Seeing the invisible: from imagined to virtual urban landscapes

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Seeing the invisible: From imagined to virtual urban landscapes

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ABSTRACT

Urban ecosystems consist of infrastructure features working together to provide services for inhabitants. Infrastructure functions akin to an ecosystem, having dynamic relationships and interdependencies. However, with age, urban infrastructure can deteriorate and stop functioning. Additional pressures on infrastructure include urbanizing populations and a changing climate that exposes vulnerabilities. To manage the urban infrastructure ecosystem in a modernizing world, urban planners need to integrate a coordinated management plan for these co-located and dependent infrastructure features. To implement such a management practice, an improved method for communicating how these infrastructure features interact is needed. This study aims to define urban infrastructure as a system, identify the systematic barriers preventing implementation of a more coordinated management model, and develop a virtual reality tool to provide visualization of the spatial system dynamics of urban infrastructure. Data was collected from a stakeholder workshop that highlighted a lack of appreciation for the system dynamics of urban infrastructure. An urban ecology VR model was created to highlight the interconnectedness of infrastructure features. VR proved to be useful for communicating spatial information to urban stakeholders about the complexities of infrastructure ecology and the interactions between infrastructure features.

1. Introduction

1.1. Urban ecology

Cities function akin to ecosystems, consisting of complex features and systems that are interconnected and dependent on one another. These urban ecosystems are fragile and face many challenges. As the population in many areas of the world continues to grow and urbanize, cities are forced to adapt and, as a result, the functioning urban ecosystem becomes stressed while trying to supply services to more people (Colding & Barthel, 2017). Additionally, the urban ecosystem is threatened by a changing climate and extreme weather events - from flooding and land subsidence in New Orleans (Qiang, 2019), to wildfires destroying areas on the west coast of the United States (Schweizer, Cisneros, Traina, Ghezzehei, & Shaw, 2017), environmental hazards test urban ecosystems worldwide with increasing frequency and extremity (Salas & Yepes, 2018). The combination of environmental threats and an ever-growing population has put unprecedented stress on aging urban ecosystems, exposing vulnerabilities and posing a risk of collapse. Improving these ecosystems and increasing the resiliency of infrastructure systems is going to be crucial for cities moving into the future.

1.2. Infrastructure systems

Urban infrastructure system (UIS) is a term that will be referred to throughout this paper. The UIS is defined as the dynamically interrelated pieces of individual infrastructure, both above and below the ground, that make cities function. The UIS can change as a whole in response to a shift in one individual feature (Pandit, Lu, & Crittenden, 2015). An UIS is expansive and is maintained by a variety of stakeholders, including local governance, municipal and public facilities, municipal utilities, and engineers (Ferrer, Thomé, & Scavarda, 2018). In the UIS framework, it is important to understand that a change or failure in one infrastructure feature can cause a ripple effect throughout an urban environment. As stated in Upadhyaya, Biswas, and Tam (2014):

> "There are multiple and layered negative effects on societal health and well-being when infrastructure systems break down and are unable to adapt to sudden increased demands … Unsustainable and inadequate infrastructure can fail causing stress on resources and endangering public health."

There have been countless incidents where a piece of infrastructure fails and causes damage and inconvenience to large urban populations. Power outages, flooding, and major repair projects are just a few

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examples of the inconveniences and dangers that occur when the UIS is disrupted (Upadhyaya et al., 2014). Unfortunately, in many municipalities care for infrastructure as separate features and approach management with a narrow technological approach rather than holistically addressing the entire system (Pandit et al., 2015). This separation in infrastructure management is demonstrated in the separation of management between above and belowground infrastructure features. Seldom do the stakeholders at the parks and recreation department interact with the water and sewage workers on coordinating repairs. This siloed approach has created an urban infrastructure management system in which there is little professional and/or public understanding of how these two infrastructure environments interact as a system (Nelson, 2016).

To understand how infrastructure below the ground affects infrastructure above the ground (Rinaldi, Peerenboom, & Kelly, 2001), it is important to distinguish between the components of above and belowground infrastructure. Aboveground infrastructure encompasses the infrastructure citizens walk on, live in, and ride on. Roads, sidewalks, buildings, parking lots, green spaces, and public transportation comprise the above ground infrastructure ecosystem (Andersson et al., 2014). Belowground infrastructure is less conspicuous but is equally, if not more, important to care for in order to reach resilient urbanization goals (Ferrer et al., 2018). Below city streets there is a complex system of utilities, transportation, biomass, and structures that enable urban areas to run. Gas lines, water pipes, sewage, stormwater management, electricity, and cable provide services to urban citizens upon which they rely (Guneralp et al., 2015). Subway lines, tunnels, and skyscrapers' massive foundations also have to find a niche underground to provide ease of movement and support for people living above the ground (Sun & Cui, 2018). In addition to these human requirements, the natural world is a strong competitor below the ground. Microbial communities and root structures compete for space in this highly disturbed environment (Mullaney, Lucke, & Trueman, 2015).

Above and belowground infrastructure features are separate “adaptive entities” that interact and relate to one another in complex ways (Pandit et al., 2015). Unfortunately, infrastructure management in many urban areas is focused on the individual utility. Shifting this focus from the current short-term ad hoc repairs to a comprehensive integrative repair plan will be necessary for cities to be more sustainable and resilient (Derrible, 2017). To make this transition possible, an increased understanding of the relationship between above and belowground infrastructure will be crucial for all infrastructure stakeholders to promote a healthy urban ecosystem.

In order to efficiently plan for cities of the future that are resilient in a changing climate and an urbanizing world, coordinated infrastructure management of both above and belowground utilities will be necessary. For this study, we focus on the City of Boston, MA and other Massachusetts municipalities that are currently tackling aging belowground infrastructure (Hendrick, Ackley, Sanaie-Movahed, Tang, & Phillips, 2016). Our team hosted a workshop for stakeholders involved in all realms of urban infrastructure management to sit down together and discuss the systematic and foundational barriers that exist for implementing a more coordinated infrastructure management approach. From the conversations,our team uncovered a need for a tool that could not only help stakeholders visualize spatial information but highlight the interconnectedness of various infrastructure features. Virtual Reality (VR) became a clear choice for communicating the complexity of interrelated spatial data to the stakeholders and so our team created an immersive VR tool to demonstrate the UIS.

2. Data & methodology

2.1. Virtual reality for urban planning (virtual landscapes)

An emerging tool with exciting and growing application in urban planning is Virtual Reality (VR) (Kersten, Deggim, Tschirschwitz, Lindstaedt, & Hinrichsen, 2018). VR is an immersive tool that allows a user to experience and “reproduce a realistic… detailed and accurate visual and audio model as similar as possible” to the real world in the comfort of their own office or home (Echevarria Sanchez, Van Renterghem, Sun, De Coensel, & Botteldooren, 2017). VR models create an environment that stakeholders can enter, providing a “common language” for them to use and relate to while making planning decisions (Lovett, Appleton, Warren-Kretzschmar, & Von Haaren, 2015). A VR environment is immersive; creating a “multisensory' visualization… [that] track[s] user movements [and] show[s] a virtual environment wherever the user is looking” (Berger & Bill, 2019). Additional benefits of a VR model is that this environment can be created in an office building, not requiring stakeholders to travel to a location to visualize infrastructure like an augmented reality (AR) model would require (Cirulis & Brigmanis, 2013). Conclusions drawn from the urban stakeholder workshop, hosted as a part of this study, demonstrated a need amongst stakeholders for a better way to communicate and visualize spatial data in the complex urban infrastructure environments, paving the way to the creation of this VR tool.

Traditionally, urban planning stakeholders have been trained with tools such as computer-aided design (CAD) and geographical information system (GIS) drawings (Wu, He, & Gong, 2010). These tools are helpful in visualizing city streets and networks but do not show the dynamic and inter-connectivity of the different features in the UIS. VR tools, however, has the ability to facilitate a more comprehensive approach to urban planning and infrastructure management by showcasing all features in the infrastructure ecosystem and demonstrating how they interact with one another (Santos, Zarraonandia, Díaz, & Aedo, 2018). Creating a VR rendering of a city street, with both above and belowground infrastructure components, provides urban planners with the answers to questions such as, what is the spatial relationship between sewage and drinking water supply? How are belowground utilities organized under the street? How vulnerable is the infrastructure network to collapse? Industry experts have a heuristic understanding of the placement of various utilities in relation to one another but a VR realization could make this more concrete (Nelson, 2016). Ideally, having a tool that enables stakeholders to visualize colocated urban infrastructure features would allow for a more coordinated infrastructure management approach that could increase the resiliency and efficiency of the entire infrastructure system.

VR, while pioneered in the gaming industry, has transformed over time through innovations in application (Edler, Kühne, Keil, & Dickmann, 2019). Recent advancements in cartographic methods and GIS technology have allowed for data representation in the third- and fourth- dimension (height and time respectively), giving cartographers access to new realms of mapping (Wolfartsberger, 2019). Unfortunately, there are technical challenges to bridging a GIS database into an AR or VR database but when done successfully, adding the third- and fourth-dimensions, 3D GIS decision support systems can create three-dimensional scenarios from overlapping spatial datasets, e.g., street measurements of different infrastructure features. This integrative model is helpful in enabling urban planners to see the interconnectedness of the urban infrastructure system and has added depth representation to spatial data and enhanced visualization (Hruby, 2019). AR is useful for many of the same applications in urban planning as VR, however, with AR technology the user must travel to the real world location in order to envision the virtual model (Carozza & Tingdahl, 2014). AR has proven useful in urban applications in countless studies (Allen, Regenbrecht, & Abbott, 2011; Imottesjo & Kain, 2018; Ishii et al., 2002) but for the immersive and portable experience associated with VR, our team decided VR would be more applicable for communicating spatial interactions in the UIS.

VR models create an environment of spatial data that enables the user to visualize, interact, and immerse themselves into the unique map from anywhere in the world (Kersten et al., 2018). VR models have huge potential to revolutionize urban planning and the mapping of

"Market Street in Anytown, USA, is a busy commercial corridor recognized to have excellent economic potential but held back by a streetscape in disrepair and daily traffic jams. Market Street has relatively high vacancy and business turnover and little foot traffic on the sidewalks. The two-way street has two lanes in either direction; sidewalks; storefronts and a few frontage surface parking lots. Market street is a 1950's design built primarily for the automobile, although it has a bus line and potential for nearby transit connections. Above the street is a tangle of electrical wires and utility poles. Underneath the street is a haphazard array of gas, water and sewer pipes of varying age and condition."

EXERCISE 1: Network/Relationship Map: Map interplay among various owners of above and below ground infrastructure.

1. Who are all of the stakeholders associated with the above and below ground infrastructure represented on your schematic? Public, private, community, regulatory, etc.
2. What are their roles in the infrastructure management process?
3. Where are the connections amongst the stakeholders?
4. What tools or communications support those connections?
5. What are barriers to connections or communication?

Infrastructure Ecology: Residents call for undergrounding the unsightly electrical wires, a request that had not been previously made, and for tree plantings and green space. Moreover, above-ground electrical utility poles and fixtures seriously constrain space available for proper sidewalks and bike lanes, and green space would compete with space for pedestrians and bicyclists. How can cities better physically allocate above- and below-ground space for street infrastructure? Are infrastructure synergies possible, wherein above- and below-ground infrastructure can be spatially co-organized?

EXERCISE 2: Determine how the city can resolve the above challenge identified by the community.

Revisit the Network Map: Is the "network" equipped to address the problem? What enhancements/improvements are needed?

1. Who "owns" the problem?
2. Are there any stakeholders not represented who are critical to addressing the problem?
3. Are the existing connections, communication channels and tools sufficient to address the issue? What more is needed?

Fig. 1. Prompt with two exercises for five randomly chosen stakeholder groups to work through and discuss. Results were collected in visual maps that were presented back to the larger audience.

'smart cities' because they allow planners to simulate future scenarios (Tao, 2013). This extensive immersion mapping technology was attractive to our team because it would allow stakeholders to envision the interactions between infrastructure features and see the dynamics of the UIS. Using VR for urban planning is not a novel idea. In a study by Fairbairn and Parsley (1997), the authors examined the use of VR and virtual reality modeling language for cartographic presentation, and provided several examples that demonstrate successful virtual campus construction. Prior studies by Batty, Dodge, Doyle, and Hudson-Smith (1998) and Doyle, Dodge, and Smith (1998) have described the 'Virtual London' project that marries a range of VR and Internet GIS technologies. Urban stakeholders benefit from VR technology because it is useful in exploring ways to plan, model, and simulate urban planning and aid in impact assessment (Kamel Boulos, Lu, Guerrero, Jennett, and Steed, 2017). The creation of these virtual models has enabled planners to interface with the complex physical and social data incorporated in planning and managing cities in a realistic and meaningful interactive way.

VR has additional applications in risk assessment and urban resiliency in a variety of contexts, including wind damage (Repetto et al., 2017), forest fires (Gaudreau, Perez, & Drapeau, 2016), and other natural disasters (Breunig et al., 2015). ESRI (the company making GIS software) has created a mobile VR solution for urban planners, architects, and GIS professionals called CityEngine that can create a VR tool to compare urban planning scenarios on a mobile device. Standard 3D GIS packages include 3D city modeling applications, such as City Engine (Neukom, 2018) and CityGML (issued by the Open Geospatial Consortium) to render and store digital 3D models of cities and landscapes (Pouliot, Larrivée, Ellul, & Boudhaim, 2018). The standard ArcGIS API enables users to build full-featured 3D applications powered by web scenes consisting of terrain, integrated mesh layers, and 3D objects. Additionally, the open-source JavaScript library Cesium can create web-based globes and maps, also useful for visualizing dynamic data. iTowns, written in JavaScript/WebGL, is frequently used for precise 3D visualization of street view images and terrestrial LiDAR point cloud. Unfortunately, due to the massive size of spatial data, web-based GIS applications can create network latency as well as bottlenecks when handling multiple users. Despite these difficulties, VR-GIS packages are becoming increasingly popular for addressing and solving urban problems because of their ability to incorporate the dynamics of aboveground and underground features (Boulos et al., 2017).

VRGIS has become an increasingly popular for tool for urban planners looking for an interactive way to model urban decision-making processes (Sameeh El halabi et al., 2019). VRGIS establishes a three-dimensional model in a virtual environment, and operates via personal computers, mobile devices and smart glasses. Examples of VR technologies include Google Daydream View VR, and its' cheaper predecessor Cardboard (2014), which utilizes a smartphone's gyroscope for head tracking. VRGIS is almost seven decades old, however, recent innovations and developments in technology, such as big data, augmented reality, graphic processing units (GPUs), and the Internet of Things (IoT), has enabled VRGIS to have better performance and more intuitive human–computer interactive modes. These advancements in VRGIS have encouraged its applicability in visualizing, experiencing, and solving more complex, real-world problems (Boulos et al., 2017; Li et al., 2015).

2.2. Workshop

In order to provide a tool to aid in implementing a more coordinated infrastructure management approach, a baseline understanding of the current management practices amongst infrastructure stakeholders had to be established. To obtain this baseline data, our team hosted an urban infrastructure workshop in June of 2017 that brought urban stakeholders together to discuss current infrastructure management protocol. Elected officials, city planners, engineers, utility workers, students, concerned citizens, activist groups, academics, and several other parties invested in making cities work efficiently attended. The goal of the workshop was to encourage groups of people who did not typically interact to discuss the systematic difficulties, educational obstacles, and/or communication barriers in managing urban infrastructure in Massachusetts.

Baseline data was collected in the form of visual maps and talk-back sessions in response to two exercises. In an effort to establish a baseline understanding of the attending stakeholders in regards to their perceptions of above and belowground infrastructure, they were asked to draw a cross-section of a typical city street. The stakeholders were randomly assigned to different groups and presented a prompt (Fig. 1) that asked them to draw a cross-section of a city street in fictional Anytown, USA and to highlight the interactions between the features of infrastructure they included and the stakeholders responsible for managing those features. For example, were they to include gas pipes and water pipes in their drawing, our hope was that they would list the water company and the gas company as the administrators of those infrastructure features and also include that those features co-existed underneath the street. Additionally, we asked the stakeholders to include what barriers existed that prevented a more coordinated management approach. For example, if the water company and the gas company ever worked together to repair pipes to avoid traffic disruption along the same segment of the street.

In the second exercise, attendees were presented with a problem posed by the fictional community requesting more green space and buried utility lines. The attendees had to work together to identify the stakeholders that would need to be involved in such a project and to list any existing partnerships or communication tools that would be useful for such a project. Lastly, they were asked to identify any institutional, systematic, or functional barriers that existed in implementing such an infrastructure project.

"*Market Street in corridor recognized to have excellent economic potential but held back by a streetscape in disrepair and daily traffic jams. Market Street has relatively high vacancy and business turnover and little foot traffic on the sidewalks. The two-way street has two lanes in either direction; sidewalks; storefronts and a few frontage surface parking lots. Market street is a 1950's design built primarily for the automobile, although it has a bus line and potential for nearby transit connections. Above the street is a tangle of electrical wires and utility poles. Underneath the street is a haphazard array of gas, water and sewer pipes of varying age and condition.*"

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Revisit the network map: Is the "network" equipped to address the problem? What enhancements/improvements are needed?

1. Who "owns" the problem?
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The five groups completed the two exercises and presented their visual maps back to the larger group. The visual maps displayed cumulative team insight into current infrastructure design and management processes in and around Boston, MA.

2.3. VR design

For the VR model, a neighborhood in South Boston was chosen as the study area, namely the Dorchester Ave corridor between the MBTA Red Line stations Broadway and Andrew because of the planned redevelopment in this neighborhood.[1] The study area (4.6 km^2) can be covered by two USGS Lidar point cloud scenes, which were obtained from USGS 3DEP (USGS, 2015a, 2015b). Building height can be derived from LiDAR point cloud. Combining with the building footprint, we can populate the VR scene with buildings with the appropriate height. A schematic of the VR tool created for this research project is shown in Fig. 2.

For this analysis, Google Street View was used. Street View is a service provided by Google that allows a user to view panoramic street-level images across the world. Google collects panoramic images using a vehicle-mounted 360-degree camera that are made publicly available on Google Maps. Google recollects Street View images every 3 to 4 years for populated areas. Information on the location and type of utilities was collected by locating pipeline locations marked on the street with spray paint. Cities around the world mark with spray paint color-coded pipeline locations on the streets indicating the utility type, the location, orientation, diameter, and material of the pipe (Fig. 3) (APWA, 2019). Obtaining spatial information about belowground utilities is difficult because utility companies limit the distribution of underground infrastructure data to the public. This is a national security issue, as utility companies do not want to put service areas in a vulnerable position, were the exact location of all infrastructure to be public knowledge.

Designing a VR environment to highlight above and belowground infrastructure features proved difficult due to these stakeholder regulations. However, by utilizing the street markings left behind by utility companies, we were able to collect enough street markings to build a comprehensive model of the pipeline network. Using Google Street View for this analysis was beneficial because of the historical record of images Google has. The spray painted utility markings can fade due to traffic and dust so looking at a selection of photos from a single vantage point enabled our team to collect as much data as possible. There are no existing tools that allow the user to collect the street marker information directly, so the tool "Underground Utility" was created for this purpose. Although time intensive, this method of collecting, converting, and visualizing natural gas infrastructure created for this study can be applied to other underground utilities.

"Underground Utility" was written in JavaScript, using the Google Maps JavaScript API. The main interface was split into two sections: the left side has the Google Maps, and the right side is Google Street View (Fig. 4). The tool allowed a user to place custom markers on the Google Street View panel that sync to the Street View panel. The markers could be customized with information such as utility type, pipe material, and pipe diameter. Addresses were reverse geocoded from the coordinates of the markers and after enough markers are placed for post-processing, the location and attributes of markers were exported to an Excel file and

[1] http://www.bostonplans.org/planning/planning-initiatives/plan-south-boston-dorchester-ave

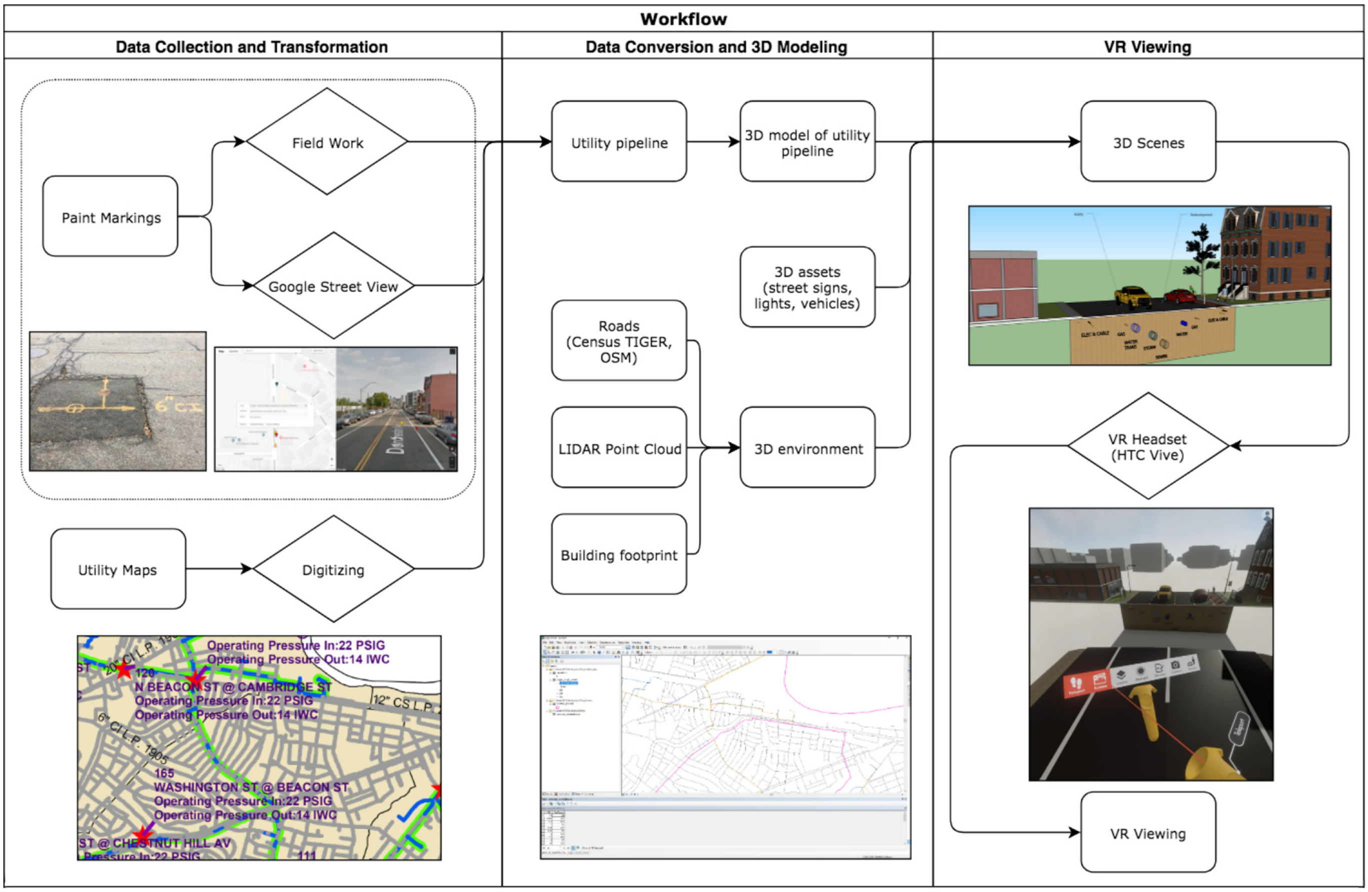

Fig. 2. Schematic representation and flow chart of the VR tool creation.

Fig. 3. Example of a spray painted marking on a road by utility company.

added to a GIS software to generate a spatial display of the underground utility data.

In some cases, utility maps were public domain, allowing us to convert these maps into shapefiles and import them directly into a GIS software. For this study, we obtained natural gas pipeline distribution maps from National Grid territory in Massachusetts (National Grid, 2010). These pipelines were represented in vector (as opposed to represented in pixel in raster maps) so it was possible to convert the polylines directly to shapefiles. To convert a PDF to a shapefile, AutoCAD was used as the medium to extract the polylines and export them to ArcMap. Then the spatial information was added using the Georeference and Spatial Adjustment tools.

Combining the utility pipeline data along with spatial information allowed us to create a tool modeling a comprehensive pipeline network. On traditional GIS platforms, we could visualize pipeline data as latitude and longitude. However, because most of the utility pipeline was buried belowground, it was difficult to differentiate above versus belowground. Therefore, a third dimension was introduced. 3D models are an excellent way of visualizing data in three dimensions. Airborne LiDAR data can be used to create DSM (Digital Surface Model). The main difference between DSM and DEM is that DSM captures the surface height, that includes the building height, canopy height. Combined with building footprints, we could create 3D models of buildings. The LiDAR data we used were USGS Lidar Point Cloud MA Sndy (USGS, 2015a, 2015b), and the first return was used to estimate building height above mean sea level.

In order to display the 3D model and to add more details, the shapefile was imported to Trimble SketchUp using a modified plugin in which we could select the field containing building height information.[2] This plugin can also be used to import roads as polylines to create road models that follow the polylines. Sketchup s useful for creating 3D models because of its access to the world's largest open source assets library. 3D models limited to shapefiles are commonly plain-looking because shapefiles contain only buildings, utility pipelines, and roads. Adding auxiliary assets, such as ground cover, cars, humans, and street lights to the 3D model created a more realistic user experience. A 3D model is useful to highlight the third dimension that distinguishes above and belowground infrastructure features, unfortunately, the

[2] https://www.sketchup.com/

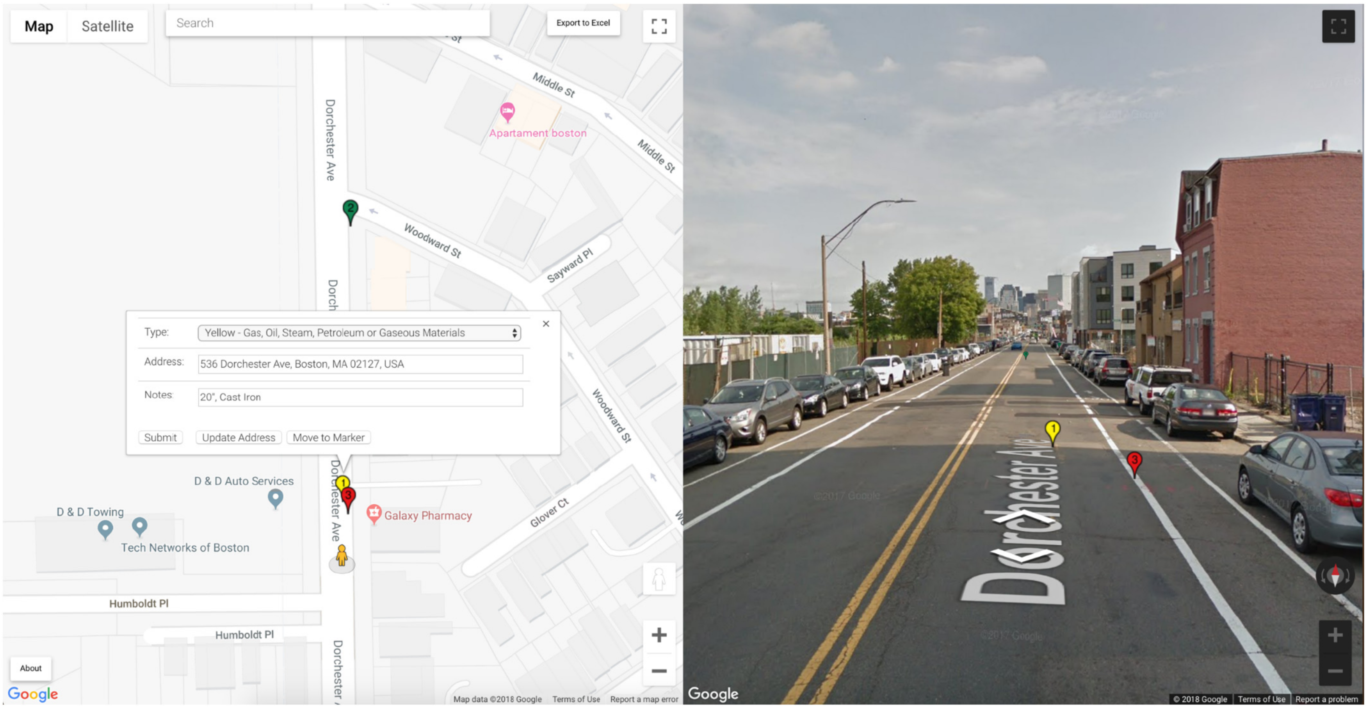

Fig. 4. Screenshot of Underground Utility interface. Google Maps display of Dorchester Ave, Boston, MA (left panel) and Google Street view of the same street (right side).

models are still constrained to a flat computer monitor limiting user perception. VR became the logical next step to creating an environment in which the user could observe and interact with objects as they are in the real world.

There are two requirements for a VR experience, hardware and software. For hardware, we used the HTC Vive platform. This platform contains a head mounted display (HMD) and a pair of hand-held controllers. Two wall-mounted lighthouses track the X, Y and Z position of the user in real time. It allows the user to move within the VR environment by moving their heads, body, and hands. A minimum of 2 m by 2 m of unobstructed space is recommended for a room scale setup because it provides the greatest user immersion. Unfortunately, rendering a VR environment is a heavy load on the computer because the graphics card needs to drive two full HD screens in the HMD at 90 frames per second (FPS). According to HTC, a GTX 970 or equivalent graphics card is the minimum requirement for VR.

There are multiple software packages possible for the user to view 3D models in a VR environment. SYMMETRY is a software tool that converts CADs, in this case SketchUp models, to VR and is currently available on Steam, a video game digital distribution service by Valve.[3] The import feature converts *.skp* files along with SketchUp layers and textures into VR. Additionally, there are two viewer modes: the "Studio Mode" that provides the user with an overview, as if viewing a model inside a studio; and the "Immerse Mode" that brings the user inside the model where they can use the markup tool, camera, and memo to communicate with other users and exchange ideas.

We created our 3D urban infrastructure experience using the HTC Vive platform. Our VR experience allowed users to dive beneath city streets and look at the variety of utilities that exist and interact with one another. The VR entitled "Virtual Reality & Urban Ecology" allowed the user not only to explore belowground utilities but also see a city block of aboveground infrastructure, including cars, bike lanes, public transportation lanes, buildings, sidewalks, and pedestrians (Fig. 5). With this VR environment, we aimed to teleport urban stakeholders to an environment which highlights the interconnections of above and belowground infrastructure features.

3. Results & discussion

3.1. Visual maps

From the five visual maps (Fig. 6) collected in response to the two *Anytown, USA* prompts, several common themes emerged, which suggested a variety of reasons as to why a coordinated infrastructure management plan is difficult to implement:

1. Elected officials expressed concern with aboveground infrastructure only.
2. Engineers and utility workers did not communicate efficiently outside of their particular utility to coordinate infrastructure repair and replacement projects.
3. There was a general lack of understanding and/or appreciation for how urban infrastructure functions as a system.
4. Budgetary and practical concerns exist, preventing future urban infrastructure innovations, like the utilidor, from being implemented.

1.) Elected officials, city managers, and park officials concentrated on infrastructure elements people can see. Elected officials especially, focused their campaigns and time in office bettering what people can see in the aboveground environment. Many admitted to an underappreciation for how the aboveground built environment was influenced by belowground infrastructure. For example, when traffic is disrupted because of pipe repair and uneven streets result from trenching and cement patchwork. Green infrastructure, like parks and street trees are also affected by belowground systems. For example, leaky gas lines pollute street tree pits with methane and kill vegetation along sidewalks (Hendrick et al., 2016). Transitioning from an aboveground infrastructure mindset to one focusing on the system dynamics of all urban infrastructure became crucial for implementing a coordinated management plan.

[3] https://store.steampowered.com/

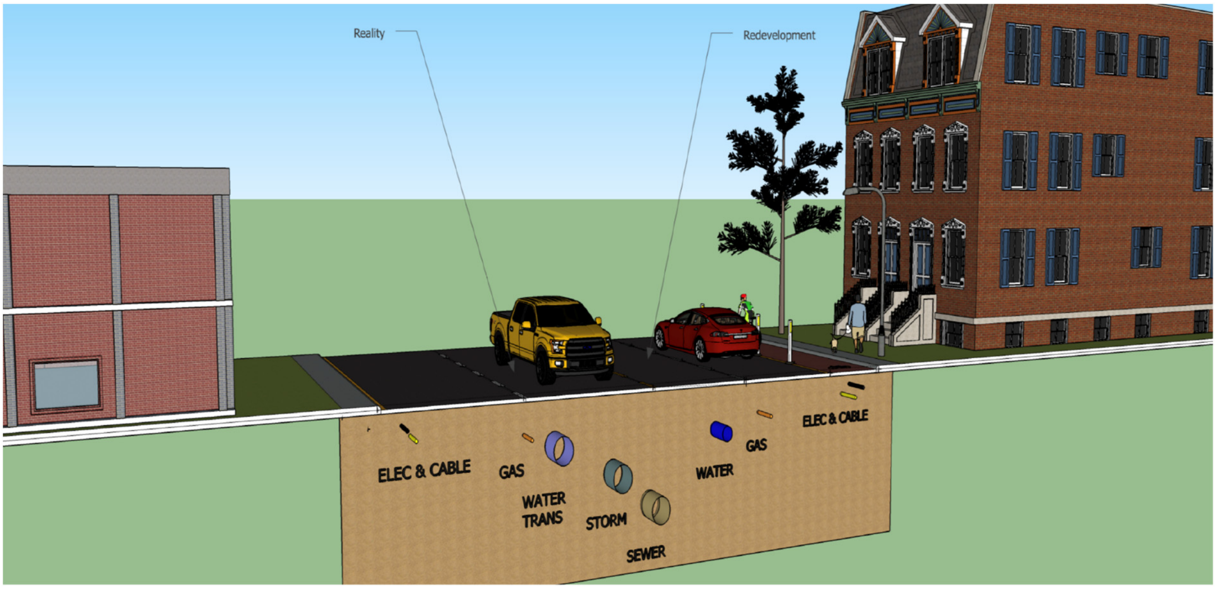

Fig. 5. Cross section of the VR model "Virtual Reality & Urban Ecology".

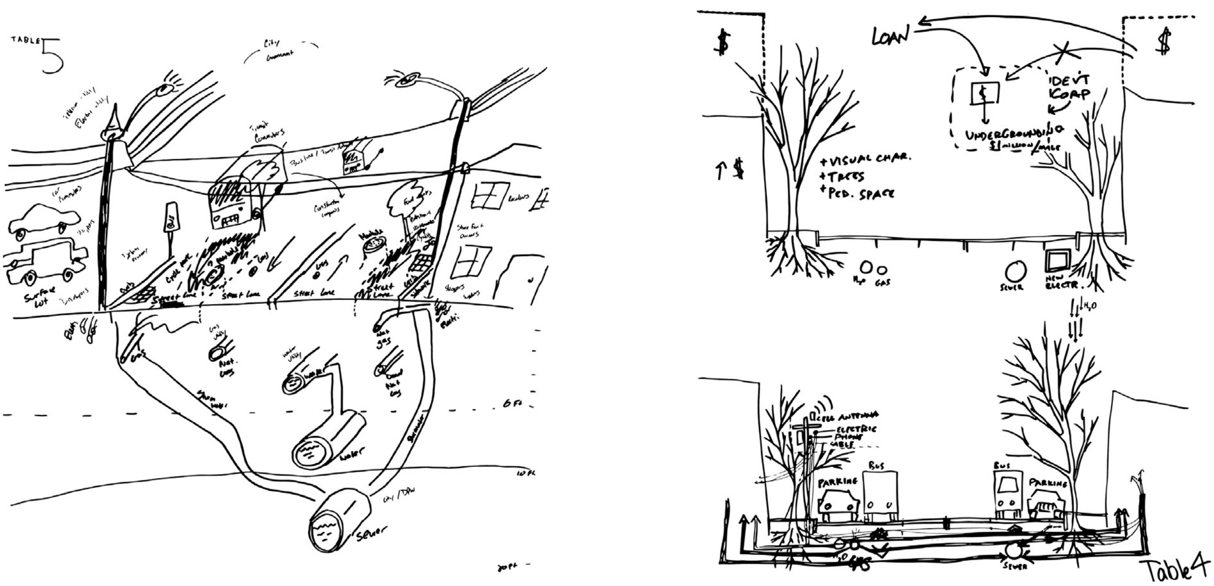

Fig. 6. Two examples of visual maps drawn by break out groups at stakeholder workshop.

2.) Inefficient communication between belowground utilities has created problems in project efficiency and coordination, resulting in more street disruptions and more expensive projects. Even though belowground utilities work in the same space, there is commonly no notification across utility companies alerting to a street dig up for repair. If all utilities needing to do repairs on that street could do the repairs simultaneously, the street and traffic could be disrupted just once. This coordination could decrease excess noise, traffic disruption, and patchy/uneven streets.

3.) Generally, workshop attendees admitted to considering above and belowground as separate entities rather than thinking about urban infrastructures as a system. However, when presented with the UIS approach many understood how more coordinated repair projects and management could benefit city functioning. The system dynamics of urban infrastructure highlights the interactions and impacts belowground infrastructure has on aboveground and vice versa. These interactions are worthwhile to educate urban stakeholders on in order to reconstruct the management of urban infrastructure.

4.) The visual maps drawn by each group modeled what stakeholders imagined as the most ideal infrastructure system. Unfortunately, many of the features were idealistic because of concerns over budgetary constraints. For revolutionizing belowground utilities, most groups preferred a utilidor solution. A utilidor is a tunnel that consolidates and co-locates multiple utilities, with street access at an easy-to-access point (preferably on the sidewalk to discourage traffic interruption) for maintenance or repair (Hunt, Nash, & Rogers, 2014). Placing all utilities in a single corridor would enable companies to complete repairs through the sidewalk without disrupting traffic or disturbing another utility. Unfortunately, discussion of utilidors amongst stakeholders uncovered safety, liability, and budgetary concerns making utilidors an unrealistic solution in the near future (Canto-Perello, Curiel-Esparza, & Calvo, 2016).

After analyzing the elements stakeholders decided to include in their visual maps, some commonalities appeared. All of the groups included private buildings, sidewalks, and lanes for traffic and public transportation. Only one group included a parking lot and only two included a utilidor or on-street parking. Only three of the five groups included belowground utilities such as water, sewer, storm water, gas, electric, and/or cable. What groups included and what they omitted provided insight into what the stakeholders considered important elements of urban infrastructure.

From the talkback session, a clear need for a spatial communication tool emerged. Stakeholders understood the necessity of viewing urban infrastructure as a system and admitted there was a challenging lack of coordination in current management tactics. Unfortunately, demonstrating the system dynamics of the UIS is a challenge because half of the system environment is out of sight below the streets. These results inspired the development of the VR tool to aid stakeholders in seeing the interactions within the UIS and to help them visualize belowground infrastructure and its influence on the street. A visualization tool would benefit all utility stakeholders because it can demonstrate how utilities interact and behave in the UIS. The VR program developed provided a good starting place because it emerged the user into an urban environment where they could interact with all features of infrastructure.

3.2. User responses: "Virtual Reality & Urban Ecology"

In response to the results gathered from the stakeholder workshop, the VR tool, "Virtual Reality & Urban Ecology" was created and user experience was collected. Two demonstrations were held in October and November of 2017 and participants included researchers, academics, students, non-profit people, businessmen, and lawyers. Each participant was fitted with the VR headset and hand-controllers and immersed in our model for a fifteen-minute session (Fig. 7). Aboveground, the user could interact with cars and cyclists, in addition to exploring the layout of sidewalks, roads, public transportation lanes, and bike lanes. By simply looking downwards, the participant could dive beneath the street and see the relative location of multiple belowground utilities. A user could explore gas, water, sewage, and other pipelines, as well as a rendering of a utilidor.

After using the VR, each user was asked to complete an exit survey where they answered questions about their likes/dislikes of the VR, what their overall satisfaction was, and whether or not they thought VR would be a helpful tool in urban planning. Nearly 60 participants were surveyed. Most users (90%) were excited about the VR and enjoyed the experience. The most common complaints included motion sickness, difficulty wearing the headset over glasses, and dizziness. Nearly all (95%) people surveyed were first time VR users and most were satisfied with the experience. Additionally, about 95% of our users encouraged the use of VR for urban planning and thought the VR model helped them further understand the system dynamics of urban infrastructure.

VR has been used in urban planning contexts over the years. VR and VRGIS has been used in urban planning because of its "powerful immersive visualization approach… [that] can be used to better engage with, and collect the opinion of, stakeholders and citizens/communities about any proposed future city plans affecting the places they live and work in" (Kamel Boulos et al., 2017). Typically, more than 90% of information required for a city's administration has a spatial component, such as location of facilities, routing delivery and provision of facilities, meaning GIS has been seen as an essential technology for urban management. Our proposed VR application for urban infrastructure management along with GIS gives planners the potential and ability to make advised choices in the spatial decision-making framework by incorporating a combination of computer and information technology, urban growth models, and computer-based visualization techniques to support community-based planning. Planners, surveyors, utilities and engineers primarily rely on GIS technology to design and map facilities in the cities to assist in the urban planning process.

Recent developments in 3D-GIS and urban data modeling are leading to innovations in the representation, storage and analysis based on 3D city and landscape models (Breunig & Zlatanova, 2011; Tang & Zhang, 2008; Wang, 2005). Incorporating the belowground urban infrastructure environment will be critical moving forward with these technologies, especially when construction activity inadvertently but commonly disrupts and damages underground infrastructure. Cities are building better models to address this problem and incorporating VR technology will advance these efforts even further. For example, the City of Las Vegas has developed a 3D CAD model of their above- and below-ground infrastructure in the core downtown area to improve safety and awareness of below ground utilities (Haala & Kada, 2010a, 2010b). The city wanted an accurate and up-to-date source of information for urban planning, designing, and maintenance of its infrastructure that included both above and belowground infrastructure components.

VR can be an exceptional tool for communicating spatial information and sparking excitement in areas of the urban environment previously unexplored. However, there are many shortcomings to this technology that can prevent its implementation on a wide scale. In the VR community, it is "widely acknowledged that creating [VR models] is challenging, and requires carefully-crafted research and technological progress" (Çöltekin, Oprean, Wallgrün, & Klippel, 2019). Additionally, because of the complexities of the interaction modalities, implementing an intuitive large-scale VR model is cost-intensive and time-consuming for urban stakeholders already preoccupied with other concerns. An ongoing area of research includes improving the accessibility of large-scale VR environments so that these communication tools can be more widely dispersed (Çöltekin et al., 2019). VR models are impressively time demanding, especially in an urban environment where an accurate model requires a large amount of geometric, satellite, LiDAR, and aerial or street-level data (Kamel Boulos et al., 2017). VR is also made to be an interactive technology and require a relatively advanced rendering technology to gain the full effect, that is not always available to people interested in utilizing the technology (Kamel Boulos et al., 2017). However, there are limitations as to what can be successfully communicated using VR. With a lack of data provided from the utilities, characteristics such as material, diameter, age, and pressure are important data that cannot be included in a VR model. Additionally, infrastructure is fragile and there are environmental factors beyond a municipality's control that can cause damage and can alter the integrity of the infrastructure. The unpredictability of the UIS is difficult to display in a VR model but can be crucial information for urban stakeholders to understand.

The VR model, "Virtual Reality & Urban Ecology", is a tool meant to be shared. It's success in our team's initial pilot launch suggested that this tool would be useful to share with stakeholders involved in all branches of urban planning. Applying this VR as an educational tool would ideally peak the curiosity of people involved in aboveground infrastructure to learn how their infrastructure features play a role in the overall UIS and vice-versa.

4. Conclusion

Providing key stakeholders with spatial information about the system dynamics of urban infrastructure will be key for managing aging urban infrastructure in the most efficient and coordinated way (Pandit et al., 2015). Unfortunately, communicating spatial data to stakeholders that highlights the interactions of infrastructure elements above and below the ground is challenging. The complex system that exists below city streets is difficult to visualize but its impact on aboveground infrastructure is critical and its role cannot be overlooked when making urban planning decisions. VR has been used in urban planning for many years as an effective method for conveying spatial data in the built environment. Our team utilized VR to visualize and communicate the specific spatial and dynamic relationships between infrastructure

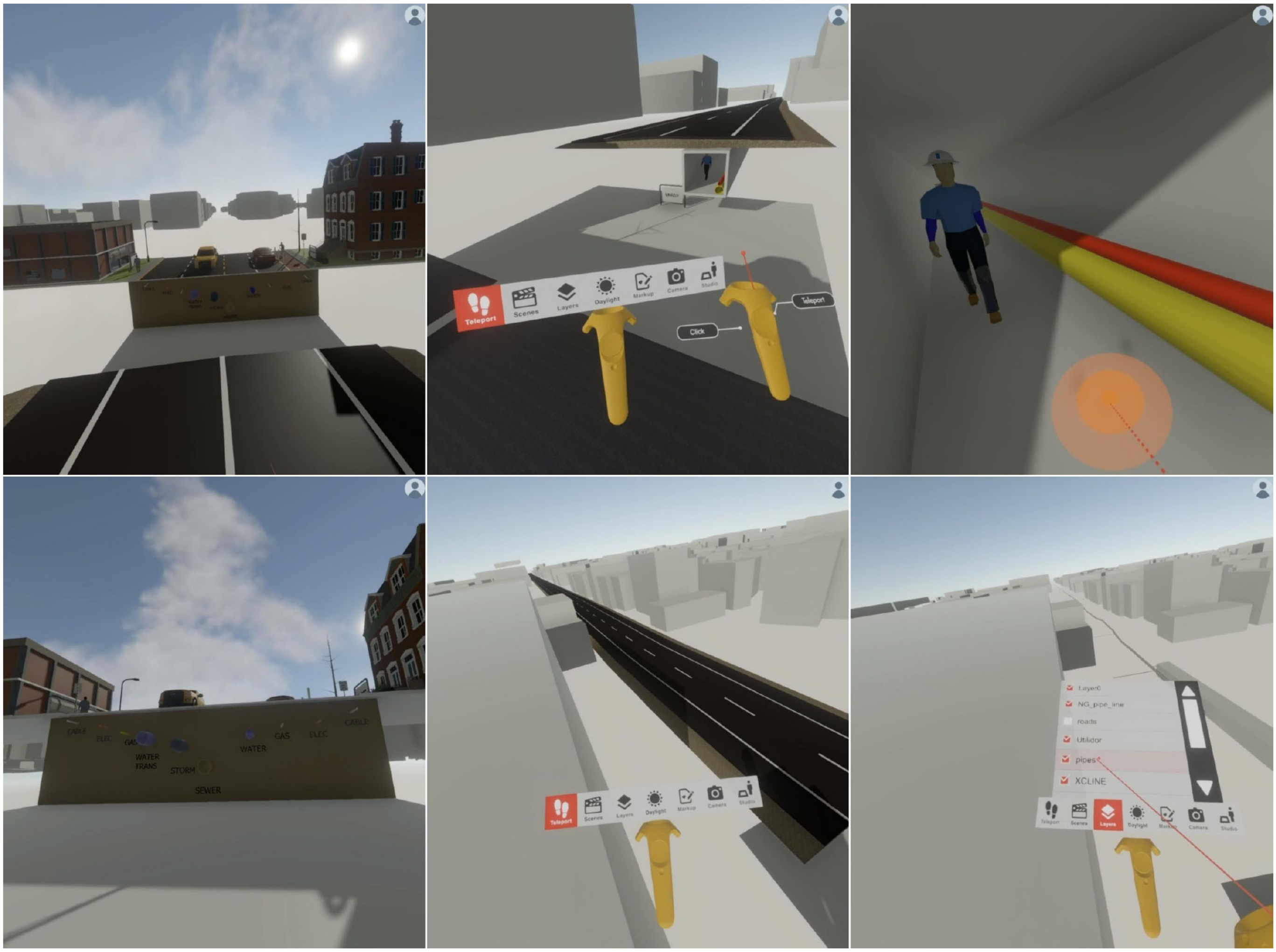

Fig. 7. VR user perspective, while using the “Virtual Reality & Urban Ecology” VR model during October 2017 test.

features above and below city streets in response to a clear lack of such a tool in current management practices. Our VR tool benefitted stakeholders by helping to address the issues uncovered in our stakeholder workshop relating to a lack of foundational understanding of the interactions of above and belowground infrastructure features. VR enabled us to provide an interactive experience to promote a better understanding of the built urban environment and the system dynamics of the infrastructure ecosystem (Billger, Thuvander, & Stahre Wästberg, 2016). Using VR as a spatial communication tool will be beneficial in informing urban stakeholders about how infrastructure features work together and encourage the implementation of a more coordinated urban infrastructure management plan (Howard & Gaborit, 2007). To build upon this research into the future, a more complete neighborhood could be modeled in the next VR, perhaps highlighting a proposed infrastructure reconstruction plan. Climate change models and growing population metrics could be incorporated into a VR to help plan a more efficient infrastructure project that would be resilient into the future.

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