Street-Level Urban Gravity: A Quantum System Approach to Human-Centered Urban Space Design

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ABSTRACT

The fundamental questions of how the built environment influences why and where people meet have intrigued philosophers and researchers for centuries. This question has been amplified as we have witnessed the evolution of streets from vibrant public spaces to traffic conduits following the advent of the automobile and highway engineering practices. More than ever, infrastructure such as public open spaces and busy transportation networks can either have the capacity to support communal gatherings and provide societal benefits to society or polarize people and communities. However, there exists little ability to quantitatively capture the relationship between infrastructure and the intricacies of walkability and street-level activities. This paper sets the stage for discussions on how the design of the built environment can influence the use of public spaces (e.g., walkability), with profound implications for engineers, urban planners, and designers seeking to create human-centered infrastructure. The history of key themes such as social interactions supported by public open spaces, walkability, and the relationship between infrastructure and well-being are introduced in this paper, emphasizing their interplay within communities. The paper illustrates how traditional traffic flow modeling has significant limitations in capturing the intricacies of walkability and street-level activities needed to understand this relationship, motivating the exploration of quantum mechanics principles as a possible avant-garde approach to understanding the indeterminate nature of human movement within urban settings. To achieve this goal, this work introduces the concept of a "street-level urban gravity" model aiming to utilize emerging technologies within a quantum system framework to enhance the connection between urban design and engineering. Such an approach would help to empower stakeholders to design infrastructure that aligns with human-centered objectives.

CCS CONCEPTS

• **Applied computing → Physical sciences and engineering**.

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1 INTRODUCTION

"Why do people meet and how does the built environment shape how and where people choose to meet?" These are questions that have fascinated philosophers and researchers for centuries. Understanding how the built environment shapes human interactions and the human experience is crucial for engineers, urban planners, and urban designers to understand how to create human-centered infrastructure (e.g., facilities, public spaces) that support and promote benefits such as social interactions, walkability, and well-being. These benefits can be, but are not necessarily, interrelated. Walkability, for example, significantly influences social interactions within neighborhoods [8, 10], and the design and quality of the built environment can either support or impede walkability. Various factors such as landscape layout or fence height surrounding houses can impact neighborhood community conviviality [18, 47]. Across street networks, higher intersection density and more connected street patterns are associated with increased walking, biking, and transit use [46].

In *Palaces for the People: How Social Infrastructure Can Help Fight Inequality, Polarization, and the Decline of Civic Life*, Klinenberg uses the term "social infrastructure" to describe physical infrastructure that has the potential to generate social gatherings and benefits in a community (e.g., parks, local businesses, religious facilities) [31]. We have seen how some social infrastructure functions better than others. One example dates back to 1675 when England's King Charles II, realizing the potential of information exchange caused by social infrastructure, tried to ban coffee houses in order to reduce the number of spaces where civilians congregate [28]. In a recent review of studies in North America, making a street more accessible by active transport—such as treating the street as social infrastructure—widely results in a positive economic impact on businesses and foot traffic in a community [62]. However, there remains little quantitative understanding of how some infrastructure design resonates with and has positive social impacts on communities while others result in fewer social activities than expected

[48]; simply put, some streets are merely pathways for pedestrians to "go through," while others are ones people want to "go to."

Historically, main streets and squares—what we would now refer to as one form of social infrastructure—were places where urban activities and gatherings took place, such as hawking, meeting, or even pillorying and public trials [49]. However, after the introduction of the automobile and highway engineering practice, conflict between traffic zones and public spaces emerged, reshaping the meaning and purpose of streets to be conduits of movement rather than public space [22, 45]. In 1935, Greenshields introduced the concept of traffic flow theory in which traffic volume and flow are emphasized as functions of speed and density [21]. Here, flow—which is analogous to flow in fluid mechanics—pertains to mobility, with little consideration for accessibility; high traffic flow can, in fact, deteriorate the attraction that connects communities together [2, 7]. Yet, the work done in this area continues to broadly measure the flow and the use of infrastructure such as sidewalks as a conduit of movement. The Transportation Research Board has defined pedestrians' Level of Service in the Highway Capacity Manual 2000 in a similar way, relying on factors such as speed and flow of pedestrians on a sidewalk [1]. More recent research accounts for bidirectional streams and stochastic travel times of pedestrian movement and crossing within a macroscopic user equilibrium traffic assignment problem framework [37, 38], or using Convolutional Neural Networks to predict the intention of crossing [36]. Some studies address the data scarcity of pedestrian infrastructure, especially the small-scale defects on sidewalks [24, 29], but do not explore the connection between such data and pedestrian modeling. The principle of modeling walking simply as the flow between an origin and a destination hinders the ability to account for, or even *encourage*, stops along the way (e.g., interactions). As a result, pedestrian movement and use of public spaces is not directly linked to the built environment or the social and business success in communities, and other possible activities supported by streets—ranging from stopping for shopping to social gathering to enjoying local street food—requiring new research to reveal how walkability is more than just walking [43].

Towards this end, we introduce the notion within the field of transportation planning of modeling the demand of movement with a gravity model as a metaphorical basis taken from Newton's gravity. Here, factors such as the population size and employment act as proxies for a "mass" pulling another mass within a travel time between two areas [23]. At a high level, existing work on gravity models has begun to uncover how the built environment influences human movement, whether a mass is producing outflow to other masses or attracting an inflow from other masses. More recent related advancements in this area have focused on the use of deep learning to account for food-related spatial points of interest, such as restaurants [58]. While this work does move the field closer to better understanding the relationship between the built environment and human movement, the intention of this gravity model remains focused primarily on macroscopic movement in large inter-city regions and less on internal city mobility. Hence, it is not suitable for generalization towards pedestrian walkability and capturing information on street-level user experiences or behaviors [22, 41].

To address the lack of street-level, human-centered gravity models needed to describe the movement of people in a community—specifically, in response to the built environment—this research takes inspiration from quantum mechanics to propose the notion of a "street-level urban gravity" model that aims to use emerging technologies to better connect pioneering work from urban design with engineering, enabling the design and management of infrastructure to achieve desired human-centered benefits (e.g., walkability). While this concept is widely generalizable across infrastructure types, we begin this exploration with a focus on streets and public spaces. The primary contribution of the paper is the discussion of the intuition and possible applications of using quantum mechanics to support a street-level urban gravity model in urban environments.

For the purpose of presenting the concept of street-level urban gravity, we first reflect on the rich history of civil engineering and explore how the field increasingly contributes to the development of vibrant and sustainable communities in Section 2. We then examine the history of traditional transportation modeling and the use of Newtonian physics to urban mobility, which motivates our postulation of a mathematical model from quantum mechanics that can predict human behavior at the street level (Section 3). We argue that this theory can be applied across various applications, which are discussed in Section 4. Finally, we reflect on this theory and its potential future development and applications in Section 5.

2 CIVIL ENGINEERING AS AN EVOLVING FIELD

2.1 Origins of Civil Engineering

Civilization is a complex and multifaceted concept that encompasses various aspects of society, including the development of social structures, cultural practices, technological advancements, and governance systems. Civil engineering as a discipline plays a crucial role in the development and maintenance of civilization. It is evident that the history of human civilization and the history of science are intertwined with innovations in civil activities, culture, science, technology, and society [63]. Civil engineering has been instrumental in shaping the built environment and constructing infrastructure such as roads, bridges, buildings, and dams that are essential for the functioning of societies. Military engineering and architecture were closely associated with early civil engineering, as societies sought to construct defensive structures, plan an attack, and construct buildings for various purposes that serve kingdoms and cities. War acted as a catalyst for the development of engineering techniques and practices, such as fortifications and siege warfare, which contributed to the advancement of civilization. Initially, the term "engineer" was associated with military-related activities during the 14^{th} century. At that time, an engineer referred to someone who built and operated military engines for warfare.

It was during the Industrial Revolution in the 18^{th} and 19^{th} centuries that civil engineering—serving civilians rather than the military—began to emerge as a distinct discipline. In 1747, the first institution for teaching civil engineering was established in France, marking the formal recognition and specialization of the field [9]. Engineers such as John Smeaton and Thomas Telford played vital roles in establishing civil engineering as a separate profession. In

1818 the Institution of Civil Engineers was founded in London [50], and in 1820 Thomas Telford became its first president. The institution received a Royal charter in 1828, formally recognizing civil engineering as a profession. Its charter defined civil engineering as [35]:

> *"The art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation, and docks for internal intercourse and exchange, and in the construction of ports, harbors, moles, breakwaters, and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns."*

Leading up to, and including, this period, people had not yet heard or comprehended the term "civil engineering" as we now know it today.

2.2 Modern Perspectives and the Evolution of Civil Engineering

In recent years, civilization and urbanism have become closely related concepts; as civilization advances and populations continue to grow, the role of civil engineering in shaping and sustaining urban areas has become increasingly important. The description by the Royal Charter may seem dated, but the core principles of civil engineering remain relevant in modern society. However, its scope has expanded to (1) encompass a much wider range of infrastructure, (2) consider the interdependencies between infrastructure (i.e., infrastructure systems), and (3) place front and center consideration for the goods and people that flow over and use infrastructure, as well as the services that infrastructure provides. The ultimate objective of construction has also been broadened to include the planning, design, operation, and *use* of sustainable and efficient transportation systems, water supply and sanitation networks, energy systems, urban planning, and environmental management, to name just a few applications. Civil engineers also work with other professionals to integrate emerging technologies and intelligent systems, ensuring that infrastructure systems meet the needs of communities and enhance the quality of life.

The evolving, multidimensional nature of the field has increasingly aligned with the conceptualization of the city as described in the scholarship of St. Isidore of Seville (560-636), who defined cities as consisting of both the physical "urbs" and the cultural-political "civitas" [3, 26]. In line with this thinking, civil engineers not only shape the physical aspects of urban areas, but also contribute to the development of vibrant and sustainable communities, with "urbs" serving as a system of physical space and "civitas" referring to the event or time in which the city functions as a social entity. As the scope of the field changes, there is an *increasing* need for civil engineers to be able to account for the social interactions and systems that built environments support [14, 15]. The work proposed in this paper is a direct response to this need.

3 STREET-LEVEL URBAN GRAVITY

3.1 Motivation of Model Selection

While gravity is considered to be a force in classical physics, according to Einstein's theory of relativity it is better understood as an effect of spacetime curvature [44], which is essential for predicting the behavior and mechanics of objects like planets and black holes [40]. The physics of subatomic particles such as photons and electrons have also been discovered to break our intuition of classical physics, leading to the exciting field of quantum mechanics [12]. With regard to urbanism, the Newtonian gravity model was adopted to describe Ravenstein's "Laws of Migration" with populations being the key variable to increase the influx that reduces as distance increases [52]. This was later modified to be more practically defined as population flux in a pair of spatial units that follow the Poisson distribution [13]. Indeed, the radial distance was criticized as it simply cannot capture the urban street patterns and the use of travel time may have been more accurate [19]. In traditional traffic and transportation engineering, with the emphasis on forecasting the demands to drive an automobile from one zone to another, the concept of gravity stems from a study in 1955 that used the retail transaction of goods and services as a measurement of trip distributions $F_{t,ij}$ for spatial zones i and j in a time interval t [11], are traditionally expressed as follows [55]:

$$F_{t,ij} = G \cdot \frac{(o_{t,i})^{\beta_1} \cdot (d_{t,j})^{\beta_2}}{(c_{ij})^{\beta_3}} \cdot \eta_{ij} \tag{1}$$

Here, G, β_1, β_2, and β_3 are constants to be calibrated, o and d are flows of an origin and destination spatial zone, c is a cost function between the origin and destination, and η is an error with an expectation to be equal to 1.

The use of the term "urban gravity" (specifically with the term "urban") has not been explored extensively or received attention as much as transportation gravity modeling. Urban gravity has once been defined in a Newtonian equation form, but was utilized differently as a measurement of how much attractiveness of each zone corresponds to the growing physical building density nearby, resulting in a cluster of mixed-use buildings near a transit station [57]. While it does scale down to a smaller scale, the goal of exploring land-used mechanisms neither encompasses nor translates to the level of pedestrian movement, or civitas. As discussed earlier, rather than focusing on estimating influx itself and addressing the lack of human-scale urban gravity, we explore the use of quantum mechanics for describing pedestrian movement in public spaces.

3.2 People as "Electrons"

So far, we have debated in essence the logic of population mass influx in civil and transportation engineering, leading to the issue of unnatural fitting to real pedestrian mobility on a human-scale model. Drawing on the notions of urbs and civitas, as well as the street-level modeling of neighborhoods, we introduce the concept of quantum mechanics into this problem to replace the Newtonian mechanics analogy. Here, we assume a user of urban space is a quantum particle—such as an electron or photon—existing in the form of a superposition of particle-wave duality on a street with an "urban" potential field. The description of urban potential is to be discussed in the next section. A user's existence, in other words, acts as an urban particle that follows a probable path, We characterize a user with a wave function $\Psi(x, t)$, where x represents spatial position on a street space and t represents time. While Ψ is a function of a complex number, its norm, which describes the probability density of finding a position, must be real, observable, and normalized such that the total probability is equal to unity at any point in time. It can be expressed as an inner product of the vector conjugate (in Bra-Ket notation [12]) or an integral of a norm of the wave function. Note that time t is not written since probability density overall does not depend on time:

$$\langle \Psi | \Psi \rangle = \int |\Psi(x)|^2 \, dx = 1 \tag{2}$$

This conservation of probability must be proper even when modeling a user in an urban space in 2D or 3D, denoted by the position $\vec{r}$. A normalization in 3D, for example, must also be equal to unity:

$$\int |\Psi(\vec{r})|^2 \, d^3\vec{r} = 1 \tag{3}$$

Similar to quantum physics, the wave function is governed by the Schrödinger equation. With an urban particle on a street line subjected to time-dependent urban potential $V(x, t)$, we have the Schrödinger equation to be as follows:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi \tag{4}$$

or in any dimension of urban space:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \Psi + V\Psi \tag{5}$$

When an urban particle is subjected to $V(x, t) = 0$, or simply put, bounded to no potential influence of any built environment or urban gravity on that 1D street line, Equation 4 is reduced to be a homogeneous form of the partial differential equation (PDE):

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} \tag{6}$$

Therefore, a general solution form of a quantum system or the wave function is in a similar form to the differential equation solution:

$$\Psi(x, t) = Ae^{i(kx - \omega t)} \tag{7}$$

Where $A \in \mathbb{C}$, k is a wave-number $k = \frac{2\pi}{\lambda}$ and considered as a spatial frequency, ω is angular frequency $\omega = 2\pi f = \frac{\hbar k^2}{2m}$ with λ and f being wavelength and frequency, respectively.

The key property of this formulation is linearity. Although it can be modeled in other sophisticated ways such that an urban quantum system is no longer linear, there are benefits to doing so. The most important benefit is the principle of superposition of many different equation solutions. Linearity allows the superposition of wave functions [12, 51]. It is an analogy of how an urban space user's wave function—which governs their position and momentum—can also interfere with the wave function of another nearby urban space user's existence. Analogous to the double slits experiment by Thomas Young [12, 20], when two sources of urban particles project to a 1D street (e.g. a pair of housing buildings), we can treat it as a single system, combing two differential equation solutions together as a total solution:

$$\Psi_{total}(x, t) = \Psi_1(x, t) + \Psi_2(x, t) \tag{8}$$

It should be emphasized that the linearity of the wave function is not the same as the linearity of wave function intensity, expressed as follows:

$$|\Psi_1(x, t) + \Psi_2(x, t)|^2 \neq |\Psi_1(x, t)|^2 + |\Psi_2(x, t)|^2 \tag{9}$$

Another property of the Schrödinger equation is the fact that a time-independent version of this equation (derived from time-independent potential energy and a separation of variables) can be thought of as a time snapshot of the wave function that evolves as time goes by. This means that solving for a solution of an urban quantum system at time t should tell us the time evolution of this urban particle, with its energy states associated with it. Assuming an eigenvalue E, which is the energy of our urban particle, the time-independent formulation is as follows.

$$\Psi(x, t) = \varphi(x)\xi(t) = \varphi(x)e^{-iEt/\hbar} \tag{10}$$

$$-\frac{\hbar^2}{2m} \frac{d^2\varphi}{dx^2} + V\varphi = E\varphi \tag{11}$$

3.3 Urban Space as a "Potential Field"

As previously described, instead of focusing on modeling urban gravity as a force, we can understand the behavior of attraction and repulsion better by directly modeling the interaction between physical infrastructure and the mechanics of urban particles. The urban potential works similarly to the potential in quantum physics. It can be considered an electron that has some spatial distance from an atomic nucleus. At every point in space, there is a potential energy value assigned to that position. A quantum particle may not enter a position where there is a high wall of potential energy blocking the wave propagation. While this phenomenon is absolute for a case of infinitely high wall $V \longrightarrow \infty$, there are possibilities where potential energy may be higher than the energy that a quantum particle is expected to carry, but it "tunnels" through that potential wall regardless, resulting in what physicists refer to as quantum tunneling. The application of the quantum tunneling effect is discussed in Section 4.

The question becomes: How can $V(x, t)$ be modeled for a street or urban space? Referring back to the concept of urbs and civitas earlier, urban potential can be broken down into two parts.

3.3.1 Urbs in Urban Potential. Any physical structure ranging from buildings, street furniture, trees, crossings, sidewalks, and geological hills, and also less-tangible influences such as weather, are assumed to be able to locally influence urban potential energy. Research conducted during a summer in New York City has found a significant response to how pedestrians adjust their walking behavior from one side of a street to another side due to solar exposure and sunshades from buildings [34]. This property is connected to a concept of "multi-sensory architecture," which, combining knowledge from neuroscience and architecture, is an approach to designing spaces that takes into account all of the human senses, not just sight [53, 59]. By considering how the space user looks at a street with their eyes, feels the street with their skin, perceives a sound with ears, and reacts to a smell with their nose, we can assess, in theory, the engagement and plausibility of that space using the potential energy model. To be consistent with the Schrödinger equation, we propose a convention that an urban space that acts as a community barrier has high potential energy and vice versa for any attractive structure. Assuming an experimental scenario where we have three modes of sensing signal (i.e., visual, sound, and touch), it should be possible to map potential as a function of histograms of visions D that an urban user sees in that field of view in their direction, frequency patterns of sound F that a human ear can hear, and temperature and humidity data G that a human skin can feel, for example, all measured at the same time $t = t_c$:

$$V(x, t_c) = f[D(x, t_c), F(x, t_c), G(x, t_c)] \tag{12}$$

Although the function is yet to be known, it remains a possible starting point for mapping urban potential. Recent research successfully made a measurement of human visual perception with semantic segmentation of street view images and spatially mapped the quantitative result score into 5 categories of streetscape perception: enclosure, walkability, openness, imageability, and greenness [60]. An algorithm known as *GraphSage: Representation Learning on Large Graphs* or *GraphSAGE-LSTM* is shown to be able to predict comfortability on a sidewalk based on features including heart rates, solar intensity, sound, altitudes, cars, pedestrians, etc. [42].

3.3.2 Civitas in Urban Potential. Human periodic or non-periodic activities that act on buildings and infrastructure, ranging from people simply positioning themselves within a workplace for a nine-to-five job to actively partying in a bar at nighttime, can also increase or decrease the urban potential field on a street in the time domain, t. An analysis of Strøget—a main walking street in Copenhagen, Denmark—investigated how people stop walking and their frequency of becoming attracted to look at a building. It is revealed that fewer stops were observed in front of banks, offices, and inactive exhibitions. In contrast, more frequent stops were observed by a building accompanied by humans, newspaper kiosks, or photography exhibits [16–18]. The time children play outdoors on the street also increases when motor vehicle traffic volume decreases [33]. We may assume that any change in time of urban potential also impacts how the probability spreads over time as a response to system change. Any disturbance of a wave function in the time domain, such as automobile traffic or time of business operation, can make a street more or less compelling and attractive for urban particles and can be thought of as a disruption of urban potential energy on that street. Operation time of businesses, events, or work time can influence urban particles' wave functions. One way to model V at any time t localized at a point $x = x_c$ is to form a machine learning function of automobile traffic flow Q on that street and various business and building operation hours data $|w\rangle = (W_1, W_2, ..., W_N)^T$ as follows:

$$V(x_c, t) = f(Q(x_c, t), |w\rangle) \tag{13}$$

3.4 Limitations

In modern physics, quantum theory has reshaped our understanding of the fundamental elements of the universe. The sun of our solar system, for instance, needs protons to tunnel through the electrostatic barrier and come close enough for the strong nuclear force to bind them together, allowing fusion reactions to occur in the sun even with lower energies than what would be classically expected [4, 56]. This probabilistic phenomenon also plays a role in electrical and computer engineering such as transistor design. As the transistor gets smaller, the probability of electron transmission between the source and drain regions increases, leading to new transistor architecture such as the fin field-effect transistor or FinFET [6, 27, 61]. Quantum tunneling in our street-level urban gravity theory is to be discussed again in Section 4.3. Nonetheless, the use of Newtonian mechanics models is still relevant for matters relatively visible and tangible to most humans. Determinism is inherited in many science and engineering branches that do not concern the sub-atomic behavior of electrons or photons. This limitation of scale is also true of this research's quantum methodology. Any macroscopic or mesoscopic transportation studies, for instance—a whole city or intercity-scale problems, or long-term time intervals—should not be modeled with the theory of urban gravity. As discussed in the introduction, the proposed idea counters the concept of traditional A-to-B flow by modeling an urban potential on a street itself and how it can draw urban particles to be on that street.

Another limitation is the requirement to make a measurement of $|\Psi|^2$ of a street or an urban space. Similar to quantum physics, a single particle, thought to behave like a wave, still collapses into a quantized number of particles when we make an observation, referred to as wavefunction collapse. It is the overall pattern of probability intensity $|\Psi|^2$ that is real and observable. In order to acquire it, a large number of quantum particles are needed for data collection. The proposed concept must be validated, or course, with a street or urban space with a sufficient amount of foot traffic.

4 APPLICATIONS OF THEORY

4.1 Implementation and Measurement

The theory of modeling street-level urban gravity as a quantum system is a challenging proposition to test experimentally. However, the potential benefits are unprecedented. Specifically, the modeling of the input of urban potential energy V and the output of the wave function Ψ has no evidence of being conducted before in this space. While significantly less impactful in its potential applications and understanding of urban spaces, the perspective of people as classical mass flow, as discussed previously, has gained significant popularity in transportation due to its simplicity. While the idea presented in this study remains largely theoretical and is intended to ignite discussions around this topic, we would like to emphasize that emerging technologies have the capacity to support the intricacies of street-level urban gravity. We have seen examples of predicting urban space attractiveness in various forms similar to our potential V that ushered in a new era of big data and artificial intelligence [42, 60]. Regardless of the perspective, classical or quantum, the potential energy remains real in our model. The use of spatial data of existing streets in a community, data of building models from digital twins, as well as traffic data are rapidly advancing through remote sensing and GIS. Moreover, applying the theory of quantum mechanics in pedestrian modeling might be even more amenable to experimental investigation than the traditional model. The advantage arises from the fact that a measurement of $\Psi^*\Psi$ or $|\Psi|^2$ is normalized at any timeframe and requires no measurement of the flow value. Pedestrian mass flow, while it can be obtained from a privacy-preserving sensors like passive infrared (PIR) [39], has difficulty in robustness and undercounting the number of people [32]. While more research in active transport counting is still ongoing and we may adapt the accurate result in our theory in a future implementation, our method of the quantum system only concerns overall $|\Psi|^2$ observable patterns over urban space. In other words, any technology that can sense and infer the amplitude of people's "waves" in an outdoor area, including a thermal camera or even PIR analog reading, has an opportunity for practical use. Therefore, the data analysis of pedestrians might be more accessible for experimental exploration than the conventional model.

4.1.1 Relevant Misconceptions in Quantum Mechanics. It is commonly assumed that the uncertainty principle in quantum mechanics implies that we can never simultaneously know both the position and momentum of a particle with precision, leading to possible misconceptions that our street-level urban gravity model would fail to know the position and momentum (correlated to velocity) of a pedestrian. The uncertainty principle, formulated by Werner Heisenberg, does not suggest that uncertainty arises from limitations in our measurements or technology. Instead, it is a fundamental property of quantum systems [12, 51, 54]. To be specific, the statement equation used the root-mean-square or standard deviation of position and momentum, not the expected value or mean. There is an inherent limit to how "precisely" we can simultaneously measure certain pairs of complementary properties, such as position and momentum. This is not due to a lack of knowledge but is a fundamental characteristic of any wave measurement that undergoes the Fourier transformation.

4.2 Business Analytics and Land Value

While there are many factors that can affect business success, gaining more customers through a physical walk-in experience is undeniably important, especially for local businesses in a community. Understanding the dynamics of pedestrians can help identify optimal locations and surrounding infrastructure design and management for businesses based on patterns of probability density. The scope of the application also includes modeling of non-permanent commerce, such as street food vendors with temporal positions and time duration.

This knowledge can be used for business analytics and land value assessments, allowing businesses to position themselves in areas with high probability density strategically. Assuming a split-rate property tax, separating the assessment of the land and the buildings, the use of the Schrodinger equation can be a way to quantify the expected land value of land ab denoted as $\langle l_{ab} \rangle$ by using the given condition of a neighborhood as an urban potential energy and solving for the wave function, then correlating a norm of the wave function in that desired land space from point x_a to x_b (normalization and calibration with other nearby land value). While there can be many factors other than location positioning in a field of urban potentials that can impact the monetary value, such as natural resource availability, one might construct a statistical or machine learning model that forms a function described as follows:

$$\langle l_{ab} \rangle = f\left(\int_{x_a}^{x_b} |\Psi(x)|^2 \, dx\right)$$

4.3 Crossing and Collision Evaluation at Intersections

Within the proposed convention, we assign a space with large potential energy as a space that an urban particle is unlikely to penetrate or position itself into. In the case of a 1D street with two sides of infinite potential at both ends, an urban particle is trapped in-between, similar to a problem regarding a quantum particle in a box problem in quantum physics. With a non-infinity potential pair of walls, a particle has a chance of escaping a box and tunneling through the barrier. By modeling an urban particle in many urban streets with junctions and a system consisting of many subsystems, pedestrian crossing can be thought of as a space with slightly lower energy potential than the orthogonal space for cars. An urban particle can quantum tunnel through such a barrier in that space, given that an urban particle has enough kinetic energy, similar to how a pedestrian may have to increase their velocity to cross a high-traffic road. This application can provide insight into traffic safety studies, provided that overall data related to urban potential can be obtained (as discussed in Section 4.1).

While the focus of urban gravity theory is primarily aimed at pedestrian movement, other modes of transportation such as passenger cars could be modeled as urban particles. Such particles would have to be assigned with different inherited properties, including mass and charge if assuming the existence of an electric field in addition to potential. This concept can also explain the phenomenon whereby any urban gravity from an urban space has a lower probability of attracting high-momentum urban particles as if they were highly excited electrons free from any nucleus. A collision of low-momentum particles may provide negligible disturbance to surrounding urban potential. Still, a collision of high-momentum particles (car-to-car crash) or low and high-momentum particles (e.g., car-to-pedestrian crash), can severely disrupt potential energy due to impulsive conversion from kinetic to potential energy and result in a high potential spot where urban particles can move away from that spot as a response of the disrupted system, or move towards the spot as a new nucleus in a system.

4.4 Social Connection in a Community

Researchers have sought to measure social connection in various ways, such as using social media data. This paper's quantum approach offers a new mathematical description of the mechanisms of urban space users. While there can be many factors influencing spatial attraction and repulsion in urban spaces not mentioned in this study, we propose formulating a study of social connection in communities with social segregation as an opposite possibility of the wave function's norm:

$$b(\hat{r}) = 1 - |\Psi(\hat{r})|^2 \tag{14}$$

While typical neighborhoods are "officially" bounded, we can use b to detect the functional edge of a neighborhood unit that resembles an area where urban particles tend to be positioned together in that space. The process then becomes an edge detection problem, requiring convolution with a filter (e.g., derivative or Laplacian of Gaussian) [25]. The filter response is a mapping of all urban edges. This concept of visualizing social connection with urban edge detection is similar to many more qualitative concepts in urban design that have explored how the design of the built environment can cause segregation. Recall our previous example of a case study in which high automobile traffic road can socially isolate residents on the same road [7]. The construction of the Interstate Highway System within the United States has also yielded noteworthy detrimental effects on impoverished and minority populations residing within urban communities [30]. On the other hand, a Dutch "Woonerf," or "residential yard" streets were established by the Dutch government as streets that give the right of way to pedestrians—including children at play—over drivers [2, 5]. This transformation enables conventional streets to safely function as a a form of a community's social infrastructure, returning the concept of the street back to being public spaces, which is where this paper began.

5 CONCLUSION

This paper aims to situate itself at the nexus of many theories and ways of thinking across civil engineering, urban design, quantum physics, and other fields concerned with the relationship between physical streets and human interaction in urban spaces at a street level. This paper deviates from simplified and limiting classical transportation models of gravity that describe the influx of trip distributions at a macroscopic scale. Instead, the proposed urban gravity model in this study describes the mechanisms of movement at an individual user level. In order to understand social behavior at a community level, the proposed concept offers a new opportunity within the field of civil engineering to switch from the analogy and application of classical science to modern science. With a derivation from modern physics theory, specifically quantum mechanics, the mechanism of urban particles can be estimated by a wave function obtained by solving the Schrödinger equation. By capturing both the urbs and civitas properties of urban streets in the form of urban potential energy, the wave function provides a new intuition of a pedestrian as a wave of probability similar to a quantum particle. The approach to validate and experimentally model real physical systems as urban quantum systems is also discussed with concerns of limitations and scopes addressed. Future work should thoroughly investigate a possible use of advanced technologies, such as machine learning and privacy-preserving sensors, to incorporate multimodal data. Ultimately, extracting both urban potential function and wave function modeling is important to various applications.

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