerns arise that they may repel low-income groups (potentially more prone to transit use than high-income residents) to settle in TOD areas. In this regard, Renne et al. (2016) analyzed housing expenditures together with transport expenditures in order to understand whether higher housing costs in TOD areas are compensated by transport savings. TOD areas were defined as station areas with a walk score of at least 70 (meaning that most amenities can be reached on foot) and a minimum density of 8 housing units per acre [AN: 4047 square meters]. Stations that met only one of these criteria were regarded as hybrids, and stations not meeting any criteria were qualified as TAD areas. It was found that home values and rental prices in TOD used to be and were still higher than in hybrids and TAD areas (in the years 1996–2015) and that the disparity in price was increasing; in particular, rental prices in TOD areas registered a record increase of 45% in 2010–2015. At the same time, mean household income in TOD areas was lower than in TAD areas and the proportion of renters was higher (72% against 63% in hybrids and 45% in TAD areas). However, transport costs in TOD areas were the lowest (approximately 14% of income, compared to 17% in hybrids and 19% in TAD areas). Since TOD residents spent around 29% of income in housing (against 27% in hybrids and 28% in TADs), in sum they might end up paying less, yet these figures were taken from a database for the years 2008–2012, and thus might not reflect market conditions that have rapidly changed after 2012. Still, this work is worth mentioning for introducing the idea of evaluating property prices in TOD areas together with the potential reduction of transport expenditures.

In contrast to the majority of studies which addressed housing prices, Yu et al. (2018) evaluated price changes of commercial properties for the newly introduced rail and BRT systems in Austin. Controlling for spillover effects, the general impact of transit proximity on commercial properties was found to be modest, except around TOD stations where the synergistic effect of TOD produced additional price premiums of $9/ft^2 within 400 m from a station, $8.3/ft^2 within 400–800 m, and $5.6/ft^2 for properties within 800–1200 m [AN: 1ft^2 = 0.09 m^2]. Similar results were reported by Xu et al. (2016) for the city of Wuhan in China, where price premium for commercial properties located within 100–400 m from a station was approximately 8% and 16.76% inside a 100-m buffer from a station.

Overall, evidence from other locations also shows that, in general, proximity to TOD leads to the increase in home prices and that the real-estate market switches towards pedestrian-friendly developments preferably served by transit (Bartholomew and Ewing, 2011).

4.3. Residential location effects

The attachment of TOD residents to their transport habits raises the discussion about the role of self-selection in observed mode choices, as one can doubt whether frequently reported higher levels of transit use in station areas are actually the result of TOD (causal relationship) or they simply reflect people's preference to reside in locations where they can continue to have the same travel behavior. This issue has been addressed in numerous studies, yet many do not distinguish between different station areas (TOD or non-TOD). In this section, we first review generic studies and then focus on a few articles concentrating specifically on TOD (Table 3).

Attempting to capture the impact of the built environment on travel behavior after accounting for self-selection effects, Mokhtarian and Cao (2008) and Cao et al. (2009) performed extensive analyses of, respectively, methodological issues and empirical evidence on the subject, concluding that the built environment does have an influence on travel choices even after controlling for those effects. However, the extent of this influence and the exact weight of specific components of the built environment are hard to assess as they may vary depending on the trip purpose, population segments and other factors sometimes omitted in the studies (like the location of a neighborhood inside a city or region). Using survey data, Kamruzzaman et al. (2015) analyzed the main neighborhood features that influence residential location, highlighting “accessibility and mobility of places”, “natural environment”, “child-centric facilities” and “ease of commuting” as determinant factors, yet without specifying the reasons to live in a TOD area.

Focusing specifically on TOD, Lund (2006) performed a stated preference survey aiming to analyze the residential location choices of TOD residents who changed their domicile in the last five years. As major reasons for their relocation, respondents mentioned “type or quality of housing (reported by 61%); the cost of housing (reported by 54%); and quality of neighborhood (reported by 52%)”. However, the significance of these factors varies across socioeconomic groups; for example, the cost is primarily important for low-income residents, followed by “access to shops and services”, since car availability in this population group might be limited and therefore proximity to commercial and service establishments is valued. The idea that cost is a fundamental factor for low-income groups was further explored by Olaru et al. (2011), who observed that, since prices tend to be higher near transit stations, the population in those groups is more likely to settle in areas further away from a station. Lund (2006) adds that these location choices might also be explained by the fact that industrial sites for low-paid jobs are likely to be easier to reach by bus or car, while station areas might be more attractive for medium or high-income residents since CBD and office employment centers are generally easily accessible by rail. High-income households and larger households were found to value mixed uses and “proximity to everything”, and generally were more willing to pay for these neighborhood characteristics (Olaru et al., 2011). However, neither of the

Table 3
Selected articles on the effects of TOD on residential location.

Reference	Methodology	Case study
Lund (2006)	Discrete choice modeling (binary logit)	San Francisco, Los Angeles, San Diego (USA)
Cervero (2007)	Discrete choice modeling (nested logit)	California (USA)
Mokhtarian and Cao (2008)	Literature review	n/a
Cao et al. (2009)	Literature review	n/a
Bohte et al. (2009)	Literature review	n/a
Olaru et al. (2011)	Descriptive statistics - comparative analysis/discrete choice modeling (latent class and hybrid choice)	Perth (Australia)
Cao and Cao (2014)	Comparative analysis/discrete choice modeling (ordered logit)	Minneapolis - St. Paul (USA)
Kamruzzaman et al. (2015)	Comparative analysis/discrete choice modeling (binary logit)	Brisbane (Australia)

studies mentions access to transit among the top-three reasons for location decision. In Los Angeles, surveyed residents preferred living in TOD for highway proximity rather than for transit availability (21.2% against 19.3%), while respondents in San Diego rated both amenities almost equally (Lund, 2006). The survey by Olaru et al. (2011) was conducted slightly before the opening of a rail line, so probably self-selection had not fully manifested yet. In short, it appears that TOD may be responding to the needs of households with different income levels (for example, quick access to CBD for more affluent groups and proximity to shops and services for low-income residents) and that TOD features are important yet to a different degree for different population groups.

Similarly, Cervero (2007), evaluating the influence of self-selection using a nested logit model for a sample of random households selected in the suburbs of San Francisco, noted that people working within a mile from a station are likely to live in proximity to transit, however, families with children tend to opt for other locations. Only 19.6% of residents living within half-mile from a station commuted by transit with this rate falling down to 8.6% beyond this limit. According to the author's estimations, around 40% of the transit ridership bonus observed in station areas may be explained by self-selection.

The weight of self-selection in residential location choices remains an object of investigation, yet most academics agree that, in any case, it is important to provide people with the possibility of living close to public transport as long as there is a demand for this amenity in order to support users' loyalty to sustainable transport modes. Otherwise, as Bohte et al. (2009) and Cao and Cao (2014) underline in their studies, neighborhoods without proper transit or pedestrian/cycling infrastructure may not only "self-select" residents with car-friendly profile but would even deepen their attachment to cars.

4.4. Urban form effects

Inverting the logic of some studies aiming to understand how land-use characteristics affect TOD in terms of trip generation and modal split, several articles have analyzed how stations affect adjacent land use and overall urban patterns (Table 4). Indeed, "the changing cityscape should help define transport investment, and transport investment should help to define urban form" (Hickman and Hall, 2008).

A work by Ratner and Goetz (2013) provides a detailed descriptive analysis of land-use changes in Denver as the city were intentionally pursuing a TOD policy by changing zoning regulations and allowing for densification and mixed uses in station areas. Considering the station typology elaborated by the city council, the authors detected a significant increase in TOD projects, both residential and non-residential, along the Central Corridor light-rail line (50% of new office spaces and 46% of new residential developments). Specifically, changes occurred around six stations in the city center, where 89% of government institutions, 62% of office buildings and 61% of cultural venues were located, accumulating 90% of all "office TODs". Thus, the public transport system is now playing a relevant role as a principal attraction of new developments able to change the urban city form and potentially reduce car use once supported by planning authorities.

Promoted by the city council of Copenhagen, a major TOD was introduced in Ørestad, at the fringe of the city. As described by Knowles (2012), this development, initially planned for a variety of uses (residential, office, educational facilities) around a light-rail line with scarce and expensive parking, eventually became an alternative to over pressured CBD, also because of specific planning permissions (notably, approval of an out of town commercial center). Besides, its advantageous location allowing fast connection to Malmö (Sweden) helped to increase the competitiveness of the site and its catchment area. Though being a single site-specific study, this work analyzes TOD as a strategy for sustainable urban growth.

Somewhat contrasting results were reported in a quantitative study by Papa et al. (2008) presenting an analysis of economic and spatial changes around rail stations in the period of 1991–2004 in Naples (Italy). An overall decrease in population density along the metro line was reported, together with a significant increase in property values. These trends were particularly strong in central areas and around stations with high levels of network connectivity. At the same time, a population increase in suburban areas generally followed a new public transport line, suggesting that population spread might be arranged along a transport corridor. However, it is unclear whether local authorities actually promoted any TOD policy or the changes occurred naturally.

In Beijing, the effects of metro on land development also appear controversial (Zhao et al., 2018). Despite land parcels located within 3 km from a station were quite actively seeded for urban development, densification and functional mix were not completely achieved. In the central area, the floor area ratio (FAR) for commercial and residential uses increased, yet in the suburban area an

Table 4
Selected articles on the effects of TOD on urban form.

Reference	Methodology	Case study
Hickman and Hall (2008)	Descriptive statistics	London (UK)
Papa et al. (2008)	Descriptive statistics/spatial analysis	Naples (Italy)
Knowles (2012)	Descriptive statistics/descriptive analysis	Copenhagen (Denmark)
Ratner and Goetz (2013)	Descriptive statistics	Denver (USA)
Papa and Bertolini (2015)	Descriptive statistics - comparative analysis/ spatial analysis	Amsterdam (Netherlands), Helsinki (Finland), Munich (Germany), Naples (Italy), Rome (Italy), Zurich (Switzerland)
Dong (2016)	Descriptive statistics/2SLS regression model (Hausman-Taylor)	Portland (USA)
Loo et al. (2017)	Descriptive statistics	Hong Kong (China)
Zhao et al. (2018)	Descriptive statistics/OLS regression model	Beijing (China)

increase in industrial uses was registered. Besides, high FAR was positively associated with proximity to a highway instead of metro. The authors explain such discrepancies by specific local planning conditions and poor dialogue between involved authorities.

Focusing on the Portland metropolitan area, Dong (2016) examined changes in land-use associated with metro stations. In a buffer of approximately 400 m from a station, proportional change of net residential density and change in the number of dwellings was evaluated in the years 2004 and 2014, differentiating between the stations opened before 2004 (mature stations) and newly opened stations. It was observed that a 7% increase in the housing stock registered in 2004–2014 was concentrated around mature stations and that 95% of this increase came from multifamily homes. Using a regression model, the author concluded that a 10% rise in ridership was correlated with 11.8% more dwellings every two years. Vacant land availability also appeared to be considerably significant and each acre was linked to approximately 4.4 more dwellings every two years. Generally, as zoning limitations were reducing the land available for development in the outer-city areas, development initiatives were channeled to already urbanized areas, including station areas, representing opportunities for urban infill. However, in some cases, insufficient supply of undeveloped land in these areas has obstructed those initiatives.

The use of TOD in the context of urban infill was further examined by Loo et al. (2017), who evaluated its implementation on greenfield and infill sites over a 10-year period in Hong Kong. Socioeconomic data used in the analysis showed that greenfield developments, which appeared on formerly non-urbanized lands, naturally experienced greater population and employment growth compared to infill developments, still, values of population or employment density on the infill sites were greater. All station areas demonstrated large growth in residential use. In terms of mobility, residents of greenfield developments used transit more than residents of infill sites, yet, in turn, the latter showed higher rates of walking trips, which may be explained by the lack of attractive sites at a walking distance in recent developments. This study is particularly interesting in a context where TOD is seen as a way to address and manage population growth and as part of an urban renewal strategy, a subject relatively unexplored in the literature.

Attempting to move away from site-specific limitations, Papa and Bertolini (2015) chose to analyze TOD impacts on accessibility ("the number of jobs and inhabitants that can be reached by rail as a percentage of the total jobs and inhabitants in the study area") in six European metropolitan areas in a cross-comparative study. Amsterdam, Helsinki, Munich, Naples, Rome and Zurich, with a population of 1 to 4 million people, were selected due to the great variety of land uses and transport infrastructure present in these cities. In all cases, the study area was a 30-km buffer drawn around the rail station with the highest connectivity level. All stations in the study area were subsequently evaluated using the "node-place" index to estimate the level of TOD. Three main urban patterns were observed: "strong core structure" in Munich and Rome, "fully networked city-region" in Amsterdam, Zurich and Naples, and "corridor structure" in Helsinki. It was found out that TOD level is associated with cumulative rail accessibility which is higher when density and mixed-use levels correspond to the hierarchical level of a station (i.e., when density and mixed-use levels are higher in sites well-served by rail). As concluded by the authors, balancing the two components of TOD (by densifying land-use in rail-served areas or by improving transit supply in high-density areas) may significantly improve the accessibility conditions offered by a metropolitan area.

4.5. Community life effects

Apart from sustainable mobility patterns and dense built environment, generating a vibrant and lively community is also frequently mentioned in the TOD context, mostly as a consequence of TOD implementation. As stated by Currie and Stanley (2008), a variety of land-uses in TOD can "address problems associated with social exclusion and SC through creating proximate opportunities for access to activities and social networks" [AN: SC denotes social capital]. It is believed that TOD features provide favorable conditions for vivid street life, hence neighborhood community links should naturally follow. Despite research on this topic is still limited, there are a few works addressing it (Table 5).

One of these works was carried out by Kamruzzaman et al. (2014), who investigated the levels of social capital in station areas in Brisbane (Australia), comparing TOD, TAD and conventional suburbs. Even though strong influence of self-selection was observed, it

Table 5
Selected articles on the effects of TOD on community life.

Reference	Methodology	Case study
Kahn (2007)	Comparative analysis/longitudinal analysis/ binomial regression model (linear probability)	Los Angeles, Sacramento, San Diego, San Francisco, San Jose, Denver, Washington, Miami, Atlanta, Chicago, Baltimore, Boston, Portland, Dallas (USA)
Currie and Stanley (2008)	Literature review	n/a
Kamruzzaman et al. (2014)	Cluster analysis/simultaneous equation model	Brisbane (Australia)

was still possible to find that TOD residents had stronger social links amongst themselves than TAD residents. However, it is important to note that independent variables (density, land use mix, PTAL) evaluated separately affected negatively social capital, meaning that improving only one variable may have adverse impacts on the community, as observed, for example, in highly dense areas where levels of social capital were frequently low.

A different perspective into the theme was brought by Kahn (2007), who concentrated on gentrification trends in TOD areas. Since TOD is likely to provoke a price increase in adjacent properties, there is some concern that low-income residents will be forced to leave an area, ceding it to well-off population groups. Potentially this shift may produce reverse effects on TOD efficiency in terms of transit use as high-income groups are frequently reported to have higher car ownership levels and drive more, so it is questionable whether they will use transit. In order to achieve more accurate results, the author differentiated between "park & ride" stations and "walk & ride" stations. The analysis of community dynamics in terms of property values and percentage of college graduates over a 30-year period in 14 cities of the United States revealed uneven gentrification patterns, since gentrification happened in some cities, for example in Washington D.C. and Boston, particularly around "walk & ride" stations, while it did not manifest in others (e.g., in Portland and Los Angeles). As the article focused only on population and real estate, it did not consider changes in commerce and services (like possible openings of new trendy shops). Interestingly, in most cities, "park & ride" station areas typically witnessed a decrease in the income level of residents.

5. TOD planning

A thorough understanding of effects is certainly critical for the planning of TOD initiatives, but there is a number of other important issues that need to be taken into account. We specifically address them here distinguishing between planning policy issues and planning tool issues.

5.1. Planning policy

Articles that consider TOD in the planning policy context generally address four main topics: policy transferability; expectations and interests of stakeholders (planning authorities, transit agencies and developers); implementation problems and solutions; and value capture mechanisms (Table 6).

Table 6
Selected articles on TOD planning policy.

Reference	Methodology	Case study
Atkinson-Palombo and Kuby (2011)	Cluster analysis/factor analysis	Phoenix (USA)
Cervero and Dai (2014)	Questionnaire analysis/descriptive statistics	Bogota (Colombia), Ahmedabad (India)
Cervero and Murakami (2009)	Cluster analysis/OLS regression model	Hong Kong (China)
Dittmar et al. (2004)	Conceptual and policy discussion	n/a
Dumbaugh (2004)	Policy discussion	Atlanta (USA)
Guthrie and Fan (2016)	Interview analysis	Minneapolis - St. Paul (USA)
Hale (2014)	Conceptual discussion	n/a
Levine and Inam (2004)	Survey analysis	USA
Lierop et al. (2017)	Interview analysis	USA, Canada, Netherlands
McIntosh et al. (2014)	Financial analysis/panel data hedonic price model	Perth (Australia)
McIntosh et al. (2017)	Policy discussion/panel data hedonic price model	Perth (Australia)
Mu and de Jong (2016)	Interview analysis	Urumqi (China)
Noland et al. (2017)	Interview analysis/focus groups	New Jersey (USA)
Pojani and Stead (2014)	Policy discussion	Amsterdam (Netherlands), Stockholm (Sweden), Vienna (Austria)
Searle et al. (2014)	Survey/interview analysis	Brisbane, Melbourne, Sydney (Australia)
Staricco and Vitale Brovarone (2018)	Policy discussion	Stedenbaan (Netherlands), Bologna (Italy)
Tan et al. (2014a)	Policy discussion/interview analysis	Perth (Australia), Portland (USA), Vancouver (Canada)
Tan et al. (2014b)	Interview analysis/focus groups	Netherlands
Thomas and Bertolini (2017)	Policy discussion (meta-analysis)	Tokyo (Japan), Perth (Australia), Melbourne (Australia), Montreal (Canada), Vancouver (Canada), Toronto (Canada), Naples (Italy), Copenhagen (Denmark), Amsterdam-Utrecht, Rotterdam-Den Haag, and Arnhem-Nijmegen (Netherlands)
Thomas et al. (2018)	Policy discussion	Netherlands
Yang et al. (2016)	Spatial analysis/longitudinal analysis/hedonic price analysis	Shenzhen (China)

5.1.1. Policy transferability

Since the concept of TOD has gained international attention and has been applied in diverse national settings, the issue of transferability is inevitably raised. As shown in the previous sections, in the absence of a formal and widely accepted TOD definition, developments with quite different characteristics end up being considered TOD, complicating the perception of the concept and the evaluation of the outcomes of TOD implementation. Overall, most researchers recognize that there is a need to standardize and systematize existing knowledge about TOD in order to make the concept more understandable for the general public and to facilitate TOD implementation by local planners: "without standards and systems, successful TOD is the result of clever exceptionalism and beyond the reach of most communities or developers" (Dittmar et al., 2004).

Attempting to provide more precise bounds for TOD, Hale (2014) suggests the adoption of a clear benchmark for these developments: sustainable transport modes have to account for at least 50% of the modal split in the station area, as sustainable modes have to be dominant in a TOD; otherwise, they should be classified as TAD. This radical measure is proposed by the author since it is expected to capture other elements of a successful TOD: if the majority of the population chooses walking, cycling or public transport, it is quite likely that an area itself corresponds to TOD standards in terms of built environment, meaning that there is not so much traffic or congestion, and streets are walking- and cycling-friendly. Such a criterion would significantly reduce the number of sites that can be classified as TOD, yet according to the author, this may be advantageous. The reason is that this would place the focus exclusively on "real" TOD and learn from them, eventually facilitating policy transferability. A possible shortcoming of such TOD differentiation is that it ignores the origin-destination pair. It is crucial to ensure that destinations can, in fact, be reached by sustainable modes. Otherwise, there is a risk to underestimate site's performance because of exogenous factors that are out of planners' control. For example, a person may live in a TOD but may be forced to go to work by car since the workplace location is not served by transit. In this case, car commute can hardly be considered a development's failure. A similar issue arises if travel cost by transit is higher than by car. Therefore, it is uncertain whether such simple forms of distinction can actually work well for the concept of TOD.

The issue of policy transferability was also addressed in a work by Thomas and Bertolini (2017) who tried to define TOD success factors that altogether increase the chances of successful implementation in different national settings. The most important prerequisites were found to be "political stability, regional land use-transportation body, relationships between actors in the region, public participation, interdisciplinary implementation teams, and certainty for developers". Even though these desirable conditions might favor TOD planning and international examples of successful TOD might inspire local authorities, developing a site-specific approach to TOD is crucial to account for specific national contexts, local planning practices, built environment and cultural distinctions (Thomas et al., 2018; Staricco and Vitale Brovarone, 2018; Lierop et al., 2017).

5.1.2. Stakeholders' expectations and interests

It is generally understood that TOD implies walkable, pedestrian-friendly neighborhoods with a variety of uses well-served by public transport, yet the problem is to define desirable thresholds for these elements accounting for the specific characteristics of a particular location. In practice, the definition of these thresholds results from the interaction of different stakeholders (notably, planning authorities, transit agencies, and developers), so it is important to analyze their interests and expectations from TOD projects. Overall, involved stakeholders show interest in the TOD concept and acknowledge the potential benefits it may bring, so on a surface TOD seems like a win–win strategy, yet detailed analysis reveals somewhat conflicting interests.

In fact, on the one hand, planners consider TOD as a means to accommodate and concentrate urban growth (especially important for developing countries) and to achieve greater competitiveness of an urban area, both through improved accessibility and mixed uses (Cervero and Dai, 2014; Pojani and Stead, 2014). On the other hand, developers see TOD as a way to satisfy market demand for compact and walkable developments: as stated by developers in the USA, at least 10% of households in the country are interested in such offer, and the number is greater in more urbanized regions (Levine and Inam, 2004). Developers regard transit access as an advantage, understanding that, all else equal, sale prices in areas with public transport are higher, and highly rate walkability, especially for residential developments (Guthrie and Fan, 2016).

Though both parties are favorable to TOD, a conflict of interest may arise when developers suggest higher densities: reductions in density represented 80% of all modifications introduced by planning authorities to developers' transit-oriented or pedestrian-oriented proposals in the USA (Levine and Inam, 2004). As developers see the potential for TOD in inner suburbs (Levine and Inam, 2004) where land may be quite expensive, increase in density allows to compensate for these expenses at the same time providing more potential customers for transit agencies. However, inner suburbs may have long-established communities, which probably settled there in times when the area was still on the fringe of a city, thus local residents are likely to value a low-density conventional suburb and oppose to densification plans. Consecutively, local authorities may be constrained by NIMBYism, by the negative perception of station areas/public transport by local residents, by the dominant car culture and by residents' opposition to parking limitations (Tan et al., 2014). Realizing potential reputational losses, local authorities may accept densification plans if essential improvements to an area come along, like mixed uses, green areas or walking-friendly design. This explains the interest shown by planners in learning more about mixed uses and means to achieve regular 24-hour use of a station area, together with means to disseminate knowledge about TOD among the general public in order to minimize potential opposition from residents (Pojani and Stead, 2014). However, for developers, providing green areas/walking-friendly environments and mixed uses increases project costs as well as the risks associated with the uncertain demand for commercial properties in non-central areas.

In these circumstances, a more flexible approach to TOD planning needs to be used to reconcile the interests of involved stakeholders and negotiate trade-offs (Guthrie and Fan, 2016). In order to achieve TOD developments in practice, specific planning regulations might be needed, as well as financial incentives to alleviate station area land costs.

5.1.3. Implementation problems and solutions

Despite TOD projects originate from different national contexts, the problems faced by their implementation are quite similar worldwide. They include, for instance, high initial investment costs, land assembly, lack of cooperation or integration between involved stakeholders, etc. Responses to these common problems vary depending on national legal and tax systems. However, these systems are relatively flexible and TOD implementation is often facilitated by specific regulations. In Tables 7–9, we aim to systematize existing findings, highlighting the problems identified by the three major stakeholders (planning authorities, transit agencies and developers) and the solutions proposed to overcome them, ordered by the frequency of occurrence.

Table 7
Implementation problems and solutions – perspective of planning authorities.

Planning authorities	
Problem	Solution
Lack of institutional coordination (Cervero and Dai, 2014; Pojani and Stead, 2014; Staricco and Vitale Brovarone, 2018; Tan et al., 2014)	- Integration of land use and transport authorities (Staricco and Vitale Brovarone, 2018; Tan et al., 2014; Thomas and Bertolini, 2017); - Establishment of a regional land-use transportation body (Thomas and Bertolini, 2017); - Staff rotation between institutions (Tan et al., 2014); - Introduction of a "cross-portfolio coordinating committee" (Mu and de Jong, 2016);
Potential lack of affordable housing (Guthrie and Fan, 2016; Lierop et al., 2017; Noland et al., 2017; Tan et al., 2014)	- Increase in permitted densities ("density bonuses") (Guthrie and Fan, 2016; Thomas and Bertolini, 2017); - - Introduction of public facilities and services in proximity to minimize residents' expenditures (Guthrie and Fan, 2016);
Lack of dedicated funding (Cervero and Dai, 2014; Searle et al., 2014;)	- Introduction of tax increment financing (McIntosh et al., 2014; McIntosh et al., 2017; Thomas et al., 2018); - Allocation of capital funds for TOD, including specific TOD plans (Cervero and Dai, 2014); - Revenue from land development (Yang et al., 2016); - introduction of "provincial tax on gasoline" (Thomas and Bertolini, 2017); - Temporary increase in local taxes (Tan et al., 2014); - Introduction of a fee for increase in permissible densities to be collected from developers (Tan et al., 2014); - Organization of a "public–private funding mechanism" (Staricco and Vitale Brovarone, 2018);
Lack of governance continuity (Tan et al., 2014)	- Elaboration of regional strategic plans and policy (Lierop et al., 2017; Pojani and Stead, 2014; Staricco and Vitale Brovarone, 2018); - institutionalizing metro at a regional level (Tan et al., 2014)
Negative perception of station areas/public transport by local residents; car culture (Tan et al., 2014)	- Promotion of public transport/community engagement (Tan et al., 2014); - Community engagement (Tan et al., 2014); - Incorporation of public facilities (parks, schools) in the plan (Tan et al., 2014); - Introduction of business improvement districts (Thomas et al., 2018); - Overlay zoning (Atkinson-Palombo and Kuby, 2011); - Introduction of short-term office spaces for rent (Lierop et al., 2017); - Development of an identity for a TOD (Lierop et al., 2017)

Table 8
Implementation problems and solutions – perspective of transit agencies.

Transit agencies	
Problem	Solution
Significant expenditure needed for new/improved transport service (Cervero and Murakami, 2009; Yang et al., 2016)	- Rail and Property mechanism (Cervero and Murakami, 2009; Yang et al., 2016); - Lease of grounds belonging to the transport company (Dumbaugh, 2004) - Exemption from federal repayment obligations is granted to development project that increase ridership levels in the USA (Dumbaugh, 2004);
Uncertain ridership levels in newly developed areas or areas under development (Lierop et al., 2017; Yang et al., 2016)	- Introduction of an overlay zoning (Atkinson-Palombo and Kuby, 2011);
High right-of-way costs in already developed areas (Yang et al., 2016)	- Greenfield development (Yang et al., 2016) - Development of non-residential sites that are usually cheaper (Searle et al., 2014);

Table 9
Implementation problems and solutions – perspective of developers.

Developers	
Problem	**Solution**
Scarce or fragmented land availability in an inner city or already urbanized areas (Guthrie and Fan, 2016; Levine and Inam, 2004; Pojani and Stead, 2014; Searle et al., 2014; Tan et al., 2014; Thomas et al., 2018)	- Readjustment of urban land (Thomas et al., 2018); - Authorization to develop formerly undevelopable lands (acquired during the infrastructure construction) belonging to transport company (Dumbaugh, 2004);
Unclear procedures of interaction with other involved actors (namely, local authorities) and lack of assumed project leader (Noland et al., 2017; Searle et al., 2014; Staricco and Vitale Brovarone, 2018; Tan et al., 2014)	- Appointment or selection of a particular actor as an assumed leader (Searle et al., 2014; Staricco and Vitale Brovarone, 2018)
Obligation to fulfill local regulations like minimum parking requirements impedes to create walkable neighborhoods (Guthrie and Fan, 2016; Levine and Inam, 2004)	- Adoption of a collaborative model of planning, adjustments to existing guidelines (Guthrie and Fan, 2016); - Preparation of specific station area plans (Searle et al., 2014)
High land price in inner city or already urbanized areas coupled with strict building regulations (Guthrie and Fan, 2016; Levine and Inam, 2004)	- Increase in permitted densities (Guthrie and Fan, 2016; Thomas and Bertolini, 2017)
High costs of initial investment and long period of project's maturity (Searle et al., 2014, Tan et al., 2014)	- Initial investment in public amenities like sewage assumed by land owner (Dumbaugh, 2004) or local authorities (Mu and de Jong, 2016)
Risk that long-term infrastructure project will be revised/cancelled (Guthrie and Fan, 2016; Noland et al., 2017)	n/a

5.1.4. Value capture mechanisms

Naturally, the feasibility of TOD projects is compromised by high costs of initial investment. These expenses can be partially addressed by various value capture mechanisms: planning authorities and transit agencies can achieve profits from leasing publicly-owned land to private investors for development (Cervero and Murakami, 2009; Dumbaugh, 2004; Yang et al., 2016), by increasing floor-area ratios (Guthrie and Fan, 2016; McIntosh et al., 2017), renting office and commerce spaces near stations and/or collecting capital gain taxes associated with property value increases (McIntosh et al., 2014, 2017). While generally these practices help to raise funds for TOD, evidences on their performance are quite varied.

Value capture has been successfully implemented in Hong Kong through the Rail and Property (R + P) mechanism that allowed taking advantage of the price premium generated by station proximity (Cervero and Murakami, 2009). In simple terms, the local transit company acquired development rights from the government before a rail line was built and subsequently resold them to developers for the price of rail-served parcels, thus raising funds for subsequent infrastructure improvements. R + P TOD stations resulted in a significant price premium (up to 34.2%). However, this is a very specific example of a dense and spatially confined metropole. In Shenzhen, a similar mechanism did not completely fulfill the expectations. Indeed, some metro lines developed outside densely populated areas did not attract developments (and passengers), thus generating large operational deficits (Yang et al., 2016). In Atlanta, the transit agency leased land adjacent to a station for development and assumed expenses for basic needs like sewage. Financial analysis estimated this station project would generate $ 156 million of net revenue in a 30-year period. However, as argued by Dumbaugh (2004), if the amount spent on this project was saved, the transit agency could have doubled its profit. Besides, project's risk was high: as ticket sales were moderate, project revenues had to be used to cover the operating deficits in the first years. Probably, a combination of different value capture mechanisms could improve the situation: analyzing developments along a recently introduced rail line in Perth, McIntosh et al. (2017) estimated a 30% increase in tax returns from 400-meter station buffer, compared to a no-line scenario. Intensification of land uses inside the buffers along the line could account for 132% of the line construction cost, and, as stated by the author: "the estimated revenue that could have been raised suggests it would have been enough for the construction and even part of the ongoing operations of the line if the project had been developed using a value capture framework."

5.2. Planning tools

Our focus in this section is on tools (systems or models) specifically developed to support TOD decision processes whose application automatically provides clear indications on the most suitable decisions to make (Table 10). Approaches that just classify TOD

Table 10
Selected articles on TOD planning tools.

Reference	Methodology	Case study
Banai (1998)	Multicriteria decision analysis/AHP	Memphis (USA)
Banai (2005)	Multicriteria decision analysis/AHP	Piperton (USA)
Lin and Gau (2006)	Multi-objective optimization	Taipei (Taiwan)
Lin and Li (2008)	Multi-objective optimization /Grey TOPSIS method	Taipei (Taiwan)
Strong et al. (2017)	Multicriteria decision analysis/AHP	Denver (USA)
Ma et al. (2018)	Multi-objective optimization/Genetic algorithm	Beijing (China)
Sahu (2018)	Multi-objective optimization/Genetic algorithm	Naya Raipur (India)

areas, as the node-place approach and others mentioned in Section 3, are therefore not covered here (despite their possible usefulness in such processes).

Two main research directions have been explored up to now with respect to TOD planning tools: multicriteria decision analysis (MCDA) and multi-objective optimization. MCDA is used to rank alternative decisions (or strategies, or courses of action) according to several predefined criteria (or success factors) and decision-maker preferences (possibly expressed by criterion weights). Multi-objective optimization is used to determine efficient solutions (i.e., decision variable values) considering a set of objectives while complying with a set of constraints, with both objectives and constraints expressed as functions of the decision variables. The outcome of their application is a Pareto front composed by the solutions that cannot be improved with respect to one of the objectives without being worsened with respect to at least one of the others (called non-dominated solutions). Finding the whole Pareto front is a complex task when the number of objectives is large (say, greater than three). The application of weights to the objectives converts multi-objective optimization into single-objective optimization problems, which are easier to tackle particularly when the functions representing the objectives and the constraints are linear and the decision variables are continuous. Nevertheless, it introduces the challenge of setting up the objective weights.

Probably, Banai (1998) is the first author to have proposed an MCDA tool to be used for TOD planning purposes. More precisely, the tool (procedure) was aimed to “assess the suitability of land use around proposed light rail transit stations of a metropolitan area” by applying the Analytic Hierarchic Process (AHP) method in conjunction with a geographic information system. Four criteria were considered: mix of land uses; density; road network (street pattern); and proximity to a transit station. The application of the proposed tool was exemplified for Memphis. Possible tool improvements to convert it into a decision support system were discussed by the same author in Banai (2005), this time using the example of a “land development concept plan” for a small city in the United States (Piperton, Tennessee).

Amongst the few other articles that also propose MCDA tools for TOD planning, we highlight Strong et al. (2017). The authors of this article recognized the “abundance of literature on TOD”, but their literature review noticed the lack of studies addressing the question of “how can a transit agency choose between alternative TOD sites to develop or build?”. In response to this question, they developed a decision support tool (framework) for making such choices “incorporating and assessing unique success factors and their weights”. Also, in this case, the AHP method was used but considering a very large set of criteria (18). In an application to Denver, and considering the opinion of experts, the most important ones were found to be “the quality and length of walking route to station”, the “number of mixed-use structures” and “the planned mixed-income housing”, whereas “parking supplies on site”, “existing or planned convenience or service retail store” and “existing or planned cultural or entertainment centers” were classified as the least important.

On the multi-objective optimization side, the first model explicitly aimed at assisting decision-makers in TOD planning has been presented by Lin and Gau (2006). These authors developed a linear continuous model considering three objectives: maximizing subway system ridership; maximizing living-environment quality; and optimizing the social equity of land development. The decision variables were the floor-space ratios for different land uses in subway station areas. The constraints included in the model accounted for restrictions on land use density, land use combinations, and level of service facilities. The application of the model was illustrated for the area surrounding the Chunghsiao-Fuhsing subway station in Taipei. The model was solved using the ε-constraints method and, presumably, off-the-shelf optimization software (the article is not clear in this regard).

Another article with the same first author, Lin and Li (2008), was published a couple of years later, also proposing an optimization model and involving a case study in Taipei. However, it differed from the previous one in several important respects. This time, the model was to be applied at the city-region level, and its decision variables represented the allocation of space to residential, employment and recreational activities, being of the mixed-integer linear-type (some decision variables were Boolean). Four objectives were considered: maximize environmental quality (i.e., minimize pollution treatment costs); maximize land-use variety; maximize the number of subway passengers; and maximize accessibility to non-residential activities. For handling the presence of uncertainty and the flexibility needed in practical planning, the inputs and outputs of the model could be grey numbers (ranges of possible values). The Grey TOPSIS method was used to solve the model.

Quite recently, two new multi-objective optimization models for TOD planning were proposed, respectively by Sahu (2018) and Ma et al. (2018), the former to decide the types and densities of land uses along a transport corridor and the latter around a transit station. The application of the models was illustrated for Naya Raipur (India) and Beijing, respectively. The objectives considered by Sahu (2018) were: maximize TOD characteristics (density of population and employment and diversity of land uses); shaping the skyline; minimize land use change; and making land uses compact. Ma et al. (2018) focused on the following objectives: maximize rail transit ridership; maximize land-use compactness (number of neighboring cells with the same land use); maximize accessibility (i.e. minimize “travel time around transit stations”) taking into account congestion effects; minimize conflicts between the land uses of adjacent cells; and minimize environmental effects (measured by pollution treatment costs). In both cases, some objectives were expressed by nonlinear functions of (some) decision variables, thus making the models mixed-integer and nonlinear, and therefore very difficult (if not impossible) to tackle through exact optimization methods. Instead, both authors have resorted to genetic algorithm heuristics. However, there is an important difference in the methods they have applied, because Sahu (2018) applied weights to the objectives, thus converting the multi-objective model into a single-objective model, whereas Ma et al. (2018) truly tackled the multi-objective model, concentrating on the construction of the Pareto front and on the analysis of some non-dominated solutions.

Overall, it can be said that significant progress has been made toward the development of decision-support tools specifically designed to be used within TOD planning processes. The essential requirements that such tools should meet have been identified. Based on the knowledge and prototypes currently available, it should now be possible to build a truly user-friendly tool that planning agencies could effectively use to support their TOD initiatives.

6. TOD research gaps

Notwithstanding the considerable achievements of TOD research, there are still several gaps to address. Below, we identify the ones we consider to be the most relevant and challenging divided into two groups: gaps related to TOD effects and gaps related to TOD planning.

6.1. TOD effects research gaps

As stated before, the effects of TOD on travel behavior have been frequently studied in the literature, yet some aspects deserve to be further examined. In particular, the longitudinal research design often applied in the evaluation of urban form modifications is still rather rare in the analysis of the impacts of TOD on travel behavior. However, this type of analysis could be very useful since, when it comes to people’s habits and preferences like the ones involving travel mode choices, significant changes hardly manifest themselves in short time periods. Instead, years may pass before the occurrence of significant changes in travel preferences or TOD-related features (mixed uses or density), and the frequently applied cross-sectional research design cannot capture these changes (Van de Coevering et al., 2015).

Analysis of modal split based on origin-destination pairs could also improve our understanding of TOD effects on travel behavior. The majority of studies uses data of TOD residents’ travel choices which inform about the mode choice selected at a particular origin, yet they omit valuable information about the destination of the trips (whether it is easily reachable by car or transit, whether it is a mixed-use or a mono-functional site, etc.). The importance of a wider regional or metropolitan transport system cannot be neglected as it actually produces a significant impact on people's choices, reducing the importance of neighborhood organization: “the form of the macro-region may be too auto-dependent for the micro-pattern of any particular neighborhood to matter. Islands of neotraditional development in a sea of freeway-oriented suburbs will do little to change fundamental commuting habits” (Cervero and Gorham, 1995). Potentially, this issue may be approached by studies which would consider origin-destination pairs, channeling the research into the domain of “accessibility-oriented development” (Deboosere et al. 2018).

Additionally, in this regard, it might be useful to distinguish between travel behavior of choice riders and captive riders (Lierop et al. 2017), and to understand which are the factors that determine the use of a particular transport mode in each situation. In the case of choice riders, analyzing the factors that determine the use of a particular transport mode might bring some insights into possible means to improve TOD performance (for example, if it happens that the proportion of choice riders in one TOD site is higher compared to others). In the case of captive drivers, such analysis might allow determining which OD pairs have poor transit connections.

Another common criticism of existing research is the focus on work trips and little interest in non-work trips which can account for several daily trips. In this regard, estimation of a site’s attractiveness based on the number of jobs is sometimes considered as an oversimplification, since the distribution of activities that attract people is not necessarily limited to employment centers, especially in non-working hours (examples include schools, restaurants, bars, cultural venues, etc.). Research involving non-work trips is frequently entangled with limited data availability, but is certainly worth pursuing because the share of such trips is increasingly large.

Considering other TOD effects, research could better develop the issue of the potential benefits of TOD for community life at a micro-scale, for example in terms of safety and comfort, improved aesthetical appearance of an area, proximity to commerce or services, or other societal improvements, since the number of studies on these matters is still limited. Such evidence could support local authorities in the promotion of TOD and repel possible skepticism of residents towards new projects.

As evidenced in the previous section, the implementation of TOD projects may provoke a variety of changes in a number of aspects and simultaneous bi-directional dependence between trends may happen, as in the case of travel behavior and residential location (Estupiñán and Rodríguez, 2008) or transit supply and urban form (King, 2011; Xie and Levinson, 2010; Kasraian et al. 2016). The interdependence between these effects and their synergistic influence, particularly on the long term, could be better explored with appropriate techniques like two-stages least squares (instrumental variables) regression analysis or Granger causality analysis, which have rarely been used in TOD studies.

6.2. TOD planning research gaps

Turning now to research gaps related to TOD planning, one of the most relevant aspects to mention is the complexity of TOD planning processes, that requires proper planning mechanisms and decision-support tools. While a significant part of studies (Guthrie and Fan, 2016; Levine and Inam, 2004; Searle et al., 2014) addresses developers’ and/or planning authorities’ perspectives on TOD, relatively little is known about the inclusion of transit agencies into the process (for the definition of service frequency, design of routes and schedules, definition of pricing policies, etc.), yet the quality of public transport supply is essential for a successful TOD implementation.

Another concern is the location choice for a TOD project: many articles about TOD planning focus on developments that emerged on the outskirts of a city or in previously non-residential areas (Cervero and Dai, 2014; Dumbaugh, 2004; McIntosh et al., 2017; Yang et al., 2016), since such placement allows the authorities to avoid potential NIMBY opposition, and still control urban growth. Eventually, peripheral areas may be provided with more investment and better access to public transport than some inner city areas. Evidences on TOD development and TOD promotion among local residents in the inner city areas are rare. In these areas, with mature communities, specific built environment and pre-defined land uses, the planning process and value capture mechanisms can be quite different and still need to be studied in order to evaluate TOD as a strategy for urban infill and regeneration.

It should be noted that current TOD typologies have been defined mainly for diagnostics purposes, revealing clusters with similar characteristics or problems on a metropolitan scale. However, the results do not seem to be used during the planning process, highlighting a gap between existing theoretical classifications and actual planning practice. More research is needed to see which typologies are useful and helpful in the planning process of site selection (for development or transport service) and land-use allocation.

Additionally, it might also be useful to evaluate how changes in the transport system (like new stations, lines or intermodal terminals) or in the urban structure (like new employment centers) influence the evolution of competing locations. Theoretically, as areas compete with each other for resources, significant improvements and investments in a certain site may limit the potential for development in another site (Atkinson-Palombo and Kuby, 2011), so urban planners would gain from being informed about the side effects of such changes.

Market forces produce a large impact on urbanization patterns and development projects, but are quite sensitive to economic downturns. In these circumstances, planners are potentially interested in selecting more resilient projects. Some developers believe that the demand for TOD properties is more stable than the demand for conventional suburban development which may be more negatively affected by an economic downturn (Noland et al., 2017). Still, little is known about the responsiveness of TOD to economic crises and whether these areas endure economic decline better or worse compared to others.

7. Conclusion

Since the 1990s, research dedicated to TOD has been steadily increasing, and in recent years approximately 45 annual articles have been published in journals listed in the Web of Science database. This trend reflects a growing interest in this urban planning concept. However, as the number of studies rises, familiarizing with TOD may become difficult due to the extent and variety of the available literature. For this reason, in this article we have reviewed TOD research and systematized its results. Hopefully our review, together with the identification of the main research gaps, shall help researchers to get better acquainted with the subject and better informed on the challenges that lie ahead.

Thanks to the research efforts made in the past, it is now possible to understand rather well the many different effects produced by TOD implementations. Because the concept of TOD is multidimensional, it involves changes in different aspects occurring at the same time (but probably not at the same pace), eventually creating a complex network of mutually dependent interrelations. Summarizing the findings, it is possible to conclude that, in general, proximity to a station offering TOD features (density, land use mix and pedestrian-friendly design) increases the use of transit and simultaneously increases property prices in adjacent areas. In turn, an increase in property prices potentially leads to successive densification and/or gentrification of station areas, being doubtful whether public transport ridership levels remain high once high-income groups settle in a TOD. Normally, the aforementioned changes occur gradually with the course of time, hence it is possible that certain TOD effects take time to fully manifest themselves. Despite the progress achieved by previous research, there are still many open opportunities for TOD research and challenges to overcome. Part of these challenges arise in respect to TOD planning and to the development of user-friendly decision-support tools that can facilitate the preparation of TOD projects with the involvement of all relevant stakeholders.

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