

Research on Moving Objects with Multimodal Transportation Modes

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ABSTRACT

In spite of massive research having been conducted on moving objects databases, existing methods can not manage moving objects with transportation modes and covering multiple environments, e.g., *Walk* \rightarrow *Car* \rightarrow *Indoor*. The current techniques target a single environment, for example road network. But humans' movement can include several environments like roads, pavement areas, buildings, which imposes new challenges regarding representation and management of these mobile data and efficient query processing in a database system. In this paper, we first present a data model for representing generic moving objects in multiple environments. The method is to let the space where moving objects are located consist of a set of called *infrastructure objects* like streets, pavements, moving buses, and then the location of a moving object is represented by referencing to these *infrastructure objects*. In the meantime, transportation modes are seamlessly integrated. Second, to evaluate the performance of a database system, a benchmark comprising of a scalable dataset and a set of queries is required. We propose a method to create all *infrastructure objects* as well as generic moving objects due to the major challenge of getting the real data. A list of queries is given which will be used for the evaluation.

1. INTRODUCTION

Recently, researchers start to explore the area of moving objects with different transportation modes (e.g., *Walk*, *Car*, *Bus*) [27, 6, 26] as humans' movement can cover several different environments like road network, pavement areas. At the same time, people can have several options of transportation modes for their traveling (not only by car) depending on locations, cost, daily habit, etc., thus their movement contains not only the position data but also motion modes. This leads to taking into account transportation modes becoming increasingly essential for moving objects.

1.1 Motivation

Consider the following two example movement scenarios of *Bobby*:

M_1 : *walks from his house to the parking lots, and then drives the car along the road and highway to his office building, finally walks from the underground garage to his office room.*

M_2 : *walks from the house to a bus stop, and then takes a bus to the train station, moves from one city to another by train, finally walks from the train station to his office room.*

Although moving objects databases have been extensively investigated in recent years due to their wide applications, e.g., nearest neighbor queries, trajectory searching and querying, the data processed so far only include outdoor and is limited in a single environment. Thus, it can not answer queries referring to multiple environments and transportation modes (e.g., "Where is *Bobby* at 8:00 am, e.g., at home, on the street or in the office room?", or "How long does *Bobby* walk during his trip?"). A challenge is posed for managing moving objects in all available environments (outdoor and indoor) in a database system.

In the literature there are already many data models for moving objects [24, 10, 12, 13, 21, 17], but none of them can represent moving objects with multiple transportation modes. The existing approaches only address the issue in a specific environment (*free space* [10, 12], *road network* [11] and *indoor* [16, 15]). The data representation and manipulation are different according to the environment, but people's movement can cover several environments. M_1 includes pavement areas, road network and indoor, while M_2 comprises pavement areas, public transportation network and indoor. Most existing methods [24, 25, 10, 12] use a two-tuple (x, y) to identify the location, obviously it can not apply for *indoor* as it is a 3D environment. It is possible to extend the two-tuple to a triple (x, y, z) to represent the location, but the method only focuses on geometric properties (e.g., coordinates). The raw location data (x, y, z) means nothing else than three real numbers so that it can not recognize which part is for walking and which is for driving. To answer the second query, one initially has to recognize the *Walk* part in the whole movement, but raw location data can not express such a kind of information. This makes the exploration of a new data model to manage the complete movement in a database system.

Although collecting large volumes of outdoor mobile data becomes practical in recent years, these data only include position information and can not answer queries on transportation modes. Microsoft *GeoLife* project [1] is to learn and discover transportation modes of people’s movement from raw GPS data to enrich the mobility with informative and context knowledge [27, 26]. The difficulty is how to partition a user’s trajectory into several segments and identify the mode for each piece, because the user’s trajectory can contain multiple kinds of modes and the velocity of a mode suffers from the variable traffic condition. [6] presents a data model for trip plannings in a multimodal transportation system which can give the answer containing different motion modes (e.g., *Walk* \rightarrow *Bus* \rightarrow *Train*) and the constraint on a specific mode, for example, less than two bus transfers. They do not focus on modeling moving objects with transportation modes, and indoor moving objects are not processed, while we propose a method for representing and managing generic moving objects covering all outdoor environments as well as indoor in a database system.

To evaluate the performance of DBMSs managing these moving objects, a scalable dataset is required. A benchmark for moving objects in free space is presented in [9] providing a well-defined dataset and a set of queries. And indexing techniques [7, 8] are used in order to enable efficient query processing. However, there are no infrastructure objects in [9] and moving objects have only one mode: *Car*. But now the datasets consisting of objects moving in several environments and referenced objects are needed. At the same time, to produce generic moving objects based on the result of trip plannings, a complete navigation system through all environments (outdoor and indoor) should be developed. Most existing work for trip plannings [23, 14, 18] are limited in one environment.

1.2 Our Proposed Approach

To represent generic moving objects in multiple environments, the *reference* method [19] can be used. We consider the geographic *space* is covered by a set of so-called *infrastructures*, where each corresponds to an environment. For example, *Road Network* is a kind of *infrastructure*, and *Indoor* is also an *infrastructure*. For each *infrastructure* consisting of a set of *infrastructure objects*, we model its available places as well as the relative position within a place. Roads and streets are *infrastructure objects* for *Road Network* and rooms, staircases, corridors constitute the *Indoor* infrastructure. Afterwards, we represent the location by *mapping* it to these geo-referenced *infrastructures*, more specifically, *mapping* it to *infrastructure objects*. In the meantime, the transportation modes are seamlessly integrated into moving objects. Furthermore, the location of a moving object is managed in a multi-scale way where both precise and rough representations are supported because for some applications [22] rough representation can suffice.

We propose a method to create all *infrastructure objects* based only on a real road dataset which can be easily obtained and public floor plans (e.g., [4, 3]) for indoor data. Consequently, the method can be available for other researchers to create their own miniworlds (roads, pavements, buildings, etc). Generic moving objects are created on the result of trip plannings which are able to provide the move-

ment through all available environments where the start and end position can be located on any infrastructure object, e.g., on the road or in an office room. The generated datasets and a range of well defined queries constitute the benchmark, which is to measure the performance of a database system managing generic moving objects.

The contribution of the existing and ongoing Ph.D project to the problem is summarized as follows:

- A data model is proposed for managing generic moving objects where transportation modes are seamlessly integrated, as well as the representation of all available infrastructure objects referenced by moving objects for location representation.
- Based on road datasets and public floor plans, we propose a method to create a miniworld consisting of infrastructure objects and generic moving objects. A benchmark is to be developed for evaluating the performance of a database system managing these data.
- The navigation in a specific environment is available, e.g., trip plannings for pedestrians, indoor navigation. A complete navigation system through all environments is to be supported.

The rest of the paper is organized as follows: Section 2 outlines the framework of the generic data model. Section 3 describes the benchmark for a database system managing generic moving objects consisting of datasets and queries. Section 4 broadly overviews the related work.

2. DATA MODEL

2.1 Space

We let the *space* where an object moves be covered by a set of *infrastructures* where each *infrastructure* covers some places and is related to a kind of transportation mode. Table 1 lists all infrastructures considered and the classification of movements on available places as well as the corresponding transportation modes. For the special case that the movement has no constraint in the environment (i.e., Free Space), we let any outdoor mode be available. Note that people also walk in the *Indoor* space, in the following when we say mode *Walk* this refers to outdoor environment by default, which is to distinguish the modes between *Walk* and *Indoor*. Let D_{tm} ¹ be the carrier set for the data type (can be considered as the enum type) representing transportation modes, which is defined in the following.

Definition 1. Transportation Mode

$$D_{tm} = \{Car, Bus, Train, Walk, Indoor, Metro, Taxi, Bicycle\}$$

Each *infrastructure* is composed of a set of *infrastructure objects* representing available places for moving objects. Different data types are used for *infrastructure objects* according

¹Using the algebraic terminology that for a data type α , its domain or carrier set is denoted as D_α .

Table 1: Classification of Movements

Infrastructures	Places	Transportation Modes
Public Transportation Network (<i>PTN</i> for short)	railways bus routes	<i>Train, Metro</i> <i>Bus</i>
Road Network (<i>RN</i> for short)	roads, highways, streets	<i>Car, Bicycle, Taxi</i>
Region-based Outdoor (<i>RBO</i> for short)	pavement areas	<i>Walk</i>
Indoor	buildings	<i>Indoor</i>
Free Space (<i>FS</i> for short)	anywhere	any outdoor mode

to the *infrastructure* characteristic. For instance, in *RN* a line value is used to describe the geometrical property of a road or a highway, and in *RBO* it turns out that polygons are to identify pavement areas for people walking. To be general, we give the definition representing all *infrastructure objects* as follows.

Definition 2. General Infrastructure Object

Let $IO(oid, s, \beta, name)$ denote an infrastructure object where $oid(\in D_{int})$ is a unique object identifier, s denotes the data type, β is the value of s , and a string value $name$ is to describe the name of the object.

Let $I = \{I_{PTN}, I_{Indoor}, I_{RBO}, I_{RN}, I_{FS}\}$ be the set of all *infrastructures*, and $Dom(I_i)(I_i \in I)$ be the set of values (*infrastructure objects*) for the infrastructure I_i . For example, $Dom(I_{RN})$ is the set of all roads and streets. Then, we define the *space* where an object moves as follows:

Definition 3. A *space* is defined as a set of infrastructure objects from all infrastructures, denoted by

$$Space = \bigcup_{I_i \in I} Dom(I_i)$$

Let *space* be the data type representing the space, its domain is: $D_{space} = Space$.

The whole space is comprised of a set of *infrastructure objects*. Note that the moving buses or trains (for I_{PTN}) are also considered as *infrastructure objects* where the places they cover are bus routes. Based on the *full* space, in the next subsection we propose the method to represent locations for generic moving objects.

2.2 Generic Moving Objects

Using the *reference* method, we represent the location of a moving object by a function from time to an object identifier corresponding to an *infrastructure object* as well as the relative position in that object. More formally, it is defined as follows.

Definition 4. Generic Location

$$Loc = \{(\delta_1, \delta_2) | \delta_1, \delta_2 \in D_{real}\}$$

$$D_{genloc} = \{(oid, i_{loc}) | oid \in D_{int}, i_{loc} \in Loc\}$$

We call it *Generic Location* as it can represent locations of moving objects in all environments listed in Table 1. Each element in *Loc* has two attributes denoted by δ_1, δ_2 for the position description. For the elements in D_{genloc} , each consists of two attributes where oid is the infrastructure object identifier and i_{loc} describes the position in the object. For example, if oid corresponds to a polygon for the pavement, then (δ_1, δ_2) denotes the relative position in that pavement. For the infrastructure I_{FS} which is an empty set, oid is set as undefined and (δ_1, δ_2) represents the location in the space. Based on Definition 4, now we give the representation for moving objects location.

Definition 5. Let f be the location function projecting from time to a location. The definition is as follows:

$$f : D_{instant} \rightarrow D_{genloc}$$

The continuous changing location data is represented by a function f where $D_{instant}$ (domain) denotes the time instant and D_{genloc} (range) represents the set of elements for locations. Table 2 lists the location functions (distinguished by subscripts) for different infrastructures and the meanings are: (1) $f_{\perp}(t)$ maps to a position in free space; (2) $f_r(t)$ maps to a region (room) and the relative position in that region (room); (3) $f_i(t)$ maps to the relative location along a road line (a bus route); (4) $f_m(t)$ maps to a moving bus.

Location Mapping	Infrastructures
$f_{\perp}(t) = (\perp, (\delta_1, \delta_2))$	<i>FS</i>
$f_r(t) = (oid, (\delta_1, \delta_2))$	<i>RBO, Indoor</i>
$f_i(t) = (oid, (\delta_1, \perp))$	<i>RN, PTN</i>
$f_m(t) = (oid, (\perp, \perp))$	<i>PTN</i>

Table 2: Different Location Mappings

We focus on the complete history movement of moving objects which can also be called *trajectory*, instead of current and future position. Using the method of *sliced representation* [10], we represent a moving object as a set of so-called *temporal units (slices)*. Each *unit* defines a time interval as well as the movement during it. The definitions of generic temporal units and generic moving objects are given as follows:

Definition 6. Generic Temporal Units

$$Gentu = \{(i, oid, i_{loc1}, i_{loc2}, m) | i \in D_{interval},$$

$$oid \in D_{int}, i_{loc1}, i_{loc2} \in Loc, m \in D_{tm}\}$$

Definition 7. Generic Moving Objects

$D_{\underline{genmo}} = \{ \langle u_1, u_2, \dots, u_n \rangle \mid n \geq 0, n \in D_{\underline{int}}, \text{ and} \}$

(i) $\forall i \in [1, n], u_i \in \underline{Gentu}$; (ii) $\forall i, j \in [1, n], i \neq j \Rightarrow$

$u_i.i \cap u_j.i = \emptyset \wedge u_i, u_j \text{ are not mergeable} \}$

We define two units u_i, u_j are *mergeable* as follows. Let T_i, T_j (e.g., $[0, u_i.i.e - u_i.i.s]$) be the relative time intervals of u_i and u_j , and p_i, p_j be the start location of u_i and u_j . We give the evaluation functions for u_i and u_j .

$f_{u_i}(t) = \{(x, y) \mid x = p_i.x + a_i \cdot t, y = p_i.y + b_i \cdot t, t \in T_i, a_i, b_i \in C\}$

$f_{u_j}(t) = \{(x, y) \mid x = p_j.x + a_j \cdot t, y = p_j.y + b_j \cdot t, t \in T_j, a_j, b_j \in C\}$

u_i and u_j are *mergeable* \Leftrightarrow (i) $u_i.oid = u_j.oid \wedge u_i.m = u_j.m$; (ii) $u_i.i$ is *adjacent* to $u_j.i$; (iii) $f_{u_i}(T_i.e) = f_{u_j}(T_j.s) \wedge a_i = a_j \wedge b_i = b_j$.

Each moving object consists of a sequence of temporal units where each unit corresponds to an infrastructure object, the movement in that infrastructure object and a kind of transportation mode. Within this framework, we can describe objects' movement in various environments. Next, we define a data type called *genrange* representing moving objects' trajectories which are curves in space.

Definition 8. Range Location

$\underline{Subrange} = \{(oid, l, m) \mid oid \in D_{\underline{int}}, l \in D_{\underline{line}}, m \in D_{\underline{tm}}\}$

$D_{\underline{genrange}} = \{V \subset \underline{Subrange}\}$

The data model represents moving objects over all environments and is consistent with previous work [12, 11] for a specific infrastructure. Transportation modes are seamlessly integrated so that the queries in the introduction can be answered by the model. With the generic location representation, one can know not only the position in space but also the environment where the object is located, e.g., a street or a room. There are two kinds of data update (1) update for infrastructure objects and (2) update for travelers where the former does not occur frequently. With the referencing method, both the update and storage cost for travelers can be greatly reduced. For example, assuming a traveler takes a bus, instead of recording the data at all possible locations that the bus speed or direction changes, now only one unit is required (referencing to the bus). And if several passengers take the same bus, all of them can *reference* to the same *infrastructure object*. Otherwise, the location data for each of them has to be stored. In addition, one does not have to update the data for travelers until they get off the bus or switch to another one. The location is represented in a multiresolution way where both precise and approximate data are managed. One can only reference to the infrastructure object where the precise movement inside can be ignored. For some applications [22], the approximate location can suffice.

2.3 Representation for Infrastructure Objects

As stated above, *infrastructure objects* are represented by different data types according to the specific *infrastructure* where I_{FS} is an empty *infrastructure*. For I_{RN} , a road or a highway is abstractly described by a polyline. Polygons are *infrastructure objects* for I_{RBO} . The public transportation system includes buses, metros and trains. As they have similar behaviors, we take the buses as an example where the elements in I_{PTN} are bus routes, bus stops and moving buses. For the indoor environment, the elements are rooms, corridors, staircases, elevators, etc. Due to space limitations, we omit describing the representation in detail in this paper.

2.4 Operators and Implementation

A group of operators is designed on the proposed data types for data manipulation where previous work [10, 12, 11] are all integrated, because the generic model is consistent with them for each specific environment. An interface is provided to exchange information between values of the proposed data types and a relational environment. A relation is used to store infrastructure objects for an environment. We give some operators as examples.

- Construct the whole space by

(1) $\underline{rel} \rightarrow \underline{space} \quad \text{createspace}$
(2) $\underline{space} \times \underline{rel} \rightarrow \underline{space} \quad \text{put_infra}$

Retrieve a specific infrastructure from the space

$\underline{space} \times \underline{tm} \rightarrow \underline{rel} \quad \text{get_infra}$

- A moving object can be restricted to a submovement by the transportation mode.

$\underline{genmo} \times \underline{tm} \rightarrow \underline{genmo} \quad \text{at}$

The operator **createspace** takes in the relevant information for one infrastructure described by a relation. The input relation can be empty. In this case, the space equals to free space. In the second step, more infrastructure relations can be added into the space so that the space can cover multiple environments. One can create a full or non-full (e.g., only road network) space according to the application requirement. **at** returns the movement only with the given transportation mode, corresponding to the movement in a specific environment. With this operator, the query in the introduction (“How long does *Bobby* walk during his trip?”) can be answered.

The global space consists of a set of infrastructures where each infrastructure includes a set of infrastructure objects. Currently, the infrastructures I_{PTN} and I_{RBO} have been developed already. I_{RN} can directly utilize the work in [11] and I_{Indoor} is still in progress.

3. A BENCHMARK FOR GENERIC MOVING OBJECTS

3.1 Datasets

The datasets consist of two parts: *infrastructure objects* and generic moving objects. For the first part, *Free Space* has no infrastructure objects and there are already many available real road datasets so that we focus on the infrastructures:

I_{RBO} , I_{PTN} and I_{Indoor} . All outdoor data like pavement areas are created based on the real road dataset Berlin [2] and buildings are created based on public floor plans, e.g., [4, 3]. [20] demonstrates the infrastructure objects. Moving objects are to be generated using the result of trip plannings.

3.1.1 Infrastructure Objects

Pavements: There are two kinds of pavements where one are those located on both or one side of roads and the other are zebra crossings allowing people to cross the street. Both of them are represented by polygons and created based on polylines representing roads.

Bus Network: The public bus transportation system consists of bus routes, bus stops, and moving buses. We develop a method to create bus routes and bus stops where one bus route has two directions, which is to be realistic. The moving buses are created by their bus routes and the speed value, and each bus route has a schedule for its bus trips.

Buildings: Buildings are created based on their floor plans. A floor plan is a diagram to show in scale the relationships between rooms, spaces and other physical features at one level of a structure. A building consists of rooms, corridors, staircases, elevators, etc. To be more general, we use the term *groom* (general room) for all of them. A *groom* is represented by a set of elements each of which has two attributes: a polygon and the height above ground level (the floor at level 0 of a building). A door builds the connection between two *grooms*, and we represent a door by two elements each of which has two attributes. The first attribute is the *groom* id and the second is a line value recording the position in that *groom*. According to the floor plan, one level of the building can be created and then we translate one floor vertically to generate more floors to construct a whole building. The placement of possible buildings in a city (e.g., office buildings, hospitals) is being investigated.

3.1.2 Moving Objects based on Trip Plannings

To create a moving object, two elements are required: the path recording where it moves and the speed describing how it moves. The path is procured by the product of trip plannings returning curves in space, and the speed can be explicitly defined. Definition 8 in Section 2.2 introduced the data type representing the curves.

We have developed navigation algorithms for infrastructures I_{RBO} , I_{PTN} and I_{Indoor} so that moving objects in each specific environment can be created (navigation for I_{RN} is already available). The trip planning for pedestrians is to provide a trip with the minimum length inside the overall pavement area. In I_{PTN} , two kinds of shortest paths are supported: minimum traveling time and minimum number of transfers. For indoor navigation, three kinds of shortest paths are developed: 1) minimum length; 2) minimum traveling time; 3) minimum number of rooms passed by. A complete navigation system through all infrastructures is under development which is in order to give the answer for such a query “give me a trip with the minimum traveling time from my office to the train station”. The result may involve $Indoor \rightarrow Walk \rightarrow Bus$ or $Indoor \rightarrow Walk \rightarrow Car$.

3.2 Queries

Interesting queries on generic moving objects are those considering: 1) interactions between different transportation modes and infrastructures instead of queries constraint in an individual environment; 2) relationships between moving objects and referenced *infrastructure objects*. We classify queries into two groups and give some examples.

1. Queries on Infrastructures and Infrastructure Objects

- Q_1 : Find all people walking through the city center area on Saturday between 10:00 am and 14:00 am.
- Q_2 : Find all people taking “Bus527” on Monday morning between 7:00 am and 9:00 am.

2. Queries on Transportation Modes

- Q_3 : Who arrived by taxi at “Fern University” on Friday?
- Q_4 : Who entered bus 527 at bus stop “FernUniversity”?
- Q_5 : Did anyone who was at the “Fern University” on floor 2 between 4:30 pm and 5:00 pm take a bus to the train station?

4. RELATED WORK

All existing data models on moving objects [24, 25, 10, 12, 22, 11, 17, 15] only consider one specific environment and do not take into account transportation modes. The closest to our work is [22, 11]. A model for mobility pattern queries [22] is proposed which relies on a *discrete* view of spatio-temporal space. The movement of moving objects is based on a discrete representation of underlying space, called *reference* space. The space is partitioned into a set of zones each of which is uniquely identified by a label. Afterwards, the location is represented by mapping it into zones and a trajectory is defined as a sequence of labels. A so-called *route-oriented* model [11] is presented for moving objects in networks. It represents the road network in terms of routes and junctions, and trajectories are integrated with road networks. As moving objects in a road network are located on roads and streets, the position can be represented by a route identifier and the relative position in that route, where a *line* is used to describe the geometrical property of a route. However, the two aforementioned work share two limitations: first, the *infrastructure* there is single, *free space* in [22] and *road network* in [11], making the model not general and only feasible for one environment; second, transportation modes are not handled. Besides, in [22] the trajectory is represented in a discrete way (a sequence of timestamps) instead of continuous. Thus, they can not represent and manage moving objects in multiple environments. A graph model based approach [15] is proposed for indoor tracking moving objects using the technology *RFID*. The raw trajectory is a sequence of RFID tags and from the raw trajectory they construct and refine the trajectory. The goal is to improve the indoor tracking accuracy, which is different from the intention of this paper, modeling moving objects.

The work in Microsoft’s *GeoLife* [27, 26] focusing on discovering transportation modes from raw GPS trajectory data is

different from ours. We concentrate on representing moving objects in various environments with transportation modes instead of inferring the modes. In addition, they only take into consideration *outdoor* movement because they infer based on GPS data where a GPS receiver will lose signal indoors. A data model presented in [6] gives the framework of a transportation system which can provide a trip consisting of several transportation modes, e.g., *Bus*, *Walk*, *Train*. It integrates moving objects and graph-based databases to facilitate trip planning in urban transportation networks. They consider how to provide a path connecting an origin and destination including multiple transportation modes so that the *shortest_path* has more constraints and choices, like different motion modes, number of transfers, etc. An interesting query called *Isochrones* is considered in [5] which is to find the set of all points on a road network so that a specific point of interest can be reached within a given time span where only two modes are considered, *Walk* and *Bus*.

A benchmark for moving objects in free space is presented in [9] which is to design scalable and representative moving object data and two sets of queries. The objects there move in a single environment with only one transportation mode *Car* while we take into account all environments including outdoor and indoor. The data from Microsoft's *GeoLife* contains neither *infrastructure objects* nor indoor data which is not feasible for the evaluation. Trip plannings have been investigated in a single environment [23, 14, 18] where the aim is to provide an optimal route for query users. A graph model [6] is proposed for in a transportation network querying trips with multiple transportation modes and constraints where the trips are described conceptually and abstractly, but without indoor environment. They do not give data types representing *legs* (a sequence of vertices and edges in the graph) used for describing trips. We focus on answering trips through all environments including outdoor and indoor, as well as representing and managing them in a database system.

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