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Does transit-oriented development (TOD) influence perceived safety and mode choice?

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Abstract: Transit-oriented development (TOD) is an established urban planning principle for increasing public transport (PT) use. However, whether TOD enhances perceived safety and increases PT use remains an open question. This study analyzes the link between mode choice, perceived safety, and TOD dimensions on a large dataset covering the Greater Copenhagen area in Denmark. Using survey data and site observations, we first estimate multiple linear regression models to show which TOD dimensions enhance individuals' perceived safety at train stations. Then, using large-scale travel survey data encompassing 21,844 trips between 2009 and 2018, including various user socioeconomic variables, we estimate a mode choice model in which TOD score and perceived safety are used as explanatory variables. Our results provide empirical evidence showing that the safety dimension of TOD significantly increases perceived safety and that perceived safety at both the home and activity ends of the trip influences the likelihood of an individual choosing PT. Only a higher TOD score at the activity end significantly increases PT use, whereas park-and-ride lots at the activity end reduce it and make cycling less attractive at both trip ends. Distance to the nearest stations/stops and service headway have a significant influence on mode choice at both ends of the trip. These results indicate that dense urban development around stations supports PT use and cycling more strongly than allocating space to park-and-ride lots. Our results are important for policymakers seeking to use TOD guidelines to increase individuals' perceived safety and PT use in cities.

Keywords: Transit-oriented development, public transport, travel behavior, ridership, active travel, perceived safety

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1 Introduction

Attractive public transport (PT) systems offer a solution to urban challenges like congestion and pollution while providing mobility to a wide range of users. However, despite ongoing efforts to support a shift from cars to PT and active travel modes, no significant change has occurred (Boffey, 2020), and cars remain the dominant mode of daily travel—about 50%— across the European Union (Fiorello et al., 2016). While it is

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widely recognized in the literature that having a strong urban railway and metro network increases PT ridership (Ingvardson & Nielsen, 2018), the decision to choose PT also depends on the stations and their surroundings.

Transit-oriented development (TOD) is an urban planning strategy that aims to combine high-quality PT with a dense mix of residential and commercial uses while also considering the design around stations, for example, ensuring a pedestrian-friendly infrastructure (Calthorpe, 1993). Since the introduction of this strategy, numerous studies have investigated TOD's effect on travel behavior. Defining TOD with variables like population and employment density, land-use mix, average block size and vicinity to stations, researchers have shown that TOD significantly reduces the share of private car use while increasing PT and active travel use (Chi & Lee, 2024; Ibraeva et al., 2020). However, most research has focused on TOD characteristics only at the trip origin, and except for a few studies (e.g., Nasri & Zhang, 2019), destination characteristics have received little attention (Ibraeva et al., 2020).

Feeling safe (i.e., perceived safety) is an important travel need for many PT users during many various trip stages, especially access, egress and waiting (Crime Concern, 2004; Iseki & Taylor, 2010; Park et al., 2021). A lack of perceived safety can cause individuals to alter their routes, avoid certain modes/times of the day, prefer private modes instead of PT or cancel their trips completely when there is no other alternative (Loukaitou-Sideris et al., 2009; Lubitow et al., 2017; Sundling & Ceccato, 2022). While actual crime levels in an area can influence individuals' perception, studies focusing on the design of stations and their surroundings have also found strong effects of the built environment (BE) regardless of crime levels (Sundling & Ceccato, 2022). In Denmark, our study area, a nationwide survey of PT users revealed that 25% of the users feel unsafe at stations, especially after dark, with station design being among the main reasons (Forbrugerrådet Tænk Passagerpulsen, 2019b). TOD, in addition to increasing PT ridership, can help create safer station surroundings, for example, through the design of bright paths without entrapment and creating visual connections around entrances (Pojani & Stead, 2015). However, researchers have not paid much attention to the relationship between TOD and perceived safety (Ibraeva et al., 2020) or analyzed their combined influence on users' travel mode choice in detail.

This study analyzes the relationship between TOD, perceived safety at stations and mode choice in the Greater Copenhagen area. Given that urban development in this area was driven along the "five fingers," representing five suburban rail (S-train) lines with TOD features (Egnsplankontoret, 1947), it is well suited for an analysis of TOD guidelines. Specifically, we build on Pojani and Stead's (2015) detailed TOD guidelines in two steps.

First, we analyze the relationship between perceived safety and TOD using observation data from PT stations and survey data on PT passengers' perceived safety at train stations. Second, we estimate a mode choice model to investigate how TOD characteristics and perceived safety together influence mode choice using data from Christiansen & Skougaard (2015), a large-scale survey representative of the Danish population. Specifically, we include TOD and perceived safety at the home and activity ends of trips, as we hypothesize that individuals' familiarity with their surroundings and access to travel resources can be different at each trip end, thus influencing their travel behavior. Our final data set comprises TOD observations and perceived safety scores for 142 train stations as well as 21,844 trips made by 12,047 individuals between 2009 and 2018 in the Greater Copenhagen area, Denmark.

The remainder of this paper is organized as follows. Section 2 reviews the literature on TOD, perceived safety and travel behavior. Section 3 presents our data, while Section 4 describes our methods. Section 5 reports the results of the multiple linear and multinomial logistic regression models. Section 6 discusses the findings, and Section 7 concludes with policy recommendations.

2 Literature review

The literature review section is organized in three parts focusing on i) the concept of TOD, ii) the relationship between TOD and travel behavior and iii) the relationship between perceived safety and travel behavior.

2.1 The concept of TOD

TOD is an urban planning strategy suggesting that Neighborhoods should have the PT station at the core, surrounded by a dense mix of housing, offices and public space (Calthorpe, 1993). Placing facilities like daycare, retail and parks en route to the PT station is essential for creating human activity in the streets while allowing travellers to run errands before/after their PT trip (Calthorpe, 1993). Good walking and cycling conditions are crucial in TOD to increase the share of active travel, facilitate access to PT and minimize car usage (Calthorpe, 1993; Thomas & Bertolini, 2017). Affordability of housing and workplaces is also key to attracting, for example, carless low-income households and businesses with many employees, which could benefit from higher PT accessibility. Lastly, there is an emphasis on regional TOD, allowing PT access to a wider range of users (Calthorpe, 1993; Thomas & Bertolini, 2017).

Numerous scholars have developed ways of measuring TOD. Cervero and Kockelman's (1997) 3Ds is one of them, according to which Density describes residential/employment density, Diversity describes the land-use mix and Design describes pedestrian-friendly design characteristics like block lengths and sidewalk provisions. This model was later extended to 5Ds with the addition of Destination accessibility and Distance to PT (Ewing & Cervero, 2010). Bertolini's (Bertolini, 1999) place-node index is another measure, which consists of the "variety and frequency of PT supply" (node) and functional mix (place). This measure is useful for identifying which station areas perform well and which need improvement in one or both axes. Later research extended this model with, for example, the pedestrian shed ratio (Vale, 2015), average block size, distance from stations to jobs/residences and intersection density (Lyu et al., 2016).

Jacobson and Forsyth (2008) created another TOD guideline with 12 dimensions under three topics (processes, places, facilities), building on a systematic analysis of good TOD practices in the USA. Pojani and Stead's (2015) TOD guidelines adapted Jacobson and Forsyth's (2008) 12 dimensions with sub-dimensions, building on other key works in the urban design literature (see Ewing, 1996; Ewing & Bartholomew, 2013; Porta & Renne, 2005; TCRP, 2002). In addition to the key premises of TOD, such as high residential and employment density around the station, these guidelines emphasize the urban design dimension and provide specific sub-dimensions to achieve, for example, high-quality public space and social interaction (Pojani & Stead, 2015). Strandbygaard (2019) later converted these guidelines into a quantitative measure by scoring each sub-dimension on a 0–1 scale to study TOD in the Greater Copenhagen area.

2.2 TOD and travel behavior

The impact of TOD on travel behavior has been investigated for a long time. According to Ibraeva et al.'s (2020) comprehensive review, earlier studies on TOD were mostly comparative. For example, Cervero (1995) compared the travel behavior of residents inside and outside the TOD catchment area and suburbs designed with and without TOD guidelines (Cervero, 2007). Cervero and Arrington (2008) compared car usage in TOD areas to the national average in the USA. These studies showed that TOD residents have higher PT and active travel use, a higher share of active travel for access/egress (Cervero, 1995, 2007) and a lower rate of car trips (Cervero & Arrington, 2008).

Following a similar approach, Griffiths and Curtis' (2017) descriptive study on Subiaco, a suburban area with TOD characteristics in Perth, Australia, showed that car use for work trips was reduced by 18.7% in the TOD catchment area between 2010 and 2016. Residents within the catchment area increased their PT use by 2.2%, reaching 31.1%, while the PT use in the whole state was only 20.3%. Thus, they argued that having a short PT distance increases car use. Interestingly, despite the TOD residents' decreasing levels of satisfaction with the walking infrastructure, active travel increased by 19.2%. Overall, the study indicated that TOD also supports active travel, without explaining the underlying factors.

Another stream of studies measures TOD with more detailed indicators to explore its effects on travel behavior. Higgins and Kanaroglou (2016) performed latent class analysis (LCA) on 372 existing and planned stations in the Toronto region in Canada to measure their performance and show travel behavior effects. They identified 10 station types (e.g., urban commercial core, suburban center) using the following indicators: density, development mix, street connectivity, interaction potential and land use. They showed that station types with high density, walkability and mixed land are associated with high PT, walking, cycling use and low household car vehicle-miles travelled (VMT).

Nasri and Zhang (2014) investigated how BE characteristics and residing in TOD areas influence VMT in Washington, DC, and Baltimore, Maryland. In both cities, increasing distance from the central business district (CBD) and average block size increase VMT, whereas higher density and land-use mix reduce it. Furthermore, residing in a TOD area significantly reduces VMT, especially in Washington, DC, when controlling for BE characteristics and distance to bus and rail services.

Kamruzzaman et al. (2014) developed a TOD typology and validated its influence on travel behavior with a mode choice model using data from 10,013 individuals in Brisbane, Australia. Clustering Neighborhoods using net employment density, net residential density, land-use diversity, intersection density, cul-de-sac density and PT accessibility, they identified four TOD typologies. "Non-TOD" and "potential TOD" residents, in areas with low density and poor PT accessibility, were 1.4 and 1.3 times less likely, respectively, to choose PT over cars, and 4 and 2.5 times less likely to choose active travel over cars, respectively (Kamruzzaman et al., 2014).

Park et al.'s (2018) study stands out as a large-scale investigation of the impact of BE on travel behavior in eight metropolitan areas in the USA. Using household travel data, they found that among the "D" variables Density has the least significant effect on travel behavior, whereas high land-use Diversity and intersection density are some of the variables reducing the likelihood of car use (Park et al., 2018). Meanwhile, the availability of heavy rail, regional compactness and regional job accessibility are variables that significantly support the decision to use PT (Park et al., 2018). Considering only home-end characteristics, they suggested that characteristics like parking supply at the destination end could be as influential on travel behavior.

To date, there has been limited investigation on destination characteristics (Ibraeva et al., 2020). One exception is Nasri and Zhang (2019), who identified TOD with a binary variable considering its residential and employment density, land-use mix, average block size and whether it is within the 800-m catchment area. Controlling for these TOD characteristics (except catchment area), they found that the binary TOD variables at both trip ends still have a significant and positive influence on PT use, although the origin effect is stronger (Nasri & Zhang, 2019).

2.3 Perceived safety and travel behavior

Perceived safety is a crucial prerequisite for a trip to take place. Several researchers have studied the impact of perceived safety on travel behavior. For example, using household survey data from Melbourne, Australia, Delbosc and Currie (2012) found a significant positive influence of feeling safe on the frequency of using PT. Using a representative national travel survey data from the Greater Copenhagen area, Denmark, Ingvardson and Nielsen (2021) found that low perceived safety at the origin station significantly reduces the likelihood of choosing public transport against all alternatives. Similarly, studies on pedestrians (e.g., Hong & Chen, 2014; Loukaitou-Sideris, 2006) and cyclists (e.g., Guinn & Stangl, 2014; Schneider et al., 2022) have shown the importance of perceived safety for active travel.

Researchers have widely investigated the relationship between BE and perceived safety. Crime prevention through environmental design (CPTED) is a comprehensive strategy for increasing perceived safety by improving the BE (Cozens & Love, 2015). Some key characteristics of CPTED include for providing natural surveillance with eyes on the street, access control with fences and territoriality with clearly defined ownership and functions (Cozens & Love, 2015). The harmony between stations and their surroundings is especially crucial, as PT users could still feel unsafe otherwise (e.g., if there are crime-attracting functions close to the station) (Cozens & van der Linde, 2015). Overall, these characteristics are closely related to the safety dimension in Pojani and Stead's (2015) TOD guidelines.

In addition to features like land-use mix, density and pedestrian-friendly environments, safety is an important aspect of TOD. Pojani and Stead's (2015) guidelines provide BE characteristics for perceived safety, with sub-dimensions including access control, lighting and round-the-clock activity. Thus far, however, few studies have investigated the impact of TOD on perceived safety (Ibraeva et al., 2020). One study of 249 TOD residents in Bangkok, Thailand, showed that perceived safety is one of the most important factors improving attitudes towards walking as an access mode (Pongprasert & Kubota, 2018). Strandbygaard et al. (2019) measured TOD at 38 train stations using Pojani and Stead's (2015) TOD guidelines and conducted observations within the viewshed of stations. They found that PT users feel unsafe at stations with poor place-making features.

2.4 Contributions

Overall, these studies show that i) perceived safety influences PT use, and ii) TOD influences car use either in terms of VMT or mode shift. For a deeper understanding of perceived safety's impact, Ingvardson and Nielsen's study could be extended with a more comprehensive mode choice model that estimates impacts relative to private car use, as their model currently does not clarify which mode public transit users would shift to. Regarding the impact of TOD, studies mainly focus on the impact of the "D" variables at the trip origin. That said, destination characteristics can have as much, if not more, impact on travel behavior (Ibraeva et al., 2020; Nasri & Zhang, 2019; Park et al., 2018). While Nasri and Zhang's (2019) study is an important step in investigating the impact of TOD at both trip ends, it was conducted solely using binary TOD dummy variables.

Therefore, there is a need for further analysis using a more detailed TOD measure, while accounting for PT service quality and park-and-ride lots.

Accordingly, our contribution to urban planning and travel behavior literature is twofold. First, we investigate the relationship between TOD and perceived safety to identify significant design measures. Second, we investigate the combined impact of Pojani and Stead's (Pojani & Stead, 2015) comprehensive TOD guidelines and perceived safety on mode choice, considering the characteristics at the home and activity ends of the trip.

3 Study area and data

The foundation for TOD in the Greater Copenhagen area started with the 1947 Finger Plan prepared by the Danish Town Planning Institute (Egnsplankontoret, 1947). According to this plan, suburban development in the region was to branch out of the center of Copenhagen (palm of the hand), along five regional and suburban (S-train) rail lines (five fingers) (Figure 1).

Similar to TOD, the key principle of the 1947 Finger Plan was the development of dense housing and workplaces surrounding train stations to make PT an attractive travel alternative in the entire Greater Copenhagen area (Egnsplankontoret, 1947). Furthermore, the plan dedicated green space for recreational and agricultural use between the fingers, easily accessible by train. Although the 1947 Finger Plan was proposed at a time of low car ownership, by the time the development was completed in the 1960s, car ownership had significantly increased in the area (Knowles, 2012). In the 1990s, the most recent major TOD development started a few kilometres away from the center of Copenhagen, in Ørestad (Knowles, 2012). With this plan, construction of the first two metro lines in Copenhagen also began, and the fingers in the initial plan extended and widened (Figure 2).

Figure 1. The original finger plan (Danish Design Review, 2017)

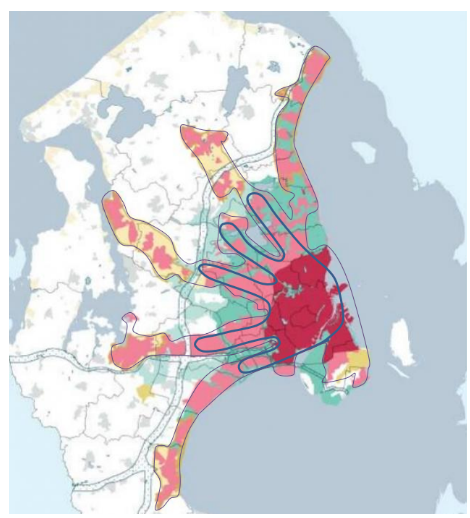

Figure 2. 2017 finger plan (with the original shown by blue line drawn by authors, and the new one by purple) (Den Offentlige, 2017)

Our data set consists of 146 train stations of around 170 stations in the Greater Copenhagen area. A total of 58.90% of the stations serve S-trains, followed by local (21.92%) and regional (17.12%) trains. Lastly, 16.44%[1] of the stations serve two metro lines (M1, M2) in the area. Figure 3 shows the train stations in the Greater Copenhagen area and visualizes the suburban development along the fingers.

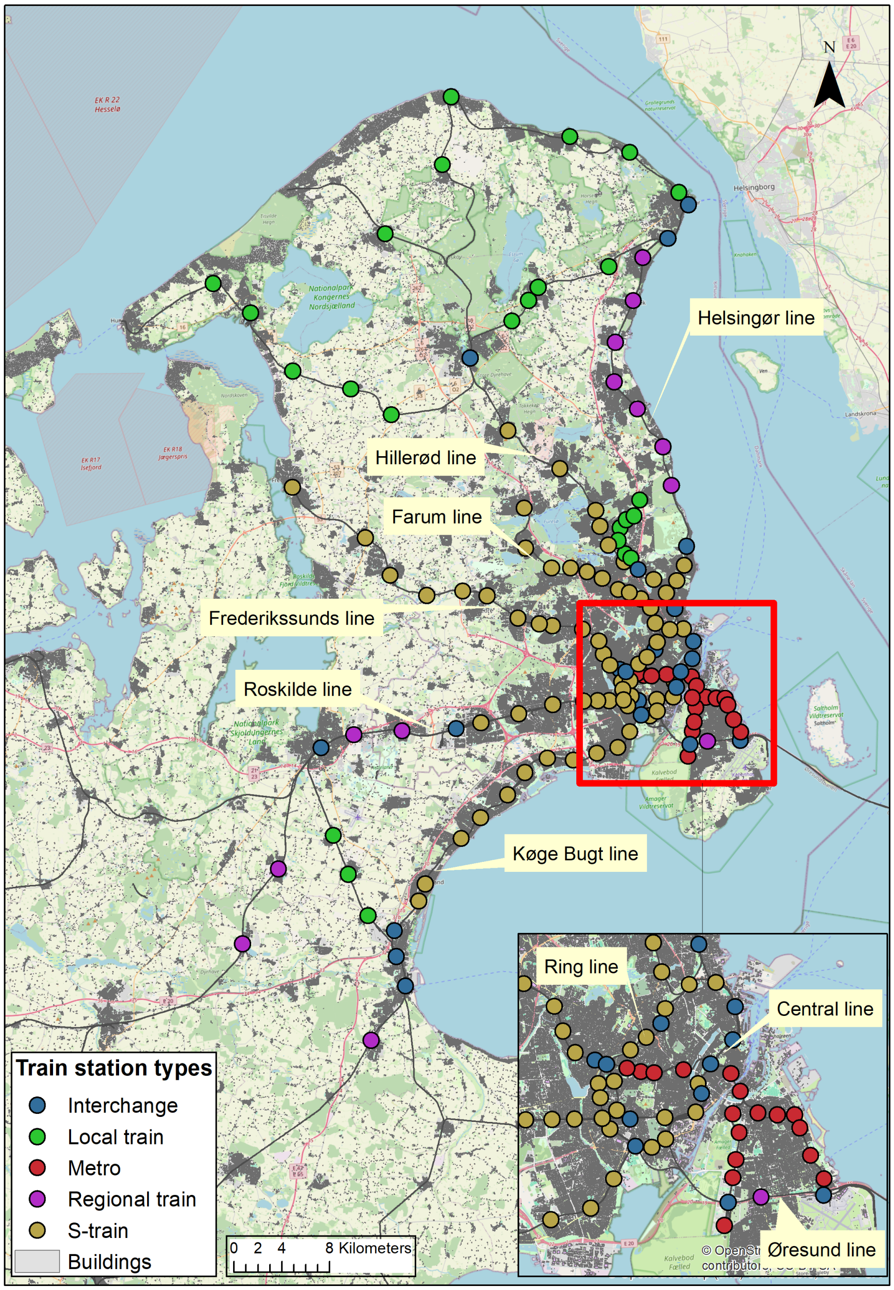

Figure 3. Map of train station types in the Greater Copenhagen area

[1] Note that the percentages do not add up to 100% as some of the stations are interchange stations serving two or more train types.

3.1 Transit-oriented development

We conducted site observations within a 500-m radius around the 146 stations to measure the TOD characteristics. Observations for 84 S-train stations were taken from Strandbygaard's (2019) study, and the remaining observations took place between 2022 and 2023. During the site observations, we assigned scores using the first eight dimensions of Pojani and Stead's (2015) TOD guidelines. We excluded dimensions 9–12 under the "Process" topic, as we only sought to focus on the design elements of TOD. Dimensions 1–8 have 47 sub-dimensions, which we measured on a 0–1 scale. For example, D3 "Safety" consists of six sub-dimensions, such as providing good lighting and avoiding blank facades. Therefore, it is a measure of how the urban environment follows these design principles rather than being a subjective measure of how safe individuals feel around a station. Finally, the weighted TOD score was the sum of these sub-dimensions on a 0-100 scale.

Table 1 describes the TOD dimensions and the weighted TOD scores of 146 stations and Figure 4 visualizes the weighted TOD scores in a map. Among the eight dimensions, D6 "Pedestrian/cyclist orientation" is the most fulfilled dimension on average, followed by D5 "Connections." D5 and D6 mainly require pedestrian and cyclist-friendly infrastructure, such as a continuous network of sidewalks and bicycle parking facilities. D1 "Scale and density" and D2 "Public spaces for human use" have the lowest average dimension scores along with a high standard deviation. D1 and D2 target high density around stations and having human use in mind when designing urban space. The range of the weighted TOD score is high, and as fig. 4 shows, stations with the highest scores lie mostly inside Copenhagen. Stations scoring under 30 mostly serve local trains in more isolated locations.

In addition to Pojani and Stead's (2015) TOD dimensions, we measured 13 additional BE dimensions that are suitable to the Danish urban context, which we hypothesized would influence perceived safety and mode choice. We describe these dimensions in Table 1 and Table 2. These variables consider the presence of pedestrian precincts and large indoor malls next to the stations, bicycle paths, access to the station through separate paths and park-and-ride lots. We also defined six variables measuring the share of different urban spaces, such as dense urban housing and one-family housing, within the 500-m buffer around the station. These variables sum up to 1 at each station.

3.2 Perceived safety and neighborhood income

Passagerpulsen (passenger representative in Denmark) provided survey data (Forbrugerrådet Tænk Passagerpulsen, 2019a) from 2016-2018 on individuals' perceived safety at stations. Respondents evaluated perceived safety on a scale from 0-10, and we calculated the average value at 142 stations. The overall perceived safety scores in the area are rather high, as the most unsafe station still scores above 5, and the average perceived safety score is 7.74/10 (Table). As Figure 5 shows, stations along the Roskilde and Køge Bugt lines in the south of the study area score lower. Most of the stations inside Copenhagen, serving mostly the metro trains, score 8 or higher.

To account for the socioeconomic status around the stations, we calculated the average neighborhood income per capita using the average values of 2017 from the Danish National Transport Model. Table describes Neighborhood income levels around the stations.

Table 1. Description of TOD dimensions, the weighted TOD score, additional BE variables, perceived safety and neighborhood income at stations (N=146), *: N=142 for perceived safety **: N= 143 for Neighborhood income

Main variable	Variable	Min.	Mean	Max.	Std. dev.	Range
TOD dimensions (Scale: 0-1)	D1: Scale and density	0	0.464	1	0.340	1
	D2: Public spaces for human use	0	0.342	1	0.317	1
	D3: Safety	0.083	0.582	1	0.229	0.917
	D4: Variety and complexity	0	0.522	1	0.258	1
	D5: Connections	0	0.616	1	0.276	1
	D6: Pedestrian/cyclist orientation	0	0.669	1	0.235	1
	D7: Transit in the urban pattern	0	0.566	1	0.258	1
	D8: Car movement and parking	0.111	0.478	1	0.185	0.889
Weighted TOD score (Scale: 0-100)	Weighted sum of 8 TOD dimensions	12.766	51.986	92.553	18.772	79.787
Additional BE variables (Scale: 0-1)	Pedestrian precinct next to station	0	0.076	1	0.221	1
	Large indoor mall next to station	0	0.114	1	0.275	1
	Bicycle paths along main access road network	0	0.605	1	0.376	1
	Seperate path network leading to staion (0=none at all, 1=in all directions)	0	0.276	1	0.294	1
Share of different urban space characteristics (Sum=1 at each station)	Dense urban housing	0	0.171	0.950	0.245	0.950
	Spread urban multistorey housing	0	0.165	0.700	0.147	0.700
	One-family housing	0	0.270	0.900	0.205	0.900
	Accessible green areas (parks, forests, etc.)	0	0.145	0.600	0.155	0.600
	Infrastructure (Parking lots, roads, rail yards, etc.)	0	0.107	0.300	0.063	0.300
	Access-controlled green areas (sports fields, non-built private, agriculture, etc.)	0	0.142	0.900	0.183	0.900
Perceived safety at station* (Scale: 0-10)	-	5.563	7.741	10.000	0.523	4.438
Neighborhood income (1000 EUR/capita)**	-	19.120	28.203	43.475	4.006	24.356

Table 2. Description of the additional BE variables at stations, continued (N=146=, *: 6 stations are both over and underground

Variable	Yes	No
Free Park and Ride next to station	56	90
Free Park and Ride with longer walk to station	79	67
Underground station*	11	129

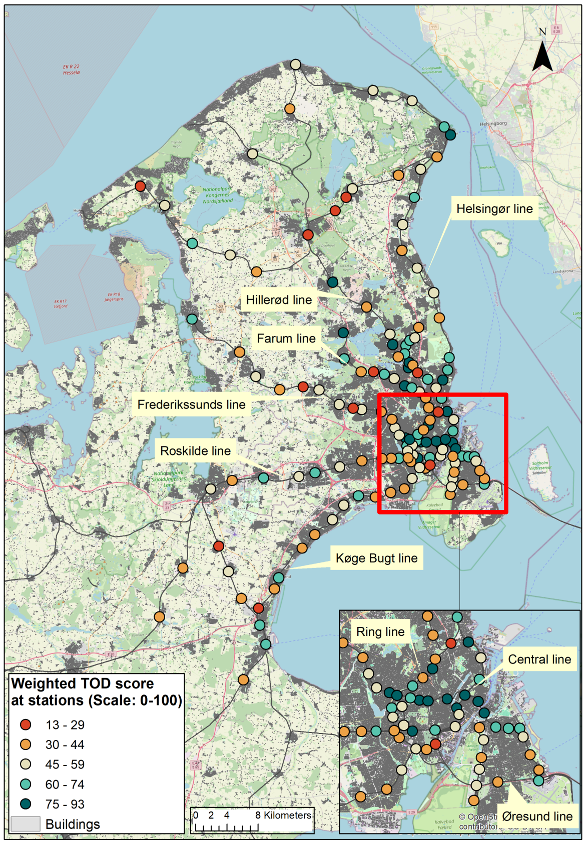

Figure 4. Weighted TOD score at 146 train stations

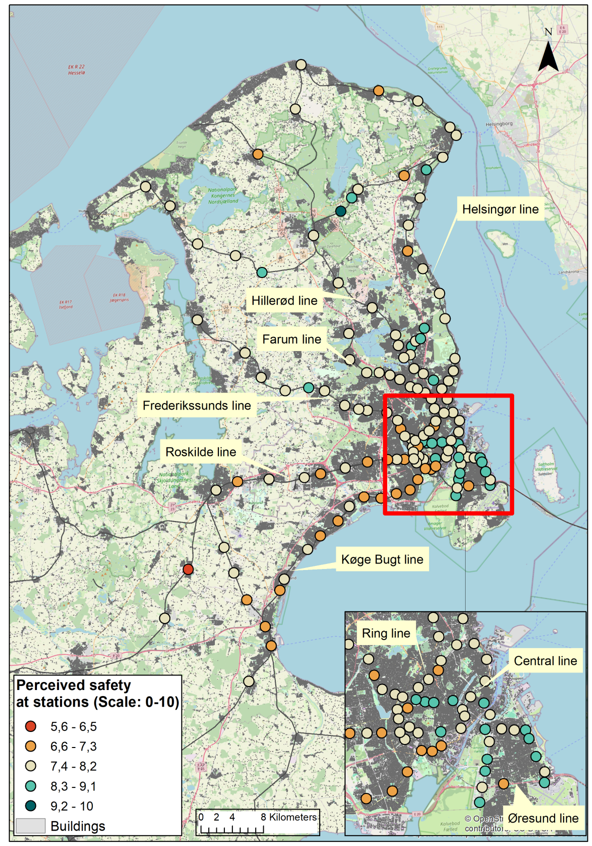

Figure 5. Average perceived safety at 142 train stations

Figure 6 shows the correlation between the eight TOD dimensions, weighted TOD score, neighborhood income per capita and perceived safety at stations. Naturally, TOD dimensions and the weighted TOD score are highly correlated. D8 “Car movement and parking” has the lowest correlation with the weighted TOD score among the eight dimensions, as most stations that fulfil the other dimensions have lower scores for dimension 8 and vice versa. Among the eight dimensions, D3 “Safety” has the highest correlation with perceived safety at stations, followed by D2, D5 and D6. Finally, there is a strong correlation between Neighborhood income and perceived safety at the station.

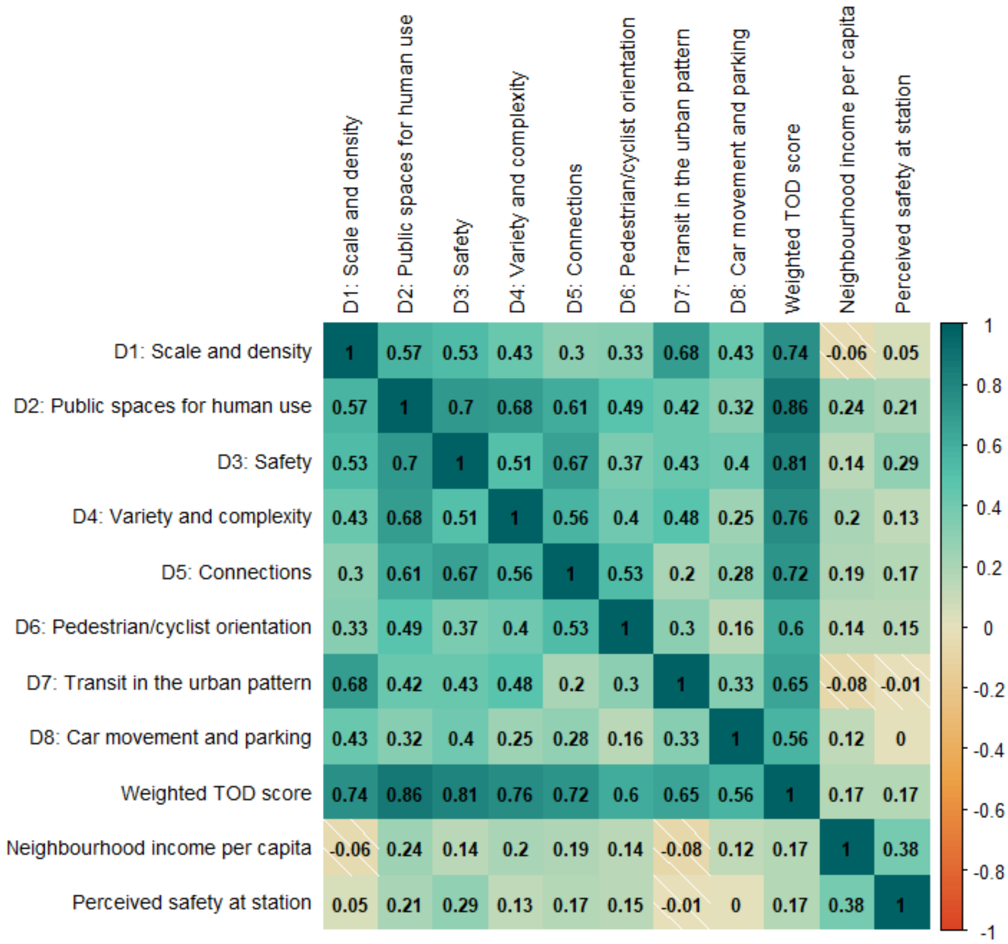

Figure 6. Correlation between the TOD dimensions, perceived safety and neighborhood income (N=142)

3.3 Danish national travel survey

To investigate the travel behavior in the Greater Copenhagen area, we used observations between 2009 and 2018 from the Danish National Travel Survey "Transportvaneundersøgelsen" (TU) (Christiansen & Skougaard, 2015). TU is a travel survey representative of all of Denmark, consisting of a one-day travel diary that individuals over six years of age can fill out. Each year around 10,000 interviews take place in Denmark, and the same method and core questions have been used since 2006.

Starting with a data set of around 100,000 trips, we kept only the following trips during the data preparation process:

1. Car, PT, walking and cycling trips.
2. Trips longer than 2 km as shorter trips have a significantly different mode choice dominated by walking and cycling (Ingvardson & Nielsen, 2021).
3. Walking and cycling trips shorter than 5 and 19 km, respectively, to achieve a more realistic mode choice scenario. 5 km corresponds to a one-hour long

walking trip, whereas 19 km corresponds to the distance threshold covering 99% of all observed cycling trips.

4. Non-business trips as their value of time differs significantly from business trips. (Fosgerau et al., 2007).
5. Trips where the nearest PT station at the origin is less than 2 km away, as we assume that station characteristics do not influence mode choice when the station is further away.
6. Individuals who provided their income levels, as income is an important predictor of mode choice.
7. Trips with level-of-service (LoS) data (calculated travel times and costs).
8. Trips with TOD and perceived safety data at the nearest stations in the origin and destination
9. Trips which have home and activity ends

Next, we restructured the data set by converting the origin and destination to home and activity ends, depending on whether the trip started or ended at home. The resulting data set includes 21,844 trips conducted by 12,047 individuals between 2009 and 2018 and is presented in Table 3.

The sample is well balanced in terms of gender and age. A high share of the respondents are employed and have medium or higher further education, corresponding to three or more years in university. Most respondents own a car and a bicycle. As Table 3 shows, a car is the most commonly used travel mode in the area, used by 60.61% of the individuals in the TU, followed by PT and bicycle (19.83% and 18.52%, respectively). Work and leisure are the most common trip purposes. A majority (67.89%) of the trips are between 2 and 10 km.

3.4 Copenhagen greater area model for passenger transport (COMPASS)

To estimate a mode choice model, travel times for the unobserved travel modes are necessary. We obtained these using COMPASS, which is a new, activity-based transport model developed by the Copenhagen municipality to support its decision-making process (Paag et al., 2019). The model covers the entire Greater Copenhagen area and provides level-of-service (LoS) matrices for car, PT, cycling and walking between the 4,077 zones in the area. We used LoS matrices from 2017 to calculate travel times for all trips in the TU data set.

For cars and bicycles, free and congested travel times were available. For public transport, in-vehicle time, waiting and walking times were available in addition to the number of transfers. For walking, only free walking time was available. However, the model does not estimate LoS for walking trips longer than 5 km. In these instances, we divided the distance between two zones by an average walking speed of 5 km/hour to obtain travel times.

We also calculated travel costs using COMPASS data. For cars, we multiplied the trip length with the marginal cost of car driving in 2017 (1.477 DKK/km), which the Ministry of Transport in Denmark provides (DTU Management, 2022). For PT trips, we used the adult fare with the travel card (Rejsekort) for the number of zones covered in the trip. However, for individuals under 15 years of age in the TU data set, we implemented the 50% children discount. Lastly, we assumed that walking and cycling trips are free of charge.

Table 3. Description of the study sample from TU consisting of 21,844 trips by 12,047 individuals between 2009-2018

Variable	Category	Study sample
Gender	Male	50.15%
	Female	49.85%
Age	0-15	6.38%
	16-25	12.76%
	26-35	16.43%
	36-45	20.11%
	46-67	36.28%
	>67	8.04%
Employment status	Employed	61.66%
	Student	7.94%
	Retired	9.68%
	Unemployed	2.13%
	Other	18.59%
Education	High school or shorter	27.16%
	Vocational	15.63%
	Short-term further education	5.55%
	Medium-term further education	28.07%
	Long-term further education	21.72%
	Other	1.87%
Car ownership	No	25.20%
	Yes	74.80%
Driving licence	No	17.89%
	Yes	82.11%
Bicycle ownership	No	20.95%
	Yes	79.05%
Individual income (1000 EUR)	0-33	46.86%
	33-66	43.24%
	66-100	7.14%
	100-133	1.80%
	>133	0.95%
Mode choice (>2km)	Car	60.61%
	Public transport	19.83%
	Bicycle	18.52%
	Walking	1.05%
Trip purpose	Work	35.28%
	Educational	6.19%
	Errand	25.33%
	Leisure	33.20%
Trip distance	[2,5) km	41.05%
	[5, 10) km	26.84%
	[10, 20) km	19.92%
	[20, 30) km	7.54%
	Over 30 km	4.64%
	Number of trips	21,844
	Number of individuals	12,047

3.5 Service quality of PT

We accounted for the service quality of PT using data on the i) distance to the nearest stations and stops and ii) service headway at the nearest PT station or stop at the home and activity ends of the trip. The former is available for metro, regional trains, S-train, local trains and S-buses (fast buses covering longer distances between stops). The latter is available for the nearest train or bus service. These data stem from Ingvardson and Nielsen (2021), in which more detailed information is available. Table 4**Table** describes the service quality variables at the home and activity ends.

Table 4. Description of the service quality of the stations at the home and activity-ends in the study sample

Variable	Category	Home-end	Activity-end
Service headway	<5 min	14.38%	24.92%
	5-10 min	56.51%	53.54%
	11-15 min	7.15%	6.31%
	Over 15 min	21.96%	15.23%
Distance to the nearest s-train station	0-200 m	0.70%	2.42%
	200-400 m	3.62%	6.12%
	400-600 m	6.36%	7.82%
	600-800 m	9.39%	9.48%
	800-1000 m	9.54%	9.46%
	>= 1 km	70.40%	64.70%
Distance to the nearest metro station	0-200 m	0.72%	2.33%
	200-400 m	2.02%	3.74%
	400-600 m	3.05%	4.26%
	600-800 m	3.39%	3.96%
	800-1000 m	2.51%	2.78%
	>= 1 km	88.30%	82.92%
Distance to the nearest local train station	0-200 m	0.08%	0.16%
	200-400 m	0.51%	0.95%
	400-600 m	0.98%	1.24%
	600-800 m	1.13%	0.95%
	800-1000 m	0.88%	1.02%
	>= 1 km	96.43%	95.68%
Distance to the nearest regional train station	0-200 m	0.29%	1.37%
	200-400 m	0.93%	3.47%
	400-600 m	1.31%	3.34%
	600-800 m	2.74%	5.19%
	800-1000 m	3.09%	4.89%
	>= 1 km	91.63%	81.74%
Distance to the nearest S-bus stop	0-200 m	3.37%	10.69%
	200-400 m	8.34%	15.49%
	400-600 m	10.67%	12.52%
	600-800 m	9.27%	9.26%
	800-1000 m	8.11%	6.52%
	>= 1 km	60.24%	45.53%

4 Methodological approach

We conducted two statistical analyses in this study, employing i) multiple linear regression and ii) multinomial logit analysis.

4.1 Multiple linear regression (MLR)

To investigate the influence of TOD, Neighborhood income and additional BE variables, we estimated a multiple linear regression model using R (R Core Team, 2021).

Our dependent variable was perceived safety at the station on a 0-10 scale. As independent variables, we introduced TOD dimensions 2, 3, 5 and 6, as they had the highest correlation with perceived safety among the eight dimensions. Furthermore, we added Neighborhood income per capita and the additional BE variables. Among the variables describing the share of different urban space characteristics, we set "dense urban housing" as a reference category for the other variables. Moreover, we controlled for geographical differences across the various radial rail lines in the Greater Copenhagen area (Køge Bugt, Farum, Roskilde, Frederikssund, Hillerød, Helsingør), the Øresund line inside Copenhagen as well as metro and local train stations. After estimating the full model with these 26 variables, we removed insignificant variables (p-value >= 0.20) to achieve our final model, which we present in Section 5.1.

4.2 Multinomial logit (MNL)

To investigate factors influencing individuals' mode choice in the Greater Copenhagen area, with a focus on the influence of TOD and perceived safety, we estimated a multinomial logit model (Ben-Akiva & Lerman, 1985).

As we were not able to identify meaningful travel time and travel cost parameters in the initial estimations, we defined generalized travel time (GTT) variables instead. Equations 1 and 2 show the equations of the GTT variables for car and PT for individual i. We used a value-of- time (VoT) of 92 DKK/hour (approx. 12.3 EUR/hour) to convert travel costs into travel time (DTU Management, 2022). As we assumed that bicycle and walking trips were free of charge, their GTT variables consist only of travel time.

$$\boldsymbol{GTT_{i,car} = TravelTime_{i,car} + \frac{TravelCost_{i,car}}{VoT}} \quad (1)$$

$$\boldsymbol{GTT_{i,PT} = TravelTime_{i,PT} + \frac{TravelCost_{i,PT}}{VoT}} \quad (2)$$

The necessary coefficients for travel time components of car, PT and bicycle follow Hallberg et al.'s (2021) and Nielsen et al.'s (2021) studies. The former estimated a mode choice model in the Greater Copenhagen area using TU data, while the latter estimated a route choice model with very detailed transfer attributes also in our study area. Equations 3 and 4 show the travel time of car and bicycle trips for individual i, where FreeFlowTime is the free flow travel time and CongTime is the congested travel time.

$$\boldsymbol{TravelTime_{i,car} = FreeFlowTime + 1.5 * CongTime} \quad (3)$$

$$\boldsymbol{TravelTime_{i,bicycle} = FreeFlowTime + 1.5 * CongTime} \quad (4)$$

Equation 5 shows the travel time of PT trips for individual *i*, where *InVehicleTime* is the time spent on board, *NoOfTransfers* is the average number of transfers between the start and end zones according to COMPASS data, *WaitTime* is the waiting time and *WalkTime* is the walking time during transfers. All coefficients except for *NoOfTransfers* and *WalkTime* follow Hallberg et al.'s study (Hallberg et al., 2021). As Nielsen et al.'s (2021) study on transfers provides more recent and detailed information on transfers, we used their coefficients related to transfers in our model. Note that the PT travel time excludes access/egress to/from stations as we instead account for the distance to the nearest stations/stops at both trip ends.

$$\boldsymbol{TravelTime_{i,PT} = InVehicleTime + 9 * NoOfTransfers + 1.5 * WaitTime + 1 * WalkTime} \quad (5)$$

We set availability conditions for cycling and walking modes to achieve a more realistic choice scenario. Cycling is not available in the choice set when the observed trip length is longer than 19 km, and walking is not available for trips longer than 5 km.

Table 5 shows the variables we added to the full MNL model along with which utility functions they were estimated for. Variables defined as "alternative specific" had a different parameter estimate for PT, walking and cycling, whereas the "generic" variables had the same estimate for all three travel modes.

Among socioeconomic characteristics, we controlled for age, gender, income, education, employment and access to cars and bicycles. We added the length of the observed trip in two different forms to walking and cycling utility functions to capture the disutility of these modes at longer distances.

We added eight variables for both the home and activity ends of the trip. We included municipalities to account for geographical differences along with population density. Service headway and distance to stations/shops were utilized in the utility function of PT as discrete variables, whereas perceived safety was estimated separately for all travel modes. We added the weighted TOD score after removing the scores of D8 "Car movement and parking" and re-scaling on a scale of 0-100. This was due to (i) the lower correlation between D8 and the weighted TOD score and (ii) the sub-dimensions of D8 making it difficult to form a hypothesis on mode choice, as they do not directly limit car use. Instead, we added D8 separately to the utility function of PT. Among our additional BE variables, we only added two variables on free park-and-ride lots at and away from the station.

After estimating an MNL model with all the variables in Table 5, we removed insignificant variables and/or merged some categories, such as those of the distance to station/stop variables, in several iterations. We present the final model in Section 5.2.

Table 5. List of variables in the full MNL model (*: Variables for both home and activity-end are in the model)

Variable	Type	Categories	Reference value	Utility functions
Age	Discrete	0-15 years-old, 16-25 years-old, over 25 years-old	Over 25 years-old	Alternative specific
Gender	Discrete	Men, women	Women	Alternative specific
Individual income	Continuous	1000 DKK/person	-	Alternative specific
Bicycle ownership	Discrete	Yes, no	No	Alternative specific
Car ownership	Discrete	Yes, no	No	Alternative specific
Education	Discrete	Highschool or shorter, short further, medium further, long further, vocational, other	Highschool or shorter	Alternative specific
Employment	Discrete	Employed, retired, student, unemployed, other	Employed	Alternative specific
Trip length	Discrete	2-5 km, 5-10 km, 10-15 km, 15-19 km	2-5 km	Bicycle
Trip length	Continuous	km	-	Walking
Municipality*	Discrete	Copenhagen, Frederiksberg, Other	Copenhagen	Generic
Population density*	Continuous	1000 residents/km2	-	Alternative specific
Service headway*	Discrete	0-5 min, 5-10 min, 12-15 min, more than 15 min	More than 15 min	PT
Distance to stations/stops*	Discrete	0-200 m, 200-400 m, 400-600 m, 800-1000 m, over 1 km	Over 1 km	PT
Perceived safety*	Continuous	0-10 scale	-	Alternative specific
Weighted TOD score (without D8)*	Continuous	0-100 scale	-	Alternative specific
D8: Car movement and parking*	Continuous	0-1 scale	-	PT
Free park-and-ride next to station*	Discrete	Yes, no	No	Alternative specific
Free park-and-ride with longer walk to station*	Discrete	Yes, no	No	Alternative specific
Trip purpose fixed effects	Discrete	Work, education, errand, leisure	Work	Alternative specific
Year fixed effects	Discrete	Years between 2008-2019	2008-2009	Generic

5 Results

5.1 Perceived safety analysis

Our first analysis involved the MLR model explaining perceived safety at PT stations. Of the 26 variables in the full model, only 10 remained in the final model after removing variables that had highly insignificant parameter estimates (p-value >= 0.20). The final model (Table 6) had a significantly better fit than the full model and a high adjusted R^2 value (0.419).

D3 “Safety” is the only TOD dimension in the final model with a statistically significant and positive influence on perceived safety, showing that the built environment characteristics of this dimension significantly increase perceived safety at the station. Neighborhood income per capita also has a significant and positive relationship with perceived safety at stations. Stations with free park-and-ride lots that lie further away have a significantly lower perceived safety score. Here, the characteristics of the parking lot or the walk to/from the station might affect individuals’ perceived safety at the station. Stations that are either fully underground or have service both over- and underground also have a significantly lower perceived safety score, probably due to the lack of visual connection to the surroundings or the poorly designed entrances and access tunnels.

Among the dummy variables we introduced to the full model to account for geographical dif- ferences, only three remained in the final model. Metro and local train stations are perceived significantly safer compared to other stations, whereas stations on the Køge Bugt line are perceived as significantly less safe.

There are two unexpected results. The first is the positive influence of having more separate paths leading to the station on perceived safety. We expected a negative influence, as the separate paths might get narrower with a higher share, thus creating a sense of entrapment and reducing perceived safety. However, these paths might also provide a shortcut to the station and create a more pleasant experience.

The second is the positive estimate of the share of access-controlled green areas around the station. We believe that this result is linked to the local train stations, which are located outside Copenhagen and have a high share of access-controlled green areas. When we removed the access-controlled green areas variable, the local train variable became highly significant with a positive parameter estimate. These stations mostly serve residents who are highly familiar with the area. Furthermore, passengers are more likely to arrive by car due to the large distance to the nearest local train station, and thus they do not experience the station surroundings to the same extent as a pedestrian or cyclist. These might be the reasons behind the positive sign rather than a direct positive effect of the access-controlled green areas.

Table 6. Results of the final model explaining the perceived safety score at 142 stations in the Greater Copenhagen area

Variable	Estimate	Std. Error	P-value	
(Intercept)	6.128	0.268	0.000	***
D3: Safety* (Scale: 0-1)	0.420	0.171	0.016	*
Neighborhood income per capita (1000 EUR/capita)	0.044	0.009	0.000	***
Separate path network leading to station (Scale: 0-1 where 0= none at all, 1=in all direction)	0.326	0.129	0.012	*
Free park-and-ride with longer walk to station	-0.146	0.078	0.064	.
Both over & underground station (Ref: overground station)	-0.419	0.176	0.019	*
Underground station (Ref: overground station)	-0.266	0.160	0.099	.
Share of access-controlled green areas (Scale: 0-1)	0.459	0.231	0.049	*
Metro dummy	0.584	0.122	0.000	***
Local train dummy	0.153	0.094	0.105	
Køge Bugt line	-0.415	0.113	0.000	***

.*p* < 0.1 ,**p* < .05, ***p* < .01, ****p* < .001

Multiple R-squared: 0.4604, Adjusted R-squared: 0.4192

Log-likelihood: -65.28065 (df=12)

[a]This dimension includes the following sub-dimensions: Physical measures such as good lighting, control access in non-public spaces, avoiding blank facades, ensuring adequate sight lines, avoiding tunnels, narrow paths, other entrapment spots and encouraging a variety of uses to ensure round-the-clock activity. See Pojani and Stead (2015) for details.

5.2 Mode choice analysis

Our second analysis involved the MNL model explaining the factors that influence individuals' travel mode choice in the Greater Copenhagen area. First, we estimated a full model as described in Section 4.2 after which we reduced it to our final model. Table 7 presents the final model, and Figure 7 shows the parameter estimates and odds ratios for the distance to the nearest stop/station variables. Lastly, Table 8 presents the model summary showing a reasonably good model fit with an adjusted R^2 value of 0.470.

Our aim in this analysis was to show the combined influence of perceived safety and TOD on travel mode choice. We initially added perceived safety at the home and activity ends to the utility functions of walking, cycling and PT. We did not find any significant influence on walking and cycling and thus removed perceived safety from these utility functions. However, we found that perceived safety significantly influences PT use. At both the home and activity ends, a one-point increase in the perceived safety score increases the likelihood of choosing PT by around 11%, with a slightly higher effect at the home end.

We added the weighted TOD score at the home and activity ends without D8 "Car movement and parking" to the utility function of PT, walking and cycling, but we included D8 separately at both trip ends in the utility function of PT. At the activity end, increasing TOD scores significantly increases the likelihood of choosing all modes against cars, with the strongest effect on walking. At the home end, the weighted TOD score without D8 was only significant for PT, with a negative parameter estimate. This is an unexpected result, as the main premise of TOD is supporting the shift from cars to PT.

However, we think this is due to overfitting by including many other variables related to attractive PT in the model. We tested this by removing the variables that are highly correlated with the weighted TOD score without D8, namely population density and municipality variables at the home end. We found that the significance of service headway and distance to station/stop variables increased, whereas the weighted TOD score without D8 became insignificant. However, if there were a strong relationship between mode choice and the weighted TOD score without D8 at the home end, this variable would be able to capture some of the significant effects of the removed variables. Therefore, we decided to remove the home-end component of this variable from the utility function of PT.

D8 “Car movement and parking” is only significant at the activity end for PT, and higher scores of this variable reduce the likelihood of choosing PT. This result is rather difficult to interpret, as D8 consists of both strict and loose restrictions on car movement and parking. We return to this result in Section 6.

We investigated the influence of free park-and-ride lots at the station and further away from the station in the full model. However, we only saw significant effects of free park-and-ride with a longer walk to the station in the final model. At both trip ends, this feature significantly reduces the likelihood of cycling (-9.1% at the home end, -17.5% at the activity end). For PT, however, the presence of free park-and-ride with a longer walk has opposite signs for the two trip ends: at the home end, it is an attractive feature, as it increases the likelihood of choosing PT by 34.7%, whereas at the activity end it reduces the likelihood by 22.8%. As individuals are more likely to have car access where they live, the positive effect at the home end is an expected result, whereas the effect at the activity end might be due to areas with free park-and-ride being more car friendly and thus reducing the likelihood of choosing PT.

Headway of PT has a significant effect on the likelihood of choosing this travel mode at both trip ends. However, the effect is stronger at the activity end, where headways under 5 minutes increase the likelihood of choosing PT by 78.2% compared to more than 10 minutes. As passengers can better time their arrival to the station at the home end than the activity end, shorter headway might be more important at the activity end. The significance of 0-5-minute headway at the activity end probably shows a preference towards choosing the metro, as the other PT alternatives rarely have such low headway, and the metro is convenient for reaching the CBD.

Figure 7 visualizes how the likelihood of choosing PT changes according to individuals’ distance to the nearest station/stop, raising three important points. First, the likelihood of choosing PT increases by a higher percentage when the nearest station/stop is less than 200 m away, and this percentage decreases almost exponentially as the distance increases. Second, individuals are less sensitive to the distance at the home end, as many distance categories were insignificant in the full model, similar to headway. This could be due to PT users having more options to access the station at the home end (e.g., bicycle, car), increasing the perceived station vicinity area compared to the activity end. Third, the perception of distance differs not only between trip ends but also PT modes. Metro, S-train and S-buses are the only PT modes that have a significant and positive effect at the home end, although the effect of S-buses is limited to 200 m away from the stop. Regional and local train variables were not significant at the home end. For regional trains, which have less frequent service with trains covering longer distances, we expected that distance matters less, especially at the home end, where people can reach the station by car. Similarly, local train stations are situated in remote locations, requiring access by car or bicycle, and have infrequent service.

We initially added population density to all three utility functions. However, it was only significant for cycling, showing that higher population density at both trip ends makes cycling more attractive. We expected a similar effect of population density on PT, but it was insignificant at both trip ends.

We controlled for municipalities to account for the presence of high-quality PT in Copenhagen and Frederiksberg municipalities compared to suburban areas. It is expected that car is a more likely alternative in suburban municipalities due to their long distance from the CBD. There is no significant difference between Copenhagen and Frederiksberg at the home end, but the likelihood of choosing the car is higher when the activity end is in Frederiksberg. Until recently, Frederiksberg municipality offered up to two hours of free car parking, which might be the cause of this difference.

We also identified significant differences based on socioeconomic characteristics. Men are approximately 24% and 11% less likely to choose PT and cycling, respectively. Teenagers and young adults are significantly more likely to cycle or use PT instead of cars. Individuals with vocational and short further education are less likely to choose PT, probably due to the acces- sibility of their jobs more, which are often located in areas with weaker PT coverage and better car accessibility. Retired individuals, who may benefit from a cheaper monthly ticket, prefer PT, whereas unemployed individuals walk and cycle more. Increasing individual income levels make PT, walking and cycling less attractive. As expected, bicycle ownership is essential for cycling and thus very significant. Car owners, however, are around eight to 10 times less likely to cycle, use PT or walk, meaning when people purchase a car, they are very likely to use it instead of considering other travel modes.

Table 7. Results of the final mode choice model of 21,844 trips where car is the reference travel mode. Note that we control for the fixed effects of year and trip purpose in the model [.p < 0.1 ,*p < .05, **p < .01, ***p < .001]

Variable	Category	Travel mode	Estimate	Odds ratio	P-value	
Alternative specific constant	-	Bicycle	-9.23		0	***
	-	PT	-0.961		0.098	.
	-	Walking	1.72		0.001	***
Generalized travel time	-	Car	-0.021	0.979	0	***
	-	Bicycle	-0.011	0.989	0.007	**
	-	PT	-0.006	0.994	0	***
	-	Walking	-0.028	0.972	0	***
Trip length for bicycle (Ref: 2-5 km)	5-10 km	Bicycle	-1.33	0.264	0	***
	10-15 km	Bicycle	-2.54	0.079	0	***
	15-19 km	Bicycle	-3.52	0.03	0	***
Trip length for walking	-	Walking	-0.351	0.704	0.001	***
Age (Ref. for bicycle and PT: older than 25 years-old)	0-15 years-old	Bicycle	-0.215	0.807	0.063	.
	0-15 years-old	PT	-0.405	0.667	0.001	***
	0-15 years-old	Walking	-0.885	0.413	0.006	**
(Ref. for walking: older than 15 years-old)	16-25 years-old	Bicycle	0.431	1.539	0	***
	16-25 years-old	PT	0.675	1.964	0	***
Gender (Ref: Women)	Men	Bicycle	-0.118	0.889	0.021	*
	Men	PT	-0.273	0.761	0	***
Education (Ref: Highschool or shorter)	Medium	Bicycle	-0.093	0.911	0.093	.
	Other	Bicycle	-0.573	0.564	0.02	*
	Other	PT	-0.252	0.777	0.124	
	Short	PT	-0.187	0.829	0.048	*
	Vocational	Bicycle	-0.571	0.565	0	***
	Vocational	PT	-0.411	0.663	0	***
	Vocational	Walking	-0.414	0.661	0.057	.
Employment (Ref: Employed)	Other	PT	0.364	1.439	0	***
	Retired	PT	0.778	2.177	0	***
	Retired	Walking	-0.581	0.559	0.028	*
	Student	Bicycle	0.155	1.168	0.138	
	Student	PT	-0.565	0.568	0	***
	Unemployed	Bicycle	0.229	1.257	0.157	
	Unemployed	Walking	0.484	1.623	0.093	.
Individual income (1000 DKK/person)	-	Bicycle	-0.031	0.969	0.081	.
	-	PT	-2.31	0.099	0	***
	-	Walking	-1.49	0.225	0.002	**
Bike ownership (Ref: no)	Yes	Bicycle	12.3	219695.989	0	***
	Yes	PT	0.37	1.448	0	***
	Yes	Walking	0.338	1.402	0.056	.
Car ownership (Ref: no)	Yes	Bicycle	-2.09	0.124	0	***
	Yes	PT	-2.45	0.086	0	***
	Yes	Walking	-2.1	0.122	0	***
Municipality, home end (Ref: Copenhagen \& Frederiksberg)	Other	Bicycle, PT, walking	-0.464	0.629	0	***
Municipality, activity end (Ref: Copenhagen)	Frederiksberg	Bicycle, PT, walking	-0.393	0.675	0	***
	Other	Bicycle, PT, walking	-0.741	0.477	0	***
Population density, home end (1000 individuals/km^2)	-	Bicycle	0.05	1.051	0.001	***
Population density, activity end (1000 individuals/km^2)	-	Bicycle	0.028	1.028	0.031	*
Headway of PT, home end (Ref: More than 15 min.)	0-15 min	PT	0.133	1.142	0.029	*
Headway of PT, activity end (Ref: More than 10 min.)	0-5 min	PT	0.578	1.782	0	***
	5-10 min	PT	0.25	1.284	0	***
Perceived safety, home end (Scale: 0-10)	-	PT	0.117	1.124	0.003	**
Perceived safety, activity end (Scale: 0-10)	-	PT	0.107	1.113	0.017	*
Weighted TOD score (without D8), activity end (Scale: 0-100)	-	Bicycle	0.01	1.01	0	***
	-	PT	0.007	1.007	0	***
	-	Walking	0.017	1.017	0	***
D8: Car movement and parking, activity end (Scale: 0-1)	-	PT	-0.274	0.76	0.004	**
Free park-and-ride with longer walk to station, home end	-	Bicycle	-0.095	0.909	0.153	
	-	PT	0.298	1.347	0	***
Free park-and-ride with longer walk to station, activity end	-	Bicycle	-0.192	0.825	0.005	**
	-	PT	-0.137	0.872	0.023	*

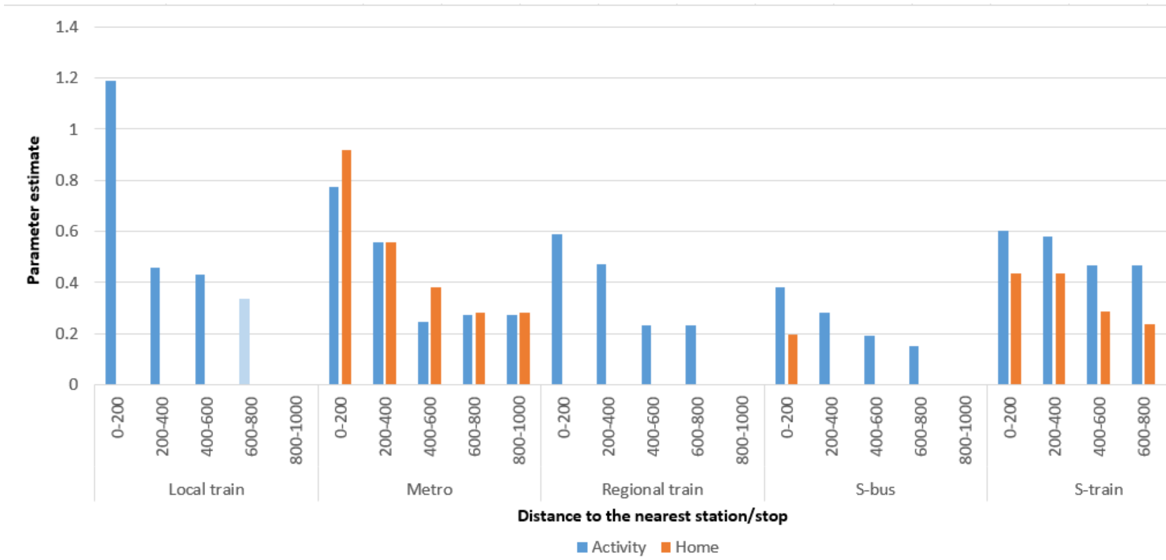

Figure 7. Parameter estimates and odds ratios of the distance to the nearest stop/station variables. Note that i) the odds ratio axis is not linear, ii) the statistically insignificant parameter estimate has a transparent bar, iii) the reference is over 800 m

Table 8. Summary of the final MNL model

Model summary	Model summary
Number of observations	21,844
Log-likelihood	-12,538.95
Adjusted R^2	0.470

6 Discussion

Our study investigated the influence of TOD on perceived safety and the combined influence of TOD and perceived safety on mode choice in the Greater Copenhagen area.

6.1 Perceived safety analysis

Our analysis of perceived safety at train stations provides empirical evidence of the positive influence of the TOD dimension D3 "Safety." In areas with good lighting, adequate sight lines and round-the-clock activity, perceived safety is significantly higher than average. D2 "Public spaces for human use," which emphasizes providing human activity, and D5 "Connections," which emphasizes improving walkability and avoiding physical barriers, did not have a significant effect on safety when controlling for D3, but their high correlation with D3 still suggests that improving these dimensions could contribute to a more pleasant and safe environment.

Neighborhood income is another important predictor of perceived safety at stations. This result contradicts the findings of Delbosc and Currie (2012), who found that individuals perceive PT to be less safe in Neighborhoods with a higher socio-economic status. However, more recently two studies (Ingvardson & Nielsen, 2021; Strandbygaard et al., 2020) found a positive correlation between Neighborhood income and perceived safety. We believe that the positive correlation might have different reasons, such as i) lower-income households being forced to reside in areas with high crime levels and higher-income households being able to afford safer areas, or ii) municipalities collecting higher tax income through higher-income households and investing in more pleasant urban design. Analysing income effects with a more detailed variable showing the income distribution within Neighborhoods rather than the average income could help partially answer this contradiction. Including crime levels in Neighborhoods could also provide more context-specific information and clarify the individual contribution of built environment characteristics on perceived safety.

Being underground or having a free park-and-ride feature with longer walk were two features that significantly reduced perceived safety at the station. While these results are not surprising, they call for improving access conditions, such as avoiding dark spots and sharp corners in tunnels leading to underground stations or creating human activity around parking lots. Note that the metro in Copenhagen has both underground and elevated stations, and the S-train and regional train also have a few underground stations.

6.2 Mode choice analysis

Our mode choice analysis shows that enhancing perceived safety at train stations significantly increases the likelihood of choosing PT. Differently from Ingvardson and Nielsen's (2021) analysis which only found significant impact of the trip origin, we considered the home and activity stations, and found significant impacts of perceived safety in both trip ends. This suggests that focusing on home and activity stations, rather than simply origin and destination points, can reveal additional insights. That said, we did not find a significant effect for bicycle and walking, contrary to previous research (Guinn & Stangl, 2014; Hong & Chen, 2014; Loukaitou-Sideris, 2006; Schneider et al., 2022). This could be because we used perceived safety scores at the station instead of in the entire Neighborhood, as walking and cycling trips do not necessarily pass the station area. Future research could investigate the relationship between perceived safety and mode choice in more detail by collecting data on perceived safety at stations as well as their surroundings.

Headway of PT and distance to stops/stations are among the strongest predictors of PT use, in line with Ingvarsdon and Nielsen (2021), and their effects are stronger at the activity end. Contrary to prior research, however, we did not find a significant effect of population density despite its significant role in TOD. One reason for this could be the rather high correlation of population density with headway and distance to the nearest stops/stations. Morevover, we added dummy variables for the downtown municipalities, which are significantly denser than the suburban areas.

We found a significant and positive influence of the weighted TOD score (however, only when excluding D8 "Car movement and parking") on choosing walking, cycling and PT over cars only at the activity end, even when controlling for PT service quality and population density. This finding emphasizes the importance of high-quality urban design in activity centers for promoting sustainable travel modes, in addition to high PT service quality. Nasri and Zhang (2019) also reported significant effects of TOD at trip origin, but in our study this disappears when controlling for PT service quality. Throughout our analysis, we found that the activity end characteristics mostly have a stronger influence on mode choice than the home end characteristics, and TOD is no exception. This suggests that the destination plays a more crucial role in mode choice than the home end, where travel alternatives are abundant. Our initial aim was to quantify the separate impact of each TOD dimension on mode choice, by including all eight dimensions in our models. This approach would allow for a meaningful comparison of each dimension's effect, as well as a comparison against other key indicators like service headway and distance to the nearest station. However, we were unable to do so due to the high correlation between the dimensions. Since we have data on nearly all train stations in the study region, reducing correlation by collecting more data and capturing more variation was not possible. Given that the weighted TOD score comprises very detailed sub-dimensions, we believe that our findings still emphasize the importance of TOD principles for research and policy.

Investigating D8 "Car movement and parking" separately, we showed that higher scores of this dimension discourage PT use at the activity end. This dimension mostly provides guidelines on the quality of parking lots, such as enclosing parking lots and creating human activity around them, rather than the quantity. Therefore, a higher D8 score does not necessarily imply limited car parking and unattractive conditions for private car users. In case there is a large enclosed parking lot with several hundred spots at the activity end, a car might become a more attractive travel mode than PT. Therefore, we recommend a redefinition of D8 "Car movement and parking" to make the sub-dimensions more tangible and suitable to the given urban context prior to future quantitative analysis and implementation.

While having free park-and-ride lots at the station is insignificant for mode choice, similar to Ibraeva et al.'s (Ibraeva et al., 2023) study, free park-and-ride lots with a longer walk significantly reduces the likelihood of cycling at both trip ends and of PT at the activity end. However, at the home end, the likelihood of choosing PT significantly increases when park-and-ride with longer walk is present. Planners often locate park-and-ride further away from the station where more space is available for a large parking lot. While this seems to benefit suburban residential areas, in activity centers with scarce space, it provides parking opportunities for private car users, thereby reducing their likelihood of choosing PT. Planners should carefully evaluate the adequate number of parking spaces and pay attention to the quality of this feature to avoid isolated, unsafe parking lots that might disturb pedestrian and cyclist flow around stations.

7 Conclusion

In this study, we used survey data and site observations from 142 train stations and a large-scale travel survey data consisting of 21,844 trips in the Greater Copenhagen area to investigate the relationship between transit-oriented development and perceived safety as well as their combined influence on mode choice. We estimated multiple linear regression models that explain perceived safety at public transport stations. We found a significantly positive influence of transit-oriented development dimension D3 "Safety," consisting of urban design measures such as good lighting and round-the-clock activity. We then estimated multinomial logistic regression models for mode choice, which revealed that high transit-oriented development scores at the activity end significantly increase the share of public transport, walking and cycling compared to car use. Perceived safety at both trip ends is another important predictor of higher public transport use.

The findings of this study have a number of important implications for future practice. In order to increase the share of public transport in cities, planners and public transport authorities should strive for short headways and a greater amount of housing and activities within close proximity to stations, as these were the strongest indicators of public transport use in our models. That said, planners should consider that the perceived catchment area depends on the train type and whether the given Neighborhood is mostly residential or commercial. Following transit-oriented development guidelines in addition to these indicators could result in safer Neighborhoods, which would not only increase the share of public transport but also walking and cycling. As the activity end characteristics played a more significant role in determining mode choice, future investments in workplaces, schools, services, etc. should take target locations accessible by public transport.

Park-and-ride lots can take up considerable space at prime locations near stations, and in our analysis their presence decreases the likelihood of cycling at both trip ends and of public transport at the activity end, mainly due to lower safety levels for public transport users and greater appeal for private car users, who can park near their destination. Therefore, planners should prioritize such features only in residential areas with spread development, where more public transport users could benefit from cars as an access mode. Instead, in denser areas, pedestrian and cyclist flow around stations should gain priority, in turn not only benefiting pedestrians and cyclists but also enhancing public transport users' experience.

In light of our findings, we recommend that while efforts to provide high-quality public transport should continue, the urban design of station surroundings should also receive more attention from policymakers. This process requires strong collaboration among stakeholders, including public transport companies, municipalities and regional authorities.

While this study provides insights into the implications of perceived safety and transit-oriented development for public transport use, certain limitations should be acknowledged. First, we were not able to account for the ridership or crowdedness level at stations when explaining perceived safety due to a lack of data. That said, we included dummy variables for station types differing in ridership levels, finding that high-ridership metro stations and low-ridership local train stations both had high levels of perceived safety. Explicitly including these factors in future research, with values specific to the time when travelers' perceived safety is measured, may help uncover the underlying reasons.

Second, in our mode choice analysis, we were unable to account for residential self-selection effects which might arise due to travelers' attitudes towards travel modes, and residential built environment (Cao et al., 2009). This is due to the Danish National Travel Survey being a cross- sectional survey which does not collect data on attitudes. This limits the causal inference of our study, although several studies find significant effects of the urban built environment, and TOD on travel behavior while controlling for self-selection effects (Chi & Lee, 2024; Næss, 2012; Nasri et al., 2020). We encourage the collection of longitudinal data with detailed attitudinal indicators for future research in this field.

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Author contributions

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