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# The knowledge economy and transit-oriented development: Effects at long-distance rail stations in Germany

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**Abstract:** The location decision of knowledge-intensive firms (KIF) depends on many factors. In a globally connected knowledge economy, long-distance accessibility is one such factor, which is provided by long-distance railway, inter alia. Areas in proximity to long-distance rail stations are therefore candidates for the settlement of KIF. At the same time, the concept of Transit-Oriented Development (TOD) posits the development of areas around public transit hubs for residential and commercial use with high densities and diversity of uses, which are additional factors for the settlement of KIF as they increase the location attractiveness of workplaces for employees. In Germany, TOD has not yet been embraced for guidance in actual planning procedures, at least not in an outspoken sense. However, we hypothesize that effects are likely to be detected: rail station areas that exhibit more pronounced TOD characteristics will be associated with higher counts of KIF. To test the hypothesis, we develop and apply a quantitative operationalization of TOD and contrast it with the settlement of KIF at 178 long-distance rail stations in Germany. The results show that the relationships between the variables are as hypothesized. Higher degrees of TOD implementation are associated with higher counts of KIF. Therefore, as our methodological innovation, we suggest adding depth of knowledge, here capturing the absolute number of KIF, as a TOD outcome dimension variable besides the conventional TOD dimensions. These results have policy relevance for (German) planning procedures as they show that more active use of TOD implementation practices is likely to entail positive feedback loops for cities by attracting the knowledge economy.

**Keywords:** TOD, knowledge economy, long-distance rail, firm locations, negative binomial model

## 1 Introduction

The knowledge economy has become an essential driver of economic growth in developed nations, where knowledge-intensive firms (KIF) function as key engines of innovation, productivity, and regional competitiveness (Castells, 2000; Florida, 2002). These firms cover a broad range of economic sectors and are characterized by highly specialized knowledge and skills, which are strategically combined from different parts of the value chain to create innovations and sustain competitive advantage (Lüthi et al., 2011). KIF create high-value employment and generate spillover effects that benefit entire urban regions (Audretsch & Feldman, 1996; Storper & Venables, 2004). Understanding the location preferences of KIF therefore is crucial for policymakers.

Multiple interdependent factors influence the location decisions of KIF. Key determinants as identified by the literature are agglomeration economies (Glaeser & Gottlieb, 2009; Krugman, 1991; Marshall, 1890; Puga, 2010), knowledge spillovers (Jaffe et al., 1993), access to skilled labor pools (Moretti, 2012) and various forms of accessibility (Graham, 2007). Accessibility, the ease of transporting goods and people to

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other locations, is crucial as economic activity has become more globally integrated and spatially distributed (Redding & Turner, 2015).

However, research linking accessibility, land use, and economic activity traditionally focuses on local and regional transport systems (Geurs & van Wee, 2004). The local emphasis, while valuable, leads to a conceptual gap when considering KIF, which operate across multiple scales and regions, both nationally and internationally. Despite the spatial distribution of the knowledge economy, periodic face-to-face contact is still required for complex interactions (Gertler, 2003; Torre, 2008). The ability to access distant locations efficiently and by comparably climate-friendly rail is a critical competitive advantage. Seminal work by Vickerman et al. (1999) has studied the link between accessibility and economic development on a regional level across Europe.

Transit-oriented Development (TOD) provides a framework for understanding how transportation infrastructure influences urban development patterns around transit nodes (Calthorpe, 1993; Bertolini, 1996). The TOD literature has established a multidimensional TOD framework comprising several dimensions that are typical of successful TOD implementation, and it has stated clear relationships among transit accessibility, built environment characteristics, and socioeconomic development (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). Yet TOD research has two understudied characteristics that we seek to shed light on. First, the TOD literature primarily focuses on local and regional transit systems such as buses, light rail, and commuter trains, while largely neglecting long-distance rail infrastructure that connects cities and regions in national networks. Local and regional rail systems are fundamental for local or regional job accessibility; however, they do not offer the high levels of national or international accessibility often deemed important for the knowledge economy. Second, TOD research usually deals with economic development in more general terms, with focus on topics as diverse as real estate, retail activity, employment, affordability and gentrification, to name a few, but ignores the specific characteristics and location preferences of the knowledge economy. The potential advantages of attracting the knowledge economy into cities have been presented above, while the literature has demonstrated the research potentials of studying the link between high-speed rail and cluster economics (Russel et al., 2024). This paper addresses this gap by examining TOD implementations and the manifestation of the knowledge economy at long-distance rail stations. The paper provides a conceptual innovation by extending TOD research to long-distance transport networks and explicitly linking it to the knowledge economy. Long-distance rail stations offer unique advantages for KIF by combining high levels of national accessibility with the potential for dense, mixed-use development characteristic of successful TOD.

Germany provides an interesting setting for this study due to its extensive long-distance rail network embedded in a polycentric urban system where KIF are spatially widely distributed across regions and because this research topic remains understudied in the German context as of today. Germany's rail network has evolved from the first rail tracks built in the 1830s into the fourth-densest network in Europe with 109.5 meters of railway per square kilometer of land (Eurostat, 2025). Unlike other European countries, such as France, the network's structure is polycentric, which aligns with Germany's polycentric population and economy (Moser er al., 2023). One crucial characteristic of Germany's rail system is the many stakeholders involved. While responsibility for rail network infrastructure planning is distributed between the country's legislative bodies and the German Federal Ministry of Transport, Deutsche Bahn's nonprofit infrastructure subsidiary, "DB InfraGO," is tasked with the construction and maintenance of the rail network and rail stations. Property rights over areas surrounding rail stations are distributed across states (Bundesländer), municipalities, Deutsche Bahn, and private stakeholders, and the different stakeholders may have dissimilar interests. This makes coordinated cooperation for targeted TOD implementations at rail stations difficult (Weiß et al., 2025) and often results in comparably unstructured, small-scale urban development at rail stations in Germany.

Using data from 178 German long-distance rail stations, we operationalize seven TOD dimensions – long-distance rail accessibility as the number of long-distance rail departures per day, local and regional public transport accessibility as the number of daily local and regional public transport departures, density as the composite density of population and buildings, diversity as the provision of local amenities, walkability and cyclability (merged from the dimensions design and distance to transit as often outlined by the literature) as composite indicator consisting of walkable and cyclable road infrastructure, distance to city center as straight-line distance between rail station and city center, and, as our innovation to TOD research, depth of knowledge as the number of KIF - to test whether conventional TOD dimensions apply at long-distance rail stations.

We hypothesize that long-distance rail stations exhibiting stronger TOD characteristics, that is, higher long-distance rail and local/regional accessibility, density, diversity, walkability & cyclability, and shorter distance to the city center, will be associated with greater concentrations of KIF.

The paper proceeds as follows: the next section reviews the literature on location preferences of the knowledge economy and TOD. After that, we present the study design and TOD operationalization. This is followed by an illustration of the empirical results of the relations between the TOD dimensions and the presence of KIF. We discuss limitations of the study design, the policy implications of our findings, and conclude by staking out worthwhile future research endeavors.

## 2 Literature review

### 2.1 The knowledge economy, agglomeration and accessibility

The knowledge economy has significantly increased its share in creating economic value in developed nations over recent decades (Thelen, 2019). This transformation reflects a fundamental shift in how value is generated, with specialized knowledge, innovation, and skilled labor becoming primary drivers of competitiveness. Knowledge-intensive firms (KIF), which span a broad range of economic sectors, are characterized by highly specialized knowledge and skills that are strategically combined from different parts of the value chain to create innovations and sustain competitive advantage (Lüthi et al., 2011).

Understanding the spatial organization of this knowledge economy is essential for contemporary economic geography. Castells' (2000) foundational work on the "space of flows" demonstrates how network society and knowledge-based economic transformation create distinct spatial patterns across global metropolitan areas. Similarly, Florida's (2002) influential framework of the creative class has shaped how scholars understand knowledge worker location preferences and their importance for regional development.

The geographic concentration of economic activity and business clusters has long been recognized as a driver of productivity and innovation. Seminal work by Porter (1998) established that geographic concentration fosters competition, raises productivity, and drives innovation across sectors. More recent research has documented how these agglomeration benefits specifically apply to the knowledge economy in urban and metropolitan contexts. Moretti (2012) demonstrated how the knowledge economy creates agglomeration effects that benefit entire metropolitan regions, while Glaeser (2011) showed how people become more productive in urban areas, reinforcing Porter's foundational insights about the productivity gains from geographic concentration.

Knowledge economy agglomeration generates productivity increases through learning and knowledge spillovers, particularly in high-skill industries (Puga, 2010). These spillover effects have been extensively documented, with Jaffe et al. (1993) pioneering this line of research through patent citations analysis; whereas Audretsch & Feldman (1996) engendered a vast literature on the geography of R&D spillovers; while research in the vein of Balland et al. (2015) and Hidalgo et al. (2007) generated insights on the spatial distribution of knowledge networks and economic complexity.

One critical dimension of knowledge economy location decisions is accessibility. An overview of the link between accessibility and agglomeration economies is provided by Credit (2019), which synthesizes how transport networks shape knowledge economy geography at different scales. Transport infrastructure hubs with high accessibility levels frequently serve as crystallization points where dense business concentrations form away from traditional centers (Hall & Pain, 2006). As economic activity becomes more globally integrated and spatially distributed, accessibility emerges as a decisive location factor (Graham, 2007; Redding & Turner, 2015).

Despite advances in digital communication, the importance of accessibility persists. Periodic face-to-face contact remains crucial for complex knowledge interactions (Gertler, 2003; Storper & Venables, 2004; Torre, 2008), which thereby creates sustained demand for efficient long-distance accessibility.

In the context of climate change, efficient and extensive low-carbon long-distance transport modes have become crucial policy considerations. Long-distance rail and high-speed rail (HSR), typically defined as rail infrastructure allowing speeds higher than 250 km/h on newly built tracks or speeds higher than 200 km/h on upgraded conventional tracks (UIC, 2015), offer comparably low carbon emissions and represent a sustainable mode of transport for contemporary and future needs (European Environment Agency, 2022). Seminal work on the relationship between rail-based accessibility and economic development across European regions was provided by Vickerman et al. (1999). However, the effects of HSR on economic geography are geographically uneven. HSR often alters accessibility discontinuously, with larger cities benefiting disproportionately compared to intermediate and smaller cities, while disconnected rural areas face disadvantages (Vickerman, 2015; Chen & Vickerman, 2018). More recent studies have begun to provide place-based evidence of these patterns. Wenner and Thierstein (2022) examining land-use changes relative to HSR service introduction at European stations, while Eichhorn et al. (2023) analyzed urban development dynamics at German long-distance rail stations through administrative data on construction activity and accessibility levels.

Understanding the relationship between transport infrastructure and economic development requires careful attention to causality. A critical question persists: do firms locate near transport nodes because of high accessibility levels, or do transport investments follow the spatial distribution of existing economic activity (Ahlfeldt & Feddersen, 2018; Redding & Turner, 2015)? Banister and Berechman (2001) provide a comprehensive framework for understanding how transport infrastructure investments promote economic growth at urban and regional scales. They formulate one of their conclusions like this: “In developed countries, where there is already a well-connected transport infrastructure network of a high quality, further investment in that infrastructure will not in itself result in economic growth.” This insight suggests that transport investments enhance productivity and regional competitiveness only when economic, investment, and political conditions align. This framework is particularly relevant to Germany’s long-distance rail network, which was built primarily in the 19th and 20th centuries and has been gradually refined since. While causality operates in both directions in general, we argue that infrastructure-led development represents the primary mechanism for long-distance rail in Germany, given the substantial upfront investments, technical constraints, and network logic that typically influence station location decisions.

### 2.2 Linking transit-oriented development to long-distance rail and the knowledge economy

Transit-oriented development (TOD) is a relatively modern term (Calthorpe, 1993), though it encompasses older ideas about urban development organized around public transport nodes (Knowles et al., 2020). Seminal European work on TOD was conducted by Bertolini (1996, 1999), who introduced the influential node-place model. This framework rests on the premise that concentrating people and diverse land uses densely around transit nodes with high accessibility creates catalytic benefits like reduced car dependency, increased transit ridership, enhanced urban vitality, and improved environmental outcomes.

Following Bertolini's seminal contribution, the field has developed standardized measurement approaches. Cervero and Kockelman (1997) introduced the three "place"-related dimensions (3D) of density, diversity, and design as key metrics for measuring TOD characteristics. This framework was subsequently extended by Ewing and Cervero (2010) into the 5Ds model, which added the "node"-related dimensions of destination accessibility and distance to transit, with the latter spanning both node and place characteristics. Further quantitative TOD measurement techniques were advanced by Singh et al. (2014), whose spatial multi-criteria assessment approach particularly refined the "design" component into more detailed sub-indicators.

Research on TOD effectiveness reveals important scope considerations. Ewing and Cervero (2001) emphasize the importance of integrating a station into the wider regional transport network to significantly impact travel behavior and urban development. Building on this insight, Papa and Bertolini (2015) studied TOD development in relation to rail-based accessibility across several European metropolitan areas, providing comparative evidence on how regional context shapes TOD outcomes.

A comprehensive review by Ibraeva et al. (2020) synthesizes standard TOD practices and challenges identified in the literature, offering practitioners and researchers a useful synthesis of what works and what remains contested across different geographic contexts. Within Germany specifically, Eichhorn et al. (2021) examined TOD potential at 747 stations in North Rhine-Westphalia, innovatively including dimensions such as "development costs" (proxied by land costs) and "development potential" (proxied by available land area suitable for development).

Despite substantial literature on both TOD and knowledge economy geography, the explicit connection between these fields remains limited. The most explicitly formulated links between TOD and the knowledge economy appear in recent U.S.-focused studies: Credit (2018), Zandiatashbar and Hamidi (2018), and Zandiatashbar et al. (2019) examine TOD implementations in the United States. However, these studies have important limitations for our context. First, the United States has a distinct urban history and planning tradition compared to Germany and Europe and second, these studies focus on local and regional transit nodes rather than long-distance rail stations, which operate at different scales and serve fundamentally different functions. TOD research is well-established for local and regional transit systems, and the macro- and meso-location factors influencing KIF distribution have been thoroughly investigated. However, the application of TOD frameworks to long-distance rail infrastructure, particularly for understanding KIF micro-location decisions, remains substantially understudied.

The few exceptions that address long-distance rail stations directly underscore this gap. Beckerich et al. (2017, 2019) provide valuable comparative evidence by examining business formations at French central and peripheral HSR stations, while Willigers and van Wee (2011) employed a stated choice experiment to understand preferences for Dutch HSR stations. Yet even these contributions do not explicitly link TOD theory to knowledge economy geography. Understanding how established TOD dimensions operate at long-distance rail stations and how these relationships vary across different types of KIF represents a significant gap in current research.

This literature review reveals a critical intersection between three well-established but separate research traditions. First, knowledge-economy geography and firm location decisions; second, transit-oriented development principles and measurement; and third, long-distance rail infrastructure and regional economic development. While each field has substantial literature, its integration remains limited.

Our study addresses this gap by systematically and empirically examining how established TOD dimensions apply to long-distance rail stations in Germany and how these relationships vary for different types of KIF. In doing so, we provide two contributions: methodologically, we adapt local TOD measures for interregional contexts and develop scalable measurement approaches for long-distance rail stations. Theoretically, we advance understanding of the relationship between long-distance rail accessibility and KIF micro-location decisions by integrating accessibility research, TOD theory, and knowledge economy geography.

## 3 Materials and methods

To test the hypothesis that high levels of TOD implementation at long-distance rail stations are strongly associated with the presence of KIF, we operationalize TOD dimensions and use them as predictors in a negative binomial model with the number of KIF as the dependent variable. In this section, we will introduce the study areas, operationalize the TOD dimensions used in this study, and briefly explain the negative binomial model.

### 3.1 Conceptualization of study areas

The preparation of the data set used in this study depends on two conceptual definitions, with the first one being the identification of long-distance rail stations in Germany and the second one being the demarcation of the areas that are to be considered in the analysis of the TOD implementation.

We define long-distance rail stations as those that had at least 12 long-distance departures on a typical weekday in 2021. Using the historical rail database provided by Grahnert (2021), we count as long-distance rail types: Intercity Express (ICE), EuroCity (EC), EuroCityExpress (ECE), Railjet Xpress (RJX), InterCity (IC), Railjet (RJ), and Train à Grande Vitesse (TGV). We eliminated all scheduling exceptions in the data to guarantee the correct number of departures. In doing so, we identify 178 long-distance rail stations in Germany with large variations in their characteristics.

The demarcation of TOD areas follows approaches put forward in the literature on TOD and walkability. Guerra et al. (2012) examined the impacts of deviating from the conventional “half-mile circle,” which roughly corresponds to a radius of 800 meters and is often used for studying TOD catchment areas. Their results indicate that the selection of other radii has only limited effects. That study deems as appropriate starting points the selection of catchment areas of a 0.25-mile circle around transit for jobs and of a 0.5-mile circle in the context of population. However, the referenced TOD studies in the context of transit for jobs focus on local or regional transit rather than long-distance rail. We argue that, in the context of the knowledge economy, the half-mile circle (radius of 800 meters) is a reasonable choice for the demarcation of the TOD catchment area as knowledge workers using long-distance rail present a different case than commuters using local public transport, because long-distance trips are usually less frequent and shaped by a longer travel time per trip. Consequently, this raises the acceptance for higher egress times from long-distance rail stations than at local transit stations.

### 3.2 TOD operationalization

The TOD literature has developed a multi-dimensional TOD framework emanating from the 3D framework by Cervero and Kockelman (1997) with dimensions density, diversity, and design as place-based qualities of the built environment (Bertolini, 1999). This framework was gradually extended to include node-based (Bertolini, 1999) dimensions called destination accessibility and distance to transit (Ewing & Cervero, 2010) to account for the advantages of higher accessibility levels. Demand management is sometimes also mentioned as a TOD dimension (Ewing & Cervero, 2010).

The literature has identified density as a core dimension that accounts for how concentrated people and the built environment are in a TOD. Diversity usually measures how mixed the land use in a TOD is and the availability of local amenities. Design can represent the station and the street network characteristics, and how conducive their implementation is for successful TOD. Destination accessibility quantifies how well transit systems serve a station. Distance to transit covers how accessible a station is from inside and outside. Demand management captures policy implementations for steering the ingress and egress travel behavior of passengers at a station.

Following Bertolini's (1996, 1999) node-place model, we operationalize TOD implementation as the interaction between the qualities of the transport node and the land use (place). We refrain from using demand management as we deem it of subordinate importance in our conceptualization. While demand management can support successful TOD, it is usually implemented through micro-travel behavior modification policies that do not adequately inform KIF's location decisions. Table 1 summarizes how TOD dimensions are operationalized in this study. We synthesize the literature on TOD dimensions and adapt them to the needs of our research. Destination accessibility was split in two components, where the first one accommodates long-distance rail, while the second one captures the local and regional public transport and therefore helps to discern the separate impacts of the two different types of accessibility. Density here is a composite indicator of multiple density-related variables and diversity captures the supply of a broad set of local and urban amenities. Two popular dimensions in the literature, design and distance to transit, were merged into one dimension called Walkability & Cyclability. We add the dimension Distance to city center to account for within-city location differences, as German cities usually grew around a historic city center.

Finally, we include the count of KIF as the outcome variable in our model, termed "depth of knowledge," to address a gap in TOD research. Crucially, depth of knowledge is not designed as an additional TOD dimension measuring conventional inputs but instead functions as an outcome measure for the knowledge economy. The count of KIF serves as a target variable that allows us to test whether conventional TOD dimensions, designed primarily in the context of local and regional transit, predict knowledge economy agglomeration at long-distance rail stations.

**Table 1.** TOD dimensions operationalized in this study

| Dimensions | Explanation | Sub-indicators | Data Sources |
|---|---|---|---|
| **1 Long-distance Rail Accessibility** | Long-distance rail service quality of the station within the overall network | Number of long-distance rail departures | *Grahnert (2021)* |
| **2 Local & Regional Accessibility** | Service quality of local and regional public transport at the long-distance rail station | Number of departures of all local and regional public transport modes on a typical workday | *GTFS (2021)* |
| **3 Density** | Density of population and built environment | a) Population.<br>b) Building surface coverage.<br>c) Average building volume | *Zensus (2022);*<br>*OpenStreetMap (2021);*<br>*Global Human Settlement Layer (Pesaresi et al., 2024)* |
| **4 Diversity** | Supply of local amenities | Number of POIs that are related to diverse urban areas: food, amenities, crafts, healthcare, leisure, tourism and retail shops | *OpenStreetMap (2021)* |
| **5 Walkability & Cyclability** | Walkability and cyclability of station area | a) Share of walkable area in 800-meter buffer.<br>b) Total length of walkable roads in TOD area.<br>c) Share of explicit cyclable road infrastructure | *OpenStreetMap (2021);*<br>*Boeing (2025)* |
| **6 Distance to City Center** | Location of station relative to city center | Straight line distance in meters | *City center defined as the historical central place of city* |
| *TOD Outcome: Depth of Knowledge* | Presence of knowledge economy | Number of knowledge-intensive firms | *Orbis (2021)* |

In the following, we present the operationalization of the TOD dimensions used in this study.

### 3.2.1 Dimension 1: Long-distance rail accessibility

Long-distance rail accessibility is key to a rail station’s attractiveness within a transport network. Higher long-distance accessibility is hypothesized to have positive implications for spatial and economic development around rail stations. It is operationalized here as the number of long-distance railway departures on a typical weekday in 2021. Historical rail schedules in Germany are available on a private website by Grahnert (2021). We refrain from using a cumulative accessibility indicator, given travel times to other rail stations and weights such as population, because this would distort accessibility. For weighted cumulative accessibility measures to work, given the international nature of the knowledge economy and the otherwise unrealistic border effects, this would require the inclusion of international rail stations and other data, which is beyond the scope of this study.

### 3.2.2 Dimension 2: Local and regional public transport accessibility

Local and regional public transport accessibility is an important complement of long-distance accessibility. It facilitates the use of long-distance railways by a larger number of people through the integration of long-distance stations into local and regional transport networks. This enables temporary proximity of persons close to and far away from major rail stations, which is favorable for businesses. Additionally, the inclusion of local and regional public transport accessibility helps to isolate the effect from long-distance accessibility. High concurrent accessibility, both long-distance and local/regional, is expected to be valuable for business settlement. Less clear is the effect on spatial development when long-distance accessibility differs in kind from local and regional accessibility, say, high long-distance and low local/regional accessibility, or vice versa. Local and regional public transport accessibility is operationalized as the number of departures from the respective long-distance rail stations. The data was taken from GTFS (2021) in July 2021 and subsequently prepared by using only connections from a typical weekday and filtering for regional trains, light rail, metropolitan railways, trams and buses.

### 3.2.3 Dimension 3: Density

The density dimension indicates how concentrated people, activities, and the built environment are in a TOD. We create a composite density indicator by combining population density, building surface coverage ratio, and average building volume. Each sub-indicator is weighted equally at one-third. Population density is the area-adjusted number of residents per 100x100-meter grid cell taken from the German Census 2022 (Zensus, 2022), the building surface coverage ratio is the share of the area in the 800-meter buffer area that is covered by buildings and taken from OpenStreetMap, the average building volume is taken from GHSL (Pesaresi et al., 2024) and represents the average height times surface area of buildings on 100x100-meter grid cells. For population density and building volume, we compute averages over all grid cells in the station area. Taken together, they robustly indicate the density in the station area, as they capture both building and residential density.

### 3.2.4 Dimension 4: Diversity

Diversity is operationalized as the mix of commercial establishments, measured by cataloguing all retail, food, crafts, healthcare, leisure, and tourism points of interest within the station's 800-meter buffer area. Data were extracted from OpenStreetMap using the "shop" tag for retail establishments, food-related amenity tags for dining and beverage outlets, select establishments listed under the tags "craft," "healthcare," "leisure," and "tourism," providing in overall a composite measure of local commercial activity and service availability. Unlike some studies, we refrain from using land-use diversity measures, as we deem them too aggregated and miss critical functional nuances, and they are too static regarding the temporal variation in passenger volume throughout the day. Additionally, operationalizing diversity in the form of inequality or diversity measures, such as Shannon entropy or Gini coefficient, first disregards the volume of commercial establishments. Secondly, it does not specify which land uses are prevalent, which is problematic because different land-use compositions can still yield the same diversity measure. However, the composition of actual land use significantly influences the nature of the station area.

### 3.2.5 Dimension 5: Walkability & cyclability

Design holds that well-designed stations and station areas enhance user comfort and increase transit ridership. Stations operated by Deutsche Bahn in Germany have a standardized design for signposting and wayfinding guidance systems, so there is little variability. Wenner (2020) has shown that station design, in terms of the architect's reputation, is not a high priority in Germany. However, a station that allows for short egress times in all directions, clever positioning of station entrances/exits, and a well-connected street network that fosters a highly walkable station area contribute to a successful implementation of TOD. We therefore combine the dimensions of design and distance to transit into a single dimension, Walkability & Cyclability. Walkability & Cyclability is a composite indicator consisting of a) the share of the 800-meter buffer area that is reachable by walking at most 800 meters from the station, b) the length of walkable roads in the reachable area, and c) the share of cyclable road infrastructure of the total road network. All three sub-indicators are weighted with 33%.

#### 3.2.6 Dimension 6: Distance to city center

The distance dimension indicates the straight-line distance between the rail station and the city center, in meters. This dimension accounts for the rail station's location within the city relative to the city center. City center is defined as the location commonly referenced as the historically most important central place, which is often the main church, square, or city hall. We researched the city center in each case and geo-coded the location by hand. Distance to city center therefore controls for centrally located stations historically embedded into the city center and that might have a centrality bonus. While lacking the potential advantages of a city-center location, peripheral stations might depend more on successful TOD implementation. However, city center locations are usually already built-up areas, often with landmarked buildings, and perceived as integral to the city's identification, which subsequently leaves less room for spatial development of station areas akin to TOD ideals.

#### 3.2.7 TOD outcome variable: Depth of knowledge

As our innovation, we add depth of knowledge, operationalized as the number of KIF, as a TOD outcome variable of interest. Traditional studies may have subsumed KIF under diversity or density as part of general employment statistics, but we argue that there is theoretical justification for the conceptual separation. KIF creates highly skilled employment, innovation potential, agglomeration economies, and knowledge spillovers, setting it apart from general commercial activities. The presence of KIF in a TOD could thus lead to "knowledge-based urban development" (Yigitcanlar et al., 2008). It can have positive feedback mechanisms, where KIF work as a pull factor to attract further KIF, while at the same time contributing to urban vitality and passenger volumes that sustain TOD. The inclusion of depth of knowledge thus helps to study the relationship between the knowledge economy and traditional TOD dimensions, which would otherwise be obscured if KIF were subsumed under density or diversity.

We use the commercial firm database Orbis (2021) to operationalize KIF. Within the 800-meter buffer of our study sample, we filtered for georeferenced KIF to establish the total KIF per TOD. In defining what constitutes a knowledge-intensive firm, we follow Eurostat (2008), as in Table 2, which uses NACE codes to classify firms into distinct economic sectors. The only change we made was to group high-tech and medium-tech manufacturing into a single group: "KI Manufacturing." Firms in Orbis (2021) each have a primary NACE code, which we use to determine whether they are knowledge-intensive and, if so, their KI category.

**Table 2.** Adjusted knowledge-intensive business sectors inspired by Eurostat (2008)

| Knowledge-intensive (KI) business sector | NACE codes | Examples |
|---|---|---|
| **KI Manufacturing** | 20, 21, 26–30 | Chemicals & Electrical Equipment |
| **High-Tech KI Services** | 59–63, 72 | Scientific Research & Programming |
| **KI Market Services** | 50–51, 69–71, 73–74, 78, 80 | Legal, Advertising & Consulting |
| **KI Financial Services** | 64–66 | Financial & Insurance Activities |
| **Other KI Services** | 58, 75, 84–93 | Publishing & Education |

### 3.3 Negative binomial model

For associative reasons, we want to estimate the relationships between the number of KIF and the TOD dimensions. The number of firms is of type count data, which calls for an appropriate model. Since the variance (155556) of the number of firms across stations far outweighs the mean (251), a negative binomial model is better suited than a Poisson model.

The negative binomial regression models the logarithm of the expected count of KIF as a linear function of the TOD dimensions, which ensures that predicted counts remain non-negative. We assume that KIF count follows a negative binomial distribution $KIF_i \sim NB(\mu_i, \alpha)$ with expected value $\mu_i$ and dispersion parameter $\alpha$. Thus follows the regression specification to predict the number of KIF at station i:

$$(1)\quad \log(KIF_i) = \beta_0 + \beta_1 accessibility_i^{long-distance} + \beta_2 accessibility_i^{local-regional} + \beta_3 density_i + \beta_4 diversity_i + \beta_5 walkability\_cyclability_i + \beta_6 distance\ to\ city\ centre_i + \beta_7 inhabitants_i,$$

where $\beta_0$ is the constant and $\beta_1$through $\beta_7$ are the coefficients of the TOD dimensions to be estimated. The number of inhabitants in a station's municipality is added as a control for the confounding influence the size of a municipality may have on the coefficients of the other TOD dimensions. The coefficients can be interpreted as the expected change in the log count of KIF for a one-unit increase in the corresponding TOD dimension, holding all other TOD dimensions constant. Equivalently, a one-unit increase in TOD dimension j multiplies the expected number of KIF by a factor of $e^{\beta_j}$.

For the sensitivity analysis, we also examine whether there are differences across KI economic sectors. We follow Eurostat (2008) in our definition of KI economic sectors as specified in Table 2.

### 3.4 Descriptives

The descriptive statistics for the TOD dimensions and their sub-indicators are shown in Table 3. All TOD dimensions were z-standardized, meaning their means are 0. Since each dimension consists of sub-indicators in non-transformed data format, we also included the sub-indicators in the descriptive table for comparison. The descriptives show that there is distributional variability between the dimensions. Except for dimensions "Density" and "Walkability & Cyclability," all other dimensions are right-skewed.

**Table 3.** Descriptives of the TOD dimensions and their sub-indicators

| Variable | Type | N | Mean | Median | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|---|
| **1a) Long-distance Accessibility** | Dimension | 178 | 0 | -0.445 | 1.003 | -0.726 | 4.178 |
| 1b) Long-distance Departures | Sub-indicator | 178 | 61.006 | 31 | 67.68 | 12 | 343 |
| **2a) Local & Regional Accessibility** | Dimension | 178 | 0 | -0.362 | 1.003 | -0.978 | 3.847 |
| 2b) Local & Regional Departures | Sub-indicator | 178 | 1,320.68 | 831.5 | 1,353.604 | 1 | 6,513 |
| **3a) Density** | Dimension | 178 | 0 | -0.028 | 0.939 | -1.794 | 2.976 |
| 3b) Population per 100×100 m grids | Sub-indicator | 178 | 40.47 | 33.53 | 29.503 | 0 | 142 |
| 3c) Buildings coverage ratio (0–1) | Sub-indicator | 178 | 0.200 | 0.203 | 0.079 | 0.015 | 0.402 |
| 3d) Average building volume in $m^3$ | Sub-indicator | 178 | 27,644 | 26,670 | 15,334 | 679 | 73,188 |
| **4a) Diversity** | Dimension | 178 | 0 | -0.25 | 1.003 | -1.125 | 3.007 |
| 4b) Supply of local amenities | Sub-indicator | 178 | 394.2 | 309 | 344.0 | 9 | 1,426 |
| **5a) Walkability & Cyclability** | Dimension | 178 | 0 | -0.001 | 0.781 | -1.892 | 2.606 |
| 5b) Walkability ratio (0–1) | Sub-indicator | 178 | 0.49 | 0.51 | 0.128 | 0.129 | 0.778 |
| 5c) Walkable street length in meters | Sub-indicator | 178 | 66,810 | 63,530 | 25,556 | 12,424 | 130,582 |
| 5d) Share of cyclable paths | Sub-indicator | 178 | 0.018 | 0.012 | 0.021 | 0.0 | 0.160 |
| **6a) Distance to city center** | Dimension | 178 | 0 | -0.26 | 1.003 | -0.578 | 7.186 |
| 6b) Distance to city center in meters | Sub-indicator | 178 | 1,462 | 847 | 2,393 | 81.754 | 18,608 |
| **Dep. Var: Depth of knowledge** | Outcome variable | 178 | 0 | -0.31 | 1.003 | -0.639 | 6.033 |
| Dep. Var: Number of firms | Sub-indicator | 178 | 251 | 129 | 394 | 0 | 2,624 |

Group indicators are z-standardized composite measures derived from sub-indicators with a mean of 0. Sub-indicators show the original variables used to construct each group measure.

The distributions of the TOD dimensions and their correlations are shown in Figure 1. The lower triangle shows the distributional relationships between the TOD dimensions in the scatter plots, along with a LOWESS trend to account for the non-linear relationships between the variables. The upper triangle shows the Pearson correlation coefficients and their significance levels. Correlation coefficients range from -0.25 (Density and Distance to city center) to 0.80 (Density and Diversity). All dimensions except Distance to the city center have a positive relationship with each other, though the relationships depend on the specific positions in the distributions. Long-distance Accessibility tends to have an almost linear positive relationship with Local & Regional Accessibility yet is marked by numerous significant outliers. Density and Walkability & Cyclability rise strongly after modest increases at the lower end of Long-distance Accessibility and flatten out at higher levels. Diversity and Depth of knowledge still grow noticeably at higher levels of Long-distance Accessibility. Local & Regional Accessibility is especially strongly positively correlated with Density and Diversity. Density and Diversity have quite pronounced relationships with the other TOD dimensions. Walkability & Cyclability can be broadly summarized as having a strongly positive relation at low to medium levels of the corresponding variable, but less so at higher levels. Distance to the city center has a clearly negative relationship to Density, Diversity, and Walkability & Cyclability. There is no correlation between Distance to the city center and Long-Distance Accessibility. Depth of knowledge is strongly and significantly positively correlated with Long-Distance Accessibility, Local & Regional Accessibility, Density and Diversity, and, to a lesser degree, with Walkability & Cyclability. To summarize, the expected relations between TOD dimensions hold in our study. Highly accessible transit hubs with station areas characterized by high Density and Diversity are associated with a higher number of KIF. Walkability & Cyclability is also positively associated with the other dimensions, but not as pronounced. More peripheral stations have lower levels of TOD implementation.

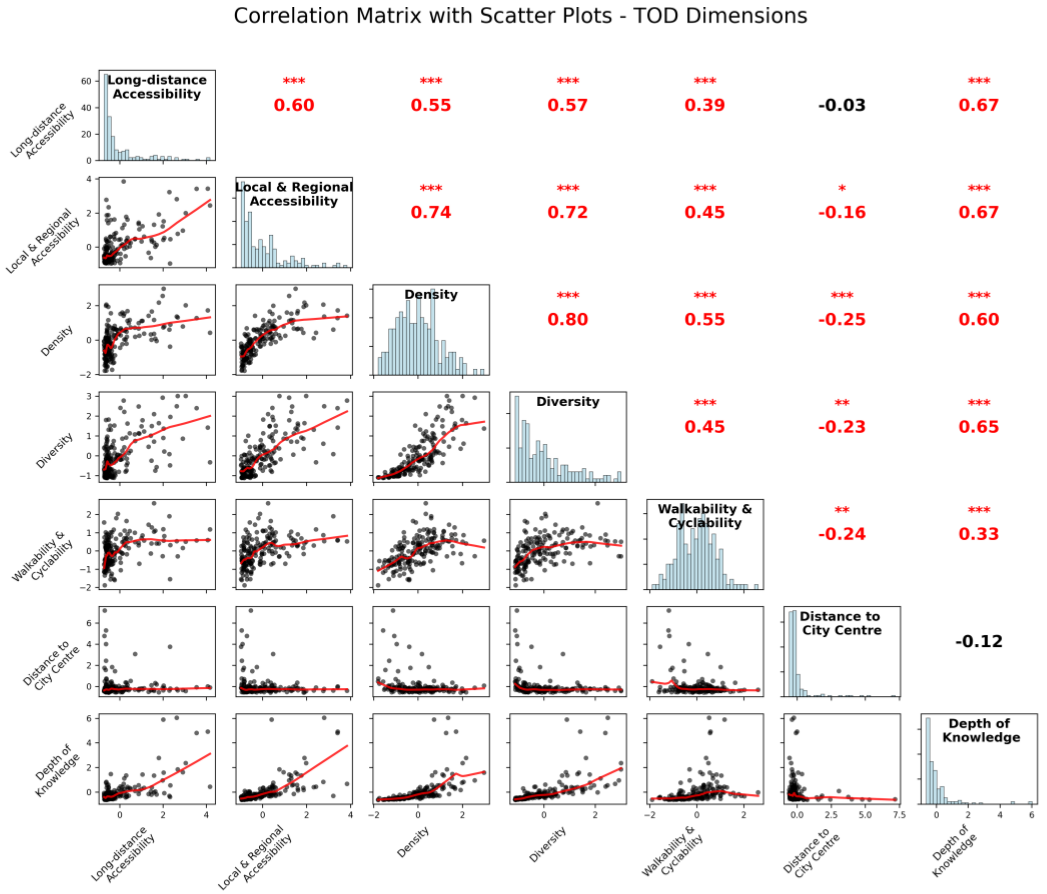

**Figure 1.** Correlation plot of the TOD dimensions. Units in scatter plots are z-standardized TOD dimensions. Red lines represent the LOWESS trend of the scatter plots—histograms showing the distribution of TOD dimensions along the diagonal. Numbers in the upper triangle represent Pearson correlation coefficients (red if significant, else black). Significance levels: **: p-value < 0.01. ***: p-value < 0.001. Figure inspired by Eichhorn et al. (2021)

## 4 Results

Table 4 shows the models' results. Column M1 represents all KIF, columns M2 through M6 show results for the respective economic sectors. Column VIF shows the Variance Inflation Factors for the explanatory variables; all are below 5, indicating no problematic multicollinearity. The model performance indicators, Pseudo R2, Log-Likelihood, and dispersion parameter $\alpha$, all show convincing results. The Pseudo R2 indicates the proportional improvement in log-likelihood compared to a null model containing only an intercept. The values range from 0.103 to 0.169, which indicates a modest yet acceptable model fit. “Other KI services” firms have the highest Pseudo R2, indicating that the actual values of TOD dimensions best predict their counts, and this sector shows the highest variability across stations. The log-likelihood values measure model fit, with higher values indicating a better fit to the observed data. Model 6 with “Manufacturing” firms has the highest log-likelihood, suggesting they have a more predictable spatial pattern. This is likely because “Manufacturing” firms have the lowest counts and are thus easier to predict than sectors with higher counts and greater variation. This is also supported by the dispersion parameter $\alpha$, which is statistically significant across all models and indicates small to moderate levels of dispersion, ranging from 0.163 to 0.527.

Model 1 has a constant of 4.507, indicating that, on average, 91 firms are expected when all TOD dimensions are at their means. All TOD dimensions have the expected positive sign except for Distance to the city center, which is negatively associated with KIF counts. The model coefficients for the TOD dimensions are statistically significant at different significance levels. Density has the highest coefficient in model 1: a one-standard-deviation increase in Density raises the expected KIF count by $e^{0.453} = 57.3\%$. A highly built-up area around stations may be seen as a precondition for firm settlement. The second-highest coefficient of Diversity suggests a favorable role for the co-location of diverse commercial establishments in dense urban areas near the worksites of knowledge workers. In terms of magnitude, the next coefficient is Long-distance Accessibility, which offers a substantial insight: it posits that a high level of long-distance accessibility may indeed be attractive to KIF. This result is corroborated by the fact that Local & Regional Accessibility has a much lower coefficient. While this does not by any means imply that local or regional public transport is irrelevant for KIF in general, long-distance accessibility is a stronger predictor of the presence of KIF at German long-distance stations, controlling for local and regional public transport, than vice versa. Walkability & Cyclability are also positively associated with the count of KIF, which confirms the literature in asserting the importance of walkability and cyclability in TODs. Finally, the significantly negative coefficient of Distance to the city center shows that, on average in Germany, KIF tend to locate in more central locations.

The comparison of the coefficients across the models shows that long-distance accessibility has the highest coefficient for “High-tech services” and is insignificant for “Other KI services.” Local & Regional Accessibility is significant for all models, except M6, and always has, by a large margin, lower coefficients than Long-distance Accessibility. Density also has the highest coefficient for “High-tech services,” but unsurprisingly, the lowest for “Manufacturing,” where KIF often needs more space. Diversity has the highest coefficient for “Financial services” and is insignificant for “Manufacturing.” Walkability & Cyclability have the highest coefficient for “Other KI services.” Due to low numbers in the sub-models, Distance to the city center is insignificant in three out of five economic sector models, but still significantly negative for “Other KI services.”

**Table 4.** Results of the negative binomial model

| Variable | M1: All | M2: HTS | M3: FS | M4: MS | M5: OS | M6: M | VIF |
|---|---|---|---|---|---|---|---|
| **Long-distance Accessibility** | 0.168*** | 0.216** | 0.211** | 0.184*** | 0.023 | 0.174* | 2.17 |
| | (0.050) | (0.071) | (0.067) | (0.053) | (0.038) | (0.071) | |
| **Local & Regional Accessibility** | 0.024** | 0.047** | 0.027* | 0.026* | 0.017* | 0.005 | 2.86 |
| | (0.009) | (0.017) | (0.013) | (0.011) | (0.008) | (0.019) | |
| **Density** | 0.453*** | 0.506** | 0.345** | 0.453*** | 0.406*** | 0.344*** | 4.20 |
| | (0.092) | (0.154) | (0.112) | (0.101) | (0.077) | (0.100) | |
| **Diversity** | 0.301*** | 0.258 | 0.432*** | 0.323*** | 0.255*** | 0.084 | 3.35 |
| | (0.073) | (0.151) | (0.094) | (0.077) | (0.057) | (0.087) | |
| **Walkability & Cyclability** | 0.126* | 0.122 | 0.156* | 0.105 | 0.162** | 0.078 | 1.54 |
| | (0.055) | (0.090) | (0.073) | (0.063) | (0.050) | (0.072) | |
| **Distance to city center** | -0.147*** | -0.076 | -0.126 | -0.098* | -0.291*** | -0.071 | 1.13 |
| | (0.039) | (0.094) | (0.068) | (0.041) | (0.071) | (0.080) | |
| **Inhabitants** | 0.085 | 0.184* | 0.129 | 0.062 | 0.048 | 0.117 | 1.73 |
| | (0.075) | (0.091) | (0.115) | (0.087) | (0.041) | (0.064) | |
| **Constant** | 4.507*** | 1.831*** | 2.482*** | 3.735*** | 3.159*** | 1.428*** | – |
| | (0.175) | (0.316) | (0.241) | (0.203) | (0.148) | (0.362) | |
| N | 178 | 178 | 178 | 178 | 178 | 178 | – |
| Pseudo $R^2$ | 0.135 | 0.158 | 0.156 | 0.137 | 0.169 | 0.103 | – |
| Log-likelihood | −1001.9 | –651.2 | –692.1 | –889.4 | –721.0 | –458.6 | – |
| α (dispersion) | 0.267*** | 0.527*** | 0.441*** | 0.335*** | 0.163*** | 0.425*** | – |

M1: All: all knowledge-intensive (KI) firms. M2: HTS: KI high-tech service firms. M3: FS: KI financial service firms. M4: MS: KI market service firms. M5: OS: Other KI service firms. M6: M: KI high-tech and medium-tech manufacturing firms. Independent variables are z-standardized. Robust standard errors (HC3) in parentheses. Significance levels: * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Figure 2 shows the model diagnostics by plotting the residuals, which are the subtraction of fitted values from observed values, on the y-axis against the fitted values on the x-axis. The observations were colored according to their mean composite TOD score, computed by averaging the z-standardized TOD dimensions, excluding depth of knowledge, to analyze the model's strength as a function of the level of TOD implementation. The R2 values range from 0.414 to 0.718, which indicates that the TOD dimensions explain a reasonable share of the variance in firm counts. The first striking observation is significant heteroskedasticity: the residuals are close to 0 for low fitted values and become more positive with higher fitted values, as shown by the red LOWESS trend lines. The second and key insight of this figure is that the model predicts relatively accurate the counts of KIF at long-distance rail stations with low to average levels of TOD implementation (blue and green points), while the model's underprediction of KIF counts gradually becomes more severe with increasing levels of TOD implementation (yellow points). This points to other underlying factors not captured by the model, such as latent agglomeration and network externalities associated with the largest metropolitan areas.

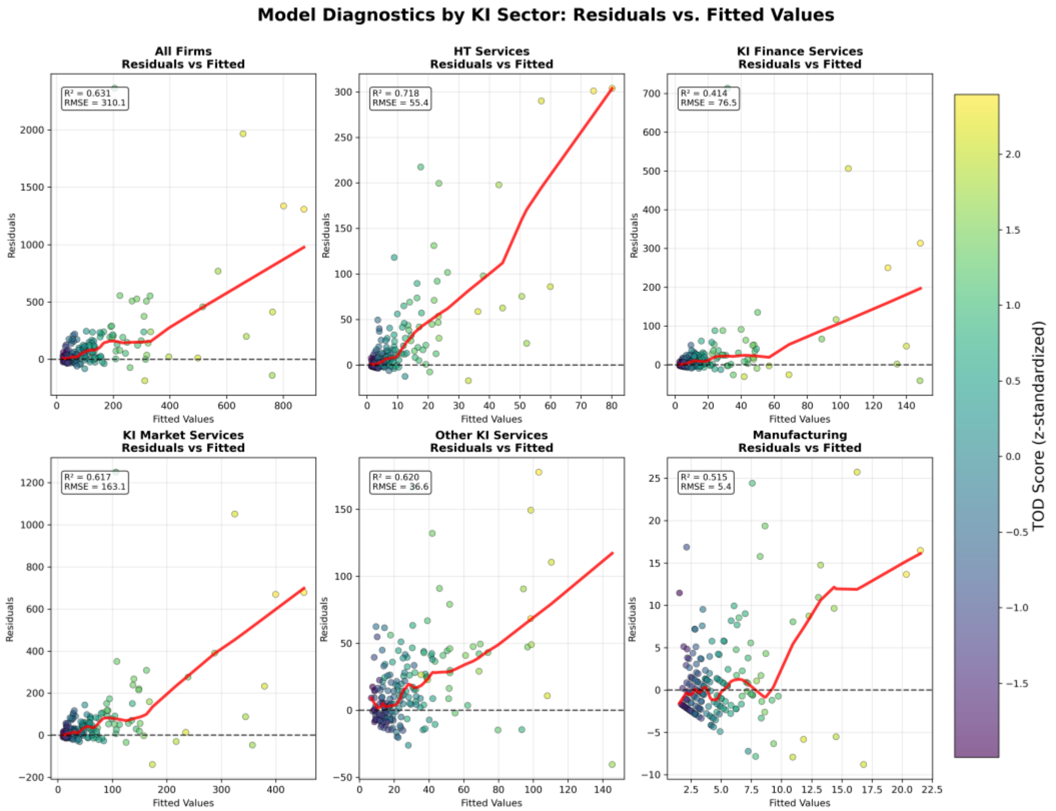

**Figure 2.** Fitted values vs. residuals for all six models. The colors of the points represent the mean of the standardized TOD dimensions, excluding depth of knowledge per station. Yellow indicates high mean TOD scores, and blue indicates low mean TOD scores. The red line represents the LOWESS trend.

These results show that the conventional TOD dimensions, Long-distance Accessibility, Local & Regional Accessibility, Density, Diversity, and, to a lesser degree, Walkability & Cyclability, strongly predict the count of KIF. The TOD literature has stressed the need for dense developments around transit hubs, which can be confirmed with these associative and non-causal models.

## 5 Discussion

The empirical analysis of 178 German long-distance rail stations confirms the hypothesis that conventional TOD dimensions strongly predict KIF concentrations. Density, referring to population and buildings, is the strongest predictor, which aligns with the literature's emphasis on the focus of concentrated development around transit hubs (Ewing & Cervero, 2010). Local amenities, here captured as diversity, are also a strong predictor for the co-location of KIF. Including two separate indicators by disentangling long-distance rail accessibility from local & regional accessibility in the model helps to isolate both their coefficients. Long-distance rail accessibility has a strong and significantly positive association with the concentration of KIF, although it is markedly smaller in magnitude than density and diversity. This suggests that long-distance rail accessibility needs to be complemented by other TOD dimensions to unfold its potential. The distinctly smaller coefficient for local and regional accessibility indicates that, given the other included TOD dimensions at long-distance rail stations, the local and regional public transport provision seems to be less crucial for the count of KIF. The strong positive correlations between all TOD dimensions, except distance to city center, prove that TOD dimensions reinforce each other at long-distance rail stations, consistent with the node-place model (Bertolini, 1999). This interconnectedness of dimensions calls for integrated TOD planning, as opposed to planning separate dimensions in isolation.

The observed variations between knowledge-intensive sectors corroborate research on location decisions of the knowledge economy, like the theoretical distinction made between different knowledge bases (Asheim & Gertler, 2006). Particularly Manufacturing, with firms that usually require more physical space, exhibits the weakest relationships to TOD dimensions, confirming intuition that TOD represents dense and compact developments and that dense urban areas attract knowledge-intensive service firms.

The results shown in Figure 2, in which high TOD levels fail to accurately predict disproportionately high KIF counts, indicate a limitation in conventional TOD dimensions and point to more latent forces at play at local spikes of knowledge economy concentrations. Agglomeration economies and network externalities seem to be the most plausible explanations, which supports Porter's (1998) work on competitive clusters. The most significant knowledge economy clusters seem to develop self-reinforcing effects that become larger than the sum of the individual location advantages.

The dimension distance to the city center confirms the compounding effect that centrally located rail stations near historical city centers may have on attracting KIF through the combination of agglomeration economies and high accessibility levels. This means that rail stations at the periphery of cities are likely to have difficulties imitating the conditions provided by city centers, regardless of the degree of TOD implementation.

This study provides three theoretical contributions. First, we show that conventional TOD dimensions focused on local and regional transit hubs are also applicable for long-distance rail stations, which was a gap as identified in the TOD literature review by Ibraeva et al. (2020). The confirmation of the applicability of TOD dimensions at long-distance rail stations also shows that accessibility benefits, agglomeration economies, and urban vitality effects operate across different transport modes and spatial scales. Second, to our knowledge, this is the first study to examine the connection between KIF and TOD in Germany. While recent research has established that particularly HSR fosters the knowledge economy in China (Wang et al., 2020), we contribute that these relationships may be at play in a different institutional setting. Third, the methodological innovation of introducing depth of knowledge as a distinct TOD outcome variable carves out the special role played by KIF, which would be lost if KIF were ignored or, at best, subsumed under more generic economic indicators. There is a bidirectional relationship at play between KIF and TOD as KIF benefits from TOD but also contributes to TOD through the channels of knowledge spillovers, the attraction of highly skilled knowledge workers, and the enhancement of urban vibrancy (Glaeser, 2011; Yigitcanlar et al., 2008).

Precisely this bidirectionality leads to a limitation in this study's model design in the form of reverse causality, which refers here to the question whether high degrees of TOD implementation entail the attraction of KIF or if the presence of KIF only fosters subsequently the development of the initial TOD dimensions. It is important to keep in mind that the purpose of this study is to promote the usefulness of explicitly incorporating the knowledge economy into working TOD concepts because this provides a relevant component for successful TOD implementations. Therefore, the results of the negative binomial model must be taken as purely associative and merely an expedient to obtain a feeling for the signs and magnitudes of relationships between the number of KIF and the other TOD dimensions. For methodological reasons, it is not possible to answer this question definitively in this study, since we lack intertemporal data consisting of both explanatory as well as dependent variables for multiple points in time, which would be needed to employ causal econometric methods such as difference-in-differences. We thus welcome future endeavors studying the evolution of TOD implementations over time vis-à-vis KIF settlements. It would be particularly interesting to see more studies using the announcement of the implementation of a TOD or the actual inception of a long-distance rail station specifically designed as TOD as the treatment variable in a difference-in-differences study design. This would allow for a causal isolation of the effect that a TOD implementation has on the knowledge economy.

We argued that investments in the long-distance rail network in Germany precede the spatial and economic development around long-distance rail stations because the network planning is partly a political process and partly transport engineering with no or little regard for individual small and medium-sized KIF. The argument would be similar for local and regional public transport, however, there is certainly evidence for the routes of local public transport lines being planned such that it provides accessibility to the worksites of exceptionally large employers. As for density, we posit that the majority of KIF rent previously existing office buildings, except, again for the largest firms that build their own campuses. The development of walkable and cyclable roads is provided by the municipal planning authorities, which usually is already in place before KIF settle around long-distance rail stations. The diversity indicator, here conceptualized as the supply of local amenities, might be the most responsive TOD dimension to the settlement of KIF. However, since long-distance rail stations usually provide high accessibility, entailing a high passenger frequency, setting up shop around the stations is often enough of a location factor for providers of local amenities. The bidirectionality or reverse causality in this context thus merits further research to obtain a better understanding of the interplay between the built environment at the transport node and emerging socio-economic outcomes.

While this study establishes a positive connection between TOD and the presence of KIF, there are also potential drawbacks created by TODs and long-distance rail for the real and perceived livability of station areas that planners need to acknowledge and mitigate. The model results show that long-distance rail, as opposed to local or regional public transport, has a higher statistical association with the presence of KIF, which could increase the real estate value and incentivize real estate owners to replace older buildings with new office blocks. In turn, the urban development brought about by TOD may thus cause gentrification with rising rent levels and changes in the neighborhood's fabric, which disproportionately affects low-income residents by pricing them out of their apartments (Dawkins & Moeckel, 2016). The systematic review on TOD and gentrification by Padeiro et al. (2019) finds some supporting evidence for TOD-led gentrification but suggests that gentrification is rather associated with existing local dynamics, built environment attributes and accompanying policies than TOD itself. However, recent research has also documented non-monetary aspects created through TOD, such as noise (Yildirim & Arefi, 2021), crime (Zandiatashbar & Laurito, 2023) and perceived safety (Basaran et al., 2025), to negatively impact residential satisfaction and neighborhood cohesion (Gong & Li, 2022). These studies show that the impact of the socio-psychological dimension of TOD perception on the residential location decisions is not only driven by accessibility and amenity availability, but also by preferences for quiet neighborhoods with a high degree of perceived safety. Ideally, future TOD implementations at long-distance rail stations should thus explicitly incorporate design considerations addressing noise abatement, station accessibility, perceived safety and community engagement strategies that account for heterogeneous residential preferences and neighborhood change. Such an integrated approach would enhance the local legitimacy of TOD projects and maximize both economic benefits and residential well-being.

However, the German institutional context is characterized by several detached planning hierarchies without a top-down planner overseeing a TOD. While rail operator Deutsche Bahn operates the rail network planned by the German Federal Ministry of Transport and several legislative bodies, areas surrounding rail stations belong in parts to Deutsche Bahn, federal states, municipalities, and private stakeholders. This creates conflicts of interest, entails planning inefficiencies, and explains the absence of large-scale TOD in Germany. Therefore, new forms of collaborative TOD planning are required to tap into the potential of TOD. Especially Deutsche Bahn and municipal planning authorities should develop strategies by integrating station accessibility, including local and regional transport connections, with land-use planning. A good overview of planning theory and practice challenges at German HSR stations can be found in Weiß et al. (2025).

## 6 Conclusion

This study establishes a theoretical connection between TOD at and around long-distance rail stations and the knowledge economy and provides an empirical operationalization thereof. At 178 long-distance rail stations in Germany, we operationalized six TOD dimensions: long-distance rail accessibility, local and regional accessibility, density, diversity, walkability & cyclability, distance to city center, and a TOD outcome variable called "depth of knowledge," which is defined as the number of KIF. The introduction of depth of knowledge here is a methodological innovation, which is justified because a distinct capture of the knowledge economy helps determine a TOD's success. The findings confirm the hypothesis that stronger TOD characteristics are associated with substantially higher KIF concentrations. This strengthens the, as of today, still sparsely discussed link between the literatures on TOD and the knowledge economy.

Our results from a negative binomial model predicting KIF counts using TOD dimensions as predictors demonstrate that conventional TOD dimensions also apply at long-distance rail stations. The density of people and buildings has the strongest association with the presence of KIF. The results also indicate that high levels of TOD dimensions reinforce one another, validating Bertolini's (1999) node-place model at the scale of long-distance rail stations. This supports the literature that high performance across multiple TOD dimensions is favorable for a TOD's overall success. The analysis of the models' residuals shows that the highest KIF counts are at the highest TOD levels. At the same time, the residual analysis also shows that conventional TOD dimensions fail to capture agglomeration economies and network externalities as they underpredict KIF counts at high TOD levels. Additionally, sensitivity analyses conducted by grouping KIF into different KI sectors largely confirm the relations to the other TOD dimensions. This also confirms that typical service-oriented KIF without any physical production is more strongly associated with TOD dimensions than manufacturing firms that require more physical space, contradicting TOD principles.

These findings have implications for sustainable transport and economic development policy, particularly given Germany's new government's plans to invest 107 billion euros in rail infrastructure until 2029. The Trans-European Transport Network (TEN-T) also aims to improve rail networks across Europe, including in Germany. These developments, in turn, offer opportunities to enhance the use of rail station areas in Germany. The strong role of density in our results suggests that rail station areas should become denser through new development, infill, vertical extensions, and brownfield regeneration. Consequently, concentrating the knowledge economy around long-distance rail stations would further reduce urban sprawl, reduce car or airplane usage, and thus contribute to a sustainable urban and transport environment, while at the same time fostering economic competitiveness. As Germany is shaped by a polycentric economy and a decentralized federal structure with limited planning cooperation across hierarchies, to realize the potential of large-scale transport infrastructure improvements for cities, planners across political institutions need to develop new collaborative planning models for better TOD implementation.

This study's cross-sectional design allows no clear causal inference regarding the argument that high TOD levels lead to large-scale KIF settlements. Future research, therefore, should use firm-level data with an intertemporal dimension to meaningfully apply causal inference methods, such as difference-in-differences, to shed more light on the causal relationships between TOD implementation and KIF settlement patterns. Another limitation of our choice of TOD dimensions is that, due to omitted-variable bias, they severely underpredict KIF counts at high TOD levels, primarily in major cities. Especially helpful would be further research addressing the omitted-variable bias inherent in the concept of agglomeration externalities at the intersection of TOD and the knowledge economy, which we alluded to in this study by showing that our TOD dimensions fail to accurately predict KIF counts at the highest levels of TOD implementation. A fruitful research avenue could thus uncover other TOD dimensions related to the knowledge economy, such as university proximity and other measures of knowledge-economy proxies often discussed in economic geography.

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## Data availability

The data underlying this study are heterogeneous in nature and subject to varying levels of accessibility. A portion of the data is sourced from OpenStreetMap (OSM) and is openly available. A further portion, while derived from open-source origins, has been processed and stored in a non-publicly accessible format. The remaining data are governed by confidentiality agreements that preclude their public release. Consequently, the dataset cannot be made available.

## Author contribution

The authors confirm their contribution to the paper as follows: conceptualization: J. Moser, F. Wenner, A. Thierstein; methodology: J. Moser, F. Wenner, A. Thierstein; software: J. Moser; validation: J. Moser, F. Wenner, A. Thierstein; formal analysis: J. Moser; investigation: J. Moser; resources: J. Moser, F. Wenner, A. Thierstein; data curation: J. Moser; writing (draft, review and editing): J. Moser, F. Wenner, A. Thierstein; visualization: J. Moser; supervision: F. Wenner, A. Thierstein; project administration: F. Wenner, A. Thierstein; funding acquisition: F. Wenner, A. Thierstein.

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