Time geographic fields: A continuous velocity theory for time geography

Harvey J. Miller[1], Scott A. Bridwell[2]

[1]Department of Geography
University of Utah
260 S. Central Campus Dr. Room 270
Salt Lake City, UT 84112-9155 USA
Telephone: +1.801.585.3972
FAX: +1.801.581.8219
Email: harvey.miller@geog.utah.edu

[2]Department of Geography and DIGIT Laboratory
University of Utah
260 S. Central Campus Dr. Room 270
Salt Lake City, UT 84112-9155 USA
Telephone: +1.801.585.3972
FAX: +1.801.581.8219
Email: scott.bridwell}@geog.utah.edu

1. Overview

Time geography is powerful but until recently has only been a conceptual framework. Over the past decade or so, researchers have improved the rigor of time geography through re-formulations suitable for computational implementation. Progress has been achieved with respect to calculating time geographic entities within transportation networks (Kwan and Hong 1998; Miller 1991, 1999; O'Sullivan, Morrison and Shearer 2000; Wu and Miller 2000), visualization of space-time paths (Kwan 2000) and software and database designs to support time geographic queries and analysis (Frihida, Marceau and Thériault 2004; Yu 2006).

A *time geographic measurement theory* provides a rigorous, analytical foundation for high-resolution measurement and analysis of time geographic entities and relationships using *location-aware technologies* (LATs) such as the global positioning system (GPS), radiofrequency identification (RFID) as well as simulation using agent-based technologies. The time geographic measurement theory distinguishes between measured and inferred components of the space-time path and prism. It also provides analytical and computational strategies for calculating the inferred components as well as relationships such as path bundling and path-prism and prism-prism intersections (Miller 2005a). An extension of this theory to encompass virtual interaction via *information and communication technologies* (ICTs) provides an analytical foundation for calculating the necessary space-time conditions for all human interaction (Miller 2005b).

A lingering issue is the uniform velocity assumption. This is the unrealistic assumption that movement occurs at a constant velocity everywhere in space. The network-based space-time path and prism relaxes the uniform velocity assumption in useful manner; however, this is a pragmatic rather than theoretical solution. Also, this approach relaxes the uniform velocity assumption only to a fixed level of resolution (the network arc) since the velocity is still assumed constant within each arc. The database and software designs for time geographic queries and analysis continue this modified uniform velocity assumption by assuming constant travel velocities within each arc or throughout each segment of a trip. The time geographic measurement theory also assumes a constant travel velocity for the inferred components of the path and prism.

This paper advances the analytical foundation and computational relevance of time geography by relaxing the constant velocity assumption within the measurement theory. Rather than assuming a uniform velocity, the extended theory admits a velocity field where travel velocities can vary continuously across locations. Consequently, the inferred travel between unobserved locations in the space-time path and prism are no longer straight-line segments but rather geodesics or minimum cost curves through the implied travel time surface.

2. Method

We assume that the space-time path and prism exist within a velocity field: characterizing each location is an isotropic (directionless) or anisotropic (direction-specific) travel velocity. Solving for the unobserved portions of the space-time path or prism requires a classic calculus of variations problem: find the path that minimizes an integral path cost function. This requires solving a second-order non-linear differential equations with analytical solutions only available under highly unrealistic assumptions regarding the velocity structure. Instead, we solve for the minimum time paths by treating the velocity surface as a discrete lattice and solving for the minimum path through that lattice. Although this introduces some unavoidable distortions (see Goodchild 1977), it is computationally efficient, compatible with GIS software and allows highly general velocities.

3. Preliminary Results

To demonstrate the viability of the approach as well as the sensitivity of time geographic entities to the velocity assumption, we conduct a theoretical analysis of the space-time prism under different velocity functions. Fig. 1 illustrates three basic velocity functions in a circular city with an urban centre: i) a *uniform velocity* (the assumption in classic time geography; ii) *linear velocity* (velocity increases as a linear function of distance from the centre, and; iii) *exponential velocity* (velocity increases as an exponential function of distance).

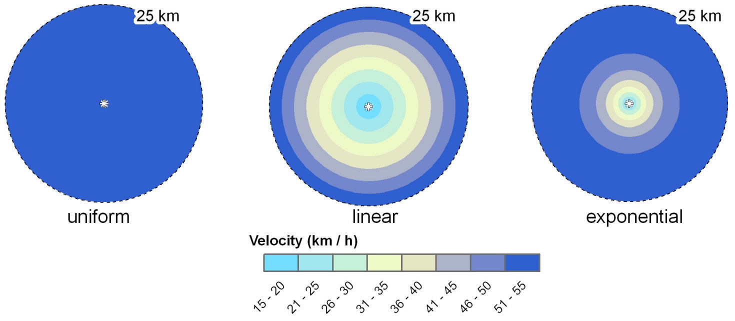

Figure 1. Three basic velocity functions

Fig 2. illustrates three space-time prisms under the different velocity function and with the two anchors defining each prism are coincident with the city centre. The uniform velocity function generates the classic prism (light green). The linear (purple) and exponential (tan) prisms are more circumscribed as expected. These non-classical prism also display curvilinear boundaries.

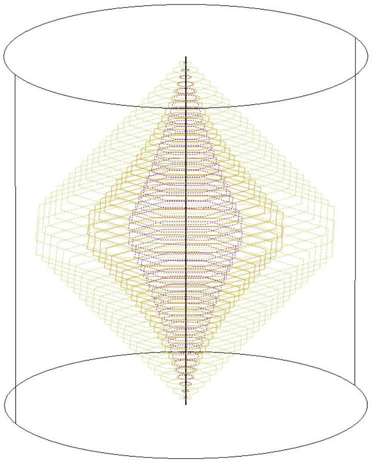

Figure 2. Space-time prisms under different velocity functions and prism anchors coincident with city centre

Fig. 3 illustrates the case where the prism anchors are coincident with each other but away from the city centre. The morphologies of the non-classical prisms are asymmetric due to the offset from the city centre and the consequent velocity asymmetries.

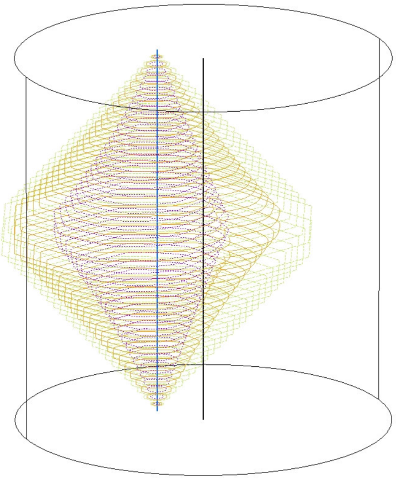

Figure 3. Space-time prisms with prism anchors coincident but away from city centre

Finally, fig. 4 illustrates a more complex case where the two anchors defining the prism are no longer coincident and are on opposite sides of the city centre. The uniform velocity function generates the prism expected from the classic theory, while the linear and exponential prisms display complex geometry including curvilinear boundaries and non-convexity.

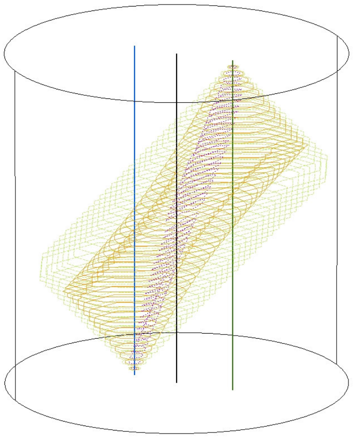

Figure 4. Space-time prisms with anchors not coincident and opposite sides of the city centre

These preliminary results suggest that the classic uniform velocity space-time prism is only a special case of a family of prisms with complex morphology that are sensitive to the velocity structure as well as changes in velocity relative to the prism locations. Intricate prism morphology emerges even with basic velocity functions operating within a highly abstract space. Empirical velocities fields should result in even more complex prisms (and paths). We are currently developing an empirical demonstration using data derived from an intelligent transportation system (ITS) and activity diary study for the Salt Lake City, Utah, USA metropolitan area.

4. Contributions

The relaxation of the constant velocity assumption is a major generalization of the analytical theory for time geography that admits the classical uniform velocity assumption as well as general velocity fields at any level of resolution. The extended theory also links time geography with the continuous space and "urban fields" traditions in quantitative geography and regional science (see, e.g., Angel and Hyman 1976, Puu and Beckmann 1999, Mayhew and Hyman 2000).

Time geographic fields provide a novel way of representing and visualizing synoptic summaries of movement and accessibility within complex urban environments. This is an increasingly critical issue as LAT-based travel and activity studies are creating a flood of detailed data that are difficult to comprehend. Time geographic fields can complement recent progress in knowledge discovery and data mining from spatio-temporal and mobile objects data (e.g., Laube, Imfeld and Weibel 2005).

5. References

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