Visualizing transport futures
The potential of integrating procedural 3d modelling and traffic micro-simulation in virtual reality applications

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ABSTRACT

In this paper we elaborate on potential use cases of Virtual Reality (VR) in transportation research and planning and present how we integrated procedural 3D modelling and traffic micro-simulation with the rendering capabilities of a game engine in a semi-automated pipeline.

Through a review of potential practical applications, we present how this pipeline will be employed to distil behavioural evidence that can guide planners through dilemmas when designing future cycling infrastructure. At the same time, we are studying efficacy of VR as a method for assessing perceptual behaviour as opposed to traditional methods of visualization. Concretely, we present how the pipeline can be adapted i) to generate parameterised visualisations for stated preference surveys, ii) as a platform for a cycling simulator and iii) to communicate different design scenarios for stakeholder engagement. The flexibility of procedural programming allows discretionary changes to the street design and the traffic parameters. Through this experience of developing procedural models, traffic microsimulations and ultimately VR models for streets in Singapore, we find that visual and temporal feedback enabled by VR makes several important design parameters observable and allows researchers to conduct new types of behavioural surveys to understand how people will respond to different design options. In addition, we conclude that such VR applications open new avenues for citizen engagement and communication of urban plans to stakeholders.
INTRODUCTION

Visualizations play an important role in planning to communicate plans and policies that support active transport modes. Since adding pedestrian infrastructure often means a large public investment or a trade-off for space with other transport modes, visualizations are often used in early stages to illustrate the gains of a project with regards to traffic safety, liveability or social inclusion. They are also used in research application to study the impact of such infrastructure on people’s behaviour. It allows researchers to quantify user reactions towards infrastructure that does not exist today and guide planners through dilemmas when designing future infrastructure.

So far, visualizations to communicate future street designs rely heavily on pictures, photomontages, maps or simulation videos. However, recent and ongoing technological development in the field of Virtual Reality (VR) opens new windows for practical applications and scientific insights. VR allows the user to immerse in the future environment, which expands opportunities for stakeholder involvement and in-depth evaluation of user perception.

In this paper we elaborate on potential use cases of VR in the field of transport planning and present how we integrated procedural 3D modelling and traffic micro-simulation with the game engine rendering in a semi-automated pipeline. Concretely, we present in two case studies how the pipeline can be adapted to generate parameterised visualisations for stated preference surveys, and to communicate different design scenarios for stakeholder engagement.

The remainder of this paper is organized as follows: the first section discusses limits of conventional methods to study travel behaviour and the potential for VR application in the field of transport planning. Next, we present our software pipeline and the related (open source) code, outlining the reasons for choosing the individual software components. This is followed by introducing two case study applications. After a summary of the lessons learned in implementing this pipeline, we critically review the case study applications and identify potential drawbacks and dilemmas when applying VR for communication and research applications. We conclude by providing a roadmap for further development and outlining further opportunities for VR applications in transport planning.
POTENTIAL FOR VR APPLICATION THE FIELD OF TRANSPORT PLANNING

The limits of conventional methods to study travel behaviour

The assessment of the impacts of the built environment on mode choice, especially for non-commuting activities, has been widely addressed in the literature. Earlier studies mainly focused on assessing the impact of aggregate built design variables (i.e. block size, number of intersections) in mobility and mode choice (e.g. (1–3)). More recently, based on the understanding that active modes of transport are more responsive to the design of the built environment, and availability of more granular spatial data, researchers have begun to study this relationship more directly.

The opening of new infrastructure can open windows of opportunity for longitudinal studies (4, 5). However, the experimental variation is limited to how the new infrastructure has been built while other design options must remain untested and the researcher usually has to deal with uncontrolled effects such as changing weather conditions or fuel prices. Cross-sectional studies (6–8) can overcome the first problem. They have clearly demonstrated that building more cycling infrastructure can unleash latent demand and influence mode choice decisions. However, the fact that comparing the attractiveness of cycling between study areas is only possible based on aggregate measures such as bicycle network density, such studies do not allow detailed insight on how different cycling infrastructure designs impact individual behaviour.

Revealed preference studies on pedestrian (9, 10) or cycling (11, 12) travel behaviour can overcome some of those problems, but due to the nature of the experiment, the validity of the findings is always restricted to features of the built environment that already exist.

Stated preference surveys

Identifying these limitations, researchers used sketches or photomontages in stated preference surveys to communicate design, for example to understand how safe from crime people feel given different street design and levels of street lighting (13), how urban design variables impact pedestrian route choice (14) and measure qualitative attributes of public spaces (15). Using a similar approach but employing simple 3D visualisations, (16) it was found that people strongly value a range of pedestrian infrastructure design variables such as presence of barriers and trees, while variables such as composition of traffic and land use are of lower importance. A key advantage of using computer-generated visualisations as compared to sketches is that it allows to easily collate design scenarios by selectively activating the relevant digital layers.

Recent advances in computer graphics and lowered barriers to entry into the field of video games has opened new opportunities for generating realistic 3D scenarios that are suitable for behavioural studies (17). Researchers also applied video game environments to study pedestrian route choice and reaction to information in evacuation scenarios. (18, 19)

Behavioural experiments

Walking and cycling is a multisensory experience which includes vision, auditory, somatic sensation, olfaction and vestibular sensory stimulation. Conducting surveys to understand the perception of various street design options based on static pictures only can be too restrictive.
Using Virtual Environments (VE) is a well-established methodology in the field of cognitive psychology. Although there are several limitations in VE, such as a smaller field of view, lower resolution, less realism and often no auditory, tactile, proprioceptive and vestibular cues (20), VE experiments have successfully been conducted in various fields of cognitive studies. For example, it could be shown that people can ultimately develop accurate spatial knowledge in large-scale VEs that is similar to knowledge acquisition gained from physical environments (21–24). Furthermore, Virtual Reality technologies have recently been applied for testing architectural design intervention prior to implementation through a pre-occupancy evaluation approach (25, 26). While the primary advantage of using VE for research is certainly the freedom and versatility in setting up experiments, it also enables scientists to measure physical reactions of test subjects using electrocardiography, skin conductance and electroencephalogy to monitor, for example stress levels. In addition, eye-tracking enables researchers to understand visual perception better by monitoring gaze behaviour (27).

**Driving Simulators**

Driving simulators have been used in transport research since the 1960’s (28) to study driver behaviour and her/his interaction with the vehicle and the road. Simulators have been used as research aids in fields such as road safety, testing innovative road designs, usability of intelligent transport systems, impaired travel behaviour and vehicle layout (29). Recently, a few research groups also developed cycling simulators (30, 31) for applications in the areas of road safety and traffic education. These cycling simulators use a projected screen and three displays mounted side by side as visualization system, a standard bicycle with sensors and actuators, as well as a surround sound system to create an immersive experience. It has been shown, that visual cues dominate by far the perception of visual depth in the majority of applications (32). Using consumer-grade head-mounted displays as part of a cycling simulation setup lead to a substantially enhanced visual immersion and allowing new applications for research (33), for example to study the perception and measure physical reactions that different street design and traffic operation scenarios trigger.

**Communication and Presentation**

A common virtual reality application for architectural design and urban planning purposes is to display detailed 3D CAD models of architectural spaces/structures and visualization of large datasets in a photorealistic fashion. Architects and planners have often used various 3D visualization tools to communicate design decisions. These tools however lack sound support, and the ability to communicate time and motion effectively, which could be better represented in VR. The application has mostly been limited to presentation, recreation, and educational purposes (e.g., review of architecture before it is actually built, cultural heritage reconstructions, 3D entertainment rides, etc.) where complex 3D spaces are constructed so they can be explored in walkthroughs (34). A majority of these projects allow for little to no interactivity beyond the user’s ability to freely navigate about the environment.(35)

**Public Engagement**

Unlike commercial presentation based applications, the development of VR as a design and engagement tool raises quite different demands. In early design phases there is no time or
resources to build every proposal or idea as a fully developed model. A simplified design model, which is capable of handling details in a different way may be sufficient to garner feedback in a public engagement or collaborative design process. (36)

Quick prototyping, interactivity in the interface and appropriate level of realism are all crucial for the development of virtual environments when used for engagement or collaboration. For example, in the specific context where politicians or designers do not wish to make a firm commitment, an artistic depiction of a proposed project may be appropriate. (35)

**PIPELINE TO GENERATE VR SCENARIOS**

For exploring the potential of integrating of Virtual Reality applications for transportation research and planning, we propose a software pipeline that integrate ESRI City Engine (procedural 3D modelling), PTV Vissim (traffic microsimulation) in Unity (game engine) supporting versatile output formats and fields of application (Figure 1).

**Figure 1: Software pipeline to integrate CityEngine and Vissim output in Unity.**

<table>
<thead>
<tr>
<th>3D Model</th>
<th>Traffic Simulation</th>
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<td>Game Engine</td>
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**3D Modelling**

Esri CityEngine is a 3D modelling software application developed by Esri R&D Center Zurich (formerly Procedural Inc.). At the core of CityEngine (CE) is the ‘procedural’ approach instead of manual interaction with the model. Street networks are first modelled on standard drafting interfaces and imported as .dwg or .shp files. A set of rules can be applied to a model. For this research, the ‘Complete Streets’ rule file, developed at ESRI R&D, Zurich, was used. It incorporates knowledge from various sources of transportation planning knowledge including NACTO, AASHTO and MUTCD standards. The goal of the rule is to represent a diversity of street configurations to support multimodal planning in urban areas (43).
In order to use this rule for street design visualization in Singapore several adjustments were made to adapt to local condition. For example, default lane widths, tree types, crosswalk styles were adjusted. New features like sidewalk cover for weather protection, bike lane on sidewalk, mixed bicycle and pedestrian traffic on sidewalk, all of which are a common sight on the streets of Singapore, were added to the rule. Figure 2 shows CE’S’s user interface and the different parameters of the complete streets rule. The adapted rule is publicly available over a software repository hosted by GitHub (44).

A .dwg file only contains geometric information, and the additional street attributes need to be adjusted manually in CE. This approach is useful during design and planning process, when the street configuration is still being determined. Alternatively, a .shp (or .osm) file may contain additional attributes attached to the geometry which can be used to populate attributes in the rule file directly. This method can be used when street configurations are clear, and CE is used only for visualization purposes.

In both cases, once the street is generated, it has to be exported to Vissim to populate it with traffic simulation. Three types of inputs are required by Vissim at a minimum from City Engine – street network, pedestrian areas and obstacles. The street network that has been created already outside of CE is imported as a .dwg file. The pedestrian areas are obtained by exporting the CE model as a .dwg file. Finally, obstacles are obtained by exporting .3ds model from CE into a standard 3D modelling tool like Sketchup or Autocad3D, and sectioned in the xy-plane to obtain
a .dwg file of all obstacles with a z coordinate. Presently, all these files need to be manually adjusted and cleaned up in a 2D modelling platform before they are usable in CE. This process can be significantly shortened by using the Python scripting interface to export specific geometries.

For the purpose of high resolution rendering, the 3D model is exported as a .fbx file into Unity. Of the three 3D export formats that CE offers – COLLADA, .fbx, .3ds - .fbx offers the most fidelity for all texture maps.

**Traffic micro-simulation**

Based on expert knowledge and the experience of other researchers that the implementation of Artificial Intelligence in a game engine to simulate realistic traffic scenarios is not a straightforward task (42), we decided to integrate microscopic traffic simulation software with a game engine to generate VE. Current traffic microsimulation software packages such as PTV Vissim, Caliper Transmodeller, Sumo or TSS Aimsun offer possibilities to model complex but realistic multi-modal traffic situations. For this research project, the traffic microsimulation tool PTV Vissim has been chosen. Vissim offers the widest range of urban traffic simulation capabilities including public transport, individual cars, trucks, bicycles and pedestrians (45). Vissim is to our knowledge also the only traffic simulation software that provides interfaces to interactively interact with the simulation, a crucial feature for immersive VR applications.

Vissim is mainly designed to quantitatively evaluate traffic scenarios with regards to vehicle and pedestrian densities, road and intersection capacities, as well as travel times or delays. But traffic simulations are also instrumental to illustrate possible design scenarios in pictures or videos to decision makers and the general public. However, while the 3D visualisation capabilities of microsimulation tools such as Vissim have considerably improved over the last few years, there are still limitations when it comes to the realistic rendering of 3D environments. The roads and objects usually can’t be represented by varying surfaces and the animated models of pedestrians and cyclists are rather basic. The 3D modelling possibilities and video rendering performance are insufficient to create high fidelity graphics.

**Integration of CityEngine and Vissim output in Unity**

Each software in the pipeline have a very specific purpose: CityEngine generates procedural city models; Vissim simulates traffic and pedestrians within those models. In order to combine both and at the same time be able to interact with the environment and present that experience on a VR head-mounted-display (HMD), we started looking at game engines, notable for their visual capabilities and VR support. Of the many game engines available, we chose Unity because of its visual capabilities, VR support, ample range of file formats and ease of use. Some of the more noticeable visual improvements when going from Vissim to Unity are:

- Physically based lighting and shadowing
- Global illumination
- Reflections
- More realistic skies
- Better texture filtering and antialiasing
- Post-process effects (Depth of field, motion blur, bloom, etc.)
- Modelling of audio

These help create much richer and realistic content such as images, videos, etc. Like most game engines, Unity is capable of handling several 3D file formats, of which FBX format was used for the model exported from CE for better performance and compatibility. Some elements of the city model had to be replaced in Unity in order to have assets that are localized and could dynamically change. A good example is traffic lights, where we not only needed lights that resembled those found in Singapore, but also were able to turn the green, amber and red.

The logic behind the existing pipeline is to simulate the desired scenario in Vissim and to export the traffic related data to Unity aiming at achieving a better quality of the 3D model animations. The main aims for the integration pipeline as defined in Figure 1 were - rendering realistic visualization of future traffic as stills, short video, 360-degree videos and Unity executables that allow users to interactively explore the simulated scenarios in 3D.

Bridging Vissim with Unity wasn’t straightforward: Unity doesn’t have built-in support for Vissim file formats. However, it was possible to write Unity scripts for this purpose (46). The export/import mainly consists of trajectories of the simulated interactions between pedestrians, bicycles and cars and the commands related to the traffic lights. The export from Vissim is a .csv file that writes simulation second, pedestrian/vehicle identifier, type of pedestrian/vehicle, x-, y- and z-coordinates. For the vehicle, two coordinates (front and rear) are required in order to extract the size and orientation of the object. Since Vissim runs its simulation at a fixed frequency (a configurable integer between 1 and 10 steps per second), and game engines tend to run at a much higher and variable rate (VR requires at least 90 frames per second for a comfortable experience), a custom script was developed to interpolate pedestrian/vehicle movement between simulation steps. The traffic light program is written in a simple, exportable XML-file.

Other scripts were also written to improve the visual quality of the traffic simulation data: to individually rotate each vehicle’s wheels in accordance to their speed and radii; randomize vehicle models across traffic data to achieve more natural results; full body animations and animation transitions for pedestrians depending on their movement speed and light animation for traffic lights.

Some of the scripts weren’t dedicated to the final visual appearance, but still they played a crucial role in development. These scripts, for example, helped us to identify issues outside of Unity by visualizing the input data. E.g. a script to generate a traffic movement heat-map, to observe which areas are more/less frequented by simulation agents, or to identify if an agent takes an undesired path which helps to verify the simulation setup.
Figure 3: Traffic movement heat-map indicating simulated traces of pedestrians (cyan), cyclists (yellow) and vehicles (magenta) projected on 3d model.

Pending challenges

Procedurally modelling of street design scenarios allows a degree of prototyping and interactivity that saves significant amount of time usually spent on handcrafting geometric models. But this method poses several limitations, especially when modelling traffic networks.

A street often has unique non-repeating conditions, not represented in a typical section, like street signs, bus stops, and curb extensions. Modelling each unique condition procedurally takes up a disproportionate amount of time. Intersection design is also a difficult problem to tackle procedurally. The street and sidewalk shape in CE are disassociated from each other with different start and end points. Street adjacencies are also not recognized, making it hard to model the intersection.

Therefore a hybrid approach that combines procedural modelling techniques with manual refinements may be most effective to create realistic 3D environments for VR application in transport planning and street design studies.

Defining a Vissim model directly based on CityEngine output is challenging due to limited compatibility of output and input file types and software object architecture. Some issues related
to import of geometric information can be addressed through the development of scripts that take the relevant information through CityEngine’s API and convert it into a format suitable for Vissim. Information such as conflict areas at intersections or pedestrian crossing can be imported as geometry. This however does not apply to information that is not defined in CityEngine such as traffic light signal plans and traffic flow information like turning restrictions. This suggests that there always be a certain amount of work that cannot be automated when setting up traffic microsimulation scenarios based on 3D models.

Due to the the high levels of realism demanded by VR, non-realistic objects are identified very quickly, and draw away from having an immersive experience. In our scenario we have identified two cases where the movement doesn’t feel natural. Pedestrians tend to follow a robotic movement with abrupt changes of speed and direction. Similarly, vehicles, especially large ones, are also noticeably affected when turning on sharp bends. This is because of how Vissim simulates vehicles using their front and back positions but not taking their wheel rotations and wheel axis into account. This causes vehicles to corner unnaturally, not following a tractrix-like curve.

With the above mentioned pipeline design (Figure 1), data only flows from CityEngine/Vissim to Unity, and to achieve a truly interactive experience we had to close the pipeline loop and feed user activity in Unity back to the beginning of the pipeline. In the case of traffic simulation it meant communicating with Vissim and sending user information such as position, orientation and speed, which would in turn cause Vissim to update its traffic simulation and send the changes back to Unity. This interaction loop is still in experimental phase, and since both programs demand high levels of CPU usage, we’re exploring the advantages/disadvantages of having Vissim and Unity running on the same machine versus having a dedicated machine for Vissim and communicating over the network. The initial observations are that the first option yields low communication latency but requires an extremely powerful CPU, whereas the later option yields high communication latency which is detrimental for virtual reality.
CASE STUDIES

To showcase the potential for transport and urban planning, we present preliminary results of ongoing work in two case study applications. Both take advantage of the various opportunities that VR offers to enhance already well-established applications of transport planning research and practice, using the pipeline illustrated earlier. However, since at the time of writing both projects are still ongoing, we cannot provide conclusive results, but focus on highlighting the application potential.

Stated preference survey

Research has identified numerous barriers to increased bicycling, including topography, weather, and trip distance, but the barrier that appears most consistently between studies is the perceived hazard associated with cycling near motorists (47). In two recent studies, researchers have successfully employed photomontages to indicate their comfort or discomfort on a series of eight multi-lane, commercial roadway designs (48) and in a stated preference survey to quantify user preferences for cycling infrastructure in an urban context (49). Rather than just using photos of existing streets in different design configurations, such montages illustrate one particular street segment under different street design scenarios and therefore allow to control for confounding effects such as unintended variations with regards to vegetation, urban design or weather conditions. However, the parameters that can be altered are restricted and sometimes difficult to depict realistically.

Using the extended Complete Street Rule allows to automatically generate numerous 3D models of streets in different design configuration quickly. To leverage this capability, we developed an experimental design for a stated preference survey employing a set of variables with related attribute levels as listed in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Attribute levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of car lanes in one direction</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>Road traffic circulation</td>
<td>One-way, bidirectional</td>
</tr>
<tr>
<td>Location of cycling facility</td>
<td>Mixed on sidewalk, dedicated lane, mixed with motorized traffic</td>
</tr>
<tr>
<td>Walkway width</td>
<td>1.5, 2.5, 3.5 meters</td>
</tr>
<tr>
<td>Motorized lane width</td>
<td>2.7, 3.1, 3.4 meters</td>
</tr>
<tr>
<td>Speed limit (indicated with signs and various amount of blurring)</td>
<td>30 km/h, 50 km/h, 80 km/h</td>
</tr>
<tr>
<td>Availability of dedicated bus lane</td>
<td>binary</td>
</tr>
<tr>
<td>Position of bus lane</td>
<td>Left most lane, right most lane (scenario is based on left-hand traffic)</td>
</tr>
</tbody>
</table>
Due to a series of dependencies among the various variables and attribute levels that have been defined as constraints, e.g. if cyclists are mixed with motorized traffic many attribute levels of other variables are not available, a full factorial design is not directly defined by the number of variables and related attribute levels. However, employing a full factorial design with 20 variable is also not a meaningful experimental setup. But using a survey experiment design software such as NGene (50) can be used to find an experimental design that maximizes the information from each choice situation. To this end, the user specifies a utility function prior parameter estimates.

In our case, we not only can use such estimates for individual variables, but also interaction terms. This allows, for example, to specify that the number of pedestrian on the sidewalk is primarily expected to impair the attractiveness when the street design foresees that cyclists and pedestrian both use sidewalks.

Figure 4 provides a rendering of two considered street design scenarios with the camera positioned at eye-level of a cyclists. We generated 200 choice situations which we will use in a qualitative, explorative pilot study to better understand which differences between the two renderings are visible for participants. Depending on the outcome, we will refine the experimental design, either by limiting the number of considered variables or including further constraints.

Issues identified in preliminary tests concern the better representation of a first-person perspective by showing a bicycle handle bar, the appropriate level of detail of adjacent building and the immediate position of adjacent vehicles which are currently randomly placed in the

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1 A design feature typical for Singapore to mitigate impact of tropical rain showers.
Complete Streets Rule. For example, we expect that if a motorized vehicle appears directly next to the cyclist, it impacts perception more directly than the actual density of such vehicles. To avoid such misleading factors, we implemented post-processing scripts to control the position of immediately adjacent vehicles, cyclists and pedestrians. In addition, inspired by (48) we intend to generate renderings also from the perspective of pedestrians and motorists.

Finally, we are reviewing various option of research questions that can be address in a stated preference survey that employs such renderings. Adding information such as the duration or distance of being exposed to each condition would for example allow to derive interesting trade-offs between perceived safety and the willingness to accept detours in a route choice survey context. Such an approach could also be expanded to a mode choice survey to understand how the willingness to cycle depends on street configuration.

Conducting surveys with short videos would not only allow more emphasis on dynamic aspects such a speeds, but also would to study preferences with regards to different intersections designs which with static rendering only seem feasible if a birds-eye perspective is applied.

**Figure 4 Examples of 9 street design configurations from cyclists perspective modelled using the extended Complete Street Rules in ESRI City engine and rendered in Unity.**

**Parking Day as public engagement opportunity**

PARK(ing) Day is an annual worldwide event where community members transform parking spots into temporary public spaces (51). In order to understand what would make Singapore more walkable and cyclable – and given the low popularity of cycling in Singapore - we will use VR to make people understand better the impact of new design and planning interventions. On
September 16, 2016, a parking lot in Seng Poh Road in Singapore’s Tiong Bahru neighborhood will showcase what Seng Poh Road might be like in the future if it is designed for slow traffic - pedestrians and cyclists.

Street design plays a significant role in determining how pleasant, safe and comfortable the walking and cycling experience is (8). It can encourage modal shift to active forms of transport. However, the prevailing rhetoric in Singapore creates an impression that cycling can be an unpleasant and unsafe experience (52). Communicating alternative design options in virtual reality can help to shift the conversation on cycling towards a more positive direction.

The exhibit will be used to conduct an experiment to understand the added value of VR as an engagement and communication tool. By recording the viewing position of the head-mounted display, we can observe where participants are looking, helping us understand if there are extraneous details distracting the viewer from our preferred area of interest. We will also hand out short questionnaires to survey the perception and retention value of VR, and the different attributes noticed in VR. A pre-experiment survey will determine the participant’s current travel behaviour and attitudes towards active mobility. Following the VR experiment, participants will be asked that given the improved infrastructure design, how would their mobility behaviour and attitude be influenced. This is a step towards understanding if VR is a compelling means of communication, that impacts public perception. Second, the participant would be asked what they ‘liked’ and ‘disliked’ about the new design, to deduce what they retain from the experience. This preliminary test will help us prepare better for larger controlled studies at a later stage.
CONCLUSION AND OUTLOOK

In this paper, we explore the potential to use Virtual Reality (VR) in the field of transport planning. Reviewing how visualizations have been used in research and practice, we identified how VR applications can fill existing methodological gaps when it comes to studying perception to support active mobility and future mobility solutions that do not exist today. VR has great potential to study how the design of the built environment influences the perception of safety and comfort for walking and cycling more directly and concisely than conventional methodologies such as longitudinal or cross-sectional approaches. VR can also be helpful to explore human interaction with future forms of mobility such as autonomous vehicles that currently can’t be studied in real environments. We also expect that the features of consumer-grade VR hardware such as display resolution and availability of suitable human machine interface devices will continue to improve offering even more opportunities for application in transportation research and planning.

We present a software pipeline that is designed to efficiently produce high-fidelity VR environments for applications in research and practice in the field of transport planning and street design. By publicly sharing the related software code and scripts to generate transport-related VR scenarios, we actively contribute to building up the know-how and support the development of an innovation eco-system in our domain. In two case studies, we demonstrate how VR applications can enhance existing stated preference survey approaches and can improve the communication of street design interventions. Although the presented case studies are work-in-progress at the time of writing, the potential already becomes clear. At the same time, there are also a series of questions to be explored and answered for VR applications in other domains such as cognitive.

In any field of application, it will be important to clearly demonstrate how VR applications can fill existing methodological gaps or lead to more effective and efficient study designs. A key research question to be answered will be whether results from studies that employ VR applications will lead to similar results as conventional, proven methods. This can for example be addressed by comparing the results of stated preference surveys that employ VR-based visualization with such that used conventional illustrations, photomontages or videos of existing environments. In addition, it will also be important to conduct qualitative studies to understand the added value of VR and identify the relevant factors related to the perception and retention value of VR, as we proposed with the Park(ing) Day case study.

There are obviously many more applications to be explored beyond what we were able to cover with the two presented case studies. For example, a direct integration of Vissim and Unity through a real-time interface can provide the fundament for implementing a VR driving simulator. There are already various groups that showcased how a conventional bicycle trainer can be converted to a human machine interaction interface of a VR cycling simulator (33, 53, 54) that allows participants to explore various street design in a controlled setting. While the first tests with such VR cycling simulators show promising results, also a few challenges for conducting behavioural studies have become clear: participants require a certain time period to familiarize with the new technology and the combination of immersive visualization but lack of
actual feedback of physical forces, e.g. when bending around a corner can cause immediate feelings of motion sickness. Multi-user settings also offer interesting field of applications that for example researchers interested in studying the behaviour in evacuation scenarios have tested recently (18, 55).

As immersive virtual environments become a more accessible technology, the potential applications are fast expanding beyond traditional gaming industries. Transportation planning, as we have illustrated, is one such domain, where given a seamless software pipeline with industry standard planning tools, virtual reality can be leveraged as a supplemental tool in transport planning workflow. While real experiences can never be entirely replicated, like other conventional methods of communication, VR is an additional tool, with evident added value, and particular limitations. These limitations are yet to be clearly understood, defined and quantified. The case studies presented in this paper, help to further clarify the applications and limitations in this regard.
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