

INVITED ARTICLE

Movement analytics for sustainable mobility

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Abstract: Mobility is central to urbanity, and urbanity is central to our common future as the world's population crowds into urban areas. This is creating a global urban mobility crisis due to the unsustainability of our 20th century transportation systems for an urban world. Fortunately, the science and planning of urban mobility is transforming away from infrastructure as the solution towards a sustainable mobility paradigm that manages rather than encourages travel, diminishes mobility and accessibility inequities, and reduces the harms of mobility to people and environments. In this essay, I discuss the contributions over the past decade of movement analytics to sustainable mobility science and planning. I also highlight two major challenges to sustainable mobility that should be addressed over the next decade.

Keywords: movement analytics, mobility science, animal movement ecology, sustainable mobility, urbanity

1 Introduction

An epochal event in human history occurred in 2008, the world became majority urban for the first time. Urbanization is accelerating: two-thirds of the global population will live in cities by 2030 [44], with some predicting an essentially urban world by the end of the century [5]. A world of 10 billion people living predominantly in cities—of which 60% globally have yet to be built [45]—underscores the critical need and immense opportunity for new scientific and policy approaches that can achieve sustainable urban systems.

Mobility is central to urbanity. Transportation is how we organize our cities [1]. While the automobile has generated stunning levels of mobility over the past century, it has also led to urban mobility systems that are utterly unsustainable; they are inefficient, costly, inequitable, unsafe, unhealthy, and environmentally damaging at local to global scales.

This is driving a mobility crisis that will worsen as the world continues to urbanize [23,37]. The COVID-19 pandemic vividly demonstrates the lack of resilience in our urban mobility systems, and tensions between sustainable practices, such as living at density and using mass transit. However, there is danger in moving away from the compact urban forms we have been nurturing for the past three decades [6]. If civilization is to survive the 21st century, we must figure out how to design, build, and manage sustainable and resilient urban mobility systems.

Thankfully, the science and planning of mobility and cities is changing. One indicator is a change in semantics from the 20th century term “transportation” to “mobility” in science and planning, shifting the focus from vehicles to humans. Another indicator is the slow but persistent death of the 20th century “predict and provide” paradigm that forecasts future travel demand and builds to meet it, not recognizing that the new infrastructure induces new demand. Replacing this Sisyphean quest is a sustainable mobility paradigm that manages rather than encourages travel and seeks to reduce inequities and harms to people and the environment [3].

There is long-standing scientific interest in the purposeful movement of humans and animals that is beginning to converge into an integrated science of movement [30]. In this essay, I discuss some major contributions of movement analytics to sustainable mobility science and planning over the past decade. I also highlight two major scientific challenges to using these advances to foster sustainable mobility and cities.

2 Progress in movement analytics

2.1 Individual movement

In the past, we relied on simple data that was easy to collect, in particular, traffic counts. But when we measure cars, we get more cars. The biggest impact movement analytics can have on planning and policy is the development of people-based measures and analytics. This allows sustainable modes such as walking, biking, and public transit to have a fair fight with automobiles in evidence-based policy and planning. It is therefore comforting that venerable mobility concepts such as the *space-time path* representing movement and activities in space and time as the underlying cause are now core to how we approach transportation and mobility [16].

Over the past decade, a key contribution from movement analytics are improved methods for map matching and trajectory annotation [49]. They facilitate better description of movement patterns within infrastructure, linking moving objects to other physical and social data, and inferring the activities underlying observed mobility [9, 12, 25, 42]—a far cry from the abstract networks and flows of 20th century transportation science. Map matching also supports insights into active transportation such as walking and biking since these behaviors are sensitive to contextual factors such as streets and buildings, design, greenery, and infrastructure condition (e.g., [22]). Embedding paths into geographic contexts also supports efficient indexing and compression of massive trajectory data [35].

Another advance is the development of measures for quantifying geometric and semantic similarity between space-time paths [8, 14, 50]. This allows sorting, clustering, and aggregation of massive mobility data, supporting mobility data mining and exploratory visualization for insights into heterogeneous mobility patterns. When linked with individual or georeferenced data, these measures reveal different mobility and activity constraints

facing individuals along socioeconomic, demographic, gender, ethnicity, and ability dimensions, and the capacity of communities to serve these diverse mobility needs [38].

A revolutionary change is the deployment of low-cost sensors embedded in infrastructure, attached to vehicles and carried by people, including environmental sensors (air quality, temperature, humidity, noise, proximity), activity logs, accelerometers, cameras, microphones, and, with wearable technology, heart rate, body temperature, stress, and other physiographic measures. Fusing sensors and mobility data can support a wide range of analyses for sustainable mobility, such as inferring travel modes [31], measuring differential exposure to air pollution, heat and stress during walking and biking [20], understanding the relationships between mobility, the built environment and physical activity [43], and capturing individual, qualitative experiences and barriers to mobility [7].

2.2 Accessibility

Accessibility is a multifaceted concept, painstakingly developed in the scientific literature for a half century. While the use of accessibility as a planning objective and performance measure has lagged, it now appears poised to transform mobility policy and planning [21]. The *space-time prism* (STP) is a core measure of accessibility in movement analytics. Major advances in the STP over the past decade include a stronger analytical foundation in planar and network space, enabling further enrichment of prism analytics and linkage with new data sources, analytics, and models (see, e.g. [10]). The STP and related concepts of *activity space* (human mobility) and *home range* (animal movement ecology) are being applied in a broad range of applications [32].

Network time prisms (NTPs) have moved beyond street networks and cars to high fidelity representations of multimodal travel, including sidewalks, bike networks, public transit networks and schedules, and real-time vehicle locations. Prisms can capture risk due to congestion and delays [11], a burden that falls differentially on the poor. Prisms also incorporate energy and emissions budgets in addition to time constraints, allowing (for example) modeling impacts of electric vehicle charging station placement on accessibility [27].

An alternative representation is movement as a space-time probability distribution, modeled as a discrete random walk or continuous Brownian Bridge. Over the past decade, researchers have integrated stochastic movement models with prisms to model random movement bounded by space-time constraints [15,26,41,46,47]. This allows more nuanced measures of space-time accessibility. It also allows linking prisms to models of energy consumption and carbon emissions for estimating the expected environmental impact of accessibility [40].

2.3 Collective movement

One of the sharper divides between human mobility science and animal movement ecology is the treatment of collective movement. Animal movement ecologists have a tradition of analyzing collective behaviors such as flocking, schooling, and social interaction [30]. In mobility science, collective movement at this level has traditionally been the purview of traffic engineers, with the objective of making cars move faster. However, sustainable mobility science planning cares less about minimizing travel time than making it reasonable and reliable. Indeed, it is often a good idea to slow movement down since this is safer and

allows other types of mobility to flourish [3]. We are seeing cross fertilization between the animal movement and human mobility communities to develop generic models for collective movement to support modeling of pedestrian and crowd behavior (see, e.g., [24,33]).

Transportation science and planning has traditionally focused on macro-scale collective movement, represented as flows through networks and between origin-destination pairs, splits among different modes, and overall travel demands. A vital scientific challenge question for movement analytics are methods for understanding the intricate and complex interactions among individual and collective mobility at multiple spatial and temporal scales, and how these dynamics link with other physical and human dynamics within urban systems.

In the next, and concluding, section of this essay, I will explain why we need to understand mobility and cities as complex collective systems. I will also describe a major challenge in communicating scientific evidence to leaders, decision-makers, stakeholders, and the public at large.

3 Scientific challenges for sustainable mobility

3.1 Mobility is complex

A need for new mobility solutions with enabling technologies such as the Internet, wireless communication, and geopositioning has led to the development and rapid deployment of new technology-enabled mobility services such as vehicle sharing, ride-sharing, bikesharing, micromobility, and microtransit. These innovations are disrupting the mobility landscape of cities, with even bigger transformations inevitable with the coming of connected autonomous vehicles [17]. This is a grand, real-world experiment with profound impacts on cities that will be difficult to unwind.

Whether new mobility services will make cities more sustainable is an open question, one that will be difficult to answer using 20th century science. The metaphor of human systems as machines has traditionally dominated transportation and urban science: we thought we could understand these systems at disaggregate and aggregate levels only, missing the sensitivity to context, intricate feedback loops, path dependency, and emergent behavior that make collective space-time systems like cities more akin to ecosystems than machines. This is why interventions often lead to unintended outcomes [34]. While complexity science tells us that we cannot predict the future of cities, we can invent these futures through more nuanced planning and policy [5].

As complex systems, mobility and cities must be understood one event or intervention at a time. Improving capabilities to collect, integrate and share geospatial and moving objects data in an open-ended, ongoing basis are creating new opportunities for opportunistic science that leverage anticipated and unanticipated events in the real world to gain deeper understanding of how complex urban systems respond to interventions and shocks [29]. This can support the growing use of *tactical urbanism*: making local, provisional changes to test impacts before wider deployment; examples include pop-up bus lanes, opening streets for walking and biking on weekends, and parklets [39]. A grand challenge for movement analytics are tools for extracting multiscale patterns from movement and other spatio-temporal data in this new world of tactical experimentation and opportunistic science.

Another domain for experimenting with complex mobility and urban systems are simulated worlds. This allows mobility experiments that are difficult, infeasible, or unethical in the real world. Also, despite limits on predicting the future of complex systems, there are needs for visioning and scenario modeling. An emerging trend in mobility and urban science is the use of *digital twins*, high-fidelity simulations of complex real world systems to support operational, tactical, and strategic decision making [13].

3.2 Mobility is wicked

Sustainability means meeting the needs of current generations without compromising the needs and aspirations of future generations, inclusive across environmental, social and economic dimensions [4,48]. However, sustainability is a *wicked problem* [36] in the sense that it is multifaceted, has contested definitions, and difficult tradeoffs among dimensions, such as balancing economic growth and environmental protection. This has led to scientific methods that explicitly represent heterogeneous perspectives for problems that are urgent but involve uncertain futures and values [18,19]

Over the past decade, there have been ground-breaking advances in visual analytics for movement data, going beyond scientific exploration to support operations, decision-making, situational awareness, and planning [2]. A challenge for the next decade is to broaden this engagement to include entire communities in shared decision making, cooperation, and collaboration to help invent future mobility systems that are sustainable and resilient. The tensions between individual and collective outcomes is perhaps the crux of the human mobility problem [28]. Helping communities navigate and resolve these tensions can move us forward to a sustainable and resilient future.

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