Transport 2.0: Meeting Grand Challenges with GIScience

By Harvey J. Miller

Transportation is vital to contemporary economies and lifestyles. But in the 21st century, we are facing unprecedented challenges. Demand for transportation has increased dramatically over the past decades. Both transportation and communication technologies have made the world more mobile and interdependent. International trade relationships have altered the dynamics of manufacturing and consumption, heavily increasing the volume of freight traffic. Personal travel demand continues to rise at all geographic scales from local to global.

While in the past the strategy for managing transportation demand was simply to build more infrastructure, we are facing severe financial, environmental, and social constraints to expanding infrastructure. The convergence of ballooning demand and limited expansion has created enormous pressures on transportation systems. Our only choice is greater understanding of these complex systems and more informed decision making by transportation professionals and the public who use these systems.

This article describes the major challenges facing transportation in the 21st century. It also discusses the role of geographic information science (GIScience) and technology in helping create new ways of exploring and understanding transportation systems with the goal of improving decision making by both professionals and casual users. We also describe an effort by the Transportation Research Board (TRB) of the U.S. National Academies to identify the research and development required to achieve this vision over a decadal time frame.

Grand Challenges in Transportation

The TRB periodically identifies critical transportation issues based on their potential impact on the nation's economy and quality of life. Other critical issues, such as institutional challenges and finance, are not mentioned here. Although these are also critical, they are less directly relevant to GIS applications in transportation.

Infrastructure. The United States, along with many nations of the world, made massive investments in transportation infrastructure during the 20th century. However, this infrastructure is now old and used beyond its designed service life. This problem is not limited to highways; inland waterways and rail networks, as well as many sewer and water systems, have similar problems. The need to rehabilitate this infrastructure is occurring when higher demands are being placed on transportation systems and public investment is declining. How do we preserve and renovate saturated transportation systems without substantial increases in resources?

Congestion. Traffic congestion is a daily fact of life for many of the nation's and world's commuters. Estimates of the costs in money and gasoline lost by U.S. commuters every year range in the billions of dollars and gallons, respectively. In most cities, congestion is no longer limited to rush hours in the morning and evening; it has spread to many locations and hours of the clock. The burden of congestion is not limited to people; freight bottlenecks at ports and shipment delays at the local and regional levels place enormous costs on businesses and consumers. The growing need for efficient and responsive transportation to support the global economy and mobile lifestyles is occurring in an era when the ability to expand networks is increasingly limited. Can we maintain current or achieve improved levels of performance without substantial physical expansion?


Illustration by Pamela Razor, ESRI

Energy and the environment. The United States, as well as a burgeoning number of countries in the world, has an overwhelming reliance on the most energy-intensive transportation technologies, namely, automobiles and planes. The ability to continue reliance on petroleum-based transportation technologies is questionable in the short run but certainly impossible over the long run. Transportation systems have a direct and large environmental footprint, particularly with respect to air quality and contributions to global climate change. Over half the U.S. population lives in cities that do not meet federal clean air standards. Transportation also has an enormous indirect footprint through inducing other systems, such as cities, to manifest environmentally unsustainable forms, such as sprawl. Can we reduce the direct and indirect environmental footprints and achieve a sustainable transportation system despite increasing population and travel demands?

Safety. The United States has been a world leader in transportation safety, and enormous progress has been made over the past century. Nevertheless, transportation continues to be the most dangerous activity experienced by a typical person. The United States is also falling behind other nations, such as the United Kingdom (UK) and the Netherlands, with respect to reducing fatalities and serious injuries caused by traffic accidents. While many of the improvements over the past century have made drivers safer, pedestrians and cyclists remain vulnerable. In the future, more people and vehicles within transportation systems with minimal physical expansion imply higher incidence of crashes with potential for injury and loss of life. Can we substantially reduce the number of transportation accidents without significantly reducing the efficiency and responsiveness of transportation systems?

Security and emergencies. September 11, 2001; the London and Madrid train bombings; and Hurricane Katrina illustrate the vulnerability of transportation systems to disruptions, both human made and natural. Transportation systems are popular terrorism targets since they concentrate large numbers of people into small spaces, increasing the likelihood of harm and enhancing psychological impact. Disrupting transportation systems can also strangle contemporary economies and lifestyles that depend on trade and mobility. Attempts to evacuate major U.S. cities, such as New Orleans and Houston, were ineffective. Can we prevent the improper and unauthorized use of transportation systems, and reduce our vulnerability to their disruption, without seriously restricting mobility or violating individual rights? Is it possible to evacuate a neighborhood, city, or region quickly and without additional injury or loss of life?

Equity. A transportation system that relies on personal vehicles creates significant disadvantages for many people, especially the poor, minorities, the elderly, the young, and others who cannot or choose not to drive. These problems will continue given current demographic and social trends. For example, most of the elderly population in the United States is aging in place, often in communities dominated by the automobile. Limited mobility can create isolation and social exclusion, establishing barriers to participating in society and enjoying its benefits. How do we meet the transportation needs of the growing numbers of diverse and vulnerable people?

Business as Usual?

Traditional design, planning, and investment methods, even those enhanced through GIS and related technologies, are unable to meet the grand challenges facing transportation systems. These methods view transportation problems as well defined and isolated. Transportation modes, such as road, rail, water, and air, cannot be viewed in isolation; transportation solutions are likely to be multimodal in nature. Transportation systems are tightly coupled with economic, social, and land-use systems: transportation networks affect, and are affected by, the broader systems in which they are embedded. There may be nontransportation solutions to problems traditionally viewed in that manner.

It is also increasingly clear that human systems, such as transportation and cities, are complex and difficult to manage, let alone control. We learn this lesson repeatedly as attempted changes in these systems lead to disproportionate, unintended outcomes. Rather, human systems must be nuanced: we can only set the framework for the evolution, not control its specific trajectory. This framework is often context specific. This is not defeatist; it simply suggests that we must be more clever and subtle than we have been in the past. We must achieve deeper understanding of these systems.

GIS for Transportation

GIS for Transportation (GIS-T) involves the application of GIScience and GIS for understanding transportation systems and solving problems associated with their planning, construction, operation, and maintenance. GIS-T has matured to the point that it is well positioned to provide useful tools and strategies to meet the challenges facing transportation systems in the 21st century. Contemporary developments that can inform efforts to meet transportation challenges include the following:

- Development and deployment of high-resolution environmental monitoring systems, such as satellite and airborne remote sensing
- Development and deployment of location-aware technologies and geosensor networks that allow fine-grained tracking of mobile objects
- Increasing ability of GIS to maintain and display spatiotemporal and moving objects data
- Improved science and tools for exploring and analyzing complex and massive spatiotemporal data
- Improved science and tools for simulating transportation, urban, and other human systems from the bottom up—at the level of the individual person, vehicle, or object
- Development and adoption of data standards and information infrastructures for integrating and interoperating data

While these scientific and technological developments clearly have great potential, the question remains—What do we do with all this new stuff? The challenges facing transportation systems are great and require new modes of thinking and analysis for their solution. Indeed, the transportation challenges offer a type of "moon shot": vital problems whose solutions will require long-term vision, as well as major scientific and technological advances.

Mirror Worlds

In his 1993 book Mirror Worlds: Or the Day Software Puts the Universe in a Shoebox . . . How It Will Happen and What It Will Mean, computer scientist David Gelernter describes a future where you look at your computer and see reality—the real-time status of an entire company, hospital, transportation system, or city.

Illustration by Fred Estrada, ESRI

You start with a broad, geographic overview, perhaps a digital globe. You zoom in to your city. As you get closer, you see patterns—colors, shapes, and flows—draped on the city, representing the real-time status of its systems and infrastructure. Some patterns are static, some change shape, color, or intensity as the city changes in real time. As you zoom in closer, the representations automatically change to reflect greater detail. At the largest scale, you see vehicles—automobiles, planes, trains, ships—moving through a photorealistic, three-dimensional model of the city's buildings, roads, tracks, and waterways. But it is not quite real. Although they reflect real conditions, most of the vehicles are synthetic, except for some of direct interest to you (your car, your fleet, a delivery truck with a package for you). Also, many of these objects are augmented with text, sound, and imagery, reflecting some status that requires your attention or may capture your interest. You can even enter some of the buildings, for example, to attend a public hearing at city hall.

During your exploration, you meet other people who are visiting and participating in the mirror world. You also interact with virtual participants—software agents who act on your behalf, finding, digesting, and reporting information of interest to you, perhaps making some choices for you but alerting you when crucial decisions are required.

At any time you can navigate the scene and manipulate many of its objects; the flows and patterns change as they aggregate or disaggregate with the changing viewpoint. The displayed attributes may change as well, either automatically with the changing perspective or through your commands. You can also change the temporal scale: running the synthetic city backward or forward in time at varying rates, even exploring simulated futures. In addition to manipulating space and time, you can also explore for semantic similarity: find analogous states of the city or other cities that are similar to a real or imagined situation and see what happens.

Perhaps you are a busy person who needs to manage a hectic schedule. You use the mirror world to check real-time conditions of the transportation system and work with a virtual transportation concierge to determine the best schedule, travel, and mode choices (including cooperating with other users through carpooling or ride sharing) that allow you to accomplish the activities that comprise your day in a timely and efficient manner. But you are also a concerned citizen, and the mirror world allows you to participate in community decision making, say, tour a realistic depiction of the proposed light-rail line through your neighborhood, see the simulated future with and without the line, and search for other places and times with similar projects.

Or perhaps you are a project manager, dealing with the difficulties of designing and implementing the new light-rail line. You issue a call for public input. You post the current design as a 3D digital model, allowing the public to walk through and even "ride" the proposed system. You also post a simulation that shows the expected effects on the city in 10 years if this project is completed. The public can comment on all aspects of the project design and planning process.

Maybe you are a traffic manager, and you notice something strange: there is a local professional sports event, but traffic isn't streaming away from the stadium as expected. You check at the stadium and see that the game is going into overtime. You search for historical analogs and discover that overtime games during playoffs lead to an unusual amount of traffic on the Elm Street Bridge. Triggered by this query, a software agent informs you that the bridge on-ramp is undergoing unscheduled maintenance due to a water main break two days ago. You alert the local traffic police, as well as hospital emergency rooms, to let them know about the situation. The mirror world also propagates this to the general public, allowing them to change their schedules and trips in response to this event. An agent also sends a message to the local air quality monitoring board, suggesting that the unusual event may lead to an abnormal amount of vehicle emissions, perhaps requiring a voluntary "no-drive" day tomorrow.

A mirror world sounds like many of the Web-based tools we have available at present, such as digital maps; real-time snapshots of traffic or weather; applets; customizable Web pages based on your profile and browsing history; and virtual worlds, such as Second Life. Indeed, we have made a great deal of progress along the path described by Gelernter in 1993. But we are far from his vision. A mirror world goes beyond these current technologies to create a real-time, comprehensive, detailed, interactive, and discoverable portrayal of a complex real-world system. Unlike existing virtual worlds, the mirror world is not an alternative reality but a *reflection of reality* that is tightly coupled to the real world. It is also an *interpreted* world: the databases and data streams feeding the mirror world may be processed using knowledge discovery and visualization tools to aid legibility, provide decision support, and protect sensitive data. Some of the data may also be interpreted and presented by software or human agents.

Four key ingredients comprise a mirror world: One is a *live picture*, a comprehensive depiction of the state of a complex system right now, in real time. Another is a *deep picture*, an integrated representation that can be viewed at different levels of detail. *Agents* operate on our behalf to help deal with the complexity of this world. Finally, a mirror world must have a sense of *experience*, not simply an archival database one can query, but a way to search and retrieve relevant information from these previous states, including states that may be different but are good analogs for the current decision at hand. This should also include the ability to imagine alternative futures in what-if scenario modeling.

Your level of immersion in a mirror world can vary. It could be as basic as current social networking sites, such as Facebook, especially if you are accessing it through a mobile device, such as your phone. Or it could be a virtual but artificial world on your screen, such as Second Life. As virtual reality technologies improve, the mirror world could become a full sensory experience. Also, as augmented reality technologies improve, you will be able to see the mirror world superimposed on the real world through devices such as eyeglasses, windshields, and data projectors.

So What?

Sounds cool. But so what? David Gelernter suggests several profound, perhaps even transformative, benefits of mirror worlds.

Getting a grip. Contemporary organizations are fantastically complex. No one person can understand and participate in all the myriad decisions and problem solving required to run a hospital, transportation system, city, nation, or global community. The good news is that no one person needs to; we can share in this decision making, leaving some tasks to software and others to human experts. The mirror world can process the data you need, allow you to explore this information, and even alert you when a decision is required. In short, a mirror world helps you understand and deal with a complex reality by delegating mundane but overwhelming tasks and involving you when a real decision is required.

The new public square. A mirror world is a type of place where you can meet and interact with others, whether they are friends, neighbors, coworkers, fellow citizens, public officials, or business leaders. You can participate in activities ranging from a simple chat to a major policy change. Although this is possible in the real world, most people do not participate fully in community decision making: the real world is too big, complex, and costly to navigate. A mirror world reduces these barriers by creating a multiscale virtual world that is more easily discovered, navigated, and engaged.

The new conference room. A mirror world can also facilitate decision making that arises when diverse groups participate in a complex project, such as designing, building, and maintaining transportation infrastructure. A nascent example is the emerging field of building information modeling (BIM) for managing the construction life cycle through a three-dimensional, real-time, spatially referenced model of the building being constructed. BIM advocates claim better coordination, greater productivity, fewer errors, and savings in cost and time. Mirror worlds can scale this technology to large-scale transportation projects, including monitoring the infrastructure after installation to support management and maintenance. Combining this idea with the new public square, mirror worlds can allow public involvement at any stage of a facility's design, construction, use, and renovation.

Seeing the whole. One of the profound benefits of a mirror world is that it facilitates what Gerlernter calls *top-sight*: seeing the big picture. Top-sight is more than just a bird's-eye view or a synoptic summary. It also means seeing interconnections of parts, as well as the links between oneself and the whole. Top-sight is a form of insight; one can pursue it avidly but only achieve it gradually. It is a quality of great leaders and participants in well-functioning communities. The increasing complexity of the world makes top-sight more difficult. Although a mirror world cannot teach people to have top-sight, it can facilitate that view by managing the complexity that inhibits this holistic perspective.

Will mirror worlds solve the major problems facing transportation systems in the 21st century? Perhaps not. Some challenges may be too great, and others may require political will and leadership that may not exist. But a mirror world can certainly facilitate a better perspective on these problems, a view that is integrated, holistic, and multidimensional. It can also facilitate community mindfulness and public involvement. And it can help empower citizens and stakeholders to make better-informed transportation decisions at all spatial scales and time frames.

Transportation Worlds: What Do We Need?

How do we create this new instrument, the combined telescope, microscope, and time machine that is a transportation world? Much of the requisite science and many of the technologies currently exist, albeit in nascent form; these include GIS, geovisualization, agent-based technologies, virtual reality, and Web 2.0 tools. However, these technologies and the underlying science must achieve levels of maturity, sophistication, and interoperability that are beyond the current state of the art. Several major research and development trajectories are relevant.

Pervasive transportation information. New location-aware technologies and geosensor networks allow the collection of geospatial and temporal data at unprecedented scales and scope. It is unclear how best to deploy and support these data collection networks and how to deal with varying levels of data quality. There is also a need for new representation models that can accommodate the increasingly diverse data. More private citizens are volunteering geographic data through cell phones and other devices; how do we treat this data?

Transportation data must be integrated and shared across many applications and domains, often in real time. How do we efficiently integrate and archive this data, as well as make the data accessible to authorized individuals while preventing its misuse by unauthorized individuals?

Individuals will have unprecedented access to data and information about transportation systems. How will this change their behavior?

New knowledge for better transportation decisions. The unprecedented scope, spectrum, and detail of geospatial data collection technologies present a major challenge with respect to making sense of this data. Required are new methods for exploring the data, confirming discovered information, and communicating this information to transportation professionals and the public at large for collaborative decision making about transportation futures. We also need methods for automated detection of relevant information and unusual patterns for real-time response to tactical problems, including those arising when using transportation systems in one's daily life.

Imagined transportation worlds. Geospatial information and technologies can bring together the real and imagined worlds. How do we interoperate models and representations that are often designed for different purposes and at varying spatial and temporal scales? How do we judge the validity and utility of imagined worlds? How do we facilitate understanding of the scientific processes involved in simulating transportation futures to decision makers, stakeholders, and the public at large?

Geospatial infrastructures for transportation. The hardware and software issues involved in creating a real-time transportation world are enormous and will require advancements in basic GIScience, including new spatial algorithms, spatial data structures and processing, cyberinfrastructures to support spatial and temporal information, geovisualization techniques, and user interfaces. These should be designed with transportation systems in mind but must interoperate with methods and technologies in broader mirror worlds.

Also required are new processes to plan, budget, maintain, and upgrade geospatial technologies within public- and private-sector organizations. These infrastructures will require enterprise-wide investments and cannot be budgeted and built piecemeal.

Educating the transportation professional. New science, technologies, and data will place unprecedented demands on the education of the transportation student, as well as the continuing education and training of the transportation professional. Students will require foundations in transportation science, as well as the science underlying new geospatial technologies and data. It will be challenging to fit these demands within two- or four-year higher education programs, particularly those with strict accreditation requirements. There will also be a need to continue education and training throughout the career of a transportation professional as the technologies and software evolve in response to continuing advances in computer science, GIScience, and transportation science.

How Do We Get There? A Research Road Map

The Transportation Research Board Committee on Geographic Information Science and Applications (ABJ60) is involved in a multiyear effort to identify the research needed over a 10–20 year time frame for developing new geospatial science and technologies to meet the grand challenges facing transportation systems in the 21st century. The article you are reading is a product of this effort, and it involved many individuals (several are listed in the acknowledgments).

These efforts will continue through 2010 and beyond. We are developing a research road map that will identify the research trajectories and major milestones required to create the advanced geospatial environment for transportation described in this article.

We invite you to get involved. We need input from a diverse range of individuals concerned with transportation, either professionally or casually. Visit our Web site at abj60.org.

Notes

For discussion of critical issues in transportation, including some not mentioned in this article, see TRB Executive Committee (2006), *Critical Issues in Transportation*, Transportation Research Board, U.S. National Academies, Washington, D.C., available at trb.org.

Acknowledgments

The goal of the ABJ60 committee is to advance GIScience, technology, and applications in the field of transportation through research in communications and visualization; spatial data; systems integration, organization, and spatial analysis; and modeling. The committee also conducts outreach through TRB to communicate the effective use of GIS to the transportation community.

Many members and friends of the committee are involved in the strategic research vision described in this article as focus group leaders or participants; they are listed at the committee Web site, abj60.org. Special thanks to Reginald Souleyrette (committee cochair), Val Noronha (chair, research subcommittee), Cesar Quiroga (secretary), and Tom Palmerlee (TRB officer). An extra thanks to Roger Petzold (Federal Highway Administration) for supporting this effort.

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