A 3D TransferSpace-based Data Model for Integrating Multimodal Transportation Networks in Smart Cities

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Abstract

In smart cities, the coexistence of diverse transport modes highlights the need for integrating multimodal transportation networks. However, existing approaches typically simplify modal transitions into single points, which do not fully reflect the spatial complexity and continuity of real-world transfer environments. To overcome these limitations, this study introduces an extended data model that conceptualizes intermodal transitions as three-dimensional space, enabling the detailed representation of internal movement paths such as corridors, stairways, and platforms. By extending point-based representations of modal transitions into spatial representations, the proposed model builds upon ISO 19134 to define transitions between different transport modes as spaces, enabling the integration of individually constructed transport networks and allowing for a detailed representation of internal movement paths within a unified multimodal transportation network. This approach allows for precise modeling of transfer paths across micro-scale spaces and supports flexible integration without requiring modifications to the original networks. We expect that the proposed model will effectively address the demands of multilayered transportation environments and serve as a foundation for developing human-oriented multimodal navigation systems.

1. Introduction

With the increasing diversity of transport modes and the growing complexity of mobility patterns in urban environments, the importance of efficient and flexible routing systems has been continuously emphasized (Smarzaro et al., 2021). In particular, route optimization through the integration of various transport modes is considered a key component in the implementation of smart cities (Gao et al., 2017). Modern passengers often combine various transport options, such as walking, public transport, and personal mobility, based on time constraints, the purpose of the journey, and the surrounding environment. Moreover, the recent emergence of new transport paradigms such as Urban Air Mobility (UAM) has expanded the concept of transfers to include multi-level movements across underground, ground, and aerial environments. Accordingly, rather than operating each transport mode, such as car, bus, and metro, as an independent system, an unified model that integrates them into multimodal transport networks has been proposed as an effective approach to capture the complexity of urban mobility (Morris and Barthelemy, 2012; Gallotti and Barthelemy, 2014). A key prerequisite for constructing such multimodal networks is the explicit definition of transfer points between different transportation modes. Traditional multimodal network studies (Lozano and Storchi, 2001; Zhang et al., 2011) have relied on the integration of individual networks through a single node or edge.

However, these simplified approaches have the limitations of failing to capture the physical and behavioral aspects of real-world transfers sufficiently. This restriction exists because transfer between transport modes is not merely a modal switch, but rather a composite activity that involves spatial movement through interconnected micro-spaces within real physical environments. As shown in Figure 1, a passenger transferring from a bus to the subway traverses a sequence of micro-spaces including sidewalks, stairs, corridors, and platforms. However, the existing method has the limitation of simplifying this sequence to a single node, which does not fully describe the continuity and spatial structure of the actual transfer process.

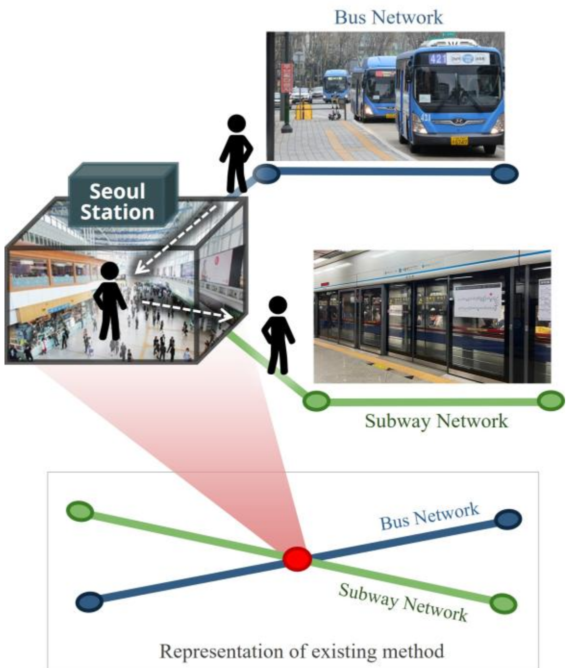

Figure 1. Real-world transfer and its representation of an existing method

Therefore, this study proposes a multimodal transportation data model that can represent micro-space during the transition between transport modes. To this end, we extend the point-based transfer representation into a three-dimensional model, enabling flexible integration of independently constructed transport networks without structural modification or segmentation. This paper is structured as follows. Section 2 reviews relevant prior work, including ISO 19134:2007-Multimodal routing and navigation, which serves as the international standard for multimodal navigation. Section 3 presents the overall structure of the proposed data model, describing the extended feature classes. Section 4 demonstrates the applicability of the model using a real-world transfer scenario. Finally, Section 5 concludes the paper and discusses future research directions.

2. Related Work

To support multimodal transportation systems, a data model is required that can consistently integrate transitions between different transport modes. To address this need, ISO 19134 defines a conceptual schema, data structure, and feature classes for multimodal routing and navigation (ISO, 2007). However, ISO 19134 represents intermodal integration solely through a single node referred to as a *TransferNode*. Representing the transition between different transport modes as a single point is a fundamental limitation because it does not account for the spatial complexity involved in planning passenger routes during real-world transfers. In particular, existing models do not explicitly represent spatial components of transfer in micro-scale spaces such as corridors, stairways, and platforms.

As shown in Figure 2, transfer locations are simplified in ISO 19134 as two-dimensional points in the existing model. This abstraction prevents the representation of vertical movements and inter-level connectivity, making it difficult to model real-world transfer scenarios, such as floor-to-floor movement within platforms.

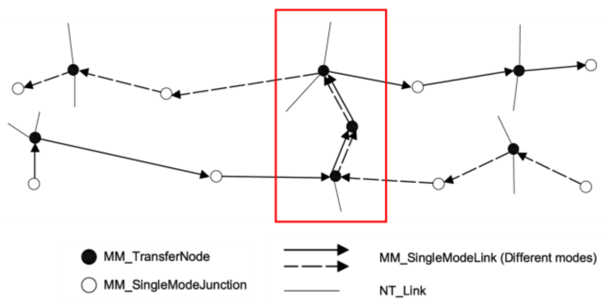

Figure 2. *TransferNode* and *TransferLink* in multimodal network (ISO, 2007)

In addition, the UML in Figure 3 lacks a topological relationship between *TransferNode* and *TransferLink*, making it impossible to define which nodes are connected to which links. This structural limitation hinders both the accurate representation of the transfer path and the application of network-based pathfinding algorithms.

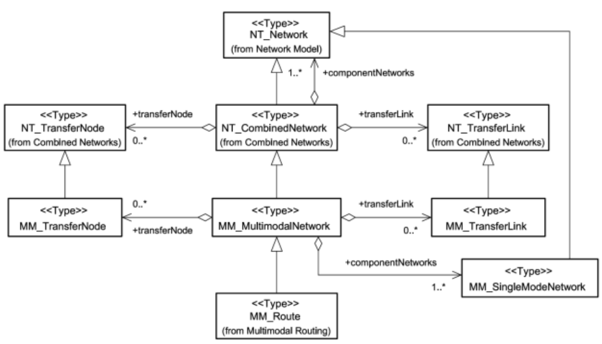

Figure 3. Context diagram for multimodal network in ISO 19134 (ISO, 2007)

Early research on multimodal network integration has primarily focused on unifying independently constructed networks for different transport modes. Zhang et al. (2011) proposed a super network in which transfer links are used to connect separately built networks. This approach was later generalized with the introduction of the multilayer network concepts. Boccaletti et al. (2014) and Kivelä et al. (2014) defined the multilayer network structure and established a conceptual foundation for explaining the relationships between heterogeneous networks. Subsequently, Aleta et al. (2017) modeled transfer possibilities by suggesting interlayer links when transit stops of different modes are within a certain spatial threshold, demonstrating that network integration considering spatial adjacency is possible. Dib et al. (2017) proposed a hierarchical structure in which major transfer points are designated as hubs, and the connections between them are optimized to enhance the efficiency of multimodal routing. Cai et al. (2022) classified transfer-related links such as alighting link, embarking link, auxiliary link, and transfer link. They proposed cost estimation methods that consider onboard movement time, walking distance, and walking time. Baum et al. (2023) introduced a flexible model that incorporates transfer graphs involving secondary transport modes, such as walking or cycling, into the public transportation network. However, their public transportation graph is based on a time-dependent model and primarily emphasizes scheduling constraints, without focusing on the structure of spaces. While these studies have laid the foundation for multimodal network integration, they simplify the integration between networks into a single link, limiting their ability to represent the continuity and spatial structure of real-world movements accurately.

From the implementation perspective, commercial software such as TransCAD and ArcGIS also supports multimodal network integration. When integrating transport networks, connections are typically made based on intersection points, requiring physical splitting of the existing network. While this approach is straightforward to implement, it compromises the consistency of the original network and reduces flexibility in terms of maintenance and scalability.

To address these limitations, recent studies have begun to model transfer points not as single locations, but spatial objects, explicitly representing the internal movement paths within these spaces using network structure. Yan et al. (2011) proposed an integrated model for indoor-outdoor navigation that defines *TransitionSpace* as a core component for intermodal transition. Similarly, Claridades and Lee (2021) introduced the concept of *TransferLink* to support seamless indoor-outdoor navigation. Claridades and Lee (2023) also extended the *TransferNode* concept into a three-dimensional *TransitionGraph*, enabling the representation of internal paths as spatial networks.

This approach complemented the expressive limitation of single-node-based models and proposed a new methodology for representing the transition space itself as a network. Therefore, this study proposes a data model that can continuously represent transfer paths by extending the points where transitions occur into three-dimensional spatial objects, termed *TransferSpace*, and introducing *TransferNetwork* within them based on these approaches.

3. Proposed Model

This study proposed an extended data model based on the conceptual framework defined in ISO 19134, which complements the limitations of the existing model and enables the representation of actual transfer spaces. In ISO 19134, each mode of transportation is represented as an independent network called *SingleModeNetwork*, which consists of *SingleModeJunction* and *SingleModeLink*. A *SingleModeJunction* represents a location where a turn or direction change can occur, while a *SingleModeLink* denotes a traversable segment between such junctions. The specific type of transport segment is described using the *routeSegmentCategory* attribute. For example, in bus mode, bus stops are represented as *SingleModeJunctions*, while the actual paths between stops are expressed as *SingleModeLinks*.

However, as previously discussed, ISO 19134 defines the integration of these *SingleModeNetworks* through a single point known as a *TransferNode*. This abstract representation of modal transitions fails to reflect the physical reality of multimodal transitions. Especially in large transit stations, critical components of the transfer process, such as corridors, stairways, and escalators, can not be represented in the existing model.

To overcome these limitations, this study introduces the concept of *TransferSpace*, which extends the existing *TransferNode* concept to a spatial object. A *TransferSpace* is defined as a three-dimensional spatial object where transitions between different *SingleModeNetworks* occur. It allows transfer spaces to be modeled as independent physical entities. To represent the internal structure of these spaces in detail, a network structure defined as *TransferNetwork* is proposed.

A *TransferNetwork* consists of *TransferJunction* and *TransferLink*. A *TransferJunction* represents key locations within a transfer space, such as entrances, elevators, and lobbies, where directional changes occur. A *TransferLink* is a linear object that represents paths connecting these junctions, expressing the detailed movement within the transfer space. Figure 4 compares the ISO 19134 structure with the *TransferSpace*-based structure proposed in the study. While the existing model abstracts transfer as single nodes, the proposed model introduces internal networks within *TransferSpace*, enabling continuous and spatially explicit representation of actual transfer paths.

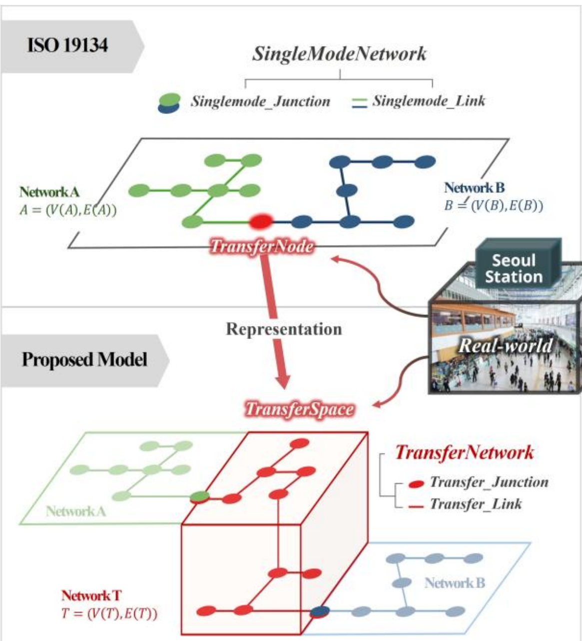

Figure 4. *TransferSpace* for representing real-world transfer environments

In addition, this study defines a new logical feature, *InterConnectionLink*, to explicitly express the connectivity between different network layers. *InterConnectionLink* is used to express topological relationships, defining the connectivity between a *SingleModeJunction* belonging to *SingleModeNetwork* and a *TransferJunction* belonging to *TransferNetwork*. This feature does not represent physical paths, but rather functions as a means of explicitly modeling transitions and structural connections between networks.

In a situation where a passenger moves through a stairway to access a subway platform for boarding, the stairway entrance is modeled as a *TransferJunction*, and the platform boarding point is represented as a *SingleModeJuntion*. A logical connectivity between these two features, corresponding to a modal transition, is established through an *InterConnectionLink*. Attributes such as transfer time, walking distance, or transition cost can be assigned to *InterConnectionLink*, allowing it to serve as a weighting factor in pathfinding algorithms.

A key advantage of the proposed model in this study is that it enables the integration of multimodal networks without requiring physical segmentation or modification of the original *SingleModeNetwork*. In contrast, existing commercial software, which requires physical restrictions for integration, the *InterConnectionLink* as illustrated in Figure 5, allows different transport networks to be logically integrated while preserving the origin network structures, thereby maintaining the integrity of each network dataset.

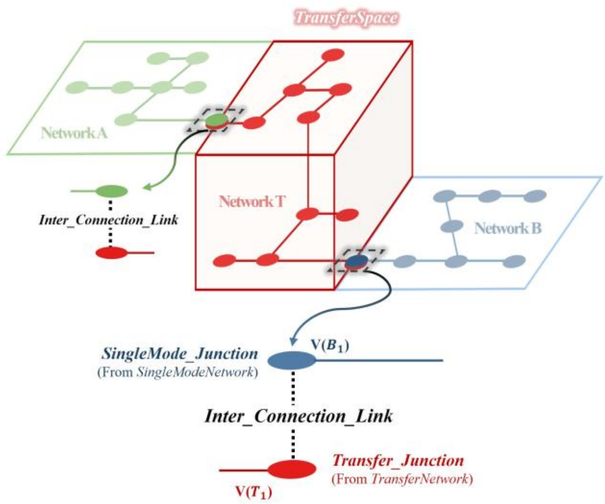

Figure 5. Integration of networks using *InterConnectionLink*

Figure 6 shows the overall structure of the multimodal transportation network data model proposed in this study based on UML. The proposed model extends the ISO 19134 framework by defining TransferNetwork as a separate network layer for representing modal transition and connecting it with existing *SingleModeNetworks*. All network classes inherit from the abstract superclass *NT_Network*, defined in ISO 19133:2005-Tracking and navigation. This superclass is extended into *NT_CombinedNetwork,* which enables the integration of multiple network instances within a unified framework.

Based on this structure, *MM_MultimodalNetwork* is defined to support multimodal routing. It aggregates three components: *MM_SingleModeNetwork*, which represents the routes of individual transport modes; *TransferNetwork*, which models the transfer paths between different modes; and *InterConnectionLink*, which defines the topological relationships between the networks. Each of these components is structured as an independent layer, but is topologically interconnected to form an integrated multimodal transportation network.

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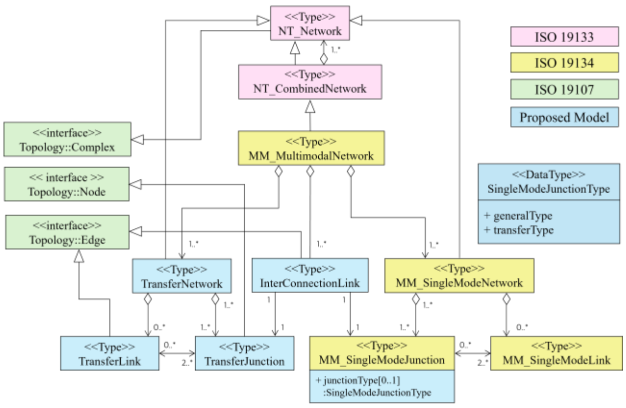

Figure 6. Proposed data model for multimodal transportation

The *MM_SingleModeJunction* includes an attribute named junctionType, which defines the functional role of each junction as either *generalType* or *transferType*. Junctions classified as *generalType* represent ordinary navigation points within a single-mode network. At the same time, those marked as *transferType* indicate intermodal transition points that are topologically connected to *TransferJunction* in the *TransferNetwork*.

The proposed classes—*TransferJunction*, *TransferLink*, and *InterConnectionLink*—are designed based on the topology schema defined in ISO 19107:2019-Geographic information-Spatial schema. These components are not limited to representing geometric entities but are explicitly structured to capture topological relationships across different network layers. In this framework, a *TransferJunction* corresponds to *Topology::Node* and represents a key access point within a *TransferSpace*. *TransferLink* and *InterConnectionLink* are modeled according to the concept of *Topology::Edge*, ensuring that network connectivity is topologically structured while maintaining independence between layers.

4. Case Study on Integrating Multimodal Transportation Networks

This section presents a complex transfer scenario centered on Seoul Station, a major multimodal transport hub, to evaluate the applicability of the proposed data model. As it serves as an interchange for buses, the subway, and trains, and has multiple entrances and platforms, Seoul Station is a suitable testbed for assessing the feasibility of the multimodal navigation data model.

Figure 7 shows the results of a multimodal transfer route generated using the routing function provided by Google Maps, a commercial closed mapping application. In this scenario, a user walks from the origin to a nearby bus stop, rides a bus, gets off at a stop near Seoul Station, and transfers to the subway to reach the final destination. However, the routing result excludes the segment involving the passenger's movement through the interior of Seoul Station from the bus stop to the subway platform. This part of the journey requires representing a complex indoor environment, but existing commercial mapping platforms do not explicitly model or visualize such movements within their routing planning.

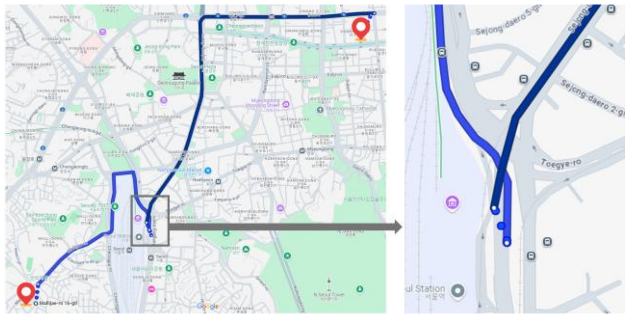

Figure 7. Multimodal transfer route from Google Maps

The proposed data model in this paper addresses this limitation, the interior of Seoul Station as *TransferSpace*, within which the internal path is modeled using a *TransferNetwork*. Figure 8 presents a comparative visualization of transfer routes derived from a commercial closed mapping application and those generated using the proposed model, highlighting the differences in how an identical transfer scenario is represented under each approach.

In existing approaches, transfers are modeled as simple links connecting bus stops and subway stations, both represented as single-point entities, thereby neglecting the internal spatial structure and actual pedestrian movement. In contrast, the proposed model explicitly incorporates TransferNetwork within the TransferSpace, and this allows for more precise and continuous representation of the transfer route within complex indoor environments.

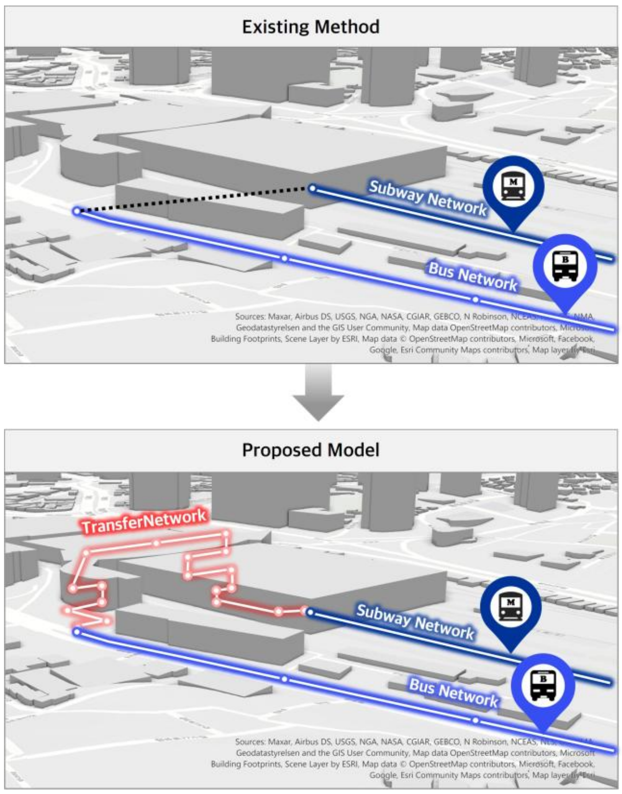

Figure 8. Comparison of transfer route representations in a multimodal navigation scenario

Each transport network retains its original structure and is logically integrated through *InterConnectionLink*, resulting in a multimodal transportation network. Figure 9 illustrates how these links are applied in the transfer scenario to establish topological relationships between junctions in the *SingleModeNetwork* and those within the *TransferNetwork*. These links provide a clear representation of modal transitions at the network level.

Furthermore, *InterConnectionLink* is designed to assign cost attributes based on physical distance or estimated travel time. For instance, if two junctions are physically located at the same location, the cost value is set to zero to enable immediate modal transition. Conversely, if the junctions are not at the same location, the dynamic cost can be calculated based on actual distance or time. This approach serves as a crucial mechanism in integrating different networks, maintaining the structural integrity of each network while enabling pathfinding algorithms to reflect the practical constraints of modal transition.

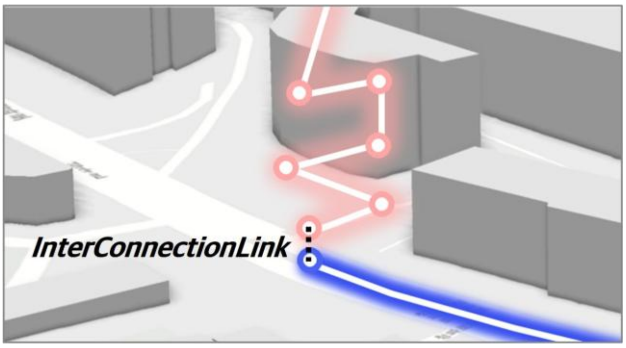

Figure 9. Topological relationship of multimodal networks via *InterConnectionLink*

5. Conclusion

This study presents an extended data model for multimodal transportation by redefining modal transitions from a conventional point-based *TransferNode* to a spatial representation referred to as *TransferSpace*. The proposed model enables the explicit modeling of movement paths within micro-scale environments by embedding a TransferNetwork within each TransferSpace, thereby facilitating a human-oriented approach to multimodal navigation. A significant advantage of this approach is its capacity to capture the three-dimensional characteristics of transfer environments explicitly. As such, the proposed model could be used not only for route guidance, but also for a range of other Smart City services, such as pedestrian congestion analysis and movement simulation. For instance, it can be used to simulate movement in complex indoor environments or to evaluate accessible routes for users with mobility impairments.

Nevertheless, the current framework has the limitation that *InterConnectionLinks* are statically defined and do not adapt dynamically based on users' movement contexts. Future research should therefore consider ways to enable dynamic linking that responds to real-time routing conditions. Furthermore, integrating emerging mobility modes, such as UAM and autonomous vehicle-based services, into the network structure is an important area for further investigation. In conclusion, the proposed data model not only facilitates seamless integration of heterogeneous transport networks but also establishes a new multimodal network framework that supports precise three-dimensional representation of transfer environments. This work is expected to contribute as a core component of next-generation Smart City transportation infrastructure.

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