Aalto University
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Interactive Visual Analytics for Agent-Based Simulation:

Street-Crossing Behavior at Signalized Pedestrian Crossing

Master's Thesis
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ABSTRACT OF
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To design a pedestrian crossing area reasonably can be a demanding task for traffic planners. There are several challenges, including determining the appropriate dimensions, and ensuring that pedestrians are exposed to the least risks. Pedestrian safety is especially obscure to analyze, given that many people in Stockholm cross the street illegally by running against the red light. To cope with these challenges, computational approaches of trajectory data visual analytics can be used to support the analytical reasoning process. However, it remains an unexplored field regarding how to visualize and communicate the street-crossing spatio-temporal data effectively. Moreover, the rendering also needs to deal with a growing data size for a more massive number of people. This thesis proposes a web-based interactive visual analytics tool for pedestrians' street-crossing behavior under various flow rates. The visualization methodology is also presented, which is then evaluated to have achieved satisfying communication and rendering effectiveness for maximal 180 agents over 100 seconds. In terms of the visualization scenario, pedestrians either wait for the red light or cross the street illegally; all people can choose to stop by a buffer island before they finish crossing. The visualization enables the analysis under multiple flow rates for 1) pedestrian movement, 2) space utilization, 3) crossing frequency in time-series, and 4) illegal frequency. Additionally, to acquire the initial trajectory data, Optimal Reciprocal Collision Avoidance (ORCA) algorithm [7] is engaged in the crowd simulation. Then different visualization techniques are utilized to comply with user demands, including map animation, data aggregation, and time-series graph.

Keywords:	street-crossing behavior, spatio-temporal trajectory visualization, space utilization, visual analytics
Language:	English

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Thank you!

Stockholm, August 18, 2019

Jiaqi Zheng

Contents

Chapter 1

Introduction

In the digitization era, traffic planners are seeking for computational visualization instruments to assist the process of analysis. Pedestrians' street-crossing behavior is one of the unexplored, whereas meaningful territories. For instance, the illegal crossing action against a red light endangers road safety, which behavior might be induced by unreasonable signal planning or crossing area design. Therefore, this thesis proposes an interactive visual analytics tool specifically for the street-crossing behavior by utilizing some spatio-temporal data visualization techniques.

1.1 Purpose and contribution

The analysis of crossing street behavior can benefit decision-making concerning traffic planning. Since the street area ought to satisfy pedestrians' requirements, it is crucial to first reveal the patterns in street-crossing behavior, which is the underlying premise for valuable traffic planning solutions. However, the information that traffic planners expect from data is not immutable but vary with cognitive demand. Therefore, the key from data visualization perspective is to develop methods and techniques that power human perception in discovering behavior patterns. To support such analysis, the concept of visual analytics [1] was brought, which addresses the research field of empowering users to interact with complex data sets. In this way, human natural perception is amplified to detect patterns more efficiently.

Additionally, the trajectories of moving agents are informative involving space, time, and attributes aspects. The complexity even increases in the street-crossing scenario, where each agent is although independent, influencing each other all the time. Researchers have been developing various applications to deal with complex spatio-temporal data sets, including the visualization of moving objects. The general challenges [4] include (1) rendering complex data sets, (2) communicating spatial and temporal phenomena, and (3) maintaining the flexibility of user interaction. The developed applications cover a variety of objectives. For instance, Geo Temporal eXplorer (GTX) developed by Buschmann et al. [4] particularly suits massive trajectories of moving objects; Nanocubes program developed by Lins et al. [11] utilized data cube aggregation to investigate the correlation among large-scale multidimensional data attributes. However, little research specifically combines the strengths of interactive visual analytics with realistic human behavior under a small-scale territory such as a pedestrian crossing.

Therefore, what is currently lacking for the street-crossing visual analytics are the tools and methodologies that efficiently simulate and visualize the real phenomena along with associated statistics, which should meanwhile provide users with the freedom to explore. In response to the requirement, this thesis proposes an animated and interactive visual analytics tool containing simulations of multiple pedestrian flow rates from small to massive. It supports 2D trajectory visualization within a 3D environment, which simulates agent-based behavior by taking care of mutual influence. Besides the visualization techniques of map animation [3], the tool meanwhile utilizes trajectory aggregation [3] to analyze space utilization. Moreover, one of the popular crowd simulation algorithms called Optimal Reciprocal Collision Avoidance (ORCA) [7] is involved in acquiring the fundamental trajectory data. The analytic results are then presented via a WebGL-powered big data visualization framework, DeckGL[1] . Finally, the efficiency regarding how the analytics tool has powered human perception is evaluated by user testing and a controlled experiment. To summarize, the contributions of the thesis include:

1. Study of a communication-efficient visualization approach that powers traffic planning, which amplifies the human capability of behavior pattern analysis by enabling data exploration.

2. Application of interactive web-based visualization frameworks to implement several visualization techniques for the trajectory data acquired by ORCA crowd simulation algorithm.

1.2 Problems and application context

The research question is:

[1] `https://deck.gl/`

How to effectively visualize street-crossing behavior at a signalized pedestrian crossing concerning various flow rates from small to massive?

As the serving purpose of this research, traffic planning is the process to define the strategies and details in relevant to urban mobility that encompass people's needs. The audience includes pedestrians, drivers, and cyclists. The planning process comprises various tasks, such as traffic modeling, building impact assessment, and the analysis especially from the perspectives of efficiency and safety. Although a traffic plan is typically large-scale on the municipal level, still integrated by smaller segments that address specific aspects. The analysis of street-crossing behavior takes a tiny territorial window with a tailored focus. Therefore, it is one of the segments worth investigation. The analysis, on the one hand, implies people's behavior itself, such as the illegal phenomena and the crossing patterns if pedestrians run against a red light. On the other hand, it can potentially support further analysis, such as the evaluation of pedestrian flow, the design of crossing space, the control of vehicle streams, and the time planning for traffic signal lights. Due to this significance, a visual analytics tool that efficiently visualizes street-crossing behavior is in high demand for assessing current situations and exploring experimental designs.

In the visualization context of street-crossing behavior, the main research challenges are on the one side, the data processing that applies ORCA crowd simulation algorithm, and the rendering of massive trajectory data at a smooth animation frame rate; on the other side, delivering the phenomena in an interactive way that facilitates insight exploration. As regards the specific visualization scenario, the research has chosen to perform behavior comparison on the same territory during the same period. The theoretical reason for this choice is explained in 2.1. Moreover, this method also keeps the flow rate as the single independent variable by evading the noise from unpredictable environmental factors, including time and location. Concretely, the visualized street-crossing scenario is based on a crosswalk during a signal cycle in the morning rush hours. The time duration is 100 seconds, with the first 75 seconds for the red light, and the rest for green. As for the location, The chosen crossing is based at the intersection of Kungsgatan Road and Sveavägen Road[2] , which region is one of the most crowded areas in Stockholm according to Stockholm City's research in 2015.

[2] `https://www.google.com/maps/@59.3353997,18.0637807,42m/data=!3m1!1e3`

1.3 Thesis outline

In the remaining part of the thesis, chapter 2 describes the theoretical framework, where the primary visualization methodology is established. Chapter 3 describes the methods, covering data and development tools. Chapter 4 is the visualization results, as the core part of the thesis. And Chapter 5 evaluates the analytics tool via user testing. Chapter 6 and 7 are discussion and conclusion, which wrap the research up.

Chapter 2

Theoretical framework

In this chapter, 2.1 introduces the fundamental visualization framework from a higher level of the application strategy, while 2.2 discusses the spatio-temporal visualization techniques, which apply to one of the crucial components within the analytics application. Besides, 2.3 elaborates several similar tools already developed. This whole chapter only introduces the relevant visualization methodologies, while their application to the use case of street crossing is explained in Chapter 4.

2.1 Behavior comparison

The design of the visual analytics tool principally follows the framework in the spatio-temporal visualization review by Adrienko et al. [3]. This paper evaluates multiple web-based visualization techniques regarding different data types and analysis tasks. The primary analysis tasks for the street-crossing scenario are illegal behavior and space utilization, both regarding various pedestrian flow rates. These are defined in the design objectives section 4.1.1. According to the denoted framework, these types of investigation tasks can be efficiently structured as ***behavior comparison on the same territory during the same period***.

Concretely, the street-crossing analysis task belongs to "when $\rightarrow$ what + where" among the categories Adrienko et al. [3] provided. As this framework has clarified, in this group of tasks, the users are interested in identifying the features of the dynamic behavior; and precisely, the features as a whole rather than the evolution over time. On the other side, it is also concluded in 4.1.1 that traffic planners are interested in the crossing behavior patterns associated with illegal behavior and space utilization. Therefore, this thesis' visualization task matches the mentioned category, and that the method of comparing homogeneous behaviors over the same time interval at the same territory is appropriate.

In the context taking the pedestrian flow rates as the independent variable, the visual analytics tool focuses on the same location of pedestrian crossing throughout the same signal cycle. It also implies that the vehicle pattern is immutable as it denotes the same period.

2.2 Spatial-temporal data visualization

Researchers have developed numerous visualization techniques for spatio-temporal data. This thesis has chosen some to implement, including:

- ***Map animation*** [3]: changes in data are represented by changes of a display that rapidly updates its contents.
- ***Data aggregation***[1] : as data mining process, to search, gather, and present data in a summarized format.
- ***Time-series graph*** [3]: a graph with X-axis for time, and Y-axis for the changing attribute, thus showing temporal variation.

The data to be visualized origins from the trajectories which contain the geographical information in time series (trajectory details see 3.1.1). When analyzing from the viewpoints of illegal crossing and space utilization, the visualization naturally involves the moving agents to present the interaction of pedestrians; and the changing numeric values such as the statistics for illegal crossing and space. The paper by Adrienko et al. [3] also summarized that the visualization techniques applicable for moving objects include map animation, and for numeric changes include data aggregation and time-series graph.

First of all, ***Map animation*** is chosen as the trajectories visualization technique. In the beginning, the objective of visualizing the location change confronts the choice of the two basic approaches: static map or map animation. As the names suggest, both of them visualize trajectories on the map, while the visual representation is either static or animated. Notably, one of the most popular spatio-temporal data visualization techniques called space-time cube [8] also belongs to the static map approach. It uses the Z-axis for time to map with the X, Y spatial dimensions, thus providing a view of the whole trajectory. Space-time cube also has multiple derivatives developed. For example, Tominsky et al. [17] proposed a stacking-based approach to

[1] `https://www.techopedia.com/definition/14647/data-aggregation`

meanwhile visualize attribute values. However, map animation is more suitable for the street-crossing scenario since the interaction among many agents should be observable. As Andrienko et al. [2] have discussed, static representation is not legible when dealing with multiple moving agents; and that it works poorly in indicating the speed. Additionally, there are three modes [2] for map animation, including snapshot in time, movement history, and time window. The thesis adopted the first one to show the in-time position at each time frame without a trail; because the tracks can be confusing when visualizing a massive amount of agents.

Second, ***Data aggregation*** is efficient in visualizing space utilization by having trajectories overlaid on the same territory. This approach is also widely engaged for the advantage in dealing with large data sets [1]. For instance, Willems et al. [18] visualized the positions of significant maritime areas using density maps. Hilton et al. [9] utilized heat maps to communicate the spatial properties of traffic fatalities.

Last but not least, ***Time-series graph*** is usually utilized in addition to the map representations [3]. As the time within a signal cycle changes, the values of behavior indicators also vary, which trend is intuitive to gauge with a time-series graph.

2.3 Related Work

Regarding the existing spatio-temporal data visualization tools, Geo Temporal eXplorer (GTX) developed by Buschmann et al. [4] especially suits massive 3D trajectories of moving objects. It utilized various techniques including map animation, space-time cube, temporal focus+context, and density map. Particularly, GTX's research has respectably proposed a fully GPU-based visualization pipeline, which enhanced the performance to render large and complex trajectory data sets. Additionally, GTX is also implemented with flexible user interactions.

The Nanocubes program developed by Lins et al. [11] implemented web-based real-time visualization focusing on data cube aggregation, primarily via heatmaps, histograms, and parallel coordinate plots. It introduced a novel data structure for data cube aggregation technology, and also the associated querying algorithms. With this improvement, the real-time exploration of large spatio-temporal data sets becomes possible.

However, these tools are better for large-scale territory, but not a small and focused region, therefore, not advisable for the street-crossing visualization use case.

Chapter 3

Method

3.1 Data set and data acquisition

The data set used in this thesis comprises 2D trajectories of moving pedestrians and the environment data. The trajectory data is essential since it records the behavior narratively by involving 2D positions and time. Some of the trajectories represent people who cross the street properly; some indicate the illegal behavior if people run against the red light. This illegal behavior is concluded from the crossing behavior study in 3.1.2. Although the trajectory data is the core, the environment data is also necessary since it establishes the visual street background and crossing environment.

3.1.1 ORCA simulation for trajectory data

There are principally two alternatives for data acquisition: to gather either real or simulated data. Considering that the visualization intends to include multiple pedestrian flow rates from small to massive; however, the real flow rate during morning rush hours at the same location does not fluctuate severely. Therefore, the data acquisition adopted simulation since collecting real data is not feasible.

As one of the most widespread crowd simulation algorithms, Optimal Reciprocal Collision Avoidance (ORCA) [7], the ORCA algorithm can compute biomechanically energy-efficient and collision-free trajectories for large-scale crowds at interactive rates. Also, the library is intuitive to use with a well-documented C++ library[1] . Concretely, scripting a viable simulation only needs the specification of several parameters, including starting position, objective position, maximal speed, calculation rate, and the distance

[1] `http://gamma.cs.unc.edu/RVO2/`

to the neighboring agents who are recognized to affect the navigation. Furthermore, the technical performance of the ORCA algorithm also meets the requirement. Specifically, this thesis expects to simulate at least 180 agents, which is the number of pedestrians under the highest setting of flow rate. ORCA is applicable since, on the one hand, Guy et al. [7] have already utilized it for thousands of agents on a desktop PC. On the other hand, a feasibility test was successfully completed to simulate 250 agents at the same time.

The implementation details are described in 4.4. To summarize about its outputs, the trajectories eventually acquired are 12 trajectory data sets respectively for various flow rates. In each data set, everybody has his/her corresponding trajectory from the time he/she appears until reaching the opposite side. Therefore a single trajectory comprises numerous geo-coordinates indexed by time. The time further contains the waiting and crossing periods, where the crossing duration is about 10 seconds, while the waiting time differs from 0 to 75 seconds. As for the temporal resolution, there are 30 calculated data points within 1 second, so every trajectory contains minimal 300 and maximal 2550 positional data samples. Moreover, talking about the total number of trajectories, the simulation has been executed 12 times, and every time it generates a set of trajectories corresponding to a different number of agents. The 12 flow rates vary from 15 people to 180 people within a signal cycle of 100 seconds. Therefore, there are more than 1000 trajectories and more than 1 million sample points.

3.1.2 Illegal crossing behavior pre-study

The ORCA simulation can produce trajectories concerning how agents navigate to avoid the collision when the position and destination are designated. However, it does not differentiate whether a pedestrian conducts the illegal crossing, which purpose is served by the behavior pre-study. Since the behavioral veracity does not affect the quality of visualization, the target of the pre-study is to grasp a basic understanding of the behavior pattern, and then summarize a scheme which determines agents' crossing or waiting states in the simulation.

For the behavior study, the approach I have adopted is associating practical observation with the related research. Many researchers have already modeled the street-crossing behavior mathematically. For instance, Li et al. [10] introduced a bilevel multivariate approach containing two models respectively for waiting time and risk-taking attitude. Yang et al. [20] developed a joint hazard-based duration model to estimate waiting time, where the behavior is classified as crossing immediately or waiting before crossing. However, directly utilizing them is difficult. First of all, these models are usually highly complicated with multifarious parameters required, such as the vehicle time headway, pedestrian types, number of crossing attempts needed, and curbside waiting time; secondly, the model is not universally applicable throughout the world due to culture differences. Because of those limitations, this thesis chooses to create a simplified agent-based model from scratch. Some significant aspects mentioned by the related work are selected as the predictors to determine whether an illegal crossing happens. The first predictor is waiting time, which appears in all the found models; the other predictor is the number of other illegal crossings in sight, as Yang et al. [19] have discussed the phenomena of following up other violative agents.

Figure 3.1: The visualized crossing and pre-study filming setup.

After studying the related work, the practical observation for real behavior was performed by filming the street-crossing. The videotaping took place on the Tuesday morning of February 12 in 2019 from 8:20 to 9:10, which period covers the commuting rush. The street scenario at Kungsgatan[2] and the camera setup are shown in Figure 3.1, which place is also used next for visualization.

The video was investigated repeatedly, with the behavior for each pedestrian recorded. The record has also classified the crossing behavior into two categories since there are two parts of the road: a pedestrian either traverses the nine or twelve meters. There is a buffer island in the middle of the crossing as also distinguishable in the photo. It divides a street-crossing process into two sequential times of decision-making since pedestrians can choose to stop by the island for another judgment of when to cross. It is worthwhile

[2] `https://www.google.com/maps/@59.3353997,18.0637807,42m/data=!3m1!1e3`

to separate the behavior samples by road width since it impacts pedestrians' risk assessment. As for the recorded variables for each crossing, they correspond to the selected predictors from the related work, including the waiting time when there is no vehicle, the number of people crossing illegally in sight, and whether the recorded agent eventually crosses illegally. The recorded data has 46 samples for the nine-meter road segment, 31 for the twelve-meter. However, deviation still exists even if the waiting time and the illegal occurrence in sight are identical because additionally, every individual has distinct violative inclination by character. Therefore, another variable called hurry level is attached to everyone as a coefficient. The hurry level ranges from 0.0 to 1.0, where 0.0 means an absolute law-abiding attitude, whereas the people designated 1.0 have zero tolerance of waiting once the road turns free. Nevertheless, it was not possible to measure the hurry levels from the video, so these values were assigned manually by estimation and some randomization.

Crossing Decision-Making State Table

Hurry Level	If width of the road is 9.0m								If width of the road is 12.2m							
	0s	1s	2s	3s	4s	5s	6s	7s	0s	1s	2s	3s	4s	5s	6s	7s
0.0	40	30	20	18	15	13	10	9	50	35	25	22	19	15	12	10
0.1	25	18	13	11	9	7	6	4	35	22	17	14	12	9	8	7
0.2	20	13	9	7	5	4	2	1	25	16	11	9	7	5	3	2
0.3	13	7	6	4	2	1	0	0	16	9	7	6	5	4	2	1
0.4	8	5	3	1	0	0			10	6	4	2	2	1	0	0
0.5	5	3	2	0					7	4	2	1	0	0		
0.6	3	1	0						4	2	1	0				
0.7	2	0							2	1	0					
0.8	1								1	1						
0.9	0								1	0						
1.0									0							

Figure 3.2: The number of people who are crossing illegally in sight. These numbers are the thresholds that an agent can resist following. For instance, if a 0.3-level-hurried pedestrian is going to cross the nine-meter street, after 3 seconds of waiting for a vehicle-free road, he/she will cross illegally only in case there are at least 4 other people crossing.

Although the behavior was not modeled mathematically, the pre-study facilitated the conclusion of some hypotheses. For example, pedestrians are more inclined to cross illegally under any of the following cases if 1) the hurry level coefficient increases; 2) the elapsed waiting time is prolonged; 3) more number of people in sight are crossing illegally; 4) the width of the road is narrower. Therefore, a decision-making state table was summarized as presented in Figure 3.2, which is the primary accomplishment of the pre-study and has been implemented later in the simulation (4.4.4). Concretely, every cell in the table contains a number referring to the tolerance threshold. Regarding how the table was filled, around half of the numbers were inferred from the real data, while the rest are the estimates that comply with the hypotheses. Therefore, if at a corresponding time, there are a larger number of illegal pedestrians than the threshold, the simulated agent will decide to cross illegally. In other words, every time frame for each agent, there is such an execution of table looking-up to decide upon the agent' action.

3.1.3 Environment data

The environment data constitutes the street scene of the target pedestrian crossing at Kungsgatan[3] , which serves as the visualization background in this thesis. To summarize, there are four types of environment data: road geographical information, buildings, vehicle stream, and crosswalk lines.

The road geographical information and the building data are retrieved via Mapbox[4] , whose street data belongs to OpenStreetMap[5] . However, OpenStreetMap data has the shortcoming that the pavements are incorrectly narrow due to the building dimensions. Since the shrunk curbside area brings negative effects on the street capacity and the positions that people stand, calibration was performed for the two buildings beside the curbsides of the crossing. The measured widths from Google Map were referred there as the right indicators for the calibration. As a result, the curbside buildings were moved several meters away from the road. Furthermore, the crosswalk lines data was measured in the Google Map as well, including the number and width of the crosswalk lines, and the dimensions of the buffer island. Unlike these data sets, the vehicle stream pattern (details see 4.3.2) was recognized from the video in the pre-study, covering the busy period and the vehicle-free duration.

All the mentioned environment data sets were implemented into graphic components as described in 4.3.

[3] `https://www.google.com/maps/@59.3353997,18.0637807,42m/data=!3m1!1e3`

[4] `https://www.mapbox.com/`

[5] `https://www.openstreetmap.org/`

3.2 Development tools

A web-based interactive visual analytics application requires multiple tools at various stages for different purposes. In short, the visualization pipeline comprises setting up the web application environment, preparing the data to a visualization-readable format, and applying the visualization packages to render. This section offers a collective overview of the utilized tools, while the implementation is presented in 4.2.

3.2.1 Web application

Essentially, the front end for a web page employs HTML, CSS, and JavaScript to develop the document object model (DOM), where HTML defines the layout and content properties, CSS for styling, and JavaScript manipulates the interaction. Based upon these, the thesis chooses to utilize ***React***[6] , which is one of the most popular JavaScript libraries that renders and updates the DOM efficiently. Moreover, ***Redux***[7] is another JavaScript library engaged jointly to manage the states as regards the various pedestrian flow rates.

Besides the frontend part closely related to visualization, some other tools were used to enable a running website. For example, ***Node.js***[8] provides the backend runtime environment, ***Webpack***[9] bundles the JavaScript modules, and ***Heroku***[10] deploys the application to the cloud.

3.2.2 Data preparation

The generation of the trajectory data was written in ***C++*** by integrating the library[11] , which has the ORCA algorithm as a built-in. However, the data structure of the simulation outputs is not recognizable by the visualization framework, so ***Python*** data processing succeeds to reorganize the data, and meanwhile, transform into geo-coordinates.

3.2.3 Visualization frameworks/libraries

The visualization techniques are map animation, data aggregation, and time-series graph as decided in 2.2. Map animation is intended to visualize the

[6] `https://reactjs.org/`
[7] `https://redux.js.org/`
[8] `https://nodejs.org/`
[9] `https://webpack.js.org`
[10] `http://heroku.com/`
[11] `http://gamma.cs.unc.edu/RVO2/`

moving pedestrians, while the other two for associated statistics.

For map animation, there are two implementation tasks, including the street geographical scene and the moving agents. The street background embedded the DOM with a customized map using ***Mapbox Studio***[12] . It is a map platform with the flexibility to specify multiple visual attributes, such as the visibility of buildings and labels. After building the scene, the crucial part of visualizing moving trajectories adopted the visualization framework ***Deck.gl***[13] . Deck.gl is WebGL-powered, suitable for rendering large data sets smoothly. Although its data size upper limit is unknown, it was proved sufficient for this thesis according to the study in 4.1.2.

Additionally, the visualization for statistics is based on the widespread JavaScript library called ***D3.js***[14] . The utilized elements include the heatmap and the area chart. However, there are some compatibility issues to make D3.js work together with React. Therefore, another React-based visualization library called ***VX***[15] is utilized as well, which packages up D3.js components to fit React.

[12] `https://www.mapbox.com/mapbox-studio/`
[13] `https://deck.gl/`
[14] `https://d3js.org`
[15] `https://vx-demo.now.sh/`

Chapter 4

Visualization results

4.1 Development requirements

To develop an animated and interactive street-crossing behavior visual analytics tool that is also useful in practice, the researcher should consider the requirements from both the users demand and the system performance.

4.1.1 User demands

The user demands were defined by interviewing two traffic planners at Atkins via two iterations. The first was a free-style discussion to hear about their general interest and some inspirations. After that, a list of ideas together with several user interface mockups (Figure 4.1) were presented again to validate the demand priority. The design was gradually improved both to match the user demand better, and to pick a more suitable representation graph.

During the user demand definition process, two user-interested categories emerged early: the ***pedestrian safety*** and the ***space utilization*** of the crossing area, especially about the buffer island. For space utilization, it was intuitive to choose the heatmap to represent the aggregated utilization data that obtained from the moving paths. This technique conforms to users' desire to evaluate whether the buffer island is appropriate in size. However contrarily, pedestrian safety was initially a vague notion to visualize. According to the conclusion eventually drawn from the discussions, pedestrian safety was divided into these accessible sub-categories that users desire:

- ***Pedestrians' movement*** depicting the real phenomena as smoothly as possible. It has the potential to amplify the capability of human

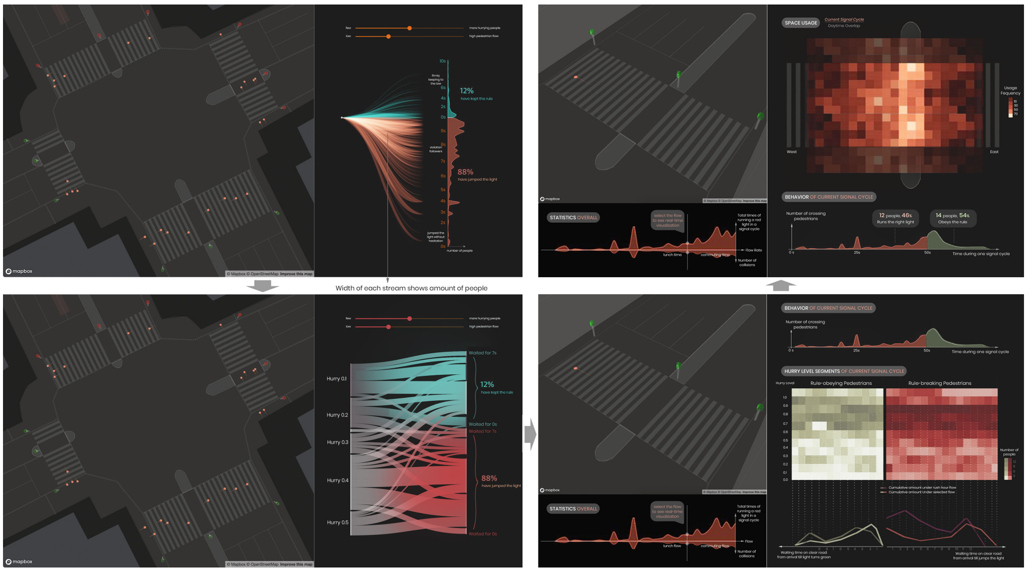

Figure 4.1: UI mockups using Photoshop as a glance to showcase the design history. The four designs were iteratively updated, and the last one on the right-top corner is closest to, but not identical as the implemented prototype shown in Figure 4.2

perception in discovering the illegal behavior patterns, which are not directly investigable on the street.

- ***Crossing frequency in time-series*** of one signal cycle covering the red and green period. The time-series graph method displays the temporal dependency for the crossing behavior, which answers the question how the illegal inclination varies over time.

- ***Illegal frequencies under varying flow rates*** including small and massive. In other words, the users would like to know how the crossing behavior differs under various degrees of crowdedness.

4.1.2 Performance feasibility

The preceding section undertakes the challenges of communicating the desired insights interactively on the strategy level. However, there is another challenge from the performance level to render complex data sets, which relies on Deck.gl in updating the web DOM content.

The most massive data set to be visualized at the same time is the moving trajectories of 180 agents over 100 seconds. As one second is divided into

30 data samples, there are around 0.5 million geographical entries in total. Therefore, the performance of Deck.gl is sufficient since the aforementioned data size is smaller than the data sources in the other two successful implementations. firstly, one of the examples[1] provided by the Deck.gl team renders billions of entries smoothly. This example is analogous because it also visualizes movements. Secondly, a simplified feasibility study was performed after setting up the street-crossing visualization pipeline. In that study, 250 ORCA simulated agents with approximately one million positional samples were rendered without delay.

4.2 Visual analytics tool overview

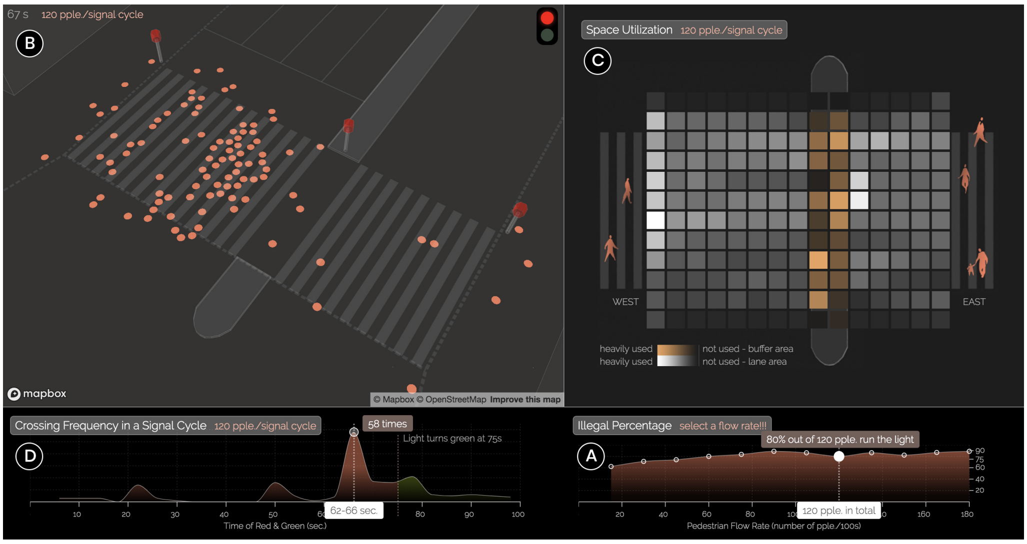

Figure 4.2: A screenshot of the web-based interactive and animated visual analytics tool used for the street-crossing behavior at the signalized pedestrian crossing. (A) The area chart shows the percentage of people who perform illegal crossing under different pedestrian flow rates. This part meanwhile functions as the flow-rate-selection control panel that all the other three units listen to. (B) The simulation results of street-crossing behavior within a signal cycle. (C) The space utilization heatmap illustrates the usage rate of the crossing area. (D) The area chart shows people's crossing frequency over time in a signal cycle.

[1] https://deck.gl/#/examples/core-layers/trips-layer/

The developed prototype for the visual analytics tool[2] (Figure 4.2) complies with the principle to compare behavior on the same location during the same period as discussed in 2.1. Concretely, this tool presents the behavior and statistics under various flow rates during the same signal cycle for comparison. Pedestrian flow rate is chosen here as the user-controllable variable, because it is one of the relevant factors involved in multiple subjects, including pedestrian safety and space utilization. As a result, for the analytics tool, the independent variable is the flow rate (part A in Figure 4.2), and its associated dependent variables come from the other three visualization components, including the behavior how pedestrian cross, the variation tendency of crossing frequency over the signal cycle, and the utilization rate of the crossing area divisions.

As for the contents of the mentioned components, they comply with the user interest respectively. Reflecting upon the user demands (4.1.1), there are four specified desired components: ***(1) pedestrian movement*** for illegal pattern discovery, ***(2) space utilization***, ***(3) crossing frequency in time-series***, and ***(4) illegal crossing percentage under varying flow rates***. As Figure 4.2 shows, the developed components include: part B, the animated pedestrian movement that accords with the first demand; part C, the heatmap for spatial data aggregation for the second demand; part D, the area chart of crossing frequency in time-series for the third demand; and part A, the area chart of the illegal crossing percentage for the last demand.

The remainder of this chapter elaborates all relevant development details, including for every component: 4.5 for part B, 4.6 for part C, and 4.7 for part A and D.

4.3 Environment and scenario

4.3.1 Street scene

The street scene was visualized as in Figure 4.3, with the main facilities drawn, including crosswalk lines, buffer island, traffic light, lanes, and buildings. Initially, the embedded map component only has the road boundaries marked out (Left Figure 4.3). Therefore, the visualization task for the street scenario is placing the indispensable components that matter for street crossing. These elements consist of the crosswalk lines, the buffer island, and the traffic light, whose dimensions influences pedestrians' behavior directly. Additionally, the curbside buildings and the lanes are also relevant. The former

[2] `https://thesis-vis.herokuapp.com/`

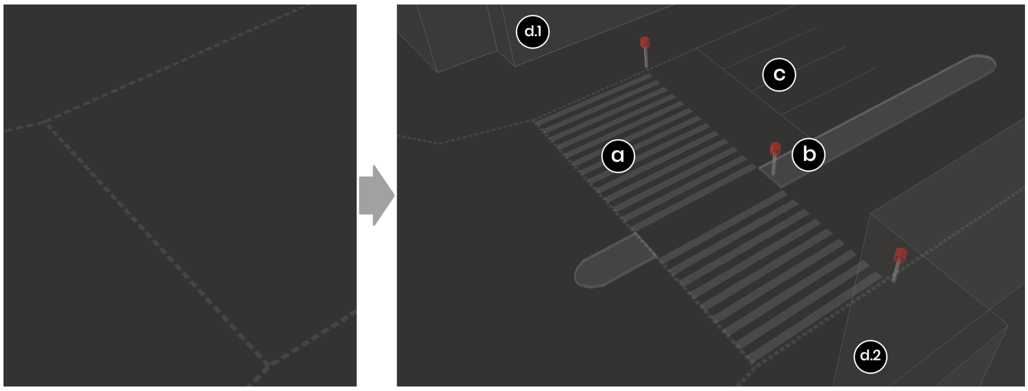

Figure 4.3: Left: Before drawing. Right: After drawing the environment. The visualized street scene with (a) crosswalk lines, (b) buffer island and signal light, (c) traffic lanes, (d) curbside buildings.

demarcates the red light waiting area, while the latter standardizes the vehicle stream.

With the calibrated environment data (3.1.3), the adopted visualization tool was Deck.gl, which has handy graphics layer APIs for reading data and setting properties. For instance, the path layer was applied to draw the strips for crosswalk lines and traffic lanes. The polygon layer can dispose of 3D objects, was therefore, used to render buildings, traffic light, and the protruding buffer island.

The street scene above is static. However, the signal color is different since it should switch by time. This feature was achieved by correlating the color attribute with the time variable. As a result, the visualization turns the red light to green at 75 seconds.

4.3.2 Vehicle streams

It is essential to define the vehicle stream pattern precisely as well, because there is a baseline assumption that nobody tends to cross illegally when there distinctly exists a traffic stream.

One vehicle stream pattern was defined as shown in Figure 4.3.2. It was noticed that each signal cycle has a similar vehicle pattern in terms of the continuous busy periods by reading from the street-crossing video (3.1.2). Moreover, the restriction is that the visualization only takes the same signal cycle regardless of the varying pedestrian flow rates. Therefore, it is adequate to define one vehicle flow pattern explicitly. Additionally, to keep the scenario simplified, the vehicle pattern only comprises the continuous traffic stream.

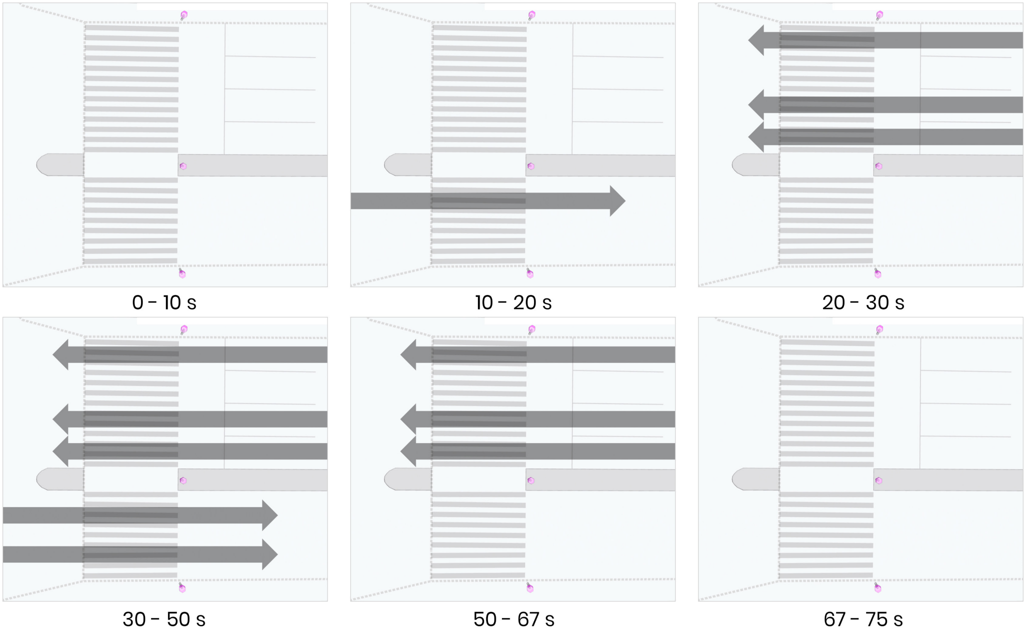

Figure 4.4: Illustration for the defined vehicle stream pattern via Photoshop.

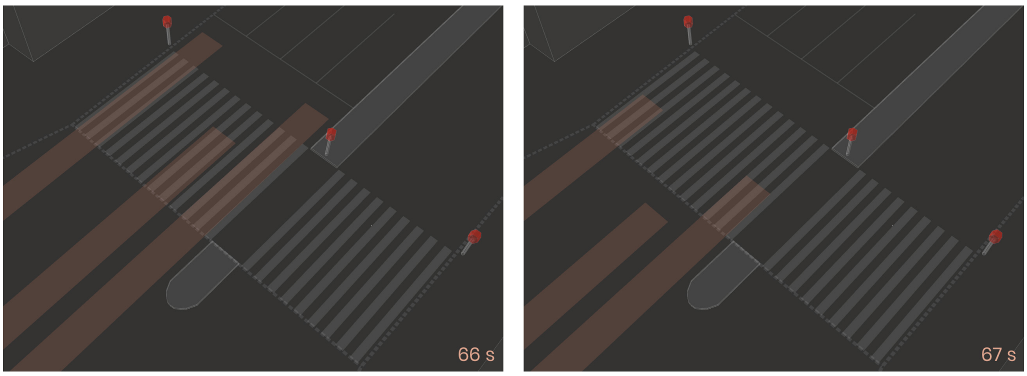

Figure 4.5: Screenshots of the visualized vehicle stream showing how the flow changes from 66s to 67s. In the analytics tool, the vehicle streams are represented by the animated brown strips.

Neither the vehicle type nor speed is considered.

As illustrated in Figure 4.3.2, the pattern only covers the 75 seconds of the red light period, since the remaining 25 seconds is irrelevant to illegal behavior. Regarding the pattern details, both in the beginning and end of the red signal, there is a short empty period for security purpose. Moreover, sometimes, one side of the road is vehicle-free. All those pieces of void fulfill the conditions that the pedestrians might cross, which is dangerous since a vehicle possibly appears suddenly.

The vehicle stream pattern above was also implemented using Deck.gl, essentially the same way as the preceding section of street scene. Concretely, the vehicle streams utilized the path layer API by modifying strips' width, color, and transparency. Moreover, their positions are associated with time. Therefore, the flow looks animated as the web DOM updates.

4.4 ORCA simulation implementation

The implemented simulation tailored the ORCA algorithm (introduced in 3.1.1) to the street-crossing scenario to output the required trajectories. Specifically, in the target scenario, people continuously arrive at the curbside by the pedestrian crossing. They all aim to get across the street; however, some cross illegally, while others keep the rule and waited till the light turns green. This behavior was determined by simulating the crossing decision-making (4.4.4). Moreover, it is worth noticing that every pedestrian undergoes two judgments to reach the opposite side since a buffer island has separated the road apart.

A rectangle area (Figure 4.6) was scoped for the simulation territory, including where pedestrians might stand and traverse. Also, for the convenience of representation, the buffer island center point was defined as the coordinate origin.

In terms of the simulation parameters, some are shared by the entire street-crossing scenario, while others vary from agent to agent. The commonly defined ones include the principles that people navigate to avoid collision (4.4.1), and the rules that pedestrians decide on a crossing action (4.4.4). On the other side, the individual dependent attributes cover arriving time, position, moving path, hurry level, and speed. These are described respectively in 4.4.2 and 4.4.3.

4.4.1 Navigation settings

Some parameters are required by the ORCA algorithm to complete the navigation principles on how agents move to avoid the collision. These properties were adjusted iteratively so as to align with the natural behavior. As a result, in the street-crossing scenario, the navigation-relevant parameters are:

- ***neighborDist = 10.0m*** The distance range to consider for navigation. For example, if someone 10 meters away is walking closer, the

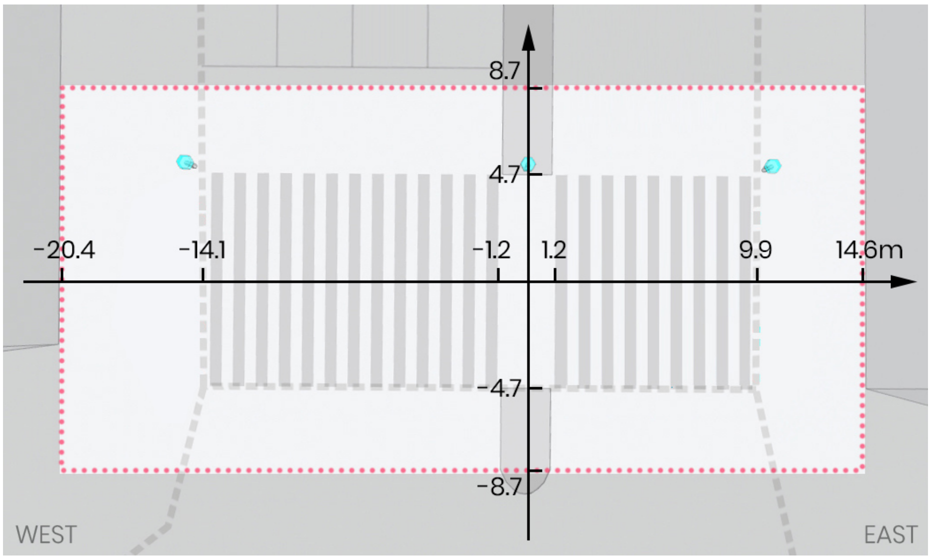

Figure 4.6: Illustration for the simulated area and its dimensions (the middle 35m × 17.4m rectangle). Pedestrians never stand or move outside.

agent will start altering the orientation.

- ***maxNeighbors = 10*** The limit for the number of considered surrounding agents. An improperly small value will result in collisions; and contrarily, a large value makes the movement overcautiously slow.
- ***radius = 0.3m*** Every agent occupies an area with the defined radius, meaning it impossible for any two to move closer than it.
- ***maxSpeed = 0.09*** This coefficient implies the walking speed of 2.7m/s, which is around twice the average pedestrian speed. Note it is only set as the average value, whereas individual deviation applies to everybody.

4.4.2 Agent initialization

Every agent indicates a pedestrian with some different properties assigned on initialization, including the ***appearing time***, ***appearing position***, ***hurry level***, and ***walking speed***. Therefore, the implementation defines an object for each agent. All these objects have several variables representing the aforementioned properties respectively.

Concretely, the appearing time variables for all agents are linear, which means the pedestrian arriving rate is constant. Differently, the hurry level

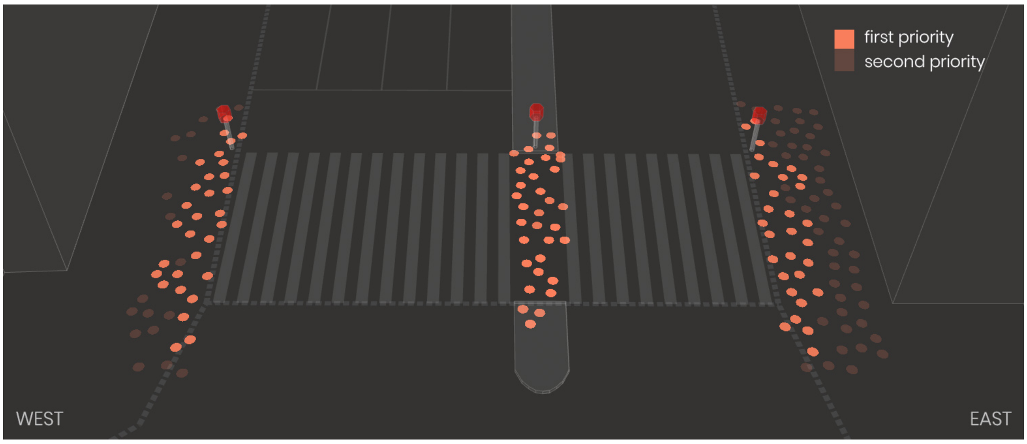

Figure 4.7: All the pre-defined positions that agents may appear at or targeting to go. The brighter dots have higher priority, while the darker ones are the backups that engaged only if all the brighter are occupied.

is randomly assigned, ranging from 0.0 to 1.0. When generating the hurry levels, verification was also conducted to make sure that the average value lies between 0.45 and 0.55. Moreover, the hurry level is associated with the walking speed, signifying that a higher hurry level causes a stronger positive deviation to the original speed, and vice versa. Additionally, the maximal speed variation is ±50%, which ensures that the simulation looks reasonable.

The assignment of the appearing position variable is more complicated than the previous ones. From a general level, these positions are still randomized. Nevertheless, there exist some constraints regarding implementation details:

- ***Pre-defined positions*** The available points were pre-defined rather than generating every time. And the generation process combines randomization and manual adjustment. As a result (Figure 4.7), there are 78 possible positions at the eastern curbside, while 48 for the west. This difference roots in the realistic flow pattern: twice the number of people are passing from the east in the morning.

- ***Positions prioritization*** The defined positions by the curbside are classified into two priorities. On each side, the 30 points closer to the crosswalk lines has a higher priority. As a result, a new agent will appear at one of the 30 prioritized positions via random selection. Additionally, there is a check to verify that the chosen position is empty. Only in the case if all the prioritized points are occupied at the same time, will the other backups come into use.

4.4.3 Starts and destinations mapping

As mentioned above, the available appearing positions were pre-defined; in reality, the mapping towards their destinations was also decided then. In terms of the mapping method, all the connections were assigned manually by the researcher considering the reasonable movement with a certain degree of random deviation. As a result, each point at the curbside is linked with a target position at the buffer island (all possible positions also marked in Figure 4.7); each point at the buffer island also points to its destinations both towards east or west. Therefore, every agent can know which direction he/she should move based on the standing position at that time.

However, there is a problem if merely following the rules above: several pedestrians might move towards the same buffer island target. According to the setting in the ORCA algorithm, the agents always attempt to reach their destinations. Therefore, having the same goal will cause a jostle, which does not accord with real life. To address the issue, another navigation rule is supplemented and compiled every time frame: if an agent heading the buffer island is based less than three meters away from the buffer area, this agent will check whether his/her goal is occupied at that point; if so, switch the goal to another point that neighbors the original one. Additionally, in case the neighboring points are also employed, the search of a new target will keep increasing its territory range until an empty one detected. Moreover, in the worst case, if none is available at all, the agent will not alter his/her direction to end up pushing each other.

4.4.4 Street crossing rules

The only setting left so far to complete the street-crossing simulation is the rule to decide on a crossing decision. Therefore, the objective is to assign behavioral states to all agents respectively. Concretely, according to the vehicle stream pattern (Figure 4.3.2), the behavioral states are classified by the periods within the 100-second signal cycle:

- ***Green period*** 75 - 100s.

  The signal light is green for the last 25 seconds, so all agents move towards their own goals then. The programming approach is assigning a new destination to each agent when the timer reaches 75s. Moreover, pedestrians will not consider stopping by the buffer island, which is

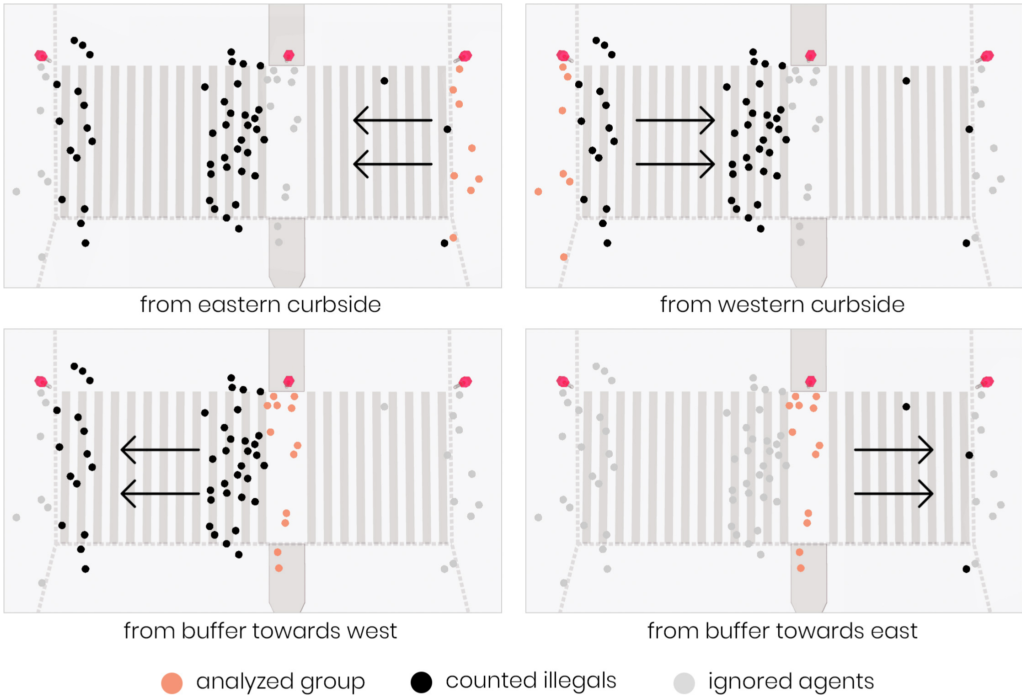

Figure 4.8: The illustration shows which illegal agents are considered to induce others to follow up. The curbside waiting agents are affected by the whole crossing, while the buffer-area waiting ones only influenced by the violations on one road segment since those rearward are not seen.

different from the red light period. To achieve this, all the allocated target positions are across the street.

- ***Red period: rule-obeying*** 20 - 67s for the western road segment; 10 - 20s and 30 - 50s for the eastern part.

  These are when there travels continuous traffic, so nobody takes risks to cross. The periods are also specific by road segment since the traffic at the farther side does not prevent the pedestrians from crossing the closer one. Additionally, from the implementation perspective, the waiting state was achieved by setting the destination the same as where the agent was, thus the "heading the goal" movement looks static.

- ***Red period: potentially illegal*** 0 - 20s and 67 - 75s for the western road; 0 - 10s, 20 - 30s, and 50 - 75s for the other side.

  During these periods, people potentially violate the red light because the road appears vehicle-free. It is where the illegal crossing pattern (Figure 3.2) is implemented: there is a calculation for each agent at every time frame regarding how many people are already crossing ahead, following the counting rules in Figure 4.8. Meanwhile, another collected value is the time waited, starting two seconds before the vehicles disappear. And then, the waiting time and hurry level are used together to locate a threshold in the table: in case if the initially counted number of illegal occurrences exceeds the threshold, another illegal crossing is determined to happen.

4.4.5 Application to various flow rates

To acquire the simulation results of various flow rates, the researcher only needs to specify a different pedestrian arriving speed. And then, all the described manipulation applies directly to generate a corresponding result.

The simulation was compiled for 12 increasing flow rates, respectively 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, and 180 people per signal cycle (100 seconds). This value indicates the total volume of the people traveling both directions. However, in real life, the number of people crossing from the east is roughly twice as much as the opposite direction. This feature was also imitated in the simulation. For example, if the flow rate values 90, then 60 of them are crossing from the east.

Even though Kungsgatan is one of the busiest street blocks, its flow rate in the morning rush hours is up to 30 people per signal cycle. Therefore, the visualized range of 180 is quite sufficient.

4.5 Trajectories rendering

4.5.1 Visual glyph

Reasons explained in 2.2, the trajectory visualization aims to render agents' in-time positions animatedly on the map. In this context, a visual glyph [12] is commonly helpful to represent the agent, which is a kind of marker indicating a particular type of objects.

In the thesis' visualization, a round glyph is used for each agent. This shape is appropriate since it conveys the position and occupied area explicitly without redundant information. Moreover, the glyph is in coral, which color is in sharp contrast to the dark map background.

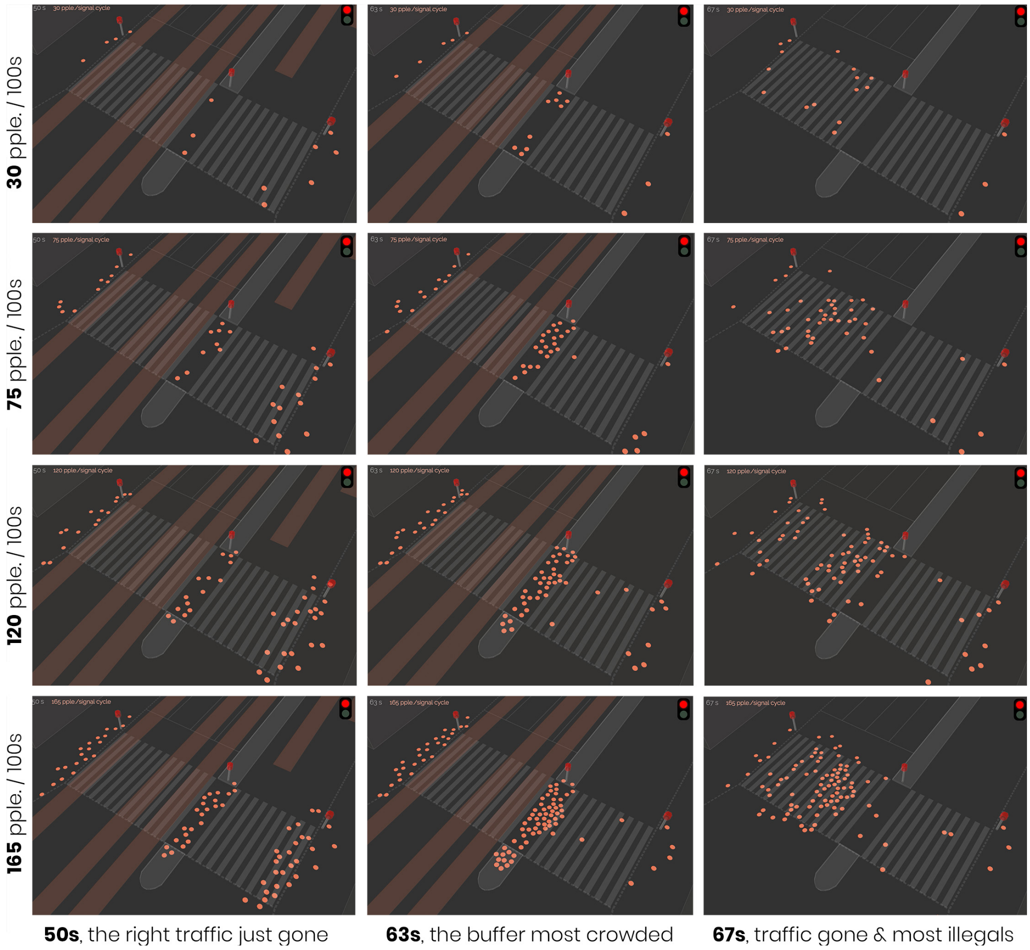

Figure 4.9: Multiple screenshots for the visualized moving agents. Every row has the same flow rate, and each column for a featured time.

4.5.2 Animated agents

The rendering from the trajectory data to animated presentation relied on Deck.gl with the formatted trajectory data sets.

The creation of the round visual glyph utilized the scatterplot API in Deck.gl, which renders visual dots according to the geo-coordinates. Then, to enable the animation, the positional variable for every dot is associated with one trajectory path, whose update is triggered by the timer. There are 30 times of positional update every second. As a result, the web DOM still smoothly animates numerous trajectories together, thanks to React's advantage that only altered content is partially re-rendered.

4.5.3 Demos and findings

Figure 4.9 demonstrates the visualization results for pedestrians' movement. The goal was fulfilled to develop a movement visualization that resembles the real phenomena as much as possible.

With help from this visualization component, it is expected that the users can explore and discover some hidden patterns by themselves. Although it is up to the users regarding what those insights potentially are, some prominent findings already emerge, for instance:

- Much illegal crossing happens right after the vehicle stream terminates; especially severe at 67s, which is shortly before the light turns green.
- The buffer island can be overcrowded as the flow rate increases. And the most severe congestion at 63s results from illegal crossing.

4.6 Visualization for space utilization

In the context of space utilization, the data aggregation technique (2.2) overlays the trajectory positions during the entire 100 seconds of the simulated period. This aggregation increases the utilization contrast at different positions by considering the temporal data as a whole. Additionally, for a more understandable presentation, the heatmap groups the data by grids, where each square unit represents a real dimension of 1.2m $\times$ 1.2m.

As for the implementation, the heatmap was built using VX, which is a D3.js based visualization library. Moreover, the frequency data was acquired from ORCA simulation by adding a block that outputs the incremented counters.

Results demonstrated in Figure 4.10: the heatmap content varies when a different pedestrian flow rate is selected. Therefore, the users have the exploration freedom to compare the utilization under a varying number of passengers. For example, it is noticeable that in the latter heatmaps, starting from the one for 120 people/100s, the white color is unusually bright near the buffer area. This means people are frequently standing outside the buffer island, which is risky.

Additionally, the visual components are also carefully designed from both the perspectives of aesthetics and user experience, for example:

- ***Background scenario*** Since the heatmap does not depict the scenario, a background that resembles the pedestrian crossing is layered

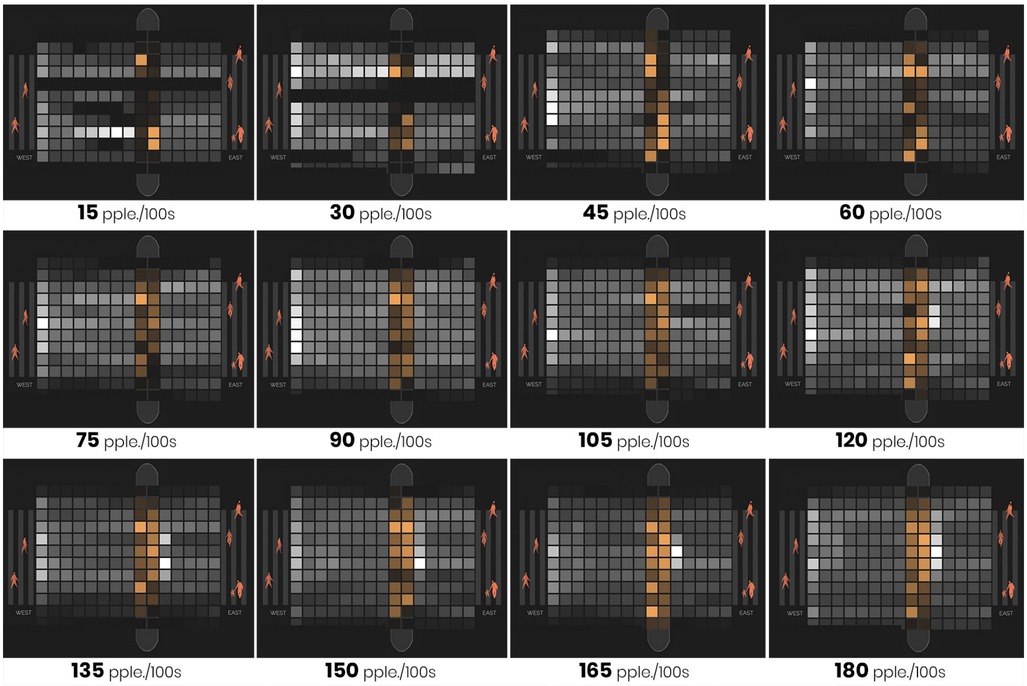

Figure 4.10: A collection of the screenshots of the space utilization under every flow rates. Brighter color implies a relative higher usage rate, where the white scale is used for the regular road, honey yellow for the buffer area.

underneath. As shown in the screenshot (part C in Figure 4.2), besides the precisely-located crosswalk lines, several human-shaped illustrations are also around to make the street scene intuitive.

- ***Color choices*** On the one hand, the pedestrian illustrations on the background share the same color with the moving agents (4.5.1). In this way, the coral color naturally builds the connection in the human mind that they represent the same concept. On the other hand, the heatmap color scale for the buffer island is honey yellow rather than coral, which prevent such misleading connection (Adjustment after the evaluation in the following chapter).

4.7 Visualization for statistics

Two complementary area charts were added to deliver numeric analysis. They both were implemented using the VX visualization library, which tool is highly customizable in manipulating the gradient and interaction. They are crossing frequency chart in time-series (part D in Figure 4.2), and illegal percentage of all pedestrians under varying flow rates (part A in Figure 4.2).

4.7.1 Crossing frequency chart in time-series

Given that the movement is already visualized, a time-series graph for crossing frequency is a compelling choice of supportive mechanism, since the visualization of moving objects does not support temporal comparison. A time-series graph can convey the temporal statistics in terms of the overall crossing behavior, such as the periods that people severely violate the red light, and the severity comparison between different periods.

In this area chart, the first 75 seconds is colored red indicating the red signal period; and green for the remaining 25 seconds. Every data point takes a duration window of four seconds to count the crossing times. Moreover, the data labels are all invisible by default to provide a clear trend. However, the label shows when the cursor hovers.

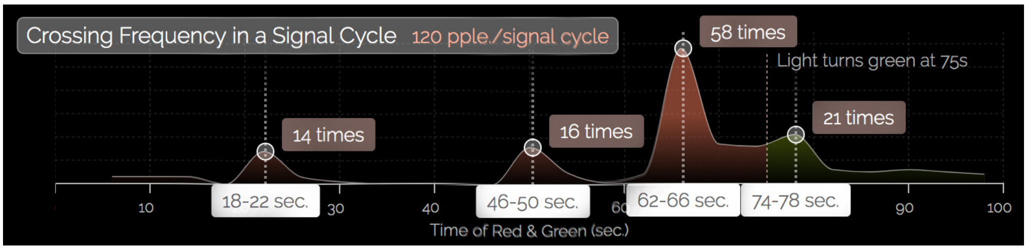

Figure 4.11: The crossing frequency chart for 120 people/signal cycle. Several featured data points temporally set as visible.

For instance, the time-series chart for 120 people/signal cycle in Figure 4.11 reveals that there are three periods that illegal actions happen seriously, all of which are immediately after a vehicle stream terminates. Most people are crossing illegally in the last period before the light turns green, and this conclusion also validated the observation from the simulation (Figure 4.9).

The same as most other visualization components, this time-series graph also alters under different flow rates, as shown in Figure 4.12. Such kind of flow-rate-featured comparison brought another finding: relatively more people waited till the light turns green if the region is less crowded.

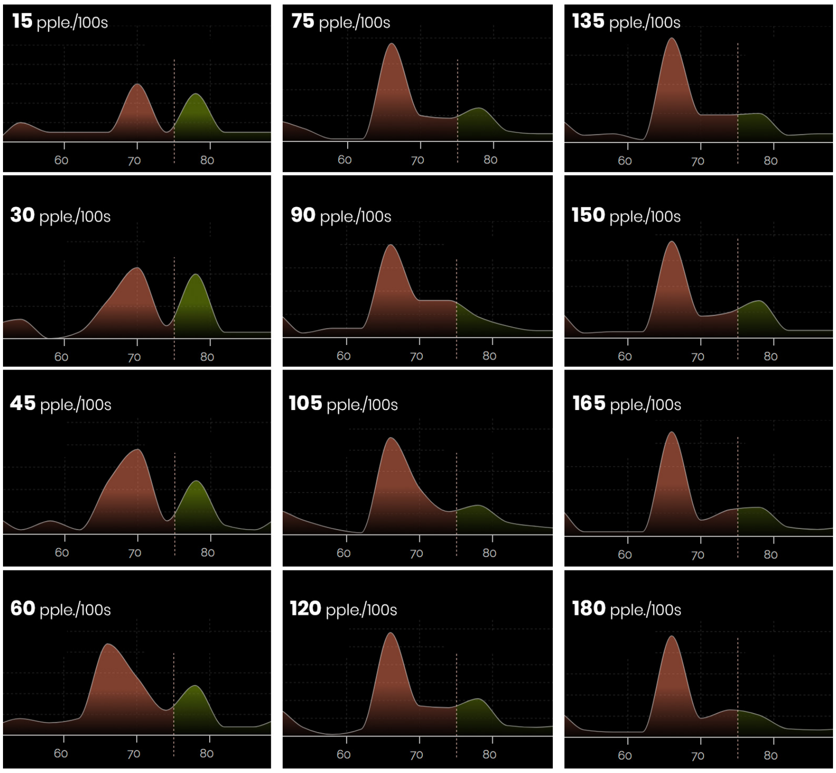

Figure 4.12: Screenshots of the time-series charts for every pedestrian flow rate. All graphs take the same temporal focus around when the light turns green.

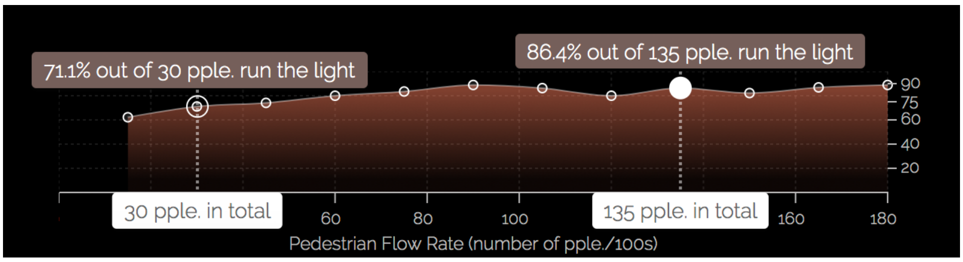

Figure 4.13: The illegal crossing percentages for different pedestrian flow rates. This illustration shows two labels for convenience of comparison.

4.7.2 Illegal percentage under varying flow rates

This area chart both delivers the statics information, and functions as the overall control panel for selecting multiple flow rates.

For the implementation, several details were considered to improve the user experience. First, the label of the selected flow rate is always visible but not others, so that the users are aware of the state regarding what the other visualization components are based on. However, other data labels can display when hovered, which makes it possible to read and compare with other values at the same time. Second, for the sake that not every flow rate can be specified, tiny circles are marked at the selectable positions to guide the users.

From the insight delivery perspective, the area chart is also appropriate since it visualizes the trend clearly. For example, users can derive from Figure 4.13: as the street area becomes more crowded, an increasing percentage of people will likely cross the street illegally.

Chapter 5

Evaluation

The evaluation aims to measure the ***visualization effectiveness*** in response to the research question of "how to effectively visualize street-crossing behavior at a signalized pedestrian crossing concerning various flow rates from small to massive." Related to the challenges in 1.1, an effective street-crossing visualization should address both the difficulty to communicate the user desired insights interactively and to render the trajectories smoothly. Therefore, ***user testing*** was utilized for evaluation. On the one side, communication effectiveness and efficiency are measured via controlled experiments [15], which is a rigorous method that studies one independent variable at a time. On the other side, the rendering performance for various flow rates is observed by the researcher throughout the tests, regarding whether any delay happens.

In this thesis, five colleagues at Atkins were invited to participate separately in the user testing. Two of them are traffic planners, while the other three urban planners specialize in other fields, including landscape and railway. The duration of each test is around 20 minutes, during which period, participants sat before the analytics tool, and completed some tasks following the same instructions. Conforming to what a controlled experiment typically needs, the test has designated the dependent and independent variables according to the testing goals. For instance, the engaged independent variables include the flow rate state and pedestrian movement, while the dependent variables are perceptual user effect, such as task completion time. The definitions of variables are explained concerning tasks in 5.2.

5.1 Methods and criteria

5.1.1 Usability metrics

ISO 9241-11:2018 [16] has stated that usability emphasizes three aspects: effectiveness, efficiency, and satisfaction. Their definitions are:

- ***Effectiveness*** The accuracy and completeness within which users achieve specified goals.
- ***Efficiency*** The resource used in relation to the results achieved.
- ***Satisfaction*** The extent to which the user's physical, cognitive, and emotional responses that result from use of a system, product or service meet user's needs and expectations.

Since ISO is a universally accepted standard, these three metrics were applied in this evaluation as general usability evaluation criteria.

5.1.2 Thinking aloud

According to Jakob's definition [13], thinking aloud is to "ask test participants to use the system while continuously thinking out loud – that is, simply verbalizing their thoughts as they move through the user interface." This method is particularly robust because a window seems to be opened on users' mind [14]. Therefore, gauging the causes and consequences becomes feasible.

The thinking aloud technique was applied throughout the user testing by a reminder before starting the test: participants should verbalize every trivial thought in mind, such as which part they are looking at, and what confusions they meet.

5.2 Test cases and scenarios

Referring to the guideline Farrell summarized [6], scenarios and test cases should strictly fulfill the testing goals. Furthermore, the testing goals are supposed to integrate the usability metrics (5.1.1) and the initial design requirements (4.1.1). In conclusion, the user testing goals are:

- Investigate how many street-crossing behavioral features users can discover. Particularly, during the process, whether they unconsciously combine the two area charts with the animated movement to amplify their insights.

For example, the possible behavioral features include 1) pedestrians are inclined to follow others' signal violation behavior, 2) many but not all people cross illegally when there is no traffic, 3) illegal crossing is most severe during the several seconds before the light turns green, 4) the illegal crossing percentage of all the pedestrians remains high, but relatively lower under smaller flow rates.

- Validate whether users can evaluate space utilization. Moreover, which visualization components they are relying on to analyze, and whether the flexibility to explore among various flow rates can benefit the evaluation for space utilization.

- Investigate users' general level of understanding difficulty and satisfaction degree.

5.2.1 Task – recognition

To validate whether users can make sense of the visualization, the scenario was provided to the participant, that he/she should image starting a new project with this brand-new analytics tool introduced, with which he/she had the freedom to play around. Then the questions were asked: "*What does each of the four visualization components mean?*"

This task assessed users' overall difficulty in understanding the visual analytics tool. To reduce the irrelevant impact, all participants were initially shown the same visualization of 90 people/signal cycle. Accordingly, the recorded dependent variable is the time consumption respectively for understanding the four visualization components.

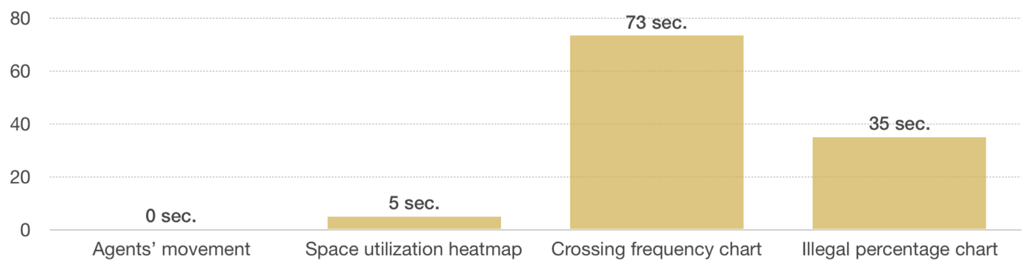

Figure 5.1: Average time spent to complete the recognition task concerning the four visualization components.

To summarize about the results as presented in Figure 5.1, all of the four visualization units are understandable, whereas the difficulty varies. The two core components of the agents' movement and the space utilization heatmap are highly self-explanatory, while the supplementary area charts require some seconds but less than two minutes to make sense, which can be improved by more explicit annotations.

5.2.2 Task – crossing pattern discovery

With the purpose to evaluate the effectiveness and efficiency regarding how users can benefit from the visualization to discover more insights about the street-crossing behavior, this question was asked: "*Can you name some features you noticed about the street-crossing behavior?*"

Similar to the previous task, all participants were initially given the same visualization under 90 people/signal cycle. During the test, participants naturally tried to obtain the answer from the visualization of movement. However, some meaningful insights only emerge when combining the information in the area charts as well.

For this task, the independent variable is pedestrian positions over time, while the dependent variable to record are first, whether or not the participants reach area charts by themselves; second, the number of street-crossing patterns they could recognize.

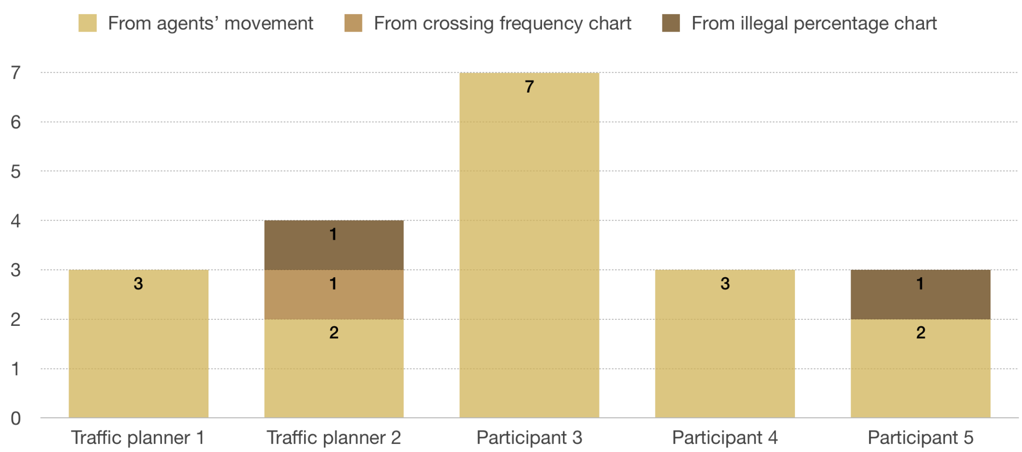

Figure 5.2: The number of crossing patterns discovered. The different colors indicate the patterns recognized from various visualization components, including agents' movement, crossing frequency in time-series, and illegal percentages of all pedestrians for varying flow rates.

The results are presented in Figure 5.2. Most participants discovered three or four insights from the visualization, while one participant was incredibly skilled at pedestrian analysis and concluded seven patterns. Moreover, three participants (60%) did not refer to the area charts for information at all, no matter the crossing frequency chart or the illegal percentage chart. Therefore, in conclusion: first, the visualization has facilitated the discovery for crossing patterns, although the investigation potentials rely on the analyst's ability; second, the complementary area charts can benefit this process as well, but the connection was not bridged efficiently enough.

5.2.3 Task – space utilization

In terms of space utilization, according to the study in 4.1.1, although users are curious about the usage rate of the whole crossing area, they are most interested in the buffer island in comparison. Therefore, this test focused on a clarified task: "*Can you tell, starting from which flow rate is the buffer island too small?*"

With the pedestrian flow rate as the independent variable, this task assessed the effectiveness and efficiency via the recorded task completion time; and also, via studying which visualization components participants were relying on.

Utilization heatmap (2)	Agents' movement (2)
50 sec.	170 sec.

Table 5.1: Average task completion time when participants read different visualization components.

Only four participants performed this task because one traffic planner was remote. As concluded in Table 5.1, two participants completed the task offering a correct answer quickly, while the other two struggled much during the process. The reason was the choice regarding which visualization unit to focus on. Therefore, in conclusion, the heatmap has effectively supported the evaluation of space utilization. However, its efficiency is reduced by the distraction from another component.

5.2.4 Rating and feedback

After all the tasks were completed, participants were inquired their overall feelings and suggestions. Meanwhile, they rated the tool with a score scaling

0 - 10. In this way, the satisfaction metric was studied both qualitatively and quantitatively.

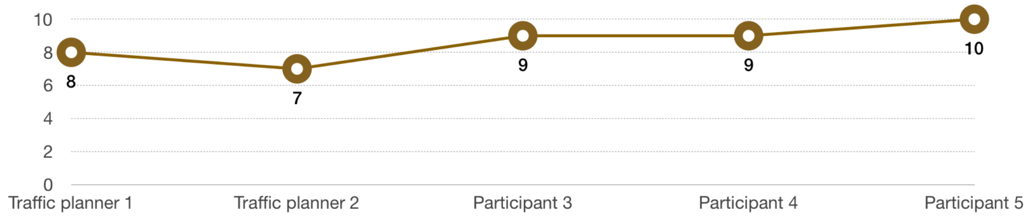

Figure 5.3: Overall rating for the analytics tool by every participant.

"It's useful, can provide a clue of people's real behavior!"

— by a participant

As shown in Figure 5.3, the analytics tool got considerably positive feedback, and the average score hit 8.6. As for the suggestions, the two participants who are experienced in traffic planning were wishing for more interactive functionality that reaches beyond the pedestrian flow rate. The other three urban planners mainly gave suggestions on annotations and colors.

5.3 Evaluation conclusions

To summarize, the evaluation proves satisfying visualization effectiveness for both communication and rendering, which fulfills the thesis target.

Firstly, for ***communication effectiveness***: the recognition task (5.2.1) implies that all components are understandable; the pattern discovery task (5.2.2) shows that the visualization has interactively powered human perception to comprehend street crossing behavior; and the utilization task (5.2.3) proves that the heatmap can benefit the understanding of the space utilization. Secondly, for ***rendering performance***: zero perceptible animation delay ever appeared even when rendering the most complex data set (trajectories of 180 agents); and that re-rendering the movement for another flow rate is swift, taking up to two seconds.

However, there is still space to improve regarding the guidance on using the tool correctly for multiple purposes, since now users are sometimes distracted. For example, the visualization units supposed for the analysts to focus on are different when analyzing street crossing behavior and space utilization.

Chapter 6

Discussion

As it an unexplored domain to develop the visualization tools and methodologies that specifically suit the analysis of pedestrians' street-crossing behavior, this thesis investigated the research potentials and proposed an efficient visualization approach to interactively communicate the user desired insights regarding the phenomena under various pedestrian flow rates.

In comparison, the other related tools for spatio-temporal data visualization have a profound contribution regarding system performance. For example, GTX [4] and Nanocubes [11] can render massive and complex spatio-temporal data sets effectively. However, only the visual analytics in this thesis can efficiently integrate the analysis with both the trajectory data and street-crossing behavior, because the scale is smaller and more sophisticated; moreover, the user demands are different

6.1 Methodology reflection

The visualization structure adopted was comparing behavior on the same territory during the same period. Additionally, the concrete visualization techniques comprise map animation, data aggregation, and time-series graph. The positive feedback from the user testing proves that the applied methodologies are reasonable.

The agents' movement unit, where map animation was utilized, is particularly essential for the analytics tool. This animated component provides a vivid depiction of the real phenomena, so rather than restricting the way how people think, it offers broader possibilities to amplify human perception. For instance, if using the space-time cube instead, on the one hand, too many trajectories will overlap; on the other hand, users will be naturally guided to focus on the temporal aspect. Nevertheless, the space-time cube is still possibly helpful if additionally involved. For example, to focus on a small crossing peak period to visualize the temporal interaction between agents and the vehicle.

6.2 Future research

If engaged in-depth with the illegal street-crossing behavior, future research can involve the visualization of agents' mutual interaction, which is one of the research field in agent-based model visualization [5]. For instance, the users can only recognize the existence of the flowing up phenomena with the help of my tool, whereas the roots were not investigated. Therefore, future visualization research can focus on the relationship between pedestrians and vehicles.

If expanding the border of the exploration flexibility, other adjustable parameters can be researched. Concretely, the visual analytics tool in this thesis scopes the pedestrian flow rate as the sole user-controllable parameter. However, according to the evaluation, an ideal tool should have some additional features, including adjustable crosswalk line width, and configurable signal waiting time.

Chapter 7

Conclusion

This thesis has presented an interactive visual analytics tool for the agent-based simulation, specifically for street-crossing trajectories under various pedestrian flow rates. The tool efficiently renders the user-desirable visualization components by applying several reasonable visualization techniques and implementation frameworks. As a consequence, the research facilitates the development of tools and methodologies for pedestrian visual analytics, which has been an unexplored domain.

Since the users are interested in pedestrian safety and crossing space utilization, the analytics tool accordingly adopted several visualization techniques, including map animation, data aggregation, and time-series graph. It also offers users the exploration flexibility to specify different flow rates, where the most massive-scale data set contains the trajectories of 180 agents during 100 seconds.

Although the developed tool takes a specific location as the target crossing, the visualization methodology can generally apply. The difference primarily concerns road width, signal pattern, and human characteristics. Therefore, this tool can potentially serve as a building block of a pedestrian analysis application that applies everywhere.

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Appendix A

Pre-study behavior data

Road is 9 m wide - table 1

Agent id	maximal illegal crossing in sight	waiting time when free of vehicle (s)	Assigned hurry level	Whether illeal
1-2	2	1.0	0.6	0
3-1	0	0.0	0.9	1
4-1	1	0.0	0.8	1
5	2	0.0	0.5	0
6	2	0.0	0.4	0
7	2	0.0	0.6	0
8	2	0.0	0.3	0
10-2	0	0.0	1.0	1
11-1	0	7.0	0.3	1
12-1	0	7.0	0.3	1
13	2	7.0	0.1	0
14	2	7.0	0.1	0
15	2	7.0	0.1	0
16	2	7.0	0.1	0
17	2	7.0	0.1	0
18	2	7.0	0.1	0
19	2	7.0	0.0	0
20	2	7.0	0.0	0
21	2	7.0	0.0	0
22	2	7.0	0.0	0
23	2	7.0	0.0	0
24	2	7.0	0.0	0
27-2	0	0.0	0.9	1

Road is 9 m wide - table 1-1

Agent id	maximal illegal crossing in sight	waiting time when free of vehicle (s)	Assigned hurry level	Whether illeal
28-2	1	0.0	0.8	1
29-1	0	0.0	1.0	1
30-1	1	0.0	0.8	1
31-1	1	0.0	0.9	1
33-1	5	0.0	0.6	1
34-1	5	0.0	0.7	1
35-1	1	0.0	0.9	1
38-1	0	1.0	0.7	1
40-2	0	0.0	1.0	1
41-1	0	0.0	0.9	1
42-1	0	0.0	0.9	1
43-1	0	0.0	1.0	1
44-1	2	0.0	0.7	1
45-1	3	0.0	0.6	1
46-1	3	0.0	0.7	1
47-1	4	2.0	0.4	1
48-1	5	0.0	0.5	1
49-1	5	0.0	0.7	1
50-1	16	1.0	0.3	1
51	17	2.0	0.0	0
52	17	2.0	0.0	0
53	17	2.0	0.0	0
54	17	2.0	0.0	0

Figure A.1: Records of illegal behavior pre-study for the nine-meter road.

Road is 12.2 m wide - table 1

Agent id	maximal illegal crossing in sight	waiting time when free of vehicle (s)	Assigned hurry level	Whether illeal
1-1	1	0.0	0.9	1
2-2	1	0.0	0.9	1
9	0	7.0	0.2	0
10-1	0	0.0	0.3	1
25	0	5.0	0.3	0
26	0	2.0	0.6	0
29-2	4	3.0	0.4	1
30-2	0	0.0	1.0	1
31-2	3	1.0	0.7	1
33-2	4	0.0	0.6	1
34-2	3	2.0	0.5	1
35-2	6	3.0	0.2	0
36	6	7.0	0.2	0
37	6	7.0	0.2	0
38-2	0	4.0	0.5	1
39-2	0	0.0	1.0	1
41-2	0	3.0	0.6	1
43-2	0	2.0	0.7	1
44-2	1	2.0	0.6	1
45-2	6	3.0	0.3	1
46-2	4	2.0	0.4	1
47-2	6	4.0	0.3	1
48-2	5	4.0	0.3	1

Road is 12.2 m wide - table 2

Agent id	maximal illegal crossing in sight	waiting time when free of vehicle (s)	Assigned hurry level	Whether illeal
49-2	9	5.0	0.1	1
55-1	1	3.0	0.5	1
56-1	11	4.0	0.2	1
57-1	11	4.0	0.3	1
58-1	11	4.0	0.3	1
59-1	11	4.0	0.3	1
60-1	11	4.0	0.3	1
61-1	11	4.0	0.3	1

Total agent numbers for both widths

Hurry level	Width 12.2	Width 9.0
0.0	0	10
0.1	1	6
0.2	5	0
0.3	10	4
0.4	2	2
0.5	3	2
0.6	4	4
0.7	2	5
0.8	0	3
0.9	2	6
1.0	2	4
Total	31	46
Average	0.452	0.463

Figure A.2: Records of illegal behavior pre-study for the twelve-meter road; and also the overall statistics after manually adjusting the assigned hurry level. As a result, the average hurry level is close to 0.5