Modeling Spatiotemporal Paths for Single Moving Objects

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Abstract

In this work, we focus on modeling paths of movement that an individual moving object follows in space and time. We introduce a set of basic components for paths that serve as the basis for formalizing movement paths. We introduce a typology of paths that describes a classification of paths as open or closed paths. A broader set of path patterns is further investigated by varying temporal granularity between paths traveled on the same day, to paths taken on different days. Distinguishing the different path patterns that are possible for single moving objects provides a basis for searching and retrieving different kinds of spatiotemporal behaviors from collections of moving object data. Based on this work, it is also possible to analyze how patterns of movement may be decomposed to sets of these elemental paths in order to give a clearer understanding of the nature of movement of objects.

1 Introduction

The topic of understanding, modeling, and representing dynamics of geographic domains has been a major focus of research in the field of GIScience (see, for example, Drummond et al. 2006; Stewart Hornsby and Yuan 2008). At a University Consortium of Geographic Information

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Science (UCGIS) meeting on computation and visualization for understanding dynamics in geographic domains held in 2006, a series of research challenges were identified by participants at the workshop (http://www.ucgis.org/dynamics_workshop/). The list of topics included:

- data modeling for dynamic geographic domains,
- computation requirements for dynamics,
- visualization for geographic dynamics,
- spatiotemporal knowledge discovery,
- geographic dynamics over multiple granularities,
- spatiotemporal uncertainty and accuracy,
- dynamic social networks, and
- feature extraction and analysis of images, video, and other unstructured dynamic information sources (Yuan and Stewart Hornsby 2007).

Many of these topics are broad and include numerous subtopics that are still open for investigation. In this paper, the focus is on modeling paths of movement that an individual moving object follows in space and time. This topic cuts across several of the above areas, for example, data modeling for dynamic geographic domains, geographic dynamics over multiple granularities, and visualization for geographic dynamics. Geographic domains refer to geographic spaces such as urban or natural areas where interactions and movements between entities foster happenings that are dynamic and commonly result in change of some type.

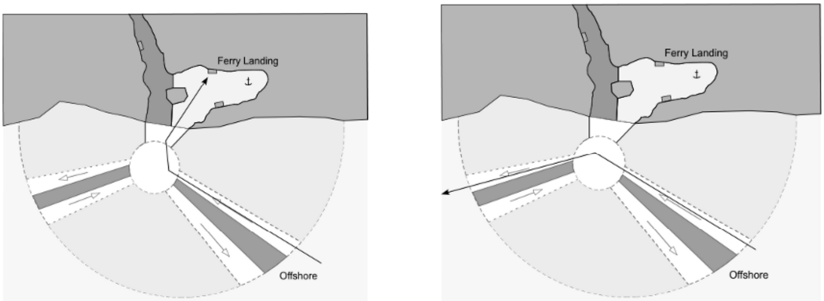
The automated collection of movement data from mobile devices captures different kinds of spatiotemporal behaviors of individuals. In this paper, we investigate a set of possible movement patterns associated with individual moving objects. We introduce a typology of different kinds of spatiotemporal paths that are associated with a single object. This typology is based on a classification of paths into *open* or *closed* paths, where movement begins at one location and ends at a different location (open path type), or *backtracking* or *looping* paths (closed path types) where the origin and destination locations are the same. Many common movements can be described based on either of these basic path types, or on a combination of types. A closer examination of open paths exposes a set of possible movement or path patterns. This set of path patterns is complementary to the work of Dodge et al. (2008) where a taxonomy of movement patterns is discussed including individual vs. group movements, generic vs. behavioral patterns, and primitive vs. compound patterns. The patterns described in this paper highlight the characteristics of individual movements in more detail based on elements of spatiotemporal paths and by considering different temporal granularities.

The rest of this paper is structured as follows: section 2 examines the topic of spatiotemporal paths and gives examples of path characteristics that researchers have studied. Section 3 introduces a formalization for spatiotemporal paths of single moving objects. A typology of paths is introduced focusing on open and closed paths. Section 4 presents a set of possible path patterns by varying temporal granularity from paths traveled on the same day to paths taken on different days. A summary and discussion of future work are presented in section 5 of the paper.

2 Modeling Spatiotemporal Paths of Moving Objects

Considerable research on modeling moving objects has focused on methods for describing the paths that a moving object follows in space-time (see for example, Forlizzi et al. 2000, Ding and Güting 2004, Du Mouza and Rigaux 2005, Güting and Schneider 2005, Dodge et al. 2008) and yet open research questions persist. A path commonly describes a spatiotemporal ordering of locations encountered by a moving object or event (Stewart Hornsby and Cole 2007). Paths are often associated with graph representations, and also with networks since graphs are frequently viewed as the more general form of a network. A path captures, for example, a sequence of nodes and edges in a geospatial network used to represent the route traversed by a moving vehicle on a road network. Common path operations include shortest path computations where a route is returned based on the shortest possible path through the network (for an overview of related research on shortest path computations, see Shirabe 2005), or computing the simplest path where the complexity of instructions is minimized (Duckham and Kulik 2003, Richter and Duckham 2008). In time geography research, analyses focus on space-time paths in order to understand patterns of peoples' activities along these paths (see for example, Miller 2008; Raubal et al. 2004; Shaw et al. 2008; Kwan and Ren 2008). Paths are also the basis for modeling movements that are not constrained by networks, such as the paths followed by birds and animals (Laube et al. 2005; Laube et al. 2007) or ships on open water (Cole and Hornsby 2005; Stewart Hornsby and Cole 2007). Paths not only model sequences of space-time locations, but they serve as a form of aggregation where individual locations visited by moving objects or events are abstracted into a path. Paths may sometimes be uncertain (Shokri et al. 2006). Using a path as a basic element of movement allow computations to be made that return solutions for queries such as *Where should I next turn?* or *How much farther is it to the Italian restauran*t? (Güting et al. 2000).

As described above, paths can be computed based on any number of attributes, for example, the path that maximizes privacy, the most scenic path, the fastest path, etc. In this way, different paths of movement suggest different semantics as for example, the semantics associated with the path a ship takes from offshore to its destination in the harbor (i.e., an expected path) (Fig. 1a) that can be contrasted with a path where a vessel returns to the offshore zone without reaching any destination zone such as the ferry landing (i.e., an unexpected path) (Fig. 1b) (Cole and Hornsby 2005).



(a) (b)

Fig. 1. (a) Expected ship movement from offshore to the ferry landing and (b) an unexpected path where the ship moves away from the harbor without arriving at any destination (after Cole and Hornsby 2005).

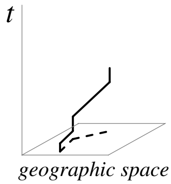
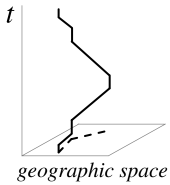
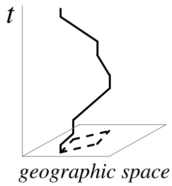
Other paths may correspond to more than one moving object and together these paths offer meaningful insights into movement. Such is the case, for example, where multiple ships are moving such that they are shown to converge in the same zone of the harbor, perhaps going to the aid of another ship or multiple ships are leaving an area, perhaps avoiding some event that has occurred (Stewart Hornsby and Cole 2007). In all of these cases, both for the single moving object and for multiple objects, paths can model expected or unexpected deviations in spatiotemporal characteristics of movement or interesting *spatiotemporal behaviors*. In this paper, we examine the topic of spatiotemporal behaviors further by deriving a typology of paths that describes the movements of single moving objects in more detail. To expand on the typology, the temporal granularity is varied from movements on the same day to movements on different days in order to investigate the range of possible path patterns and understand how they vary according to different temporal granularities. Adopting this framework for modeling paths may impose a certain perspective on movement related, for example, to studying movement patterns of people's daily activities. But of course, a modeler could also choose to select a temporal granularity that avoids this type of discretization and corresponds, for example, to discrete timestamps. Here, our interest is in developing a classification of paths and so we explore different temporal choices.

3 Modeling Spatiotemporal Paths of Movement: Open and Closed Paths

To facilitate the discussion of paths, we introduce a formalism where the notation ${}^{date_k}_{id_j}P_i$ is used to represent paths P_i *where* $i = 0, 1, ..., n$. The notation id_j *where j= 0,1,…,m* distinguishes different moving objects that travel along a path on a given $date_k$, where *k=0,1,…,r.* Note that in this work we distinguish both date and time separately such that it is possible to describe varying temporal semantics including day, week, month, and year (i.e., dates) and also hours, minutes, and seconds (i.e., times). A path can be modeled as a set of locations visited by a moving object over time such that ${}^{date_k}_{id_j}P_i = \{loc_{0,t_0}, loc_{1,t_1}, ..., loc_{n,t_n}\}$ where $t_0 < t_1 < \ldots < t_n$, and < refers to precedence (i.e., $t_0 < t_1$ means that time t_0 is before t_1). In this work, loc_{0,t_0} is the *source* or origin location at time t_0 (start_time) and loc_{n,t_n} is the *destination* location at time t_n (end_time). In addition to the source and destination, a path may have *route* components that model a set of key locations that distinguish the path (i.e., locations where the moving object turned, paused, stopped for a period of time, or was simply being recorded as having been there by, for example, a GPS tracking system). These route elements correspond, for example, to any of the locations visited between locations loc_0 and loc_n such as loc_1. This treatment of route elements may differ from formalizations used for other modeling tasks involving moving objects, but our focus here is on an abstract or higher-level view of paths in order to develop a classification of paths and their patterns of occurrence.

Such a classification begins with paths that correspond to the movement of a single moving object moving from a source location to a (different) destination location (i.e., an *open* path). These paths correspond to movements over a set of locations that range from *0,1,…,n* where *n* is the number of locations visited beginning with the source location and ending with the destination location (e.g., Table 1, *P1-1*), and the number of observed time steps that range from *0,1,…,n* where *n* corresponds to the last location that is visited, such that $loc_{0,t_0}(P_i) \neq loc_{n,t_n}(P_i)$ (i.e., source and destination of a path are *not* the same) (Table 1, *P1-1*). This common type of path can be contrasted with a *closed* path, the case where a moving object moves some distance from a source location and returns to that same location for its destination, i.e., $loc_0(P_i) = loc_n(P_i)$. These two basic path types have also been distinguished in studies on geospatial lifelines, where, for example, modelers are interested in capturing all the possible locations a moving object may visit when travelling between a source and destination (Hornsby and Egenhofer 2002; Miller 2006). The routes of closed paths can take different forms resulting in two types of closed paths (Table 1, *P1-2* and *P1-3*). In Table 1, the second column contains graphical representations of these path patterns. The vertical axis *t* represents the temporal dimension, and the other two axes are the *X* and *Y* axes of the geographic space. The solid line in the graph represents the movement path in time and geographic space, and the dashed line represents the projection of this path on the surface of the geographic space. A vertical segment in the graph that projects to a point on the geographic space represents the elapsed time that the moving object spends at a stopping point (i.e., route element). In the second case, the route out and back is the same (capturing the semantics of backtracking), i.e., for this case, locations range from *0,1,…,n* such that loc_0 is the source location, $loc_{n/2}$ models the location that represents the farthest distance travelled before turning back, and loc_n models the location of the destination that is the same as the origin (e.g., path *P1-2*). For this case, the temporal properties of the path has times that range from *0,1,…,n*, i.e., $t_{n/2}$ models the time that corresponds to the location of the farthest point visited before turning back on the route and completing the movement at time t_n. The third case of closed paths is where the route out and back are different to each other, forming a closed loop that ends back at the source location (e.g., *P1-3*). For this case, the source location is the same as the destination location (i.e., $loc_0 = loc_n$) although locations in between are different from each other (i.e., $loc_1 \neq loc_2 \neq, ..., \neq loc_{n-1}$) and the times associated with the path vary from *0,1,…,n.* Also for this case, there is usually no need to distinguish the point of maximal travel, unlike the backtracking case where it is useful to distinguish the point where the moving object turns back.

Table 1. Patterns of paths for single moving objects

Pattern		Spatial properties	Temporal properties
P1-1		$loc_{0,\ldots,n}$ where $loc_0 \neq loc_1 \neq,\ldots,\neq loc_n$	$t_{0,\ldots,n}$
P1-2		$loc_{0,\ldots,n}$ where $loc_0(P_i) = loc_n(P_i)$ and $loc_x = loc_{n-x}$ where x=1,…,n-1 and $loc_{n/2}$ is the last location visited in the set of locations before turning back	$t_{0,\ldots,n}$
P1-3		$loc_{0,\ldots,n}$ where $loc_0(P_i) = loc_n(P_i)$ and $loc_1 \neq loc_2 \neq,\ldots,\neq loc_{n-1}$	$t_{0,\ldots,n}$

Given these two basic types of paths, open and closed, it is possible to describe paths that are based on a combination of both these path types. There may be combinations that are *open-open*, *open-closed*, *closed-open*, and *closed-closed*, as well as sequences of these types (e.g., *open-closed-open*). The first combination, *open-open*, refers to a single path that is combined with another single path. This is a common setting for moving objects and could describe pairings of paths that a single moving object follows. In this case, spatial granularity or level of detail is obviously an important consideration since an *open-open* combination emphasizes the path characteristics as being composed of two distinct paths where the destination of the first path equals the source of the subsequent path.

Given this understanding about granularity, the *open-closed* combination could describe the case where a person drives to a trailhead and then hikes a loop trail that end up back at the trailhead. A *closed-open* combination describes a drive around a loop road in a park followed by a drive to a restaurant. *Closed-closed* combinations model successive loops such as made by vehicle circling the block looking at a house for sale (and possibly doing a different sized or shaped loop each time), searching for a parking space by circling the block, or could also describe separate repeated trips up and down a street. For example, within one day, sets of paths may correspond to *P1-3* and *P1-2* and a combination of *P1-1* and *P1-3* (Fig. 2). The role of time is important for distinguishing these different semantics and capturing the notion of *repeated* (i.e., same path at different times or dates) or *successive* trips (different paths that follow on from each other, e.g., in the course of one day).

Fig. 2. Paths of a single object over one day. One path corresponds to a closed path (P1-3), another path corresponds to an open-closed combination (P1-1 and P1-3) and a third path (P1-2) corresponds to a closed path with backtracking.

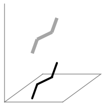
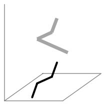
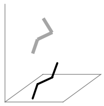
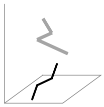
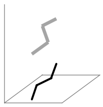
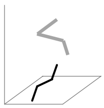
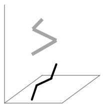
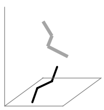
From the basic path types, open or closed, the classification can be extended by considering the set of possible open paths that occur when the start and end times of the paths are different (but, for example, the date is held constant). Since the source and destination locations of a closed path are the same, the focus here is on a classification of different kinds of open path patterns. A set of path patterns based on the components of *source*, *destination*, and *route* for different combinations of start and end times, exposes a number of spatiotemporal path characteristics. These different patterns have both spatial *and* temporal properties that set one pattern apart from another. In this work, we focus particularly on patterns that correspond to the movements of individual objects. The movements of groups of objects are not considered further in this study. In this way, we distinguish the range of path patterns possible for single moving objects and show how these paths change when the spatiotemporal parameters vary.

4 Possible Path Patterns for Single Moving Objects

We investigate possible patterns of paths by looking at paths over different temporal granularities, within the same day and over different days (and the temporal granularity can be altered here to other date types (e.g., week, month, year)). This allows for a wider range of assumptions relating to start and end times. For example, for the first set of paths, movements are assumed to occur during the course of one day (i.e., paths are for the same day, $date(P_i) = date(P_j)$), although not *all* the movements an object makes during a day are assumed. Grey and black paths represent different paths of the same moving object on the same granularity of date (e.g., day) (Table 2). For the graphics in Table 2 (and in subsequent tables), the vertical axis represents time (*t*). A spatiotemporal path is represented symbolically using only three segments, with the starting and ending points of the middle segment as an extremely simplified representation of the route of the path. Since for this group of paths, all movements are assumed to happen on the same date, it is understood that the start times (and end times) of different paths must be distinct from each other and path P_1 is before path P_2 (i.e., $t_n(P_1) < t_0(P_2)$). One pattern of paths is where the source, destination, and routes are the same (*P2-1*), for example, a parent driving to a child's school using the same route each time at different times during the day. Another case is where the source and destination are the same, but the routes taken are different (e.g., travel to a child's school more than once in a day but taking different routes to get there each time) (*P2-5*). Another pattern, perhaps less common, has an object moving at different times such that the source and destination locations of the paths are different, but the route is common for both paths (*P2-4*). A different case is where the source is common for different paths, but the destination and route are changed (*P2-7*). This could correspond to paths taken to fulfill different errands, where the distinct destination for each trip causes a different route to be chosen. Path pattern *P2-8* describes the case where the individual movements are independent, i.e., source, destination, and routes vary for each path. This set of eight path patterns represent a basic set of movements for single moving objects and our studies reveal that many of these patterns are prototypical for movements at other temporal granularities.

If we examine the set of path types that correspond to cases of a single moving object over *different dates* with the same or different route, additional patterns are revealed. Investigating paths over different dates now

Table 2. Open paths for a single moving object on same date with different start and end times.

No.	Spatial properties	
P2-1	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) = loc_{1,\ldots n-1}(P_2)$	
P2-2	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) = loc_{1,\ldots n-1}(P_2)$	
P2-3	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) = loc_{1,\ldots n-1}(P_2)$	
P2-4	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) = loc_{1,\ldots n-1}(P_2)$	
P2-5	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) \neq loc_{1,\ldots n-1}(P_2)$	
P2-6	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) \neq loc_{1,\ldots n-1}(P_2)$	
P2-7	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) \neq loc_{1,\ldots n-1}(P_2)$	
P2-8	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$ $loc_{1,\ldots,n-1}(P_1) \neq loc_{1,\ldots n-1}(P_2)$	

allows for start times (or end times) to be the same, unlike the cases shown in Table 2. The first set of paths that correspond to a single object moving on different dates describes paths where the paths have the same source and same destination and occur along the same or different route (Table 3, where black and grey paths represent paths taken by the same object over the same temporal period on *different* dates). Some of these paths evoke spatiotemporal behaviors that are common or even routine, and are elemental for a population of moving objects over time. Patterns *P3-1*, *P3-2,* and *P3-3* describe cases where the same path is taken on different days but with varying start and end times. *P3-1* where the two paths completely overlap each other, captures routine movements, for example, traveling to work or school where movement is from the same source to the same destination along the same route at the same times each day. *P3-2* involves different start times (leaving from a source earlier or later), while *P3-3* involves different end times (getting to a destination earlier or later). Patterns *P3-4*, *P3-5*, and *P3-6* describe cases where the path of movement on different days occurs along *different routes* and over varying start and end times. Perhaps some local factor (e.g., construction or a festival) requires a different route to be used by the moving object on different days. These combinations of paths are common to many types of moving objects. *P3-4* describes the case where start and end times are the same each day. Path patterns *P3-5* and *P3-6* capture cases where the start times and end times respectively are different. It should be noted that combinations of paths where $t_0(P_1) \neq t_0(P_2)$ and $t_n(P_1) \neq t_n(P_2)$ over different dates are not presented in Table 3 as they are not significantly different to the patterns *P2-1* and *P2-5* already identified in Table 2. *P2-1* and *P2-5* are basic path patterns that hold over multiple temporal granularities.

When paths have different sources, destinations, or both, a new set of possible patterns emerges (Table 4). Path patterns *P4-1* through *P4-9* describe cases where the source, destination, or both the source and destination vary, but follow a common route (i.e., $loc_{1,\ldots,n-1}(P_1) = loc_{1,\ldots n-1}(P_2)$). The temporal characteristics of these combinations of paths vary for each case. This set of patterns may not be as common as other path types for certain domains. Pattern *P4-4,* for example describes the case where the sources and routes are the same, as are the starting and ending times for each path, but the destinations are different. *P4-5* allows for different starting times, while *P4-6* captures different ending times. Again, for this set of path combinations, the complete set of possible cases includes three cases that are omitted from Table 4 as they are not significantly different from *P2-2*, *P2-3*, and *P2-4* (although they occur over different dates), and have already been presented as part of Table 2. These cases have the characteristics, $t_0(P_1) \neq t_0(P_2)$ and $t_n(P_1) \neq t_n(P_2)$.

Table 3. Open paths for a single moving object on different dates with same sources and destinations

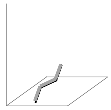
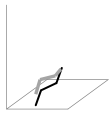
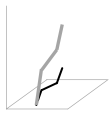
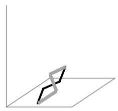
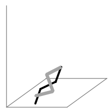
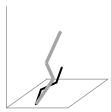
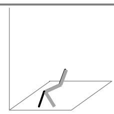
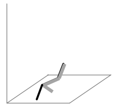
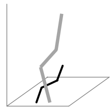
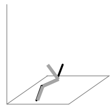
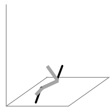
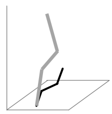
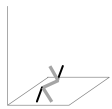
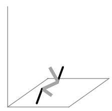
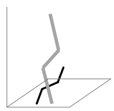
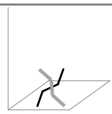
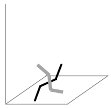
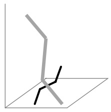
No.	Spatial properties	Temporal properties	
P3-1	$loc_{0,\dots,n}(P_1) = loc_{0,\dots n}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P3-2	$loc_{0,\dots,n}(P_1) = loc_{0,\dots n}(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P3-3	$loc_{0,\dots,n}(P_1) = loc_{0,\dots n}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	
P3-4	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\dots,n-1}(P_1) \neq loc_{1,\dots n-1}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P3-5	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\dots,n-1}(P_1) \neq loc_{1,\dots n-1}(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P3-6	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$ $loc_{1,\dots,n-1}(P_1) \neq loc_{1,\dots n-1}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	

Table 4. Open paths for a single moving object following the same routes on different dates with different sources and destinations

No.	Spatial properties	Temporal properties	
P4-1	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-2	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-3	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) = loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	
4-4	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-5	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-6	$loc_0(P_1) = loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	
P4-7	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-8	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
P4-9	$loc_0(P_1) \neq loc_0(P_2)$ $loc_n(P_1) \neq loc_n(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	

Another set of possible paths highlights independent movements of a single object in more detail. For these cases sources, destinations, and routes are all different (i.e., $loc_{0,\dots,n}(P_1) \neq loc_{0,\dots n}(P_2)$) (Table 5). Pattern *P5-1* describes the case where independent movement occurs, but the start and end times are the same. Other path types have different start time (*P5-2*) or end times (*P5-3)*. For these cases, therefore, the temporal characteristics, rather than the spatial characteristics become the basis for comparison.

Table 5. Open paths for a single moving object on different dates with different sources, different destinations, and different routes.

No.	Spatial properties	Temporal properties	
5-1	$loc_{0,\dots,n}(P_1) \neq loc_{0,\dots n}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
5-2	$loc_{0,\dots,n}(P_1) \neq loc_{0,\dots n}(P_2)$	$t_0(P_1) \neq t_0(P_2)$ $t_n(P_1) = t_n(P_2)$	
5-3	$loc_{0,\dots,n}(P_1) \neq loc_{0,\dots n}(P_2)$	$t_0(P_1) = t_0(P_2)$ $t_n(P_1) \neq t_n(P_2)$	

5 Summary and Future Work

Distinguishing the different path types that are possible for single moving objects provides a basis for searching and retrieving different spatiotemporal behaviors from collections of moving object data. If these patterns are considered as basic movements (i.e., movements common to a wide range of moving objects), it is also possible to analyze how patterns of movement may be decomposed to sets of these elemental paths to give a clearer understanding of possible movements. This paper presents a basic set of path types, open and closed, where open paths capture movements where the destination and origin are different from one another. Closed paths refer to cases where the origin and destination are the same, common in round trips or looping movements. Although many movements can be characterized by a combination of open and closed paths, this study examines cases of open paths further to expose a larger set of possible patterns of paths for single moving objects. Paths may be described as they occur over a single day or over different days. Examining paths over different days allows the start and end time of the paths to be the same (not plausible for paths on the same day). For example, paths may be taken at the same time on different days, or paths may follow a different route to the same destination on different days. Certain paths may appear to be characteristic of a moving object over a time period and then movement may change, evoking a different path type. In this way, the framework can serve as a basis for searching for sudden or gradual changes in paths and movement patterns. Further work will focus on the formalizations necessary for modeling combinations of open and closed paths, as well as studying additional parameters for paths that support more semantics, for example, distance and speed, where shifting between shorter or longer paths may suggest new spatiotemporal behaviors.

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