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著者(和文)	Zou Lubing
Author(English)	Lubing Zou
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Exploring Future Public Space Forms for Pedestrians: Development and Utilizations of Envelope Theorem

by

Lubing Zou

School of Environment and Society
Department of Civil and Environmental Engineering
Urban Design and Built Environment
Tokyo Institute of Technology

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Dissertation Committee Members:

Professor Tetsuo Yai (supervisor)
Professor Shinya Hanaoka
Associate Professor Yasunori Muromachi
Associate Professor Satoshi Nasu
Associate Professor Toru Seo

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Abstract

As future mobilities are gradually introduced into human society, mixed spaces with multiple road users will increase with new problems. In fact, problems like electric scooter accidents have crept into human life, it is urgent to consider human-machine coexistence and pedestrian safety in new circumstances. Based on the contributions and limitations of previous studies, this research proposes the envelope theorem from physical and mental perspectives to provide a theoretical basis for handling mixed traffic and ensuring a safe and comfortable walking environment for pedestrians. For future utilizations, the envelope theorem will be applied for handling human-machine interactions, evaluating comfortable quality of spaces, and considering the rule-making and space utilizations in the future, which will contribute to improving the human-machine coexistence.

This dissertation is organized into six chapters to introduce this research.

Chapter 1 introduces the background of this research in terms of the social tendency and problems of human-machine coexistence, the limitations and controversies of previous studies, and the current situation and possible problems of mixed traffic in Japanese society. The objectives, research scope, and structure of this dissertation are also presented.

Chapter 2 describes the published research findings and opinions related to this research from three perspectives of concept design, conceptual validation, and application effect validation. For the concept design, the contributions and limitations of the robot envelope, interpersonal space, and the ethical boundary between humans and machines are introduced. For conceptual validation, methodologies, and related factors in studies of transportation and robotics fields are referenced. For the application effect validation, studies about secondary developments of the social force model and related factors of improving the reality of simulation are introduced. These previous studies are important references for this research.

Chapter 3 presents the contents of the envelope theorem. The envelope is divided into physical and mental envelopes (PE and ME) in this research. In the ME, there are subject mental envelopes (SME) and object mental envelope (OME). The attributes of PE and ME are also introduced, including the strength of PE and ME, four different expressions of ME, and the relationship between PE and ME. For the possible

applications of ME, it can be used as an indicator for evaluating space comfortable quality from different perspectives and a new perspective of rule-making, which will contribute to improving the humanization of machines' movements. Moreover, the envelope theorem for realizing OME and related proof further explain the idea of a kind of OME's application taking effect for multiple road users in public space, which is instructive for further study of OME.

Chapter 4 focuses on demonstrating the perceptual existence of ME and exploring the structural relationships among ME and influencing factors. The online questionnaire survey is used for the exploration. The results show that the idea of OME expressions is accepted by participants, and is greater affected by negative emotions (stress and danger) than SMEs. The characteristics of SME are consistent with previous studies, indicating that SME can be described as a substitution of IPS in the definition. These results are in line with the definition. Also, the relationship between SME and OME is found, showing that OME positively affects SME. The reciprocal causation of OME and subjective priority order showing in results will be beneficial to explore the future application of OME.

Chapter 5 introduces the development of the envelope theorem and presents the related applications in considering future public space through the simulation study. We consider different types of envelope spaces as possible forms of future public spaces, and develop a simulator to reproduce them. The simulation results clearly represent the movements of objects in different situations by animations, and show the effects of envelope spaces under different social goals through outputs of efficiency and safety/comfort evaluation indicators. For future applications, this simulator can be applied to help people directly observe and discuss public space utilization and management, and find possible problems for preparing in advance. Based on the simulation results, this research also discusses the desired future public space forms and future expectations, and provides some recommendations for applying the envelope theorem.

Chapter 6 presents the conclusion of this research in terms of the major findings, contributions, and limitations. The recommendation for future works is also proposed, including the further expansion of ME's concept, the more comprehensive proof of envelope theorem, the further exploration of ME forms and expansion of its application, and the further development of the envelope spaces.

For the future outlook, the envelope theorem is expected to be developed and applied in various fields, not only limited to solving traffic problems and human-machine relationships in physical space. It is also desired to inspire more consideration from researchers, which will pave the way for the coexistence of humans and machines or even new things in the future.

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This is the fifth year in Japan. In Yai laboratory, I learned amounts of knowledge and abilities, and gained many precious friendships and memories. It was undoubtedly the most valuable and meaningful time of my life. I feel fortunate and honored to be a member of Yai lab.

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Lubing Zou
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Abbreviations

Abbreviated words in envelope theorem:

PE	: Physical envelope
ME	: Mental envelope
SME	: Subject mental envelope
OME	: Object mental envelope
SE	: The division that encloses the subject in a small area
OE	: The division that constrains the object within a small area
FES	: Full envelope space
PES	: Partial envelope space
NES	: Non envelope space

Other abbreviated words:

AI	: Artificial intelligence
AV	: Autonomous driving
AVE	: Average variance extracted
CFA	: Confirmatory factor analysis
CFI	: Comparative fit index
CR	: Composite reliability
DO	: Distant object
DUI	: Driving under the influence
Eq.	: Equation
EU	: European Union
GFI	: Goodness of fit index
ICT	: Information and communication technology
IoT	: Internet of things
IPS	: Interpersonal space
MaaS	: Mobility as a service
MLIT	: Ministry of Land, Infrastructure, Transport and Tourism

NACTO : National Association of City Transportation Officials
NFI : Normed fit index
pd : Percentage difference
ped : Pedestrian
PMV : Personal mobility vehicle
PS : Personal space
RA : Rotation angle
RMSEA : Root-mean-square error of approximation
SDI : Subjective danger index
sec : Second
SEM : Structural equation modeling
SFM : Social force model
SNM : Social navigation model
SRMR : Standardized root-mean-square residual
TLI : Tucker–Lewis index
U.S. : The United States
US : Usable space

Mathematical symbols in social force model:

p_i : Pedestrian i
p_j : Another pedestrian j
p_k : A static obstacle k
m_i : Mass of p_i
v_i : Velocity of p_i
F_i : Force explaining the movement of p_i
F_i^{pers} : Self-driving force of p_i
F_i^{soc} : p_i's social force for keeping distance from other individuals or infrastructures
F_i^{phys} : Physical force generated by physical collision on p_i
$\hat{v_i}$: p_i's intended velocity
$\hat{e_i}$: p_i's intended direction of the movement
τ_i : Relaxation time required for p_i to reach the intended velocity and intended direction
O : The set of all static obstacles
P : The set of all people in the environment

k : The union of P and O

$r_i/r_j/r_k$: Radii of p_i, p_j, p_k

$d_{i,k}$: Euclidean distance between p_i and p_k

$n_{i,k}$: The direction of the force from p_k to p_i.

c_k : Magnitude of the exerted force

Mathematical symbols in envelope theorem for realizing OME:

l_i^{OME} : The distance i's OME (fixed).

$L_{i,j}(t)$: The distance between i and j at time t.

$minL_{i,j}$: The minimum value of the distance between i and j.

$maxL_{i,j}$: The maximun value of the distance between i and j.

P_i : Priority between i and j. If i's priority is higher than j, $P_i = 1, P_j = 0$. i's OME can stop movement of j. j's OME cannot stop movement of i. If $P_i = 1, P_j = 1$, there is no priority.

$CP_{i,j}$: An imaginary crossing point between i and j (i and j may not colide at $CP_{i,j}$ due to the difference in their speed).

Chapter 1. Introduction

1.1 Background

1.1.1 Tendency and problems of space sharing between humans and machines

With the development of advanced automated technology, machines gradually play an important role in various supports in the daily life of human beings. Personal mobility vehicles (PMV), robots, autonomous driving (AV), etc. will be introduced in society for satisfying the travel and service needs of people. For example, the door-to-door delivery services, information navigation services, sharing services of intelligent transportation devices for short distances, etc. Under this development tendency, slow-speed mobility devices and robots are more likely to share spaces with pedestrians instead of running on separate streets in the near future, especially in Asian countries with complicated and changeable traffic environments. For example, mixed traffic in Indonesia and Thailand with two- and three-wheeled vehicles (Kaltheier,2002), and pedestrian-cyclist mixed traffic in Japan (Road Traffic Act, 2007) (figure 1.1).

Thailand Indonesia Japan

Source from : https://www.dreamstime.com/search.php?srh_field=three+tricycle; https://www.pref.aichi.jp/douroiji/image/jitensya.pdf

Figure 1.1 Mixed traffic in Asian countries

As a matter of fact, human-machine space sharing is gradually penetrating people's lives (in this research, machines refer to new types of road users with advanced technology, such as robots, electric scooters, electric robot wheelchairs, etc.). In recent years, small and low-speed mobilities such as electrical scooters and electrical robot wheelchairs have appeared on sidewalks and public spaces. For instance, Beams continues to expand the electric scooter sharing service by partnering with cities in many countries such as South Korea, Thailand, Malaysia, and Australia. (Beams, 2021,2022a, 2022b). WHILL uses self-driving technology in electrical wheelchairs and combines them with the business of Mobility as a service (MaaS) in cities to provide rental and traveling services to people in public places such as airports, museums, and hospitals (WHILL, 2020a, 2020b, 2022). Also, some indoor public spaces begin to use robots for supporting people. Police robots patrol public places and connect with surveillance cameras, information from elevators, and other facilities and areas. when they find someone who is suspicious, these robots will warn or capture them by using cutting-edge technology (Designboom, 2022). Robot guides can help visitors in museums and explain the background and knowledge of artworks (Themayor, 2022). And delivery robots not only serve as waiters in restaurants but also can work in libraries as guides and book carriers (Ferguson, 2022).

However, the application of these new mobilities and machines inevitably raises various problems and accidents. Harris (2021) reported that a delivery robot in Northampton nearly caused a traffic accident by crossing a street in front of an oncoming car. Holmes (2020) reported that police robots in the United States (U.S.) ignored pedestrians who tried to report emergencies and knocked down a child while on patrol. In the U.S. and Japan, the lack of strict relevant rules or laws for electric scooters in many cities increased driving under the influence (DUI) and serious accidents with electric scooters (Schlosser, 2019, Oyama, 2021). Also, in the U.S., Yang, et al. (2020) found that 169 electric scooter accidents had been reported from 2017 to 2019. And Kobayashi, et al. (2019) discovered that accident injuries on electrical scooters in 2017~2018, among the 79% who were tested for alcohol, 48% were considered DUIs. In the study by Stigson et al.(2021), 321 electric scooter accidents were found in Sweden from 2019 to 2020. Most injured road users are electric scooter riders, and 44% of them had head injuries.

Some possible reasons for these accidents are considered. For the accidents from new mobilities devices: Firstly, technical deficiencies of new mobilities devices cause safety hazards, such as difficulty in adapting to non-smooth road surfaces, poor safety systems and security reminders, etc. Secondly, riders may be unfamiliar with the use of new mobility devices so that their improper operation cause collisions. Thirdly, the position of new mobility riders is not clear. As new members of road users, they do not know whether they belong to pedestrians or vehicles. Fourthly, the legal restrictions and speed limits for new mobilities are not well defined. For the accidents from robots, in addition to problems in technology, theoretical and methodological deficiencies in human-machine communication seriously affects smooth human-machine interaction and cause accidents. It is means that robots are difficult for both understanding what people think about and transmitting their own signals to people.

Despite the many security issues associated with the use of these mobilities, these convenient devices and services raise people's expectations for a better future, and draw the attention of researchers and governments to the development of human-machine space sharing (Barr,et al., 2021, NACTO, 2016). In 2022, Japanese government released a guideline that depicts a blueprint for human-machine coexistence and concepts of road planning for satisfying needs of multiple mobilities (MLIT, 2022).

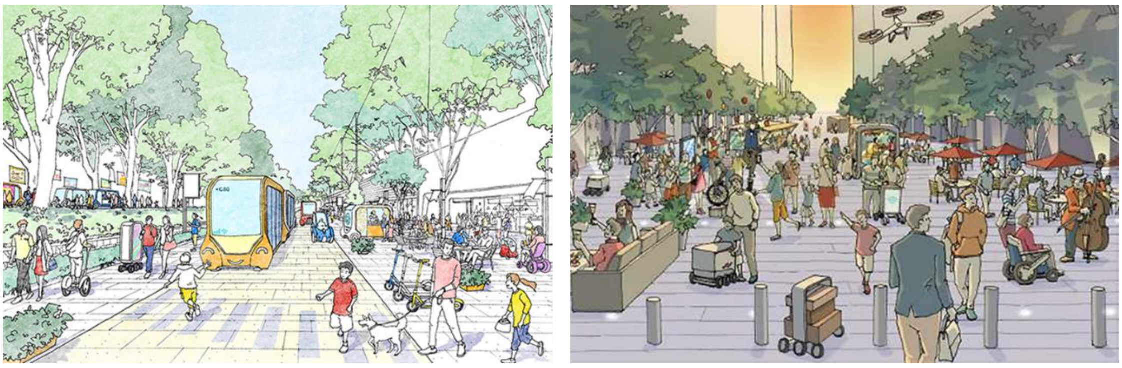


Figure 1.2 Images of human-machine coexistence (MLIT, 2022)

Therefore, to achieve human-machine coexistence and ensure comfortable and safe public spaces, dealing with spatial relationships between people and machines and solving problems from different perspectives are significant.

1.1.2 Limitations and Controversies

Researchers in various fields attempted to investigate the feasibility of human-machine coexistence from multiple perspectives, such as theory, methodology, and policy requirement. However, there are still limitations.

In the field of artificial intelligence (AI) and automation, researchers tried to distinguish the activity scope of humans and machines, to ensure both human safety and the working efficiency of machines. Floridi (2014, 2019a) defined the robot envelope for explaining the human-robot relationship. It is a sphere for limiting machines' abilities or working environments in order to ensure their effective operations for satisfying people's requirements. For instance, machines efficiently deliver heavy goods in unmanned factories. Or dishwashers allow consumers to spend less time doing household chores. Similar concepts were introduced by Bostrom (1998, 2017), Daugherty and Wilson (2018), That is, machines have a limited scope in physical places, division of labor, or social positions to enable their smooth operation and coexistence with humans. Also, the envelope concept in the research of autonomous vehicles (AVs) is described as a physical approach to separating areas and controlling actions for maintaining regular operations of AVs and traffic safety (Brown, et al, 2017, Erlien, et al, 2013, Beal and Gerdes, 2012). These approaches could help machines better integrate into human society. However, the tendency for space sharing between humans and machines is inevitable. The robot envelope may hinder human-machine interactions and keep safety. In this case, not only machines may ignore or misunderstand people's feelings and consequently lead to safety hazards, but also people may gradually lose motivation to actively comprehend machines.

In the field of transportation and robotics, researchers are more concerned with applying psychological knowledge to explore the appropriate distance between humans and machines to achieve human-machine coexistence. The interpersonal space (IPS) in the proxemics was widely used as an indicator of people's perceptions (Hall, 1966, Aiello, 1987). Some transportation researchers tried to find the appropriate distance between pedestrians and personal mobility vehicles (PMV) by observing the discomfort caused by PMV riders invading the pedestrian's IPS and their avoidance behaviors (Hasegawa, et al., 2018, Dias, et al. 2018, Nishiuchi, et al, 2010, Nakagawa, et al., 2012, Morales and Murase, 2018). Some robotics researchers developed algorithms based on IPS and tested the behaviors of robots in human-machine interactions. (Ghandour, et al., 2016, Ratsamee et al., 2013, Sato, et al., 2018). However, new situations of pedestrian perceptions in mixed traffic with various mobilities would be generated, which may be difficult to be fully explained by IPS when exploring the psychological perception of interpersonal relationships. The limitations of IPS have also been gradually demonstrated in recent studies. For example, Vassallo et al. (2017, 2018) discovered that people avoided machines even though they maintained safety distances throughout interactions. Unnoticed perceptions of people may lead to machines misunderstanding people's behaviors (facial expressions, actions, etc.) and increasing the discomfort of pedestrians on walking.

From the above studies, researchers focus more on exploring the relationship between people and one type of machine or mobility device from a microscopic perspective by using existing theories, but neglect the theoretical development and the macroscopic exploration of the spatial relationship among multiple road users. This may affect the exploration of future public space and human-machine coexistence. Therefore, the theoretical development of more comprehensively explaining the future spatial relationships and interactions is important.

Moreover, as PMVs such as electric scooters and electric wheelchairs emerge as new road users, their policy requirements on public spaces become a hot topic of debate among researchers and transportation policy professionals in recent years, but with still no clear conclusions. Some researchers considered that PMVs are accident-prone because of their high speed and difficulty in maintaining balance, so they are not advisable to share sidewalks with people. PMVs will cause discomfort to pedestrians and affect their walking behaviors when sharing sidewalks with them (Miller, et al., 2008, Sikka, et al., 2019, Goodridge, 2003). Moreover, another group of researchers proposed that PMVs are much slower than automobiles, which will affect the traffic flow and comfort, and therefore should not be run on car lanes (Siuhi, et al., 2021, Muchuruza & Mussa, 2005). PMVs' characteristics and their dilemma position make it difficult to establish a clear requirement in law. Due to the PMV's dilemma position, establishing a clear legal requirement for it could be difficult.

At the current stage, the legal regulation of using PMVs on the streets still has limitations and controversies in countries (Akter, et al., 2021). The use of PMVs on roadways and sidewalks is banned in some Asian areas such as Hong Kong, Singapore, etc. In Europe, even though the European Union (EU) does not allow the use of PMVs on sidewalks, each European country has different regulations, such as France, Finland, and Italy allowing PMVs on roads. In the U.S., each state has its regulations. For instance, California allows PMVs to run on roadways and sidewalks, while Wyoming does not allow them to be used on public roads. In Japan, PMVs are allowed on roads with requirements. As table 1.1 shows, many regulations in countries are still unclear. In order to smoothly introduce robots and PMVs into human society and achieve human-machine coexistence, the improvement in the legal requirements is still necessary.

Table 1.1 Policies of PMVs from different areas

Country	**Status**	**Minimum Age Limit**	**Maximum Allowed Speed,km/h**	**Safety Gear Required**	**License Required**	**Registration Required**	**Ref.**
Hong Kong, China	Banned	Not Specified	Not Specified	No	Yes	Yes	(Hong Kong Transport Department, 2016)
Japan	Allowed on Roads	16	Roadway: 20, sidewalk: 6	Recommend	No	No	(Road Traffic Act,Japan, 2022)
Singapore	Banned	Not Specified	Not Specified	No	Not Specified	Not Specified	(Abdullah, 2020)

European Union	Not Allowed	Not Specified	Not Specified	No	Not Specified	Not Specified	(European Committee for Standardization, 2017)
Finland	Allowed on Sidewalk and Roadway	Not Specified	15	Yes	Yes	Not Specified	(Ministry of Transport and Communication, 2015)
France	Only Bike Lane	12	25	No	No	Not Specified	(Insurer’s Council, 2019)
Germany	Allowed Segway on bike lane, hoverboard is restricted	14	20	Insurance and Protective Gear	Yes	Yes	(Germany Federal Law Gazette, 2013)
Italy	Allowed on Sidewalk and Bike Lane	14	20	Protective Gear	Yes	No	(Modo, 2019)
United Kingdom	Only at Private Area	14	25	Insurance and helmet	No	Yes	(E-bikes Scotland, 2015, The Ethical Choice, 2020)
Australia	Allowed in Queensland, Canberra, and Western Australia, Rest Not.	12–16	25	Helmet	No	No	(Electric Bicycle Guide, 2013, The State of Queensland, 2020)
Canada	Allowed on Sidewalk & Roadway with Limitations	14	32	Helmet	Yes	Yes	(Ministry of Transportation Ontario, 2014)
U.S.(California)	Allowed - Sidewalk & Roadway	No	20	Protective Gear	No	No	(California, 2007)
U.S.(Wyoming)	Not permitted to public roads	Not Specified	20	No	Not Specified	Not Specified	(HG.org, 2020)

1.1.3 Current situations and possible issues of Mixed traffic in Japan

From the current road condition in Japan, there will be difficulties in introducing robots and PMVs on roads. Firstly, spaces for pedestrians and bikes are narrow. Table 1.2 shows that the average width of the space outside car lanes on municipal roads is 1.4m. The improvement rate of roads (proportion of roads that have been repaired to meet the legal requirements) is only 59.5%, and the installation rate of sidewalks is only 9.2%. Secondly, the Road Traffic Act of Japan allows bicycles to share sidewalks with pedestrians (Road Traffic Act, 2007). So, pedestrian-cyclist conflict is a significant issue. In 2020, 43% of accidents between pedestrians and cyclists occurred on sidewalks (Cabinet Office, 2020). Under these circumstances, the traffic environment of Japan may be more complicated when robots and PMVs are used as slow mobilities on sidewalks.

Table 1.2 Road basic information in Japan

(Source from: MLIT, 2020)

Classification	**Actual length**	**Maintenance rate**	**Improvement rate**	**Sidewalk installation rate**	**Average road width**	**Average width of car lanes**	**Average lane width of reminding space**
	(km)	**(%)**	**(%)**	**(%)**	**(m)**	**(m)**	**(m)**
National highways	55,874.2	67.7	92.9	60.0	13.5	8.2	5.3
Prefectural roads	129,754.0	58.4	70.7	40.4	9.9	6.2	3.7
National/Prefectural roads	185,628.2	61.2	77.4	46.3	11.0	6.8	4.2
Municipal roads	1,031,840.3	59.5	59.5	9.2	5.3	3.9	1.4
Total	1,217,468.5	59.8	62.2	14.9	6.2	4.3	1.9

**Improvement rate = Road that conforms to the regulations of Road Structure Ordinance / Total length*

**Maintenance rate = improved road length - road length (congestion level > 1.0)*

In recent years, accidents from PMV riders in Japan have emerged, affecting the safety of pedestrians. In 2021, there are 28 accidents causing injury or death and 304 traffic violations from electric scooters nationwide (Table 1.3). To solve these problems, the government published the amendment of the Traffic Road Act in April 2022, which is expected to be implemented in 2024. This amendment requires that PMVs riders should be over 16 years old, and the speed of PMVs is limited to below 20km/h. Moreover, PMVs can be used on car lanes and bicycle lanes. These also can be used on sidewalks if the speed is less than 6km/h (Road Traffic Act, 2022). Despite the new regulations, people are still concerned about its effectiveness in preventing accidents and how to deal with the hazards and damages after accidents. For example, the new regulations do not require PMV riders to have a driver's license and use safety gears obligatorily, which is not conducive to improving traffic safety. Therefore, there are still many issues in the related legislation to be considered.

Table 1.3 Accidents and violations of e-scooters in 2021, Japan

(Source from: National Police Agency, 2022, Metropolitan Police Department, 2022)

Accident type	**Count**	**Traffic violation type**	**Count**
Accidents causing injury or death (Nationwide)	28	Defective maintenance	113
Accidents causing injury or death (Tokyo)	18	Wrong turning direction	66
Property damage accidents (Tokyo)	50	No license	69
		Others	56
		Total	304

1.2 Research objectives and scope

1.2.1 Objectives

Due to the complexity of public space and the inevitable tendency of people sharing public spaces with machines in the future, it is important to handle mixed traffic with multiple road users and ensure a safe and comfortable walking environment for pedestrians. However, previous studies focused on exploring the interaction between humans and one type of mobility using existing theories, but lacked attention to the theoretical development of spatial relationships and interactions among various road users, causing the current theories such as robot envelope and IPS to be insufficient to explain the human-machine relationships for dealing with future mixed traffic. Based on the contributions and limitations of previous studies, this research expends the concepts and elements of public space relationships, so as to redefine them as the envelope theorem, which will be more suitable to explain the spatial relationships among various road users in mixed traffic. For future applications, the envelope theorem can be used as the theoretical basis for the developments of robotics and new mobilities, improving the humanization of their movements. Moreover, the envelope theorem can be further developed for considering rule-making and possible forms of future public spaces, which will contribute to space utilization and management of human-machine coexistence in the future society.

There are some goals in each research step. First, redefining the envelope theorem to explain spatial relationships of road users in mixed traffic. Second, preliminarily verifying the existence of novel ideas (ME) in envelope theorem and exploring their influencing factors and relationships. Third, developing the envelope theorem to consider the rule-making and possible forms of future public spaces and demonstrating effects of rules applying in different public space forms. These will be covered in detail in Chapter 3, Chapter 4, and Chapter 5.

Here are key points in these three goals:

1. Proposing the envelope theorem：
    a. Definition of the envelope: physical and mental envelope (PE and ME)
    b. The attribute of PE and ME
    c. The relationship between PE and ME
    d. Possible applications of ME
    e. The envelope theorem for realizing OME and its proof

2. Preliminarily exploring the existence of ME and influencing factors:
    a. Investigating public acceptance of ME (questionnaire survey)
    b. Exploring influencing factors of ME
    c. Exploring structural relationship among ME and influencing factors

3. Future utilization of envelope theorem in public spaces:
    a. The development of envelope theorem
    b. Simulation development for showing future public space forms
    c. Evaluating the effects of rules in different spaces
    d. Comparing performance and finding possible issues

1.2.2 Research scope

The research focus and originality of are described from the research scope shown in figure. 1.3. The research scope is about the envelope studies of human-machine coexistence. Previous studies focused on exploring the relationship between people and a type of machines by using existing theories and concepts, such as machine development of critical distance and avoidance in human-machine interactions, and models for explaining movement phenomena of the new mobility devices. However, those studies paid little attention to the theoretical development for interaction and spatial relationships, which caused some phenomena in human-machine interactions difficult to be explained by existing theories (section1.1.2), as well as affecting the further exploration of dealing with future mixed traffic. This research considers the interaction and spatial relationship between humans and various machines from different aspects, and redefines the envelope theorem by integrating and expanding existing concepts and elements of human-machine relationships, which will be more suitable for dealing with mixed traffic and considering space utilization in the future.

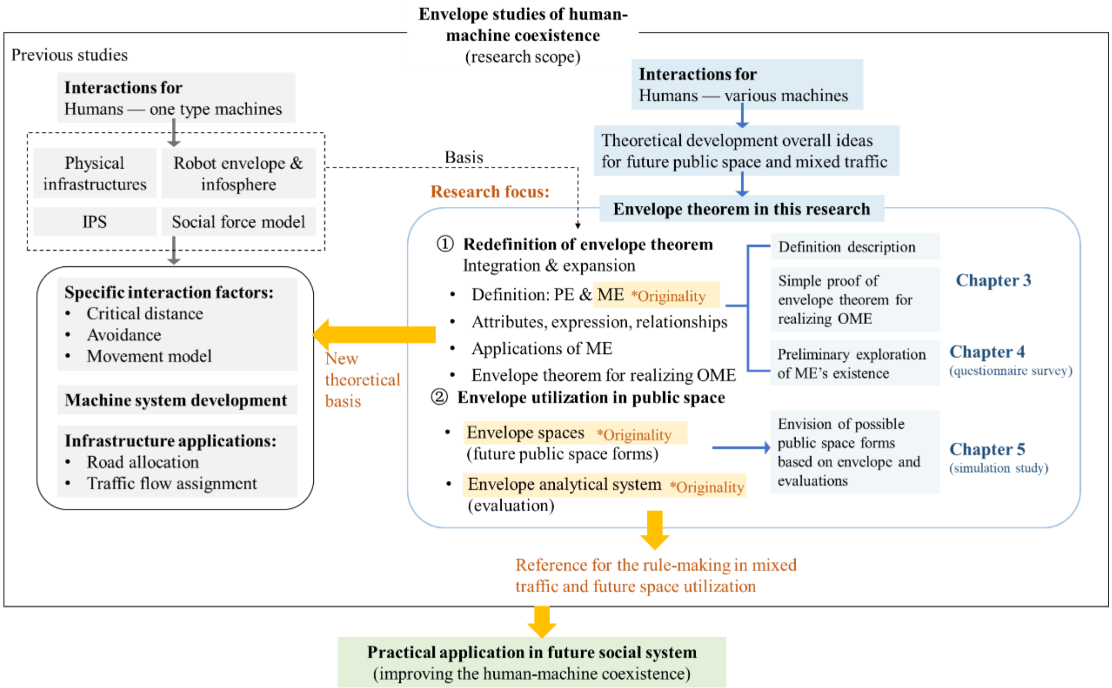


Figure 1.3 The illustration of research scope

In the redefined envelope theorem, physical envelope (PE) and mental envelope (ME) are used to explain the spatial relationship between pedestrians and various machines (robots and mobilities), while the envelope space and envelope analytical system are used to consider the rule-making of mixed traffic and future space utilization. This research mainly focuses on ME, envelope space, and envelope analytical system, showing the research originality. ME explains pedestrian perceptions and their expressions from different perspectives, and questionnaire survey is used to preliminarily verify the existence of new contents in ME. The envelope theorem for realizing OME and its simple proof further explain the new idea of applying ME in public space. The envelope spaces describe possible forms of future public spaces based on the envelope theorem and envelope analytical system is considered to evaluate their effects, which are reproduced through simulation development.

For the research significance, the development of the envelope theorem in this research not only provides a new theoretical basis for machine developments (previous focuses in human-one type machine interaction), but also provides a new perspective and method for considering rule-making and public space utilization. These contribute to dealing with the human-machine mixed traffic in the future social system and improving human-machine coexistence.

1.3 Structure of the dissertation

This dissertation has six chapters. Figure 1.3 shows its overall structure.

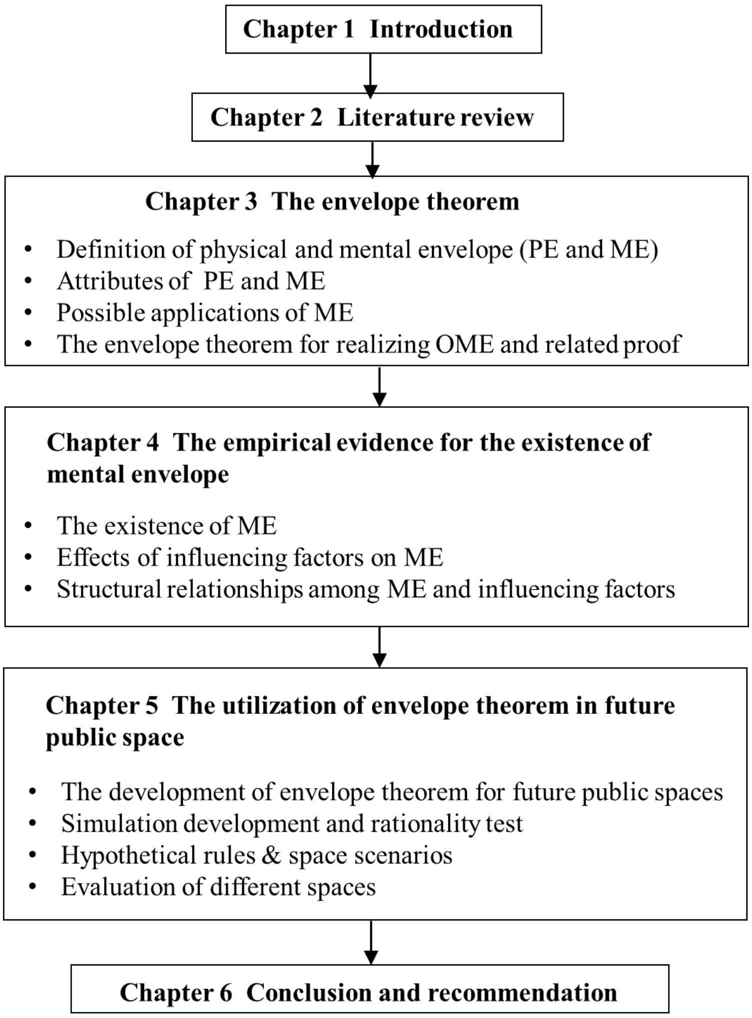


Figure 1.4 Structure of dissertation

Chapter 1 and Chapter 2 introduce the research background and related previous studies. Chapter 3 explains the contents of the envelope theorem, including the definitions of physical and mental envelopes, their attributes, and their relationships. Chapter 4 describes the process of preliminarily proving the existence of the mental envelope. It includes detailed contents of the questionnaire survey, the analysis method, and the related results. Chapter 5 introduces the future utilization of the envelope theorem in rule-making and space utilization through the simulation study. It contains the further development of envelope theorem, the simulation development of reproducing the future public space forms, the rationality test of the simulation model, the output for evaluating the effects of different future public space forms, and discussions about the desired future public space and recommendations of applying envelope. Chapter 6 is the conclusion and future work recommendation of this dissertation.

Chapter 2. Literature reviews

2.1 Introduction

This chapter introduces the published research findings and opinions related to this research. Based on the research process, this chapter will be explained from three perspectives: concept design, conceptual validation, and application effect validation. Section 2.2 describes the studies that are closely related to the concept of the envelope, including the physical, psychological, and ethical perspectives (related to the Chapter 3). Section 2.3 introduce research related to validation of the envelope, focusing on the internal influencing factors of human-machine interactions (related to the Chapter 4). Section 2.4 presents studies as references for exploring the effects of envelope applications in the simulation study, including models referenced in simulation and factors improving simulation realism (related to the Chapter 5). Section 2.5 provides a summary of this chapter.

2.2 Envelopes in different fields

The meaning of envelope in the vocabulary is a container enclosing or enfolding completely something with a covering (Staff. Merriam-Webster, 2004). In different research fields, the envelope is commonly used as a physical method of isolation or security protection. For example, in the automobile and maritime industry, the envelope is a spatial area used for preventing collisions (Davis, et al., 2009, Stephen, et al., 2016). Or in the architecture field, the envelope is the physical separator between the conditioned and unconditioned environment of a building for resistance to air, heat, noise, light, and water (Alireza, et al., 2019). In practice, there are many definitions of the meaning of enveloping and wrapping in theoretical studies that are useful for explaining social and psychological phenomena.

2.2.1 Robot envelope and infosphere

In the field of artificial intelligence, many researchers have thought about philosophical and technical perspectives on theories and methods of human-machine coexistence. The robot envelope proposed by Floridi is an important viewpoint. It is an area for limiting capabilities or working environments of machines to ensure their effective operations and satisfy people's requirements (Floridi, 2014, 2019a). For example, machines quickly and efficiently carry goods in unmanned factories. Or dishwashers assist consumers to spend less time performing housework. Floridi proposes this idea of separating the activity scope of humans and machines because he thinks there will be negative effects from robots constantly entering human society. Humans' thinking and actions will be restricted when machines share social environments and resources with them. For example, when autonomous driving vehicles are widely used, people may not be allowed to drive because they are more likely to be at risk of accidents than AI drivers (Floridi, 2019b). Or people's comments on the Internet will be controlled and categorized as meaningful or meaningless words (Floridi, 2018a, 2021a).

Other researchers in the field of artificial intelligence also have similar opinions. They consider that although machines replace humans to do many tasks, they would deprive their rights and some social attributes. Owens and Cribb (2019) present that people may be accustomed to obtaining information about their health or appearance from machines in the future, and the motivation to be healthy may be forced by machines rather than by their intention. These similar phenomena are unconsciously appearing in the current life of people. For example, wearable technology devices score the daily health and exercise of users. Even though they feel tired, the devices will still signal and encourage them to continue to take another 2,000 steps. In this case, people may not feel healthy from their bodies, but by these numbers. Bostrom (1998, 2017) proposes that machines or AIs need to be cognitively capable in limited ranges or fields. In the future, the boundary between humans and machines will become blurred. As machines completely come into people's lives and keep developing into superintelligence, they are possible to replace or control humans. Therefore, a boundary is necessary between humans and machines. Daugherty and Wilson (2018) also consider the situation that the social status of humans and machines becomes blurred. They suggest that achieving human-machine coexistence requires a clear division of labor, ability, and work environment, which will reach a consensus within a limited scope.

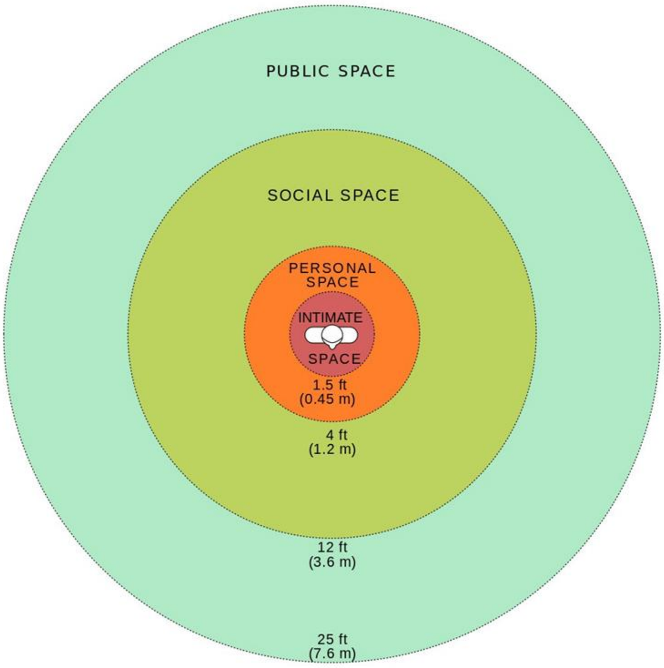
However, the way to segregate people from machines has limitations. Because of limited social resources, people have to interact with machines and share social and spatial environments with them. Also, people expect machines to represent them in boring and repetitive tasks that put a huge burden on their bodies. Therefore, in the future, achieving human-machine coexistence is not simply considering human-machine boundaries for using spaces respectively, but allowing machines to take more into account human perceptions and feelings.

In addition, Floridi reinterprets the definition of the infosphere, which is an informational environment made up of all informational agents, as well as their properties, processes, interactions, and mutual relationships (Floridi, 2014). He believes that humans, environments, things, and events are information agents, which would be connected through nodes. The infosphere described by Florid seems a form in which humans cater to machines and integrate into a society of machines. For example, people learn programming languages and use electronic devices to communicate with machines and send commands more smoothly. These interactions in which humans actively adapt to machines are already occurring in people's life. As physical space continues to integrate with information space, the social position of humans and machines will become ambiguous. How to deal with the relationship between humans and machines is a significant issue. It not only occurs in the physical space but also in the psychological perception of people's minds or the moral boundary of human beings.

2.2.2 The interpersonal space (IPS)

In psychology, there are also concepts similar to the envelope for describing the spatial and interpersonal relationships between humans. The interpersonal space (IPS) in proxemics Hall proposed is widely known. It describes the interpersonal relationship between people through spatial relations, which is divided into four levels: intimate space, personal space, social space, and public space (Hall, 1966). The intimate space is from 0cm to 45cm for embracing, touching, or whispering. The personal space is from 46cm to 120cm for conversations among good friends or family. The social space is from 120cm to 360cm for interactions with strangers. The public space is from 360cm to 760cm or more for public speaking (Figure 2.1).

Some researchers consider that this concept is excessively focused on distinguishing small differences between the boundaries of categories, so that try to improve the concept. Gifford (2013) proposes that IPS should be explained as a dynamic continuum that will be changed based on relationships and environments. Aiello (1987) considers that the degree of intimacy is one of the factors affecting the behaviors and distance between people, which establishes a balance with relations such as conflict. Argyle and Dean (1965) made functions of people maintaining different intimate relationships by using the force of approach and avoidance. Uzzell and Horne (2006) distinguished three functions of IPS. The protection function allows people to perceive risks or threats. They will adjust their perceptions by fleeing or resisting if their own space is invaded. The arousal regulation function indicates that IPS prevents people from being overstimulated by controlling the amount of incoming information. The communication function indicates that IPS as a communication medium can express information about the relationship between individuals, such as the degree of intimacy.



Source from: https://medium.com/@BarbMaiberger/proxemics-and-nonverbal-communication-in-emdr-therapy-f0ee5b73353d

Figure 2.1 The illustration of interpersonal distance in proxemics

Also, researchers tried to measure the actual distance of the IPS in different ways. Aiello (1987) and Joosse (2017) used experiments to observe points or boundaries of interaction at different levels of intimacy. They used projections and allow participants to imagine themselves in a depicted situation, such as being approached continuously by some objects or people. Participants expressed signals to make approaching objects stop when they felt uncomfortable. Bailenson, et al. (2001) and Iachini, et al. (2014, 2016) used virtual scenes to observe IPS. The technology of immersive virtual reality reproduced situations of people in contact with various things and other people. Participants watched virtual images from head-mounted displays and responded when they felt discomfort.

These improvements have made IPS a theoretical basis for research in different fields for many years such as public space design and social environment.

Researchers in robotics and transportation fields have also started to explore human-machine interaction by using IPS. In the field of transportation, some researchers tried to use Segways and electrical wheelchairs to explore the interaction distance between humans and personal mobility vehicles (PMVs). Nakagawa, et al. (2010, 2012) explored the relationship between PMVs and pedestrians based on the concept of IPS. In experiments, they found that physical attributes of PMVs such as size, form, and speed have effects on the size of personal space of pedestrians. When the width and height of PMVs become larger, the front of personal space of pedestrians will expand. Also, when the speed of PMVs increases, discomfort, and fear of pedestrians will increase, leading to a significant change in personal space as well. Pham, et al. (2015) used the concept of IPS to investigate the impact of PMVs on pedestrian flow in public spaces. They combined experiment and simulation models and use the rate of PMVs invading personal space and interaction time as indicators to measure the safety and comfort of pedestrians. Also, the authors proposed an assistance system based on IPS to improve road safety and comfort. The results showed that the invasion of personal space increased due to the increase in density, and brought more discomfort to pedestrians. The assistance system can alleviate pedestrian discomfort at low densities. Morales et. al (2018) proposed a navigation approach for PMVs referring to the concept of IPS to handle the PMV-human interaction and ensure safety in movements. The authors considered distances, passing sides, and velocities as parameters and applied this approach on PMVs to experiments on real sidewalks. The results showed that navigation allows PMVs to avoid pedestrians more frequently, but pedestrians actively avoid them more often. Hasegawa et al. (2018) observed subjective danger perception of pedestrians to PMVs by using IPS. In the experiment, the authors considered the factors of relative distance, speed, and direction to observe the degree of participants' danger perceptions when PMVs interact with them from different situations. The results indicated that participants showed high sensitivity to PMVs from ahead.

In the field of robotics, the use of IPS to explore human-machine interaction is widely used. Mumm and Mutlu (2011) explored whether the human-machine distance can be explained by the concept of IPS. They used friendliness (whether they felt close to machines) and gaze behavior (the factors that triggered people to keep their distance) as variables in the experiment. The result was similar to interpersonal interactions. Participants keep a greater distance from the robots as they gazed at each other. Participants who disliked robots maintained a larger distance from robots. Similar results were obtained by Takayama and Pantofaru (2009). Participants who considered the robot to be friendly or had the experience of using robots reduced the range of personal space for the robot. Participants expanded the range of personal space when gazing at the robot, which is more obvious in females. Pacchierotti, et al. (2006) also observed the lateral distance between humans and machines. They found that participants felt uncomfortable when the robot entered their intimate distance, but felt unnatural if the robot stay too far away. Lauckner, et al. (2014) further verified the lateral and vertical distance between humans and machines. In their experiment, participants were less sensitive to robots in their lateral personal spaces. Compared with frontal contact, robots laterally contacting people can provide a greater sense of security. Iachini, et al. (2014) compared the difference in IPS between interpersonal interaction and human-machine interaction through an Immersive Virtual Reality experiment. The result showed that participants kept a greater distance when facing the robot as compared to facing a person. They maintained a shorter distance to the anthropomorphic robot than to cylindrical robots.

Researchers also applied IPS to robots to control their movements. Nakauchi and Simmons (2002) used IPS in modeling, which allowed robots to mimic human social behavior and determine the distance of keeping with people in front of them. The control of robot movement was further improved by Chung and Huang (2010). They not only used the concept of IPS but also added models that mimic people's perception of the environment, allowing machines to understand the intentions of people when moving. Ratsamee et. al (2013) considered the case where the robot interacts with more than one person. They proposed a model allowing robots to take into account people’s face orientation and personal space to predict human trajectories, such as approaching and avoiding. Robots will maintain an appropriate distance from people based on this model.

These previous studies contributed to human-machine interactions, but there are still limitations. Human-machine interaction differs from interpersonal interaction. People will feel differently when facing machines as compared to when facing humans. Although people may feel similarities to machines due to their anthropomorphism, they will not consider machines as social beings or have attributes of humans, such as emotions (Appel, et al., 2012). Therefore, it is unreasonable to directly use the concept of IPS to explain human-machine interactions. The distance between humans and machines may be greater than the distance between humans (Torta, et al., 2013). In complicated public environments, such as mixed traffic with multiple mobilities, people are more likely to generate new perceptions of machines, which may be difficult to fully explain by IPS. Recent research also illustrates this point. Vassallo, et al. (2017, 2018) found that participants preferred to avoid moving robots during the interaction even though they kept a safe distance. Pacchierotti, et al. (2006) found that participants became uneasy with robots without any cueing signal, even if they maintained sufficient distance for safely passing.

2.2.3 ICT and ethics in the information society

In exploring human-computer interaction, some researchers found that the appropriate distance between humans and machines is not only required in spatial relationships but also in moral relationships.

Floridi said the digital age will inevitably emerge in human society, and ethical issues will be also raised at this time (Floridi, 2014). People’s opinions or words may be automatically judged by AI to be commercially valuable, and various advertisements and promotions are served while the user is involuntarily and unwillingly (Floridi, 2018, 2021a). People's privacy and rights will become ambiguous. For example, apps for keeping social distancing under the pandemic of COVID-19 are widely used, but there are no effective regulations for preventing unfair location information and information anonymization (Floridi, 2020). And the artworks of artists will lose their original values due to AI's precise reproduction technology. Because the reproduction is exactly the same as the original created by artists (Floridi, 2018b). Autonomous driving should achieve extremely high levels of safety on roads through information technology, but the misuse of information from remote monitoring becomes an important ethical issue (Floridi, 2021b). Therefore, Floridi considers that it is necessary to setting ethical boundaries between humans and machines. He proposed the concept of digital ethics and divided it into hard and soft ethics (Floridi, 2018c, 2018d, 2019c). Hard ethics refers to the values, rights, duties, and responsibilities that should be considered in the process of formulating regulations. Soft ethics is what should or should not be done over and above the regulations. Digital ethics will be combined with digital regulation to establish policies and standards to guarantee the proper use of information. Meanwhile, the ethical infrastructure is needed in establishing digital ethics. Not only sufficient physical facilities (transportation, communication, services, etc.) but also good values are needed to support ethical construction (Floridi, 2017). In addition, he also suggests that the integration of robots and AI into human society requires protecting the basic rights and dignity of human beings so that machines should be regulated by laws consisting of the values of people (Floridi, 2021b).

Some researchers consider that moral boundaries between humans and machines are necessary because machines may affect the personal autonomy of people, that is, the ability to make decisions for themselves and the desire to dominate their lives. In the future, Information and Communication Technology (ICT) will create a global network of surveillance capabilities, invading people's lives so silently that people may not notice their willingness is controlled. Under such an environment, people's personalities, self-esteem, and sense of self-ownership will be reduced (Daly, 2010). Advanced passenger information systems and biometrics use ICT to attach the physical data of passengers such as fingerprints and voices to their passports. Although this method does ensure security, people's privacy and self-esteem are violated at the same time. Sports bracelets with wearable technology automatically implement some "penalties", such as making users feel guilty and encouraging them to over-exercise when they are tired. This way of being forced to stay healthy deduce people's autonomy (Owens and Cribb, 2019). Formosa (2021) mentions that if machines can replace people to make decisions, such as autonomous driving to choose the driving path, people will lose some of their autonomy. For example, a robotic nurse may call for emergency medical help by over-monitoring the breathing and heart rate of a person. At this time, the person loses the right to determine whether they need help and call for it for themselves. The decision made by the robot may be against the will of the human being. Meanwhile, technological intrusions in the virtual space over-expose people's information, such as networking pushes and geolocation displays on Facebook, which will weaken the right to dominate personally identifiable information of people (Chandra, et al., 2020). For example, A surprise marriage proposal of a man to his girlfriend was scuttled by the exposure of his geographic location information in social network. Although they got married successfully, they lost the right to have an unforgettable memory.

The discussion of machines violating the personal autonomy of people prompts researchers to consider human well-being in the information society. Zuboff (2019) argues that people will be accustomed to the environment of sacrificing privacy and autonomy to obtain convenient services, such as unilaterally agreeing to terms of online consumption and app use, which is detrimental to people's long-term well-being. This topic still remains controversial. However, it is undeniable that considering the boundaries of human-machine interaction from multiple perspectives is significant.

2.3 Related factors of human-machine interaction

In the human-machine interaction, there will be a variety of factors affecting the distance of people and machines. This section will introduce its influencing factors from the perspective of human physical attributes, emotions, machine's attributes, surrounding environments and priority representing a social rule/consensus.

2.3.1 Factors of human physical attributes

(1) Gender

Physical attributes of people will affect the response to machines in interactions. One of the important effects is gender. In interpersonal interaction, many experiments have demonstrated differences in IPS for people of different genders. The distance between males is the largest, female-female is the shortest, and the male-female is in the middle (Hayduk, 1978, Aliakbari, et al., 2011, Hecht, et al., 2019). So, the gender differences in human-machine interactions also attract attention. Some researchers found differences in the distance between machines between males and females. Takayama and Pantofaru (2009) experimented using a weakly anthropomorphic robot with a height of 1.35m. the result showed that when the robot was faced up to participants in interactions, females maintained a greater distance from the robot than males, and males tended to approach the robot more than females. But when the robot was face down, this difference was not shown. Lauckner et al. (2014) used a cuboid robot for experiments and explored human-machine interaction from both front and side dimensions. It was found that females preferred to maintain a greater frontal distance from the robot than males. But this effect did not occur in lateral conditions. The experiment from Iachini, et al. (2014) used robots in virtual spaces. The results showed that females kept a greater distance from robots than males, especially when facing non-anthropomorphic robots (Figure2.2).

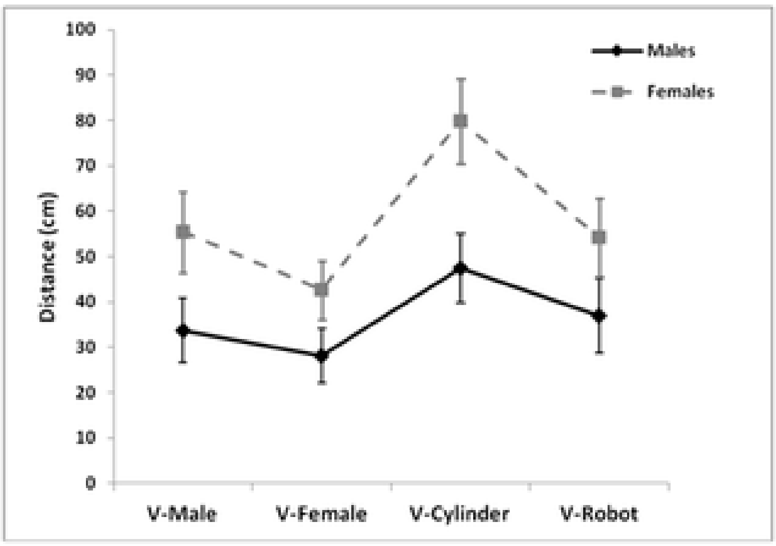


Figure 2.2 The gender differences in human-machine distance (Iachini, et al., 2014)

However, some researchers came to the opposite opinion. Brandl, et al. (2016) and van Oosterhout and Visser (2008) found no significant differences between males and females in the distance they kept from machines. In addition, some studies considered that biological sex can't fully explain the effects of sex. In recent years, the influence of psychological gender on IPS received greater attention but remains in much debate. Some researchers proposed that gender should be divided into physical gender, gender roles (having the masculine or feminine temperament and images), and psychological gender (being psychologically male or female). Pulling and Stark (2000) said that gender roles can make stereotypes about groups of different biological sexes. Uzzell and Horne (2006) distinguished sex (biological sex), gender role, and sexuality (psychological sex) and observed their effects on IPS. As a result, the gender role had a greater impact.

Although using traditional biological sex to explore the gender effect in human-machine interaction has limitations, the new concept of gender is still uncertain and unstable at current studies. Therefore, this research will refer to the effect of traditional gender, rather than the new concept.

(2) Age

Age is another influential factor in studies related to IPS. Aiello (1987) found that the older the age, the greater the distance of IPS in interpersonal interactions. This may be because children's ability to estimate distance is different from that of adults, and the decline in physical quality and ability of the elderly causes them to move differently and thus maintain greater distances (Webb and Weber, 2003). The experiment from Iachini et al. (2016) found that participants kept a shorter distance for children than for adults and elders, and they also tended to keep a greater distance from elders than adults.

However, the effect of age is still controversial in the study of human-machine interaction. Many researchers proposed that age has an impact on the distance between humans and machines. van Oosterhout and Visser (2008) used both large and small robots to observe the differences in distance between humans and machines at different ages of people. The height of the large robot is about 1.75m similar to that of an adult. The small robot is about 1.12m close to that of a child. The experiment took place in a technology festival venue, where people randomly interacted with these robots. The result showed that compared to adults, children kept a shorter distance from robots, especially the small robot. Also, adults kept a greater distance from the small robot than the larger robot. Walters et al. (2005) used a robot with a 1.12m high in their experiments and compared the differences between children and adults in the personal space creating robots. They found that children are more willing to let the robot enter their social space of IPS (1.2m~3.6m). But adults didn't mind allowing the robots to come closer and enter their personal space. Okita et al. (2012) used a humanoid robot to compare the difference in the human-machine distance by age. In the results, children maintained a greater distance from the robot without any signal (verbal or physical action). In contrast, there was no significant difference between adults and children if the robot sent warnings or signals. However, a part of some researchers held the opposite opinion. Brandl et al. (2016) found that the significant influence of age in human-machines interaction was not found in their experiment. This research considers the factor of age as one of the possible influencing factors, which will be used as a reference.

(3) Height and posture of people

Human height and body posture have impacts on interpersonal interactions. People tend to keep a greater distance from larger people, especially when there is a large height difference. The reason may be that a taller appearance of people creates a greater sense of stress and danger (Aiello 1987, Caplan and Goldman, 1981). Recent research also supports this tendency. D'Angelo et al. (2019) used virtual reality technology in their experiment to observe the effect of body height on IPS and changes in IPS after the height of participants changes (becoming taller or becoming shorter). They found that the range of IPS decreased when participants were in the taller virtual bodies, and significantly increased when they were in the short virtual bodies. The experiments from Hecht, et al. (2019) found that taller people were more likely to invade the personal space of shorter people, while shorter people tended to keep a larger distance from others. Pazhoohi et al. (2019) came to similar conclusions but found significance only shown in the response of male participants.

Studies in human-machine interaction have demonstrated the effect of human height. In these studies, researchers not only used physical height but also body postures to represent different heights of people. Sitting indicated that people are in a shorter position than machines. Standing means that they are in a higher position than the machines. Torta et al. (2013) explored the effect of body height on human-machine interactions by using two experiments. One experiment used participants' actual standing height in the interaction and found a significant positive correlation between height and the distance between participants and robots. Another experiment observed the situations when participants standing and sitting. They found that in either case, the human-robot distance was greater than the interpersonal distance. When the robot approached participants from the front, seated participants maintained a greater distance from the robot than standing participants. While, when the robot approached from the side, the seated participants kept a smaller distance from the robot than the standing participants (Figure 2.3).

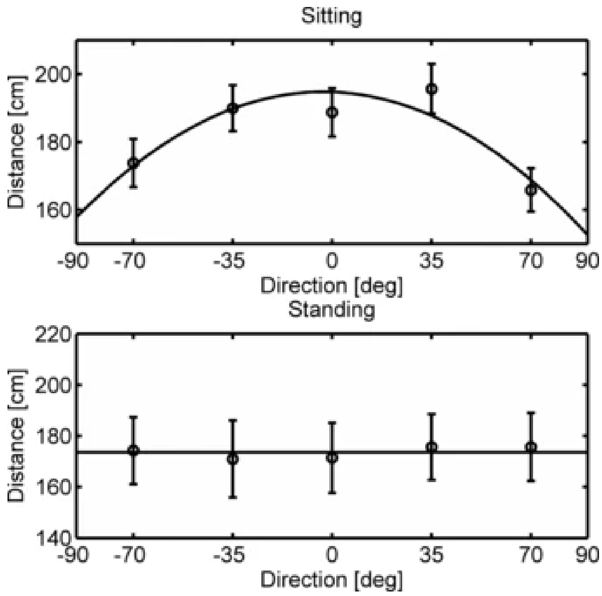
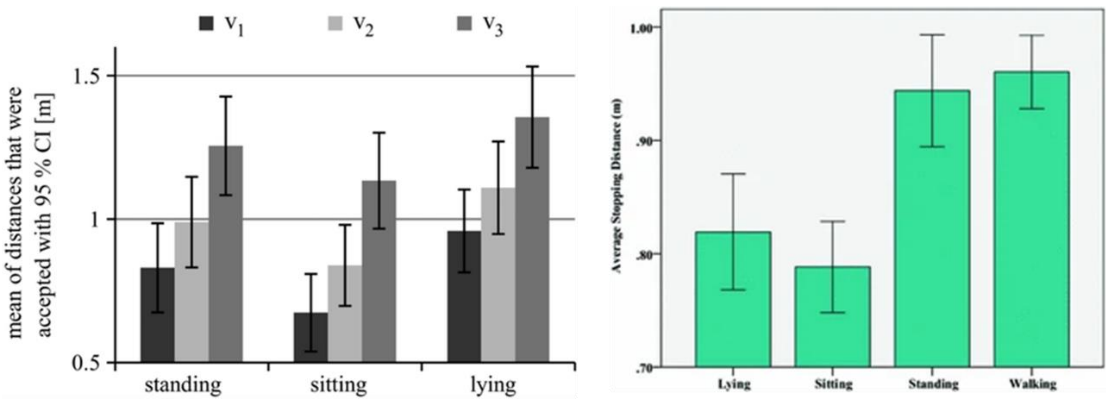


Figure 2.3 Human-robot distance when participants sitting and standing (Torta, et al., 2013)

Brandl, et al. (2016) tested the effect of height in three situations on human-machine interaction: sitting, standing, and lying. They found that participants kept the greatest distance from the robot when they were lying down. While, they kept less distance from the robot when sitting than when standing (Figure 2.4, right). Rossi, et al. (2017) explored the effect of lying, sitting, standing, and walking on human-machine interaction. The results showed that participants maintained the shortest distance from the robot when sitting, and kept the greatest distance from the robot when walking. Standing and walking participants maintained a greater distance from the robot than sitting and lying participants (Figure 2.4, left).



Brandl, et al. (2016) Rossi, et al. (2017)

Figure 2.4 Influence of different postures on human-robot distance (Brandl, et al. 2016, Rossi, et al., 2017)

Some researchers noticed that the height difference between machines and humans is also important. Obaid, et al. (2016) observed differences in distance between humans and robots when they stand or sit. It was found that the human-robot distance was affected by the posture of the robot, but not by the posture of the human. Participants tended to maintain a greater distance from the robot when it was standing. The experiment of Lauckner, et al. (2014) explored that taller people maintained a greater distance in human-machine interaction than shorter people. The authors concluded that if the height of the robot increased, the personal space thresholds of participants became larger, meaning that the distance between people and machines became larger. In contrast, if the height of the robot decrease, the distance between people and machines became smaller.

However, the topic of the effect of height is also controversial. For example, in the experiments from Obaid et al. (2016) and Kamide, et al. (2014), height does not have significant effects on human-machine interaction. Despite the controversy, height would be an important factor in this research. We consider that the difference in height of people also represents the difference in the height of the sight line, which will affect people's perceptions when moving.

(4) Experience

Researchers have found that familiarity from experience can reduce behaviors that compensate for inadequate control by keeping distance in interpersonal interactions (Hayduk, 1983, Edney et al., 1976). This means that when people are with unfamiliar people, they try to reduce anxiety by maintaining a greater distance. Hence, people feel more comfortable when staying in close range with friends than when with strangers.

There are similar situations in human-machine interactions. Takayama and Pantofaru (2009) found in their experiments that people with more than one year of experience in using robots are more willing to approach the robot than inexperienced people. They also found that increased contact and human-like actions of increasing the closeness (turning the face toward people) reduced the distance between people and machines. Other researchers also received similar results. Mead and Matarić (2016) found that as the number of human-machine contacts increased, the familiarity between humans and machines increased, thereby reducing their distance in interactions. In the experiment from Obaid, et al. (2016), participants who previously had experience interacting with robots maintained a shorter distance from the robot. They felt more comfortable and allowed it to come closer. Moreover, Haring, et al. (2013) found that increasing the degree of anthropomorphism of the robot was beneficial to promoting familiarity between humans and machines. They used a highly anthropomorphic robot in experiments and found that participants became more familiar with and keep a shorter distance from the robot as their contact time increased.

(5) Culture

Culture is an important factor in interpersonal interaction. Due to cultural differences, people in different countries and regions have different standards of judging the distance between people, leading to a large difference in their IPS (Hall, 1966). For example, Americans and Europeans greet similarly, but Americans keep a greater distance from others in conversations (around 1.2m) than Europeans (0.6m~0.9m). Sorokowska, et al. (2017) also found differences in personal space among different regions. People in Romania, Hungary, and Saudi Arabia kept more than 120 cm from strangers, while the distance between people was less than 90 cm in Argentina, Peru, Ukraine, and Bulgaria.

The influence of cultural differences in human-machine interaction is also observed. Eresha et al. (2013) invited Arabs and Germans in their experiments to observe the influence of culture on human-machine interaction. They found that German participants were more likely to maintain a greater distance from the robot than Arab participants. The experiment from Joosse (2017) combined a questionnaire to explore the differences in the appropriate distance from robots in the United States, China, and Argentina. The result showed that Chinese participants tended to stay closer to the robot than American and Argentinean participants. However, the differences between participants from the United States and Argentina were smaller.

2.3.2 Factors of human feelings

(1) Unease

Human feelings are intuitive expressions in interaction, especially negative emotions such as stress and anxiety. Hall (1966) and Aiello (1987) mentioned that people feel uncomfortable, angry, or anxious when their personal space is invaded. For example, someone feels uneasy in crowded trains, elevators, or streets, even if they know these are common situations in cities. Therefore, researchers have used this obvious response to explore human-machine interaction. Most experiments use some stimulation to make participants stressed or keep them alert, so as to observe the appropriate distance between humans and machines. There are two ways of recording negative emotions in these experiments. One is to let participants respond immediately when they feel discomfort recording the data. Takayama and Pantofaru (2009) observed multiple situations of participants actively (participant walking towards the robot) and passively (robot moving towards the participant) approaching the robot. In this experiment, the authors told the participants to move to the other side of the experimental area if they felt the robot was too close to feel uncomfortable. In the experiment from Lauckner, et al. (2014), frontal and lateral human-machine distances were measured. They asked participants to control the robot to move toward them with remote control. They can stop the movement of this robot when felt uncomfortable. Iachini, et al. (2014) showed virtual images of robots to participants in the head-mounted display. They gave participants a button that can stop the movement of these virtual images and asked them to press it when they felt uncomfortable with the virtual stimulus.

The other is that participants will fill out a questionnaire for emotional evaluation after completing the experiment set by the author. Pacchierotti, et al. (2006) set different avoidance distances cases of the robot when meeting participants in experiments. At the end of the experiments, each participant will answer a questionnaire to evaluate their comfort level during the interaction (level from very uncomfortable to very comfortable). Pham, et al. (2015) used a similar way in a human-PMV interaction experiment. In this experiment, participants passed through the sidewalk in a straight line, while PMV riders avoided the participants when interacting with participants. After the experiment, participants responded to the degree of discomfort (from comfortable to very uncomfortable) and fear (from unfearful to very fearful) of PMV through questionnaires. The experiment from Hasegawa, et al. (2018) asked PMV riders to approach participants in different body orientations (front, side, back). Each participant filled out a questionnaire about the danger perception of PMVs after each scenario experiment (0: no danger, 6: significant danger).

Negative emotions such as anxiety and stress are also affected by personal attributes. For example, females feel uncomfortable more obviously when their personal space is invaded by robots, which may be because they are more likely to develop self-protection mechanisms and show vigilance than males (Iachini et al., 2014, Bailenson, et al., 2003, Fisher and Byrne, 1975). Also, children tended to maintain a greater distance from the robot than adults, which is possible to the higher vigilance of children toward machines (Brandl et al. 2016). Therefore, this research considers that the uneasy feeling of people is an important factor in exploring pedestrians' perceptions on roads or public spaces.

(2) Closeness

In interpersonal interaction, increasing the sense of intimacy can shorten the distance between people. For example, people are more alert to strangers and keep a greater distance, while they are closer to families and friends (Hall, 1966, Aiello, 1987, Hayduk, 1983). A similar phenomenon can be observed in human-machine interaction. Experiments by Iachini, et al. (2014) found that participants held a closer distance to the humanoid robot than the non-humanoid robot (cylinder). Because the human-shaped robot allowed participants to feel more familiar and close. Therefore, increasing the anthropomorphism of robots is a way to bring a sense of intimacy to people and reduce the human-machine distance.

Many researchers have observed changes in the distance between humans and machines by varying the degree of machine anthropomorphism. Haring et al. (2013) used highly anthropomorphic intelligent robots in experiments. They found that the distance participants maintained for this robot was similar to the distance in personal space of IPS (around 1.2m). Also, in a trust game, participants can give any part of the money to the robot. This robot controlled by researchers will return the money to participants again. As a result, participants showed a tendency to trust robots. Kim, et al. (2013) observed human-robot interaction by adjusting the speaking style of the robot. In the experiment, they set four cases in the robot: calling or not calling the participant's name, honorific or familiar speaking style, and observed changes in the distance participants kept from the robot after talking to it. The results showed that participants felt the robot was more friendly when the robot called their name and used honorifics. They also showed closeness to the robot that called them by name and were more willing to provide personal information to it, such as school year and department. In this case, they kept a shorter distance from the robot than when the robot was not called them by name.

Some studies have also improved intimacy by adjusting the movements and postures of robots, thereby reducing the human-robot distance. In experiments by Ham, et al. (2012), participants shortened the distance to the robot when the robot posed in an approachable posture. Mead and Matarić (2016) used a robot wearing human clothes and having a face in experiments. When the robot spoke to participants and explained its meanings by assisting with gestures, participants kept less distance from it. Mumm and Mutlu (2011) adjusted the robot's likeability and gaze behavior to observe the human-robot distance. They set humorous words in the robot to adjust its likability, and use eye orientation to control the degree of gaze (staring, avoiding, etc.). The result found that participants who disliked the robot maintained a greater distance when the gaze of the robot increased. The distance kept by participants who liked the robot did not change significantly even though the gaze of the robot increased.

Therefore, intimacy (closeness) has great relevance in adjusting the human-machine distance. It may be because machines are seen as social beings in the interaction, people think they are possible to communicate with them. However, if machines are not seen as social beings, but as simple technological devices, this effect of closeness may not be present. For example, Syrdal, et al. (2008) found that people maintained a shorter distance from a machine-shaped robot than a humanoid robot. Because they did not think they need to socialize with robots.

This research focuses on the situations in mixed traffic. Robots in this case are more likely to be social beings. Hence, we consider closeness is an important factor.

2.3.3 Priority

This research considers that road priority is also an important factor for mixed traffic. In previous studies, road priority has been widely used to solve traffic congestion and accidents. Generally, priority is used for traffic diversion at intersections. The complex traffic flows at the intersection will be divided into different ranks. The higher the level, the earlier the vehicle is allowed to pass (Eva and Andrea, 2019, Tracz and Chodur, 2011). With the development of society, the concept of road priority has gradually expanded to coordinate the relationship between different traffic modes, such as pedestrians, bicycles, public transportation, etc. One of the widely used approaches is transit signal priority, which provides priority to buses by controlling traffic lights at intersections to reduce their waiting time and improve service capacity.

Furth and Muller (2000) experimentally measured the effect of priority at signalized intersections. They measured three situations: no priority (not using signal priority), absolute priority (all vehicles are given signal priority), and conditional priority (a part of vehicles can use signal priority). The results showed that conditional priority caused a significant reduction in traffic disruptions compared to absolute priority, as well as improved the quality of service. In the study of Ma, et al. (2010), the strategy of using traffic signal priority was improved. They proposed the coordinated and conditional bus priority to reduce bus delays by combining two strategies. The results of the field application showed that this method can reduce the delay of buses without affecting the delay of other vehicles. He, et al. (2014) focused on priority traffic signal control of multiple modes. They proposed a model to use transit signal priority more flexible for a more coordinated relationship between pedestrians, cars, and buses. Results of experiments showed that this model can reduce the average delays of buses, pedestrians, and passenger cars, especially in highly congested conditions with a high frequency of priority requests from vehicles. Santos-González, et al. (2019) proposed a dynamic traffic signal system with the priority for pedestrians and emergency vehicles (ambulances, police cars, and fire trucks) to solve vehicle-vehicle and vehicle-pedestrian intersection collisions. The system will add alerts to car drivers through smartphones or light sensors on roads. Drivers will be alerted to stop when encountering pedestrians and will be guided to give way when encountering emergency vehicles.

Moreover, road priority is used to achieve new social goals of transportation. Haitao et al. (2019) and Desta and Tóth (2021) proposed a method of using the bus-only transportation network to reduce the mixed situations with other vehicles, thus reducing delays and traffic congestion on roads. In this way, the priority of buses on urban roads will be improved, which can promote people to use public transport and achieve the purpose of sustainable development of cities. Martens (2018) proposed the idea of a transportation network for prioritizing the elderly and the disabled, which will provide a reference for improving the inclusiveness of the transportation system in the future.

In the interactions of public spaces, the subjective views on priority of people is significant, which are related to values. Paschalidis et al. (2016) observed the perceptions of cyclists in conflict with pedestrians and cars on mixed roads, that is, which side will be blamed by cyclists when a conflict occurs. They found that cyclists were more likely to prioritize pedestrians than cars. When cyclists shared spaces with pedestrians, they slowed down and felt self-blamed in collisions. On the contrary, when cyclists ran with cars, they blamed cars if conflicts occurred. It is because pedestrians are seen as the weak of traffic in society, while cars are powerful road users and more threatening to other road users. In human-machine interaction, it is commonly believed that pedestrians have higher priority than machines. However, in the future, the application of ICT and the introduction of machines may change human values, so that the weak will become difficult to be simply distinguished. At this time, people may not always have priority over machines. For example, people who wear technological equipment will be much taller and stronger than delivery robots. In this case, robots that carry valuables will be considered more vulnerable, and pedestrians may need to give way to machines. Although the evaluation of the priority of road users in the future is unclear, this research still considers that it is an important factor as a reference.

2.4 Simulation about human-machine interactions

2.4.1 Social force model (SFM)

Many researchers used simulation studies to explore human-machine interaction. The social force model proposed by Helbing et al. (1995, 2005) reproduced the phenomenon of pedestrian movement, which is a theoretical basis model commonly used in pedestrian traffic studies. This model based on Newton's second law of dynamics and psychology explains the movement of people by using forces from different aspects, such as self-driving force for reaching the destination, the psychological force to avoid other pedestrians and physical facilities (walls or buildings), the resistance generated by physical collisions of the body. The following formula will explain the principle of the social force model.

The social force model uses forces from the environment and psychology to explain the movement of individuals. In Eq. (2.1), F_i represents the force explaining the movement of pedestrian p_i, which consists of self-driving force (F_i^{pers}) driving p_i to move forward, the social force (F_i^{soc}) for keeping distance from other individuals or infrastructures, and the physical force (F_i^{phys}) generated by physical collision. The motion of p_i follows Newton's second law (m_i is the mass of p_i and v_i is the velocity of p_i). Figure 2.5 illustrates the relationship between them.

$$F_i = F_i^{pers} + F_i^{soc} + F_i^{phys} = m_i \frac{dv_i}{dt} \qquad Eq. (2.1)$$

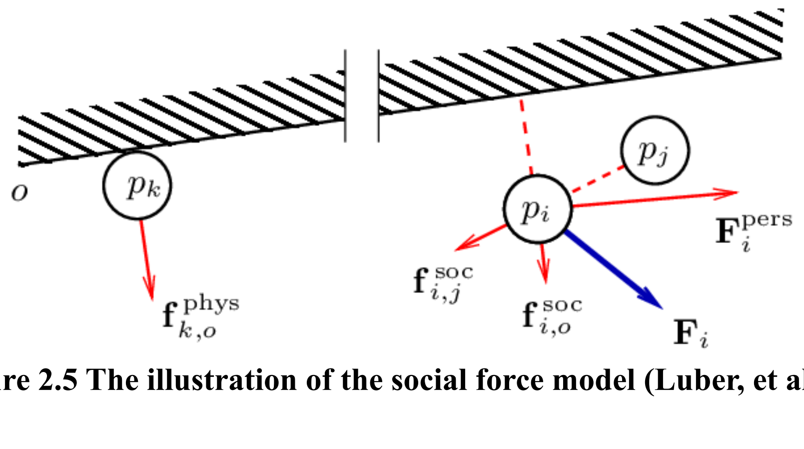


Figure 2.5 The illustration of the social force model (Luber, et al., 2010)

The self-driving force (F_i^{pers}) describes the expectation of an individual p_i moving toward its desired destination. In Eq. (2.2), $\hat{v}_i$ and $\hat{e}_i$ represent p_i's intended velocity and intended direction of the movement. τ_i is the relaxation time required for p_i to reach the intended velocity and intended direction. Hence, the motivation of p_i can model the change in velocity.

$$F_i^{pers} = m_i \frac{\widehat{v_i}\widehat{e_i} - v_i}{\tau_i} \qquad Eq. (2.2)$$

The social force describes the repulsive influence from other individuals or static obstacles that an individual p_i encounters when moving toward its destination. It is a psychological resistance of p_i that causes it to deviate from the intended direction and velocity. In Eq. (2.3), F_i^{soc} represents the sum of all social forces generated on p_i (P is the set of all people in the environment, O is the set of all static obstacles, and k is the union of P and O). f_i^{soc} is a social force generated by p_i encountering another individual p_j or a static obstacle p_k. Both p_i and p_j/p_k are assumed to circle with radii r_i and r_j/r_k. In Eq. (2.4), a_k and b_k are the magnitude and range of the force, and $r_{i,k}$ is the sum of the radii of p_i and p_j/p_k. $d_{i,k}$ is the Euclidean distance between p_i and p_j/p_k, and $n_{i,k}$ is the direction of the force from p_j/p_k to p_i. λ is the strength of the anisotropic factor.

$$F_i^{soc} = \sum_{j \in P \setminus \{i\}} f_{i,j}^{soc} + \sum_{o \in O} f_{j,o}^{soc} \qquad Eq. (2.3)$$

$$f_i^{soc} = a_k exp(\frac{r_{i,k} - d_{i,k}}{b_k}) n_{i,k} (\lambda + (1-\lambda) \frac{1 + \cos(\varphi_{i,k})}{2}), (k \in P \cup O) \qquad Eq. (2.4)$$

$$\cos(\varphi_{i,k}) = -n_{i,k} \cdot \widehat{e_i} \qquad Eq. (2.5)$$

The physical force expresses the physical constraints on an individual p_i in the environment, which can restrict p_i's movement. Examples include collisions between pedestrians or pedestrians hitting the walls of a building.

In Eq. (2.5), F_i^{phys} is the sum of physical forces exerted on p_i by other pedestrians or static obstacles. In Eq. (2.6), f_i^{phys} is the physical force pi encountering another pedestrian p_j or static obstacles p_k, which is described as a force from touching. The effect occurs when circles representing bodies of p_i and p_j/p_k are overlapped, that is, $g(x) = r_{i,k} - d_{i,k}$ $(x \geq 0)$. Also, c_k is the magnitude of the exerted force, and $n_{i,k}$ is the direction of the force from p_j/p_k to p_i.

$$F_i^{phys} = \sum_{j \in P \setminus \{i\}} f_{i,j}^{phys} + \sum_{o \in O} f_{j,o}^{phys} \qquad Eq. (2.6)$$

$$f_i^{phys} = c_k \cdot g(x) \cdot n_{i,k}\ , (k \in P \cup O) \qquad Eq. (2.7)$$

$$g(x) = \begin{cases} r_{i,k} - d_{i,k}\ , (x \geq 0) \\ 0, (x < 0) \end{cases} \qquad Eq. (2.8)$$

2.4.2 Applications of the social force model

The social force model (SFM) explains the principle of pedestrian movement and can simulate the movement of pedestrian groups in the public environment. So that it is widely used in the studies of pedestrian flow modeling to solve problems. For example, Helbing et al. (2002, 2000, 2005) and Parisi and Dorso (2007) used SFM to simulate the escape behavior of people induced by panic in disasters. They used simulations to observe the bottleneck of pedestrian flow and proposed escape plans to prevent stampedes based on the "faster is the slower" effect. Buchmueller et al. (2006) used SFM to simulate the dynamic process of pedestrian traffic and put forward suggestions for the planning and design of pedestrian facilities. Yu et al. (2005) proposed a centrifugal force model based on the SFM, which reproduced the phenomena of lane formation and sparse flow of pedestrians, and congestion at the exits of public spaces.

With the continuous application of the SFM in solving pedestrian problems, many studies on space sharing and human-machine interaction have begun to use SFM to simulate the movement of humans and machines and explore the possibility of human-machine coexistence. Tamura et al. (2010) developed a robot response system for robots for avoiding collisions with pedestrians. In the system, robots will predict the trajectories of pedestrians by using the SFM and detect them with laser range finders. Also, the authors used experiments to verify the effectiveness of the system. The results showed that the robot had a 67% chance of making avoidance responses when using the proposed system. Ratsamee et al. (2013, 2015) proposed a social navigation model (SNM) based on the traditional SFM that can control the robot to avoid collisions with pedestrians in interactions. They added the factor of human face direction to the model so that robots can judge the probability of pedestrians intending to avoid robots when they predict the movements of pedestrians. Thus, robots can avoid pedestrians based on the results of SNM in human-machine interaction. Their experiment verified that the robot had a 75% chance of successfully responding with avoidance. Kato et al. (2017) proposed an estimation model for allowing humans and machines to mutually understand moving intentions of each other by improving the SFM. They separately construct proposal models for pedestrians and robots based on the simplified SFM. For pedestrians, the authors added the factor of intention estimation as another psychological force. In interactions, pedestrians will consider the possible moving intention of robots and try to avoid them. While for machines, in addition to the factor of intention estimation, the vector field model was added, that is, allowing robots to move along a specific target path when in the absence of pedestrians and obstacles and after avoiding them. The results of the simulation experiments showed that the proposed model can reduce more collisions compared to using SFM only.

Researchers in the transportation field also used SFM to explore the relationship between pedestrians and mobilities in mixed traffic. Anvari et al. (2015) proposed a micro-mathematical model describing the behavior of vehicles in a shared space. The model extends traditional SFM to reproduce the movement behavior of vehicles when interacting with pedestrians. The authors considered the shape of the car as an ellipse rather than a circle and represented the motion limitation of cars by using the relationship between steering angle and velocity. In this model, not only the avoidance behavior of vehicles but also the pedestrian-car interaction and right-of-way negotiation were considered. Schönauer et al. (2012) also used SFM to simulate the movement of vehicles in the pedestrian-vehicle interaction. They modeled vehicle dynamics by using a discrete monorail approach and added the game-theoretic approach to resolve pedestrian-vehicle conflicts. These two models were calibrated by using simulation experiments and verified that models can describe the vehicle movement behavior in mixed traffic. Huang et al. (2016) added fuzzy logic to traditional SFM to simulate the dynamic movement of cyclists on non-signalized intersections. They collected field data at four unsignalized intersections and used statistical methods for parameter calibration. Li et al. (2021) also reproduced the behavior of high-density bicycle flow at intersections by improving SFM. In this improved model, they added a dynamic boundary to capture the dynamic characteristics of the lateral diffusion of bicycle flow and added a behavioral force model with a decision-making process to consider the possible interactive behaviors of bicycles (following, overtaking, or freely moving). The model is calibrated through simulation experiments. Both models are beneficial for reproducing the movement behavior of bicycles and solving conflicts between bicycles and pedestrians at intersections.

In recent years, researchers have begun to focus on using SFM to consider the relationships between pedestrians and new mobilities. Dias et al. (2017, 2018) tried to use SFM to explain the behavior of Segway riders avoiding pedestrians while moving. To improve the interpretability of the SFM in Segway, authors extracted parameters affecting pedestrian-Segway interaction from the traditional SFM and calibrate the parameters and model by experimentally collecting trajectory and avoidance distance of pedestrian and Segway. The results showed that the calibrated SFM can reproduce the movement behavior of Segway under uncongested conditions. Hasegawa et al. (2018) proposed the subjective danger index (SDI) inspired by SFM for evaluating the sense of danger of pedestrians when interacting with PMVs. They considered that psychological forces acting on an individual will cause it to avoid other pedestrians so that when feeling dangerous, the individual would change its trajectory for preventing further generating these feelings. The SDI is used to evaluate the danger perceptions when individuals expect to change the trajectory, which is calibrated experimentally. These studies are conducive to further exploring the mixed traffic of pedestrians and PMVs.

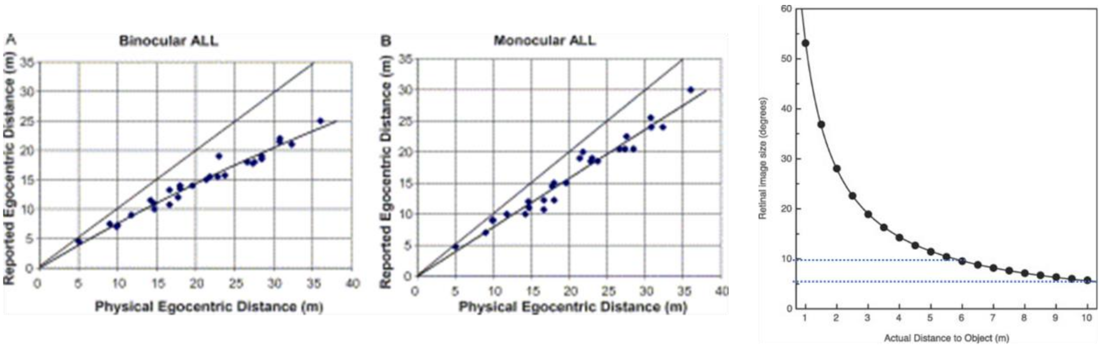
However, the previous studies focused more on reproducing the movement behavior of one type of existing mobility by SFM in the interaction with pedestrians. Before the arrival of future mixed traffic of pedestrians and various machines, using SFM to prevent possible conflicts is also an important issue.

2.4.3 Factors for improving the reality

In simulation experiments, researchers usually use some factors or parameters to improve the reality of the model. For example, Ratsamee, et al. (2013, 2015) added the factor of human face orientation into the model, so that the robot can better predict the movement of people in avoidance behavior. Kato, et al. (2017) added an intent estimation factor to the model to simulate a condition of mutual consideration between humans and machines. Therefore, this research considers the following factors used to improve the reality in the simulation experiment of pedestrian- machine mixed traffic.

(1) Visuospatial perception

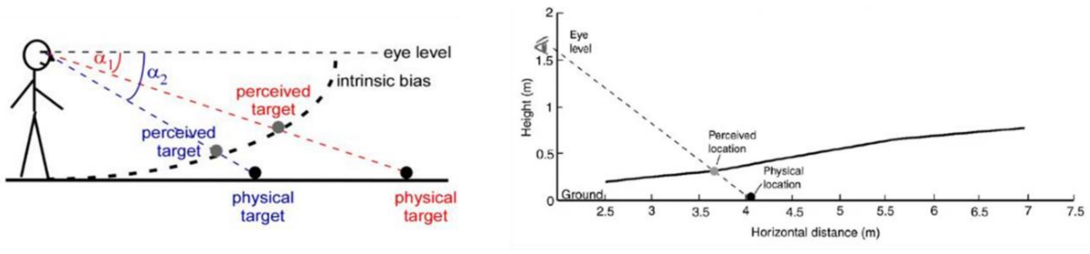
The visuospatial perception of people is an important factor. The farther the distance between a person and an object, the greater the error in person's judgment and perception of the distance to the object. Foley et al. (2004) experimentally explored human visuospatial perception at long distances. In their experiment, participants judged the actual distance of the object (pile) at different distances, and completed monocular and binocular cases. The results showed that participants made greater errors in distance judgments for objects at greater distances, and the errors expressed more obvious in the monocular case (figure 2.6, left). The experiment from Kunnapas (1968) described the visuospatial perception at a short range. In the results, the retinal image size of objects in human eyes changes with distance. As the distances between a person and objects increase, he/she will be more difficult to distinguish the difference in distance to these objects. This phenomenon will be more obvious if the distances between a person and objects are close to or exceed 10m (figure 2.6, right). For example, a person may think that piles that are 10m and 11m away from him/her seem to be in the same location.



Foley, et al. (2004) Kunnapas. (1968)

Figure 2.6 The relationships of visuospatial perception and distance (Foley et al., 2004, Kunnapas, 1968)

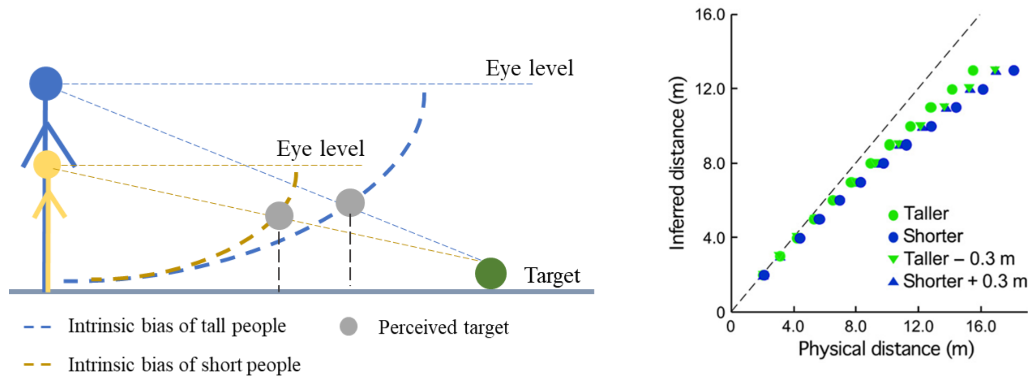
Zhou et al. (2013) proposed that the angle between the eye level and the eye-to-target projection line will affect people to judge the distance to targets. The smaller the angle, the greater the error of judging the distance to targets. And people are more difficult to distinguish the distance differences between distant objects than near objects. These errors would form an imaging surface called intrinsic bias (figure 2.7, left). Moreover, in their experiment, participants judged the distance to targets and the perceived size of targets under different distance conditions. The results showed that when the angle between the eye level of participants and the eye-to-target projection line is close to 10 ° (the distance is about 6.75m), the error of perceived distance of participants becomes larger, and their distance and size perception to different objects are similar. Yang and Purves (2003) also observed a similar conclusion. They measured the perceived distance of people (judgment of the distance between people and objects) and fitted a curve similar to the intrinsic bias from Zhou, et al (2013) (figure 2.7, right). However, the authors found a critical point (5.5m) on the curve of perceived distance. People will underestimate the distance to objects when exceeding the critical point.



Zhou et al., (2013) Yang and Purves (2003)

Figure 2.7 The illustration of intrinsic bias and perceived distance (Zhou et al, 2013, Yang and Purves, 2003)

Moreover, different heights of people have differences in visuospatial perception. Zhou et al. (2016) proposed that taller people will have smaller visuospatial perception errors than shorter people, that is, taller people can judge the distance to objects more accurately than shorter people. They are explained this phenomenon by the intrinsic bias curve in their previous study and demonstrated it experimentally (figure 2.8, left). In their experiment, participants were divided into taller and shorter groups and considered four situations: taller people, tall people sitting (-0.3m), shorter people, shorter people standing on a box (+0.3 m). the results showed that shorter participants had greater errors in visuospatial perception than taller participants. This difference was more obvious if the distance between the participant and the object become larger (figure 2.8, right).



Zhou et al., (2016)

Figure 2.8 The difference of higher and shorter people on visuospatial perception (Zhou, et al, 2016)

However, the differences in judging object sizes between different heights of people are unclear. Van Der Hoort et al. (2011, 2016) allowed participants to judge the size of distant objects when they used different types of virtual bodies (tall and short bodies) in the virtual reality experiments. They found that participants had greater errors in estimating the size of objects when they were in the tall body than in the short body.

This difference in error increased as the distance from the object increased. But the height difference between the tall and short virtual bodies used in the experiment is very large (tall: 300~400cm, short: 60~80cm), and the difference in participant's perception error of the object size under these two heights is relatively small (10cm). Therefore, the effect of height on the judging of distant objects will not be considered in this research.

Based on the previous studies mentioned above, this research takes into account the maximum distance of 10m at which a person can clearly perceive a machine in interaction. The effect of body height of people on visuospatial perception is also considered.

(2) Size and speed of road users

The physical properties of road users that pedestrians encounter may be used as parameters to influence pedestrian perception in human-machine interactions.

In general, the speed of mobilities affects the discomfort of pedestrians in the interaction. According to a survey by the Cabinet Office of Japan (2011), 60% of pedestrians considered bicycles with fast speed to be dangerous on the sidewalk. In human-machine interaction, the speed of machines will also affect the perceptions of pedestrians. Some researchers have considered the significance of machine's speed in interactions with pedestrians and machines. Butler and Agah (2001) observed the effect of robot speed on comfort of pedestrians in human-robot interaction. They considered three different situations: direct-slow (the robot approaches participants at a slow speed, maximum speed: 0.25m/s), direct-fast (the robot approaches participants with at a fast speed, maximum speed: 1.02m/s), indirect (the robot approaches participants by turning a corner, maximum speed: 0.5m/s). The results showed that participants felt comfortable when the robot speed was 0.25-0.38 m/s, while they felt uncomfortable when the robot speed was 0.5 m/s. The opposite conclusion was shown in the experiments from Pacchierotti, et al (2006). Some participants felt uncomfortable because the speed of the robot in the experiment (0.6m/s) was too slow. Hasegawa et al. (2018) considered speed as a factor affecting danger perception of pedestrians in human-PMV interactions. In their experiment, the authors allowed PMV riders to approach different parts of the participants' bodies (front, side and back) at different lateral distances and speeds, and then observed danger level perceived by the participants. In the results, when PMV riders approached to participants at the same lateral distance and body orientation, participants perceived more danger to faster PMVs than slower PMVs. A similar conclusion was also obtained by Nakagawa et al. (2012). In their experiment, the authors let PMV riders drive through flows of participants and measured the participants' discomfort. As the speed of the PMVs increased, the discomfort and fear of participants increased. In mixed traffic with multiple robots and mobilities, their speed may be variable, so as to affect pedestrian perceptions. Therefore, the speed of machines is considered an important parameter.

Moreover, pedestrians will create different impressions of road users with different body sizes. It is well established that people feel more stressed and vigilant to other people or things with larger bodies, and feel closer to that of with smaller bodies (Aiello 1987, Caplan and Goldman, 1981). The human-machine interaction follows the same pattern. van Oosterhout and Visser (2008) used tall (175cm) and short robots (112cm) for a study of human-robot interaction. The results showed that participants preferred to stay closer to the shorter robot than the taller robot. The experiment from Butler and Agah (2001) used a cylindrical robot (35 cm) and a humanoid robot (170 cm) to measure the discomfort of participants in the human-robot interaction. As a result, participants showed higher levels of discomfort and maintained greater distances to the humanoid robot than the cylindrical robot. Takayama and Pantofaru (2009) used a robot smaller than human bodies in the experiment. They found that some participants with pet experience kept closer to the robot because they felt the robot was like a pet. A similar result was found by Obaid et al (2016). They used a 58 cm tall humanoid robot in the experiment to observe the human-machine distance. In the results, females were more willing to keep a shorter distance from the robot than males because they saw the robot as a stuffed toy or doll so that let down their guard. Consequently, the body size of machines is another important parameter in human-machine interaction.

(3) Environment

This research considers the spatial size of the road as a factor affecting human-machine mixed traffic. In transportation field, the social force model (SFM) often used to simulate the dynamic process of people or mobilities. The different spatial sizes reflect different mobility phenomena. Helbing et al. (2002, 2005) used SFM to simulate the movement behavior of people in narrow public spaces, and found that the slow-is-faster effect is effective in preventing people from stampedes when escaping the disasters. Huang et al. (2016) used SFM to simulate the movement of bicycle flows in outdoor public spaces. They described the range of force on the bicycle force as an ellipse and proposed a model that can reasonably reflect the movement behavior of bicycles. The actual data of bicycle movement conditions they measured (speed, trajectory, and turning conditions) at two-line unsignalized intersections calibrated the model so that it better reflects the avoidance and hazards of bicycle in collisions. Li et al. (2021) considered the case of wider public spaces. The improved model of SFM they proposed described the movement behavior of bicycle flows at a signalized intersection (50m).

Since the considered situation is in a wider roadway, the dynamic characteristics of the lateral diffusion of bicycles and the interaction of overtaking or following other vehicles were added into the model. The lateral diffusion of the bicycle flow in the model better reproduced the movement bicycles in the wider public space, as distinguished from situations in narrow spaces. Therefore, in the mixed traffic of various mobilities, the space size of the road environment would be considered.

2.5 Summary

This chapter presents previous studies related to this research from three perspectives: concept design, conceptual validation, and application effect validation. For the concept design, studies closely related to the envelope concept from physical, psychological, and ethical aspects are introduced. Firstly, the Robot envelope is an idea of separating the activity scope of humans and machines for allowing machines to integrate into human society more smoothly. However, it is an inevitable that people and machines will share the social and spatial environment in the future. To achieve human-machine coexistence, it is not simply to consider the spatial boundaries between humans and machines, but to make machines more considerate of human perceptions and feelings. Secondly, interpersonal space (IPS) describes the psychological division of spaces, which is the theoretical basis for studies on exploring appropriate human-machine distance. However, IPS is a theory to explain phenomena of interpersonal interaction. There are limitations if IPS is directly used in explaining human-machine interaction. When more and more machines as new road users are introduced in public spaces, traditional IPS may be difficult to fully explain pedestrian perceptions. Thirdly, as machines continue to be introduced into people's lives, the topic of the ethical boundaries between humans and machines attracts more attentions from researchers. Although the view of how to protect human autonomy and well-being when people live with machines is controversial, the related studies of this topic are beneficial for considering boundaries of human-machine interaction from multiple perspectives.

For the conceptual validation, the related methodologies and influencing factors of human-machine interaction from the perspective of human attributes, feelings, and subjective view of priority are presented. Among the human attributes, the age, gender, and height of people affect their judgment of the comfortable distance to machines in interactions. It is generally accepted that females, short people, and children prefer to keep a greater distance from machines. People’s cultural differences and their experience with robots also cause people to keep different levels of distance from robots. In addition, the unease and closeness feelings of people to machines affect their perceptions and behaviors in interactions. People will show unease (discomfort, vigilance, or anxiety) when their personal space is invaded by machines, causing them to maintain a greater distance. While increasing the intimacy of machines to people can relieve people’s uneasy feelings and shorten the human-machine distance. Moreover, people's subjective view of priorities is also important. When ICT and machines are widely used in the future society, it will be hard to say that a pedestrian with high-tech equipment always take higher priority over robots carrying valuables. Although the evaluation of future road user priorities is unclear, priority is still an important factor in human-machine mixed traffic. The results of studies of influencing factors in human-machine interactions are still controversial. For example, the finding in some studies get opposite conclusion that children prefer to keep a shorter distance from robots. This research considers that there still are important references for conceptual validation.

For the application effect validation, models referenced in the simulation study exploring the application effects of concept and factors improving simulation reality are introduced. Social force model (SFM) is commonly used to simulate human dynamic behavior to explore traffic phenomena and solve traffic problems, and in human-machine interaction recently. SFM is considered an effective reference model in exploring human-machine mixed traffic. Moreover, to improve the reality of the model, this research refers to visuospatial perception of people, the physical attributes of robots, and the size of the road space as important parameters.

In the following chapters, this research will introduce how to further develop and improve the envelope theorem for mixed traffic based on the contributions and limitations of previous studies, and verify the theorem and its application effect through the social survey and simulation study.

Chapter 3. The envelope theorem

3.1 Introduction

This chapter introduces the contents of envelope theorem. The envelope theorem in this research is proposed to explain the human-machine relationship in the future mixed traffic, which is different from the envelope theorem in mathematics and microeconomics. Section 3.2 describes the definition of the envelope, divided into physical and mental envelopes (PE and ME). The object mental envelope (OME) in ME is the novel idea of this research. Section 3.3 presents the attributes of physical and mental envelopes, including their strength, expressions of the mental envelope, and the relationship between physical and mental envelopes. Section 3.4 presents possible applications of the mental envelope in the future from two perspectives, which is used as the evaluation indicator or the new idea of rule-making. Section 3.5 introduces the envelope theorem for realizing OME and the related proof. Section 3.6 is the summary of Chapter 3.

3.2 The definitions of envelope

The envelope in this research is a division of separating the public space into two relative parts. We initially consider envelope from both physical and mental aspects. In real life, various envelopes such as guardrails, yellow lines, etc. are utilized to maintain safety and traffic smoothness. These envelopes with physical boundaries refer to the physical envelope (PE). Compared with PE, the mental envelope (ME) is considered a psychological division for expressing a pedestrian's comfort and discomfort with others. For instance, people acquire a sense of comfort in interaction through maintaining distance from each other to prevent their personal space from being invaded. This research explains the ME from two perspectives, the subject and object mental envelopes (SME and OME), showing the originality of this research.

In order to clearly explain the definition of SME and OME, the terms subject and object are used. The subject represents the discussed pedestrian who generates ME to the object. The object is the opposite side of the subject in the interaction relationship, which can be a pedestrian or other mobilities, such as a bicycle, robot, electrical scooter, etc. Two perspectives of ME emerge from the mind of the subject. The definitions of the ME from two perspectives are as follows:

1. **Subject mental envelope (SME):** A psychological division in the subject's mind surrounding the body of the subject at a close range (left of figure 3.1).
2. **Object mental envelope (OME):** A psychological division in the subject's mind surrounding the body of an object at a close distance (right of figure 3.1).

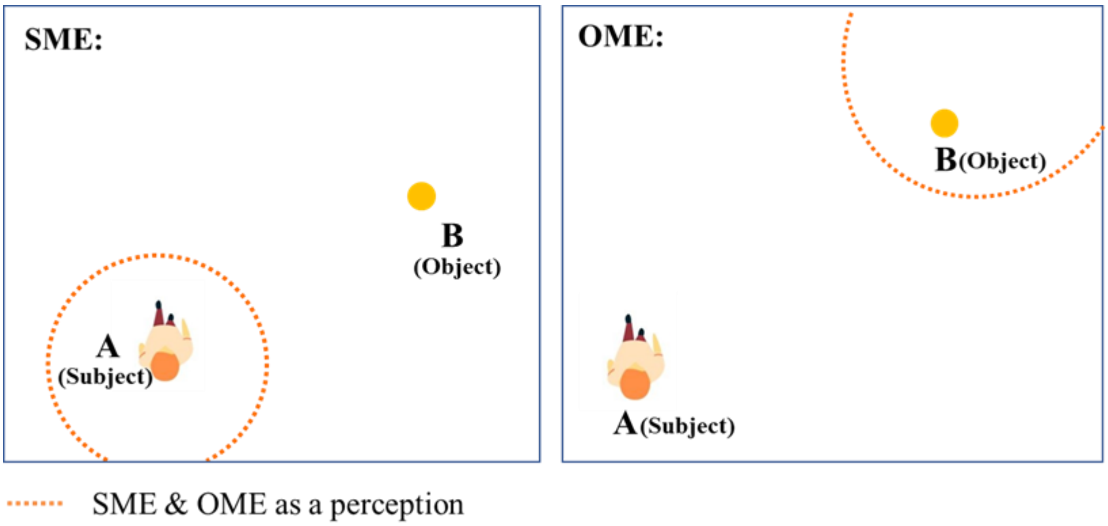


Figure 3.1 The illustration of subject and object mental envelope (SME & OME)

Different pedestrian perceptions are described by SME and OME. SME is feeling around the subject's body, reflecting that the subject does not want the object coming too close to them. For example, pedestrians get nervous when strangers approach them too closely. In this research, SME is regarded as a substitution of IPS (Hall, 1966). Moreover, OME as the opposite feeling to SME shows a feeling of the subject wanting the object to stay away from them as possible. For example, A pedestrian may feel anxious when he/she encounters a dog without a rope and hopes the dog can be restrained or kept away from him/her. OME is a new perspective of this research, which is considered from the object's perspective. Noticing that the circles for expressing SME and OME in figure 3.1 are only used to explain the definitions, not to show the shape and size of ME. At the current research stage, the form of ME is uncertain. The forms of ME would be diverse depending on personal characteristics. The circle as one of the forms of ME is used to easily explain ME's definition.

ME representing the pedestrian perceptions in interactions can be estimated in various ways, such as strength or distance. If the scale of strength is used, the size of ME is related to human perception. For example, the strength of ME will be stronger as the increase in the perceived fear and stress of subjects to objects. It does not occur when subjects do not have any perception of objects. If the scale of distance is used, the size of ME is related to the attributes of the object (size, speed, etc.) or the subject's trust in the object. For example, subjects prefer to keep shorter distances for trusted objects but larger distances for distrusted objects. In the future, different scales of estimating ME will be used depending on the situation. At the current stage, the scale of strength is used in this research.

In this research, both the physical envelope and two mental envelopes are collectively referred to as the envelope theorem.

3.3 The attributes of physical and mental envelope

3.3.1 The strength of physical and mental envelope

This research considers that both physical and mental envelopes (PE and ME) will present different levels of strength. In PE, the stronger the characteristic of the physical border, the stronger the PE. For instance, the walls are quite sturdy, but the bicycle lanes drawn with lines constructed with lines are significantly weaker (upper part of figure 3.2). In ME, strength is used as one of the scales of ME. The more discomfort and attentiveness of people, the stronger the ME. As an example, a pedestrian's ME will be stronger when he/she encounters a bicycle than another pedestrian (lower part of figure 3.2). Hence, people can expect to maintain a greater distance from other road users as ME is enhanced, especially the OME.

In the practical application of ME, the strength of ME is plays an important role in evaluating the discomfort or unease of pedestrians in mixed road environments, and in serving as a judgment foundation when making rules for mixed traffic. The detailed contents are presented in section 3.4.

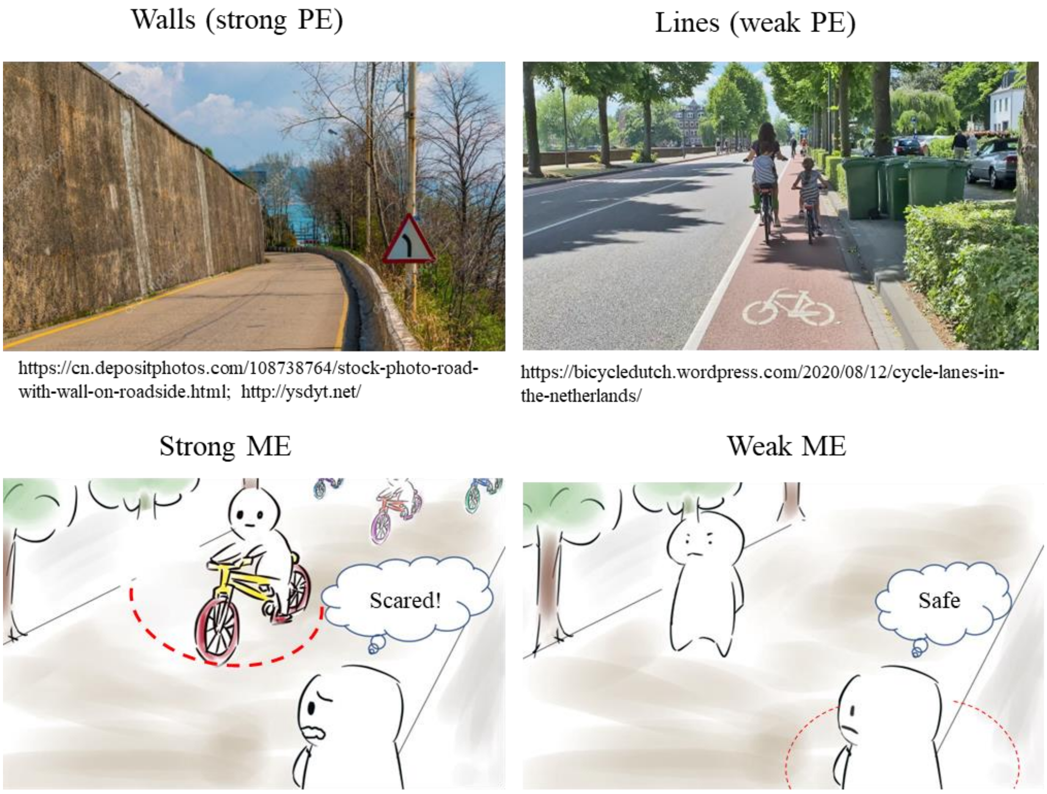


Figure 3.2 Examples: the strength of PE and ME

3.3.2 The expressions of mental envelope

SME and OME in the definition describe different pedestrian perceptions. In order to further explain the perception situations, this research purposes expressions of ME from different aspects. Two related areas of public spaces separated by the boundary of ME present two perspectives of ME's expressions, the enveloped area inside the ME's boundary and the remaining area outside this boundary (Figure 3.3). The perspective of the enveloped area directly reflects the definition of ME, which emphasize the feeling of self-protection from subjects. SME shows the small-scale protection surrounding the body of the subject, indicating that the subject does not want the object to invade its enveloped area. OME expresses the willingness from the subject to restrict the object to a small area from a far distance, implying that the subject doesn't want the object to go out of the enveloped area and come close to him/her. If the object crosses the boundary of ME (the object invades the enveloped area of SME, or goes out of the enveloped area of OME), the subject will feel uncomfortable or threatened.

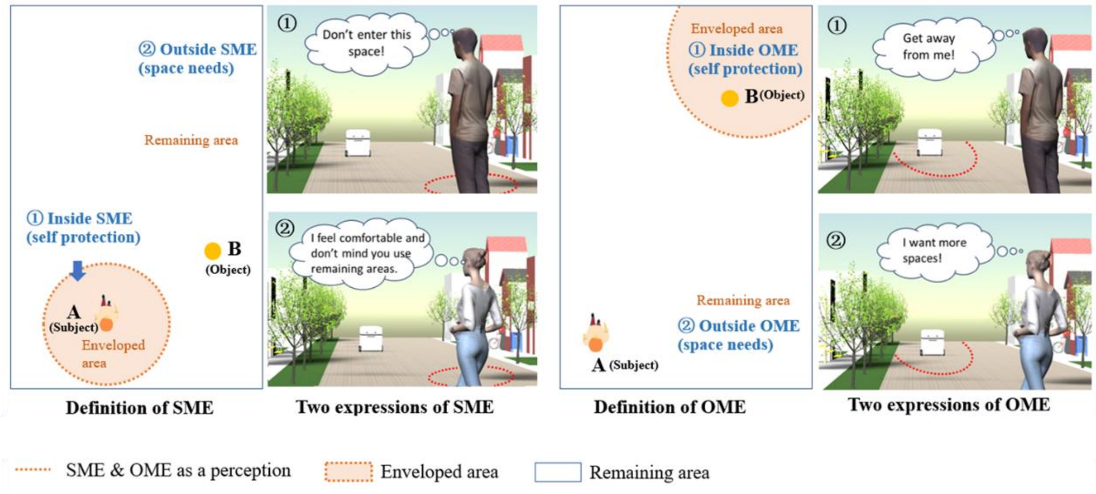


Figure 3.3 The expressions of SME and OME

In addition, the perspective of the remaining area outside ME's boundary reflects the space needs of the subjects. SME shows that the subject feels comfortable and relaxed in a small space surrounding the body, and is less concerned if the object occupies the remaining areas. OME expresses that the subject desire to use the larger remaining spaces while forcing the object to use the small enveloped area.

At the current research stage, we propose that ME's expressions in these two perspectives are sufficient to fully explain pedestrian perceptions in public spaces.

3.3.3 The relationship between physical and mental envelope

This research considers PE and ME can interact with each other. ME as a kind of subjective feeling expresses pedestrian perceptions or views on objects in interactions. When the concept of ME is accepted by the public, it can serve as a basis for human-centered rule-making in society. In order to support rules to be more effective, PE will be used. At this time, PE will reflect rules in society in different forms, such as guardrails, dividing lines, etc. In the future, PE will be expressed in various forms due to the development of technology, such as dividing lines made of light, ICT-based guardrails that can be changed according to traffic situations, etc. When PE is applied for a long period of time in society, it will affect ME again, causing a change in people's perceptions. The changed ME then will generate new rules based on new purposes and social consensus, which will influence PE again (Figure 3.4).

Rule-making in society also conforms to this relationship. For example, people found automobiles are dangerous, so that driveways and sidewalks were divided by guardrails to protect the safety of pedestrians. As the development of safety and self-driving systems in automobiles, people's viewpoints on automobiles will be changed. In this case, guardrails may be unnecessary in the future. Pedestrians and automobiles may share spaces within the constraints of new rules.

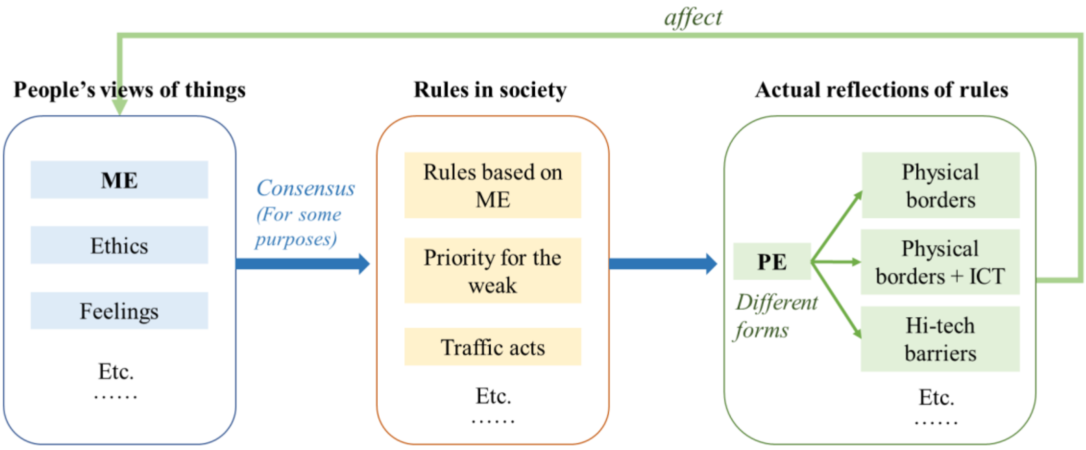


Figure 3.4 The relationship of PE and ME and the rule-making in society

3.4 Possible applications of mental envelope

This research proposes that the concept of ME can be practically used in the future to deal with mixed traffic and provide a safe and comfortable road environment for pedestrians. Two types of ME's applications are considered: MEs are used as indicators for evaluating road quality, MEs are applied as a basis for rule-making.

3.4.1 Mental envelope as indicators

Based on the definitions of ME (section 3.2), this research considers that both SME and OME are potentially useful indicators for exploring interactions among road users and evaluating road quality. In previous studies, IPS has been used as an indicator for clarifying interaction relationships and evaluating space qualities from the discomfort and unease of space invasion (Hall, 1966, Aiello, 1987). ME can also serve similar purposes.

Since the forms of ME are still uncertain, these will be various according to ways of application in the future. For example, a point means that the subject wants the object to stop at a certain point, a line means that the subject does not want the object to cross a certain barrier, or an area means that the subject does not want the object to go out of a particular range. The forms of ME would change depending on conditions. This research introduces one of ideas for presenting ME forms used in the indicator application, which show the strength change of SME and OME in different distance (figure 3.5). SME shows a basic comfort distance of the subject around its body. When the object comes close to the subject, the subject's SME grows stronger and reflects as discomfort and vigilant. OME expresses rejecting feelings of the subject to the object from far distance. As the subject stares at the object, the subject's OME will be constantly become stronger. The detailed explanation of the strength change of OME is as follows: First, when the subject notices the object that he/she is afraid of or feels uncomfortable, OME at first will be relatively weak. Then, if the object approaches the subject, unpleasant feelings of the subject are triggered, OME will become stronger at the next moment. For instance, someone becomes more vigilant and fearful when a dog keeps approaching from afar. Finally, OME disappears when the subject passes through, meaning that he/she cannot perceive the object.

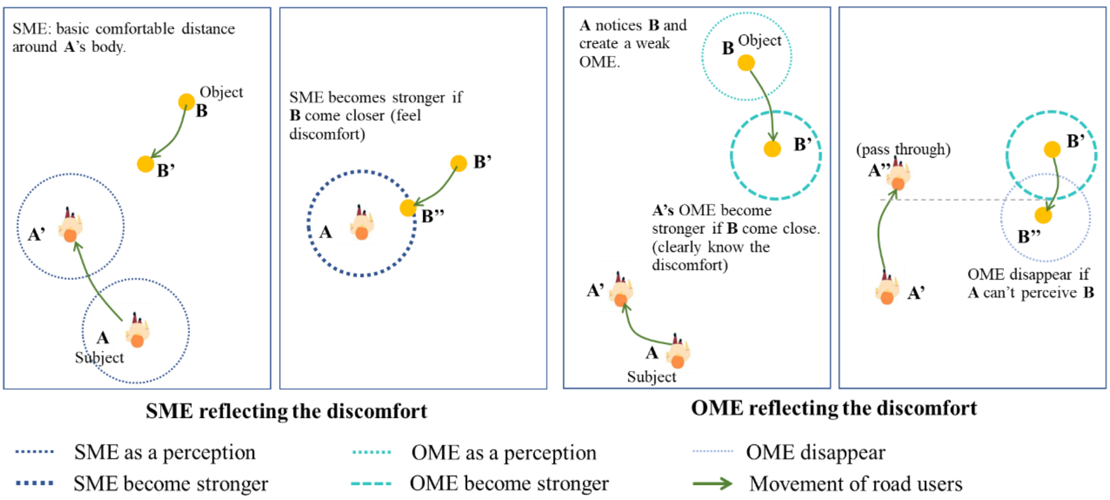


Figure 3.5 The strength changes of SME and OME in interactions

This research considers that using both SME and OME as evaluation indicators in interactions will be more flexible and adaptable than that using the traditional indicator of IPS only (Hall, 1966), which is possibly beneficial to design a comfortable walking environment for pedestrians. The ME's application as evaluation indicators would serve as a reference for developing comfortable walking environments.

3.4.2 Mental envelope as a new perspective of rule-making

Another possible application of ME is used as a theoretical basis for rule-making of mixed traffic in the future. This application requires public consensus (that is, the concept of ME is recognized by people) and advanced technology to connect and transmit information between road users in public spaces, such as the Internet of Things (IoT). Figure 3.6 illustrates how SME and OME apply to rules.

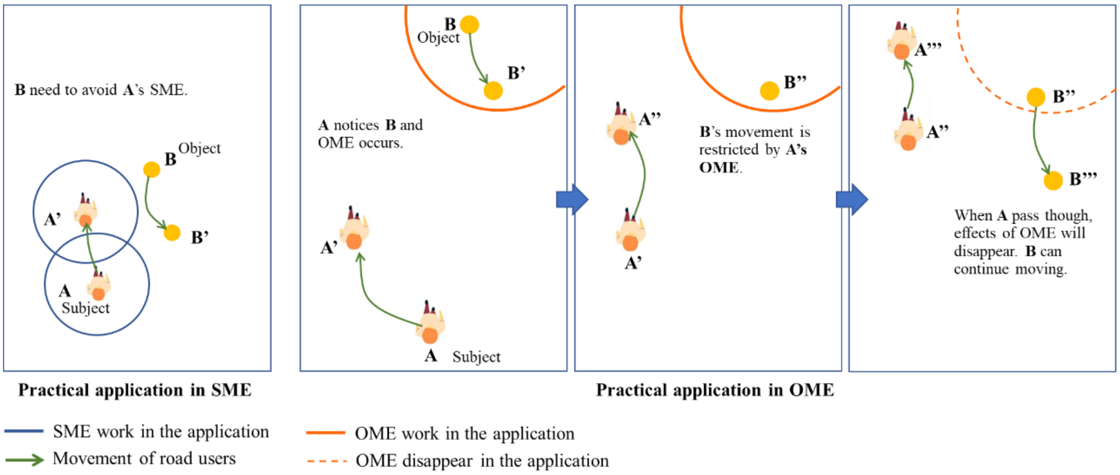


Figure 3.6 The application of SME and OME in rules

If objects follow the rule based on SME, they cannot come close to A's comfortable distance and need to avoid them. If objects follow the rule based on OME, they need to be restrained at far distance until subjects pass through. When rules work, two types of envelopes (divisions of public spaces) with restraining effects will be formed between the subject and the object. The division that encloses the subject in a small area is called subject envelope (SE). The division that constrains the object within a small area is called object envelope (OE). Here, when applying SME and OME in rules, the division produced by SME-based rules is SE, while the division created by OME-based rules is OE. SE and OE work as new types of PE for constraining the movement of road users, which are achieved with rules and advanced technologies. When ME is applied in rules, there will be various forms (SE or OE) showing its effects. For example, a point means that the object perceives the subject's ME and stops moving at a certain point, a line means that the object perceives the subject's ME and moves on the other side of the barrier (object cannot crossing the barrier), or an area means that the object perceives the subject's ME and moves in a particular range. These forms will change depending on the rule settings.

When the concepts of SME and OME apply to rules, considering the priority of mixed traffic is essential. Subjects represent higher priority road users in interactions, who can generate ME. Objects with lower priority need to detect the ME from subjects and be restrained by rules. This research primarily considers vulnerable road users as subjects. When varieties of mobilities increase in public spaces, pedestrians, the most vulnerable road users, may feel more uncomfortable and threatened when walking. In this case, applying ME to future traffic rules is beneficial to ensuring safe and comfortable walking environments for pedestrians. For example, robots detecting pedestrians' ME can avoid or wait for these pedestrians until they pass through. At this time, pedestrians would not cause discomfort due to the invasion of SME or break out of OME.

In the future, the application of ME in rule-making will be beneficial for the development of future mobilities and robots. With the rapid development of advanced technology, machines have gradually begun to integrate into public spaces. In recent years, studies in the robotics field and electric scooter-sharing companies have been trying to use ICT and IoT to improve the safety of mobility devices. For example, beams company uses pedestrian shield technology on electrical scooters, which automatically slows them down to prevent collisions when meeting pedestrians or entering residential areas (Beams, 2022c). However, the application of these new technologies still lacks a suitable theoretical basis for handling new situations. The envelope theorem can serve as one of the theoretical bases for improving their humanization and the feasibility of applying related new technologies. It will contribute to achieving the human-machine coexistence.

3.5 The envelope theorem and related proof

3.5.1 Significance of envelope theorem for realizing OME

According to the definition, OME as a new idea of expressing pedestrian perception shows a feeling of the subject wanting the object to stay away from them as possible. It is a psychological division in the subject's mind surrounding the body of an object at a close distance. OME has physical effects only when applied. The application of OME in rules (section 3.4.2) is considered a method to restrain the movement of the object, which is closely related to priority. This application will be an important reference for securing a safe and comfortable environment for pedestrians in the future human-machine coexistence environment. At current research stage, we preliminarily propose the envelope theorem for realizing OME and provide a simple proof with a mathematical explanation. The simple proof of the theorem considers cases of OME from multiple road users taking effects in public spaces, which shows our idea of future OME applications in more detail, and is instructive for further study of OME.

3.5.2 The contents of theorem and its proof

(1) The envelope theorem for realizing OME:

When objects with effective OME approach each other, if there isn't priority between them, they will stop moving due to the OME taking effect.

(2) Symbols and assumptions as premise:

1. Symbols:

$\boldsymbol{l_i^{OME}}$**:** the distance i's OME (fixed).

$\boldsymbol{L_{i,j}}$**:** the distance between i and j.

$\boldsymbol{minL_{i,j}}$: the minimum value of the distance between i and j.

$\boldsymbol{maxL_{i,j}}$**:** the maximun value of the distance between i and j.

$\boldsymbol{P_i}$ **:** priority between i and j. If i's priority is higher than j, $P_i = 1, P_j = 0$. In this time, i's OME can stop movement of j, but j's OME cannot stop movement of i. If $P_i = 1, P_j = 1$, there is no priority.

$\boldsymbol{CP_{i,j}}$ **:** an imaginary crossing point between i and j (i and j may not colide at $CP_{i,j}$ due to the difference in their speed).

2. Assumptions as premise:

1. Objects will approach each other.
2. For the OME:
   - All the objects' OME will exist and can take effect (objects with effective OME, explained in (2).3).
   - The distance of OME taking effect (l_i^{OME}) is fixed.
   - When an object's OME takes effect, approaching objects will stop moving

when reaching its distance of OME (l_i^{OME}).

- OME takes effect and disappears between two objects ($i\ and\ j$):
  - Before $i\ and\ j$ reach to $CP_{i,j}$, $i\ and\ j$ approach each other and their OMEs are possible to take effect.
  - If j is stopped by i's OME, when i passes the $CP_{i,j}$, j can move again (effect of i's OME disappears).

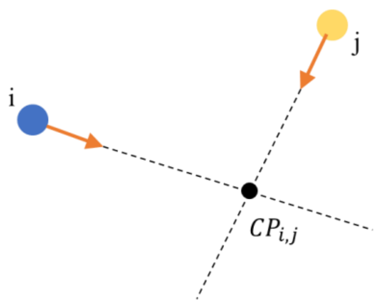


Figure 3.7 The crossing point of $i\ and\ j$

3. Priority shows a mutual relationship between two objects (who has the higher priority between $i\ and\ j$). When there is priority between objects, the OME of the higher priority object can stop the movement of object with lower priority. But the OME of the lower priority object cannot stop the movement of object with higher priority.

3. **Meaning of objects with effective OME:**
   Objects with effective OME means their OME can take effect to stop others. If $minL_{i,j} \leq min(l_i^{OME}, l_j^{OME})$, OME of $i\ and\ j$ can take effect. So, j stop moving when reaching l_i^{OME}, or i stop moving when reaching l_j^{OME}.
   If $min\ L_{i,j} > max(l_i^{OME}, l_j^{OME})$ or $min\ L_{i,j} > min(l_i^{OME}, l_j^{OME})$, OME of $i\ or\ j$ (or both) cannot take effect, meaning that $i\ or\ j$ (or both) cannot reach to l_i^{OME} or l_j^{OME} and be stopped.
   This proof considers the case of objects with effective OME, so: $min\ L_{i,j} \leq min(l_i^{OME}, l_j^{OME})$.

(3) The proof of envelope theorem:

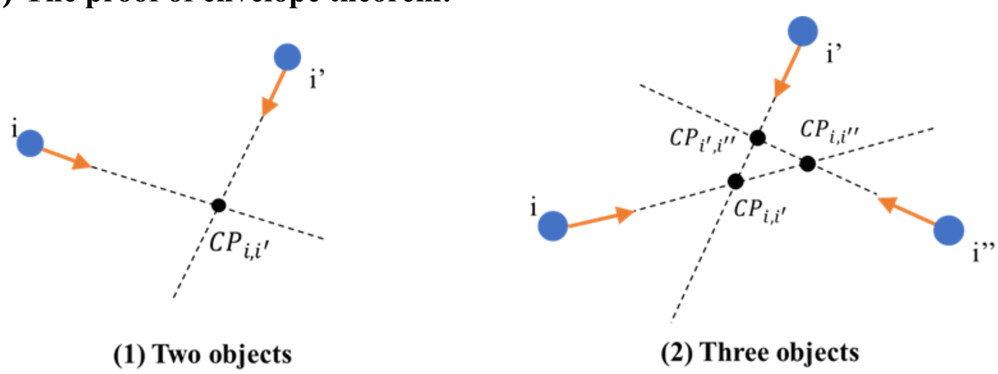


Figure 3.8 Different cases of objects coming close in proof

1. **The case of two objects $\boldsymbol{i, i'}$:**

① **If $\boldsymbol{i, and\ i'}$ without priority,**

$P_i = 1, P_{i'} = 1;\quad minL_{i,i'} \le min(l_i^{OME}, l_{i'}^{OME}),$

a) If $\boldsymbol{l_i^{OME} \ge l_{i'}^{OME}}$:

When $L_{i,i'} = l_i^{OME}$ → i' stops, i keeps moving;

and then $L_{i,i'} = l_{i'}^{OME}$ → i stops,

$i\ and\ i'$ will be stuck and will not move again.

b) If $\boldsymbol{l_i^{OME} \le l_{i'}^{OME}}$:

When $L_{i,i'} = l_{i'}^{OME}$ → i stops, i' keeps moving;

and then $L_{i,i'} = l_i^{OME}$ → i' stops,

$i\ and\ i'$ will be stuck and will not move again.

So, two objects will stop moving and cannot move again if there is not priority.

② **If $\boldsymbol{i, and\ i'}$ with priority: $\boldsymbol{i > i'}$**

$P_i = 1, P_{i'} = 0;\quad minL_{i,i'} \le min(l_i^{OME}, l_{i'}^{OME}),$

a) If $\boldsymbol{l_i^{OME} \ge l_{i'}^{OME}}$:

When $L_{i,i'} = l_i^{OME}$ → i' stops, i keeps moving;

and then $L_{i,i'} = l_{i'}^{OME}$ → i continues moving;

when i passes $CP_{i,i'}$ → i' moves again.

b) If $\boldsymbol{l_i^{OME} \le l_{i'}^{OME}}$:

When $L_{i,i'} = l_{i'}^{OME}$ → i' and i keep moving;

and then $L_{i,i'} = l_i^{OME}$ → i' stops, i continues moving;

when i passes $CP_{i,i'}$ → i' moves again.

So, two objects can move if there is priority: Higher priority object can keep moving. Lower priority object is stopped by OME of higher priority object, and can move again when higher priority object passes the crossing point.

2. **The case of three objects $\boldsymbol{i, i', i''}$:**

① **If $\boldsymbol{i, i', i''}$ without priority,**

$P_i = 1,\ P_{i'} = 1;\ P_{i''} = 1;$

The situations will similar to the proof of 1.① (two objects):

- $\boldsymbol{minL_{i,i'} \le min(l_i^{OME}, l_{i'}^{OME})}$ **($\boldsymbol{i\ and\ i'}$):**

As in the case proved by 1.①, i is stopped when $L_{i,i'} = l_{i'}^{OME}$, and i' is stopped when $L_{i,i'} = l_i^{OME}$. After being stopped, they cannot move again.

- $\boldsymbol{minL_{i,i''} \le min(l_i^{OME}, l_{i''}^{OME})}$ **($\boldsymbol{i\ and\ i''}$):**

As in the case proved by 1.①, i is stopped when $L_{i,i''} = l_{i''}^{OME}$, and i'' is stopped when $L_{i,i''} = l_i^{OME}$. After being stopped, they cannot move again.

- $\boldsymbol{minL_{i',i''} \le min(l_{i'}^{OME}, l_{i''}^{OME})}$ **($\boldsymbol{i'and\ i''}$):**

As in the case proved by 1.①, i' is stopped when $L_{i',i''} = l_{i''}^{OME}$, and i'' is stopped when

$L_{i',i''} = l_{i'}^{OME}$. After being stopped, they cannot move again.
* If i is stopped by OME of i', and then $minL_{i,i'}$ is larger than l_i^{OME}, even though i' cannot be stopped by OME of i, it can still be stopped by OME of i'' (i and i'' continue approaching each other).
So, three objects will stop moving and cannot move again if there is not priority.

② If i, i', i'' with priority (no cyclic order): $i > i' > i''$
The situations will similar to the proof of 1.② (two objects):

- $P_i = 1, P_{i'} = 0$:

As in the case proved by 1.②, i' is stopped when $L_{i,i'} = l_i^{OME}$. And then, i' can move again when i passes $CP_{i,i'}$.

- $P_i = 1, P_{i''} = 0$:

As in the case proved by 1.②, i'' is stopped when $L_{i,i''} = l_i^{OME}$. And then, i'' can move again when i passes $CP_{i,i''}$.

- $P_{i'} = 1, P_{i''} = 0$;

As in the case proved by 1.②, i'' is stopped when $L_{i',i''} = l_{i'}^{OME}$. And then i'' can move again when i' passes $CP_{i',i''}$.
So:
For i'' (the lowest priority object):
i'' is stopped by OME of i and i'.

- As 1.②, $P_i = 1, P_{i''} = 0$, $minL_{i,i''} \le min(l_i^{OME}, l_{i''}^{OME})$:
  When $L_{i,i''} = l_i^{OME}$ → i'' stops,
- As 1.②, $P_{i'} = 1, P_{i''} = 0$, $minL_{i',i''} \le min(l_{i'}^{OME}, l_{i''}^{OME})$:
  When $L_{i',i''} = l_{i'}^{OME}$ → i'' stops,

when i passes $CP_{i,i''}$ and i' passes $CP_{i',i''}$ → i'' moves again.
For i' (the second priority object):
i' is stopped by OME of i.
As 1.②, $P_i = 1, P_{i'} = 0$, $minL_{i,i'} \le min(l_i^{OME}, l_{i'}^{OME})$:
When $L_{i,i'} = l_i^{OME}$ → i' stops,
when i passes $CP_{i,i'}$ → i' moves again.
For i (the highest priority object):
i keeps moving because of its highest priority.
So, three objects can move if there is priority without cyclic order: The highest priority object can keep moving. Lower priority objects are stopped by OME of higher priority objects, and can move again when higher priority objects pass crossing points.

③ If i, i', i'' have priority with cyclic order: $i > i' > i'' > i$
The situations will similar to the proof of 1.② (two objects):

- $P_i = 1, P_{i'} = 0$:

As in the case proved by 1.②, i' is stopped when $L_{i,i'} = l_i^{OME}$. And then, i' can move again when i passes $CP_{i,i'}$.

- $P_{i'} = 1, P_{i''} = 0$;

As in the case proved by 1.②, i'' is stopped when $L_{i',i''} = l_{i'}^{OME}$. And then, i'' can move again when i' passes $CP_{i',i''}$.

- $\boldsymbol{P_{i''} = 1, P_i = 0}$**:**

As in the case proved by 1.②, i is stopped when $L_{i,i''} = l_{i''}^{OME}$. And then, i can move again when i''passes $CP_{i,i''}$.

So,

- As 1.②, $P_i = 1, P_{i'} = 0$, $minL_{i,i'} \leq min(l_i^{OME}, l_{i'}^{OME})$:
  When $L_{i,i'} = l_i^{OME}$ → i' stops,
- As 1.②, $P_{i'} = 1, P_{i''} = 0$, $minL_{i',i''} \leq min(l_{i'}^{OME}, l_{i''}^{OME})$:
  When $L_{i',i''} = l_{i'}^{OME}$ → i'' stops,
- As 1.②, $P_{i''} = 1, P_i = 0$, $minL_{i,i''} \leq min(l_i^{OME}, l_{i''}^{OME})$:
  When $L_{i,i''} = l_{i''}^{OME}$ → i stops,

Since there is no object with highest priority, in this time:

- i'' is stopped by OME of i', i' is stopped by OME of i,
  so that i' cannot pass the $CP_{i',i''}$ → i'' cannot move again,
- i' is stopped by OME of i, i is stopped by OME of i'',
  so that i cannot pass the $CP_{i,i'}$ → i' cannot move again,
- i is stopped by OME of i'', i'' is stopped by OME of i',
  so that i'' cannot pass the $CP_{i,i''}$ → i cannot move again,

they will be stuck and will not move again.

So, three objects will stop moving and cannot move again if there is priority with cyclic order.

The cases of more than three objects are similar to the above proof:

- **If objects without priority:** all the objects will be stopped and cannot move again.
- **If objects with priority (no cyclic order):** objects can move. The highest priority object can keep moving. Lower priority objects are stopped by OME of higher priority objects, and can move again when higher priority objects pass crossing points.
- **If objects have priority with cyclic order:** objects will be stopped and cannot move again.

These will be not enumerated here.

Therefore, objects with effective OME will be stuck if there is no priority. Maintaining the movements of these objects requires priority without cyclic order at least.

OME may take effect other than the premise of this proof, which is not proofed at the current research stage. This will be further explored in future study.

3.6 Summary

This chapter introduces the related contents of the envelope theorem. From the definition of the envelope theorem, it is divided into physical and mental envelopes (PE and ME). In the ME, the subject mental envelopes (SME) and object mental envelope (OME) are classified to explain the pedestrian perceptions from different angles. These two MEs have expressions on spatial relationships in human-machine interaction from the perspectives of self protection and space needs. For the future applications of ME, there are two aspects. For one, ME is used as an indicator exploring interactions among road users and evaluating road quality from different perspectives, which is more flexible and adaptable than that using the traditional indicator of IPS only. For another, ME is used as a new perspective of rule-making. When ME is applied to rules, the effects of rules will be expressed as subject envelope (SE) and object envelope (OE). Moreover, for explaining the idea of future OME applications in more detail, this research preliminarily proposes the envelope theorem for realizing OME and provide a simple proof with a mathematical explanation. The simple proof of the theorem will be instructive for further study of OME. In the future, the applications of ME will be beneficial for the development of future mobilities and robots, which can improve their humanization for contributing to achieve the human-machine coexistence.

Chapter 4. The empirical evidence for the existence of mental envelope

4.1 Introduction

This research proposes the SME and OME to explain perceptions of pedestrians from different perspectives expanding the traditional IPS (Hall, 1966). However, OME as a new perspective may have not been realized by people. This research uses a questionnaire survey to preliminarily explore the existence of OME, demonstrating that OME as another explanation of pedestrian perception is acceptable to the public in Japan. The term "existence" in this research means the perceptual existence in people's mind, rather than physical existence as things. For the existence of OME, if a person has the feeling of OME, it exists in his/her mind. If a person does not have this feeling, OME does not exist in his/her mind. Some possible influencing factors as indices are also considered to explore the characteristics of OME. Meanwhile, the acceptance and characteristics of SME are investigated for comparing with OME and reverifying the results of previous studies (explaining SME can be the substitution of IPS). Furthermore, the influencing factors are used to further observe the difference between SME and OME and their structural relationships. The results of the questionnaire survey and related analysis will provide the basis for future explorations of ME's existence and applications.

Therefore, this chapter focuses on the preliminary verification of the existence of OME and the relationship between MEs and the influencing factors. Section 4.2 presents the methods of data collection and possible analytical methods. Section 4.3 shows the results of public acceptance of SME and OME in different interaction situations. Section 4.4 expresses the effects of different influencing factors on SME and OME. Section 4.5 explores the structural relationship between two MEs and their influencing factors. Section 4.6 explains the limitation of the questionnaire survey. Section 4.7 is the summary of chapter 4.

4.2 Data collection and analytical methods

4.2.1 Possible influencing factors of mental envelope

Some possible influencing factors are used to observe the characteristics of ME. In the definition of ME mentioned in section 3.2, SME is the substitution of IPS, while OME is the original idea of this research. Therefore, it is assumed that the factors affecting IPS in previous studies influence both SME and OME. Moreover, in order to make a basis for the exploration of future applications of MEs, the priority is also considered an important influencing factor. The detailed contents are as follows:

1. **Negative emotions (danger and stress):**
   People's negative emotions, such as discomfort and hostility, as intuitive expressions in interactions, are commonly used to explore human perceptions. Hall (1966) and Aiello (1987) mentioned in the characteristics of IPS that people feel uncomfortable, angry, or anxious when their IPS is invaded. Many researchers mentioned in section 2.3.2 tried to investigate the suitable distance in interpersonal and human-machine interactions by stimulating people to generate stress or be alert, such as Takayama and Pantofaru (2009), Lauckner, et al. (2014), Hasegawa, et al, (2018), Iachini, et al, (2014), and Pham, et al, (2015). Therefore, in the questionnaire, questions for estimating the level of stress and danger perceived by participants toward different road users are set.

2. **The closeness (friendly and experience):**
   Previous studies of interpersonal and human-machine interactions (section 2.3.2) confirmed that the friendliness and familiarity (interaction or association experience) people feel can affect IPS, which will shorten the distance between people or people and machines. Familiarity reduces the tendency of maintaining distance to compensate for insufficient control in interpersonal interactions. People are more likely to keep closer distances with friends than with strangers (Hayduk,1983, Edney, et al, 1976). In addition, some robotics experiments show that people keep shorter distances from robots when their interaction experience increases or when robots show friendly behaviors, such as smiling, speaking with gestures, wearing clothes, etc. (Mead and Matarić, 2016, Iachini, et al, 2014, Haring et al, 2013, Kim, et al, 2013). Hence, in the questionnaire, we consider the questions about the friendly that participants feel from road users and the experience of walking with road users.

3. **The personal attributes (age, gender, body height):**
   Personal attributes as important factors are commonly employed in many interaction experiments. The previous studies (section 2.3.1) demonstrated that IPS varies by gender, age, and body height. For example, males are more likely to keep shorter distances to other people than females (Aiello, 1987, Aliakbari, et al., 2011, Hecht, et.al, 2019). Also, females maintain more distance and show defensive behaviors when meeting machines (Iachini, et al, 2014, Takayama and Pantofaru, 2009, Lauckner et al., 2014). In addition, shorter people or elders tend to show softer and closer distances with other people in interactions. (Aiello, 1987, Webb and Weber, 2003, Okita, et.al, 2012, Hecht, et.al, 2019, Iachini, et.al, 2016). Thus, in the questionnaire survey, personal attributes of age, gender, body height, and body strength will be asked to participants.

4. **Comparison factors (body strength and attention):**
   This research also considers two comparison factors, the body strength of the pedestrian compared with the encountered road user, and their attention to the encountered road user. Previous studies (section2.3.1 and section 2.3.2) proved that people prefer to keep a farther distance from people who have higher and stronger bodies than they own (Aiello 1987, Caplan and Goldman, 1981, D'Angelo et al., 2019). Additionally, the greater the difference in body strength, the farther the distance that people maintain in interactions. For example, children will keep a greater distance from an adult-sized robot (175cm high) than from a robot with a similar body of its own (112cm high) (van Oosterhout and Visser, 2008). The effect of human attention on encountering road users is also considered. In general, people care more about encountering road users when they have negative emotions about it, but pay less attention to them if these users express friendly and closeness. We assume that human attention will influence ME.

5. **The subjective priority order:**
   This research considers that priority order is an important factor in exploring the characteristic of ME. In previous studies (section 2.3.3), road priority has been used to solve traffic congestion, coordinate the relationship between different transportation modes and achieve new social goals (Eva and Andrea, 2019, Ma, et al., 2010, He, et al., 2014, Santos-González, et al, 2019). In interactions in public spaces, it is significant to explore people's subjective viewpoints of priority, which is beneficial to the further exploration of ME’s applications in future rule-making. In the questionnaire survey, participants will evaluate vulnerable road users subjectively (rank the priority order of different road users), which is used for preliminary understanding the subjective priority order of people in mixed traffic.

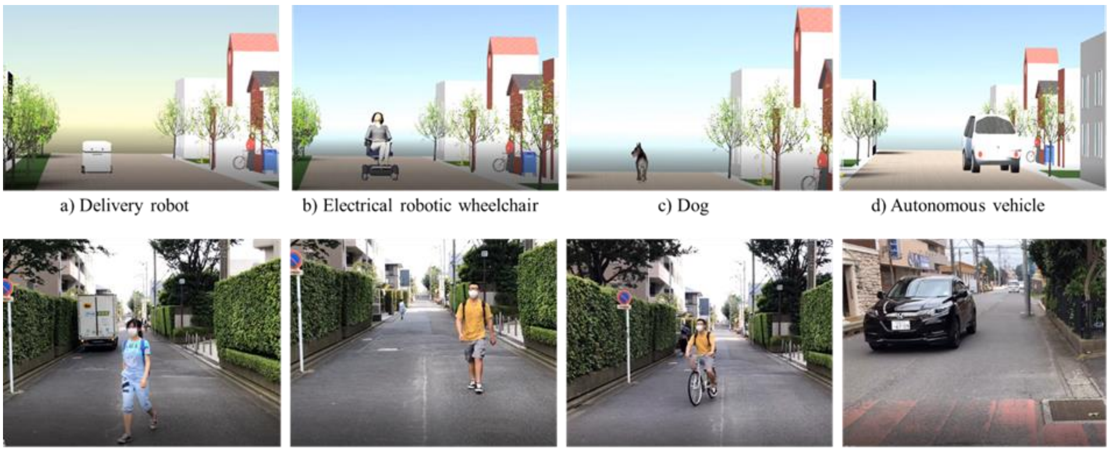
Therefore, the following factors will be set as observation questions in the questionnaire: two unease feelings (danger and stress), two closeness feelings (friendly and experience), three personal attributes (age, gender, and body height), priority, and two contrast factors (body strength and attention).

4.2.2 Data collection: questionnaire survey

An online questionnaire survey was carried out to investigate pedestrian perceptions in various scenarios. Many previous studies have been used questionnaire surveys with pictures, videos, or virtual scenes to explore human perceptions in pedestrian-cyclist mixed traffic (Kang and Fricker, 2016, Jensen, 2007, Kang, et.al, 2013, Herrero-Fernández, et.al, 2020, Miller, et.al, 2000). It was found that this approach is effective and can be used to know the views of participants when sharing spaces with existing and future mobilities in this research. In the preparation of this survey, two pretests were conducted in order to confirm the effectiveness and difficulty of questions. 15 university students and staff completed the questionnaire of each test and provided feedback and comments. From August 25th, 2020 to August 29th, 2020, the final version of the questionnaire was distributed on a website with a crowdsourcing service named Lancers (https://www.lancers.jp/). To avoid the influence of cultural differences, target respondents were all the Japanese in their native country in different age groups. Eligible website users were randomly selected. Finally, answers from 292 respondents were used as valid data. After completing the full tasks of this survey, every participant can get 200 JPYs as remuneration.

The questionnaire is divided into four parts. The first part uses a video with simple descriptions to let participants easily understand the background of future transportation and the purpose of this survey. In this video, the definition of SME and OME do not be explained directly. We use the personal distance to lead the topic of pedestrian perceptions and show some pictures and animations to express the possible psychological situations in interactions. This video helps participants to imagine the environment of human-machine coexistence before answering questions. The information about personal space and pedestrian perceptions can also support them to understand the related questions about different interactions. The second part collects demographic information from participants, including age, gender, body height, and living region.

The following two parts mainly ask the questions of pedestrian perceptions and their influencing factors in feelings. In the third part, there are eight scenarios showing representatives of existing and future road users (Figure 4.1). The female and male pedestrians, bikes, and private cars scenarios are representatives of existing road users. The robots, electrical robotic wheelchairs, autonomous vehicles (AVs) scenarios present future road users with different characteristics. Delivery robots reflect automatic mobilities with the fully attributes of machines. Electrical robotic wheelchairs represent automatically slow devices with passengers, which is considered a traffic mode between driving and walking. AVs is a representative of automatically quick vehicles. The dog scenario is an unusual case to obviously observe pedestrian perceptions. In addition, both real videos and virtual animations are used to simulate different interaction situations in a public space. Virtual scenes show situations of walking with future road users and the specific situation (dog). Real videos display situations of walking existing road users. In the future, there will be many different types of mobilities and robot. Hence, we selected the eight scenarios showing in figure 4.1 to prevent the questionnaires from being too cumbersome.



a) Delivery robot b) Electrical robotic wheelchair c) Dog d) Autonomous vehicle

e) Pedestrian (female) f) Pedestrian (male) g) Bike h) Private car

Figure 4.1 Eight scenarios used in the questionnaire

The scenarios in the questionnaire are some inescapable limitations. Foremost, responses from participants may be different if visual materials of each type of road users are changed. We make efforts to reduce the response bias and receive general responses as much as possible as follows:

a. Common materials in scenarios rather than extreme materials (such as fierce dogs or cars with fast speed) are used.
b. For guiding participants to imagine the common situations in public spaces and avoid them paying too much attention to specific appearances of objects in videos, pictures of road users with different appearances beside videos or animations in scenarios are set.

c. Before participants answering questions, some messages can remind them again to imagine situations of walking with different road users combining videos and pictures.

Furthermore, to reduce the influence of orders of presenting scenarios on responses, the virtual scenarios (such as robots and AVs) and real (such as pedestrians and bikes) scenarios are displayed alternately in the questionnaire.

In order to explore the acceptance of ME, four perception questions in the third part will be asked after showing all the visual materials of each scenario. The perspectives of self-protection and space needs based on ME's expressions in the definition (section 3.3.2) are described by simple words. From the perspective of self-protection, questions explain the feeling of keeping comfortable distance at close range and the willingness to restrain movements of road users far away. The questions are (* PS: personal space, DO: distant objects):

a. **QPS:** Do you agree with this view: "I don't want this (road users in scenarios) to enter my personal space (less than 1m)."?
b. **QDO**: Do you agree with this view: "If it is possible, I hope this can keep far away from me or stop moving."?

From the perspective of space needs, questions inquire about the comfortable feeling when staying in small or large spaces. The questions are (*US: usable space):

a. **QUS-small**: Do you agree with this view: "As long as my personal space is not occupied, this can use the remaining spaces."?
b. **QUS-large**: Do you agree with this view: " If it is possible, I hope this will be confined to a small space that far away from me, so that I can use the remaining spaces freely."?

Moreover, in order to understand the impressions of road users from participants in scenarios, six different emotions are asked:

a. **Stress:** do you feel stressed when encountering this?
b. **Friendly:** do you think this is friendly?
c. **Comparison of body strength:** do you think the body of this is stronger than yours?
d. **Danger:** do you feel dangerous when encountering this?
e. **Experience of walking with road users:** do you have experience of walking with this?
f. **Attention:** do you care about this?

In order to observe the relations between feelings and the influence of personal preferences, we set up favorite-related questions in the dog and robot scenarios, that is, do you like dogs? And are you interested in robots?

All the questions in the third part use the five-point Likert scale (Likert, 1932), a widely used approach of scaling responses, **(1: disagree; 5: strongly agree)**, which is as a relatively simple scale to allow participants to understand the intent of questions and answer them as easily as possible. The results are analyzed after considering of scale's limitations.

The fourth part investigates the views of subjective priority order. Participants are required to rank the priority order for eight types of road users showing in the pictures. The eight road users are: elders, children, adults, robots, bikes, autonomous vehicles, electrical robotic wheelchairs, and private cars. The higher the score chosen by participants, the lower the priority of road users **(1: the highest priority; 8: the lowest priority).**

The virtual scenes of scenarios in the questionnaire are made by using SketchUp 2016 and Unity 2019. The real scenes are taken with the assistance of students in this laboratory. All the videos are edited by the Windows movie maker.

4.2.3 Analytical methods

The data analysis of this survey consists of four parts. First, the descriptive statistics is used to preliminary understand the characteristics of participants and their views of road users in different scenarios. Second, we use the cross-tabulation analysis to extract responses of acceptance of SME and OME and get five accepter groups of ME based on the ME's definitions. The accepter groups are used to further observe the difference of SME and OME in eight scenarios. Third, differences in SME and OME are further investigated by evaluating influencing factors using the multinomial logistic regression model. Forth, the structural relationships of ME and their influencing factors are explored by the structural equation modeling. All the analyses are conducted with R (4.0.2).

4.3 Analysis of acceptance of mental envelope in publics

4.3.1 Participant characteristics

In the dataset of the survey, 57.19% of participants are males, and 42.81% are females. The age of participants varied in age from 18 to 76 years old. The majority of participants are between 30 and 49 years of age. (69.18%). And some small groups age between 18 and 29 years old (11.3%) and over 60 years old. (4.79%). The average body height of participants is between 161 and 170 cm (36.64%). Most of the participants are from the Kanto area of Japan (39.38%). Table 4.1 shows the characteristics of respondents in detail.

Table 4.1 Participant characteristics in the survey

		N	%			N	%
Gender	Male	167	57.19%	Area	Hokkaido	18	6.16%
	Female	125	42.81%		Tohoku	10	3.42%
Age	18~29	33	11.30%		Kanto	115	39.38%
	30~39	101	34.59%		Chubu	52	17.81%
	40~49	101	34.59%		Kinki	42	14.38%
	50~59	43	14.73%		Chugoku	17	5.82%
	60~	14	4.79%		Shikoku	7	2.40%
Height	~160cm	94	32.19%		Kyushu	31	10.62%
	161~170cm	107	36.64%				
	171~180cm	84	28.77%				
	181cm~	7	2.40%				

Total number of respondents: 292

Table 4.2 shows the means of responses in the questions of different influencing factors. In the comparison to the results on feeling questions, participants have more negative emotions (stress and danger) and pay more attention when encountering road users that are stronger than themselves. They have much lower experience for future road users (robot, electrical wheelchair, and AV) than for existing road users (pedestrians, bike, and private car). Moreover, differences in participants' views of dog scenario are founded. Participants feel more dangerous and stressed when encountering the dog than pedestrian, but also feel more friendly. This is because different participants have different preferences for dogs. Figure 4.2 (left) shows the favorability of participants in dog scenarios. Participants who did not like dogs would feel more afraid, and those who like dogs would feel more friendly. But the results in the robot scenario does not show the significant effect of people's preference on negative emotions (figure 4.2 right). The reason may be that people have less experience on interacting with robots and tend to use impressions such as appearance to evaluate them. We consider that responses are reasonable and in line with reality.

Table 4.2 Means of responses in influencing factors

	stress	danger	strength	attention	friendly	experience	priority
pedestrian(female)	2.09	2.32	1.82	3.28	1.69	3.90	1.18
pedestrian(male)	2.75	2.64	3.20	3.39	1.97	3.99	1.19
electrical wheelchair	2.50	2.82	2.72	3.95	2.46	1.76	4.02
bike	3.12	3.54	3.59	4.14	2.17	3.82	4.91
robot	2.72	2.86	2.85	3.87	2.60	1.19	6.37
car	3.51	4.17	4.78	4.54	2.07	3.80	6.79
autonomous vehicle (AV)	2.85	3.66	4.54	4.25	2.35	1.49	6.89
dog	2.86	3.18	3.24	3.92	3.02	3.17	N/A

*Scores in questions of unease and closeness:**1 (disagree) ~ 5 (strongly agree)***

*Scores in the question of priority: **1 (the highest priority) ~ 8 (the lowest priority)***

**Significant differences between scenarios when: stress:>0.29(p<0.05); danger: >0.27(p<0.05); strength:>0.26(p<0.05); care:>0.23(p<0.05); friendly:>0.25(p<0.05); experience:>0.23(p<0.05); priority:>0.28(p<0.05)*

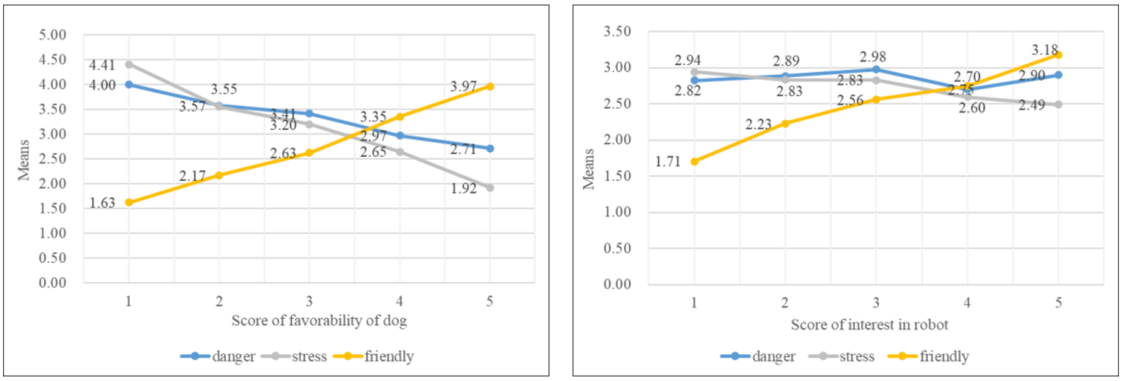


Figure 4.2 the effects of favorability in other feelings (dog and robot scenarios)

Moreover, the means between different scenarios are pairwise compared for each influencing factor. Based on the statistical significance test, mean values of scenarios between robot and electrical wheelchair, and between bike and AV have less differences in stress, danger, strength, and attention. The responses on future road users are less different in friendly and experience questions. Additionally, in the question of ranking priority for road users, there is less difference between private car and AV scenarios. The responses show the priority order determined by subjective values of participants.

The subjective priority order for road users tend to (from high to low): pedestrians (1.18, 1.19) > electrical wheelchairs (4.02) > bicycles (4.91) > robots (6.37) > cars (6.79) > AVs (6.89). Dog is not included in the priority question.

4.3.2 Data extraction: Cross-tabulation analysis

Four perception questions answered by participants are extracted for exploring the acceptance of SME and OME. We conduct the cross-tabulation analysis twice for extracting effective responses and checking logical contradictions based on the ME's expressions (mentioned in section 3.3.2). In the first cross-tabulation analysis, responses of four perception questions are divided into two categories from different perspectives. Category 1 presents the ME's expression of self-protection through QPS and QDO questions. Category 2 shows the ME's expression of space needs by QUS-small and QUS-large questions. Table 4.3 presents the interpretation.

Table 4.3 The cross-tabulation of perception questions in two categories

Category 1 (5 levels)		Q_{DO}: others	Q_{DO}: strongly agree
		1 2 3	4 5
Q_{PS}: others	1 2 3	not care	logical contradiction
Q_{PS}: strongly agree	4 5	subject awareness	object awareness

Category 2 (5 levels)		$Q_{US\text{-}large}$: others	$Q_{US\text{-}large}$: strongly agree
		1 2 3	4 5
$Q_{US\text{-}small}$: others	1 2 3	not care	object awareness
$Q_{US\text{-}small}$: strongly agree	4 5	subject awareness	object awareness

Responses scored by the five-point scale are separated into two groups. Answers of 4 and 5 points indicate a strong agreement with the descriptions in questions. Responses of 1 to 3 points show weak agreement and disagreement with them. We extract the perceptions of "not care", "subject awareness" and "object awareness" into two categories. In category 1 (self-protection expression), subject awareness shows that the participants do not want road users to invade the comfortable spaces surrounding their bodies. Object awareness expresses the willingness of maintaining far distances with road users or limiting their movements. One logical contradiction is found in category 1, showing the inconsistent view that participants strongly want road users to stay far away from them for protecting the safety, but don't feel unpleasant if these road users approach or enter their personal space at the same time. In category 2 (expression of space needs), subject awareness presents the comfort of staying in small spaces surrounding bodies. While object awareness expresses the desire of getting more spaces they can freely use. According to the descriptions of perception questions (mentioned in section 3.3.2), participants with strong agreements in both QUS-small and QUS-large questions are possible. They may think it is comfortable in small spaces currently and preferable in larger spaces if these are available. This viewpoint still presents a tendency of generating object awareness in the expression of space needs. Responses with a low score of perception questions in two categories indicate that participants do not care about road users.

In the second cross-tabulation analysis, another logical contradiction between the two categories is found (Table 4.4). Based on the definition of ME and its expressions, object awareness in category 1 and subject awareness in category 2 cannot generate simultaneously (see the number of 62 in table 4.4). The contradictory idea shows that participants desire to keep far away from road users or limit their movements (worry about road users approaching them), but allow them to freely use remaining space other than their personal space at the same time (do not mind road users approaching them). Furthermore, table 4.4 expresses the count of cross-tabulation (total number of 8 scenarios: 2336 answers). Two cross-tabulation analyses reject 93 (3.9%) answers with logical contradiction. The remaining responses are used to further extract the acceptance of SME and OME by considering meanings of different awareness in two categories.

Table 4.4 The count of cross-tabulation between two categories

		Category 1 (Q_{PS}, Q_{DO})			
		Not care	Logical contradiction	Subject awareness	Object awareness
Category 2 ($Q_{US\text{-}small}$, $Q_{US\text{-}large}$)	Not care	369	*12**	314	164
	Object awareness	18	*7**	70	287
	Object awareness	31	*5**	60	121
	Subject awareness	493	*7**	316	*62**

**: Answers with logical contradictions.*

After eliminating logical contradictions in data set, the meanings of SME and OME are further extracted from the combinations of different awareness in two categories (table

4.5). Based on the definitions of ME, SME as a substitution of IPS represents an existing pedestrian perception around their bodies. OME as a novel idea of this research will be discovered preliminarily in this questionnaire survey. In order to observe all the possible situations of OME, the combination as long as object awareness will be deemed to have a tendency of generating OME. In addition, the meanings of all the SME and OME situations are explained by using the ME's expressions from two perspectives (self-protection and space needs). Table 4.5 shows the results.

Table 4.5 Extraction: count and meaning of accepting SME and OME

Category 1	Category 2	Counts	Meaning	ME	Group
not care	not care	369	don't agree with both SME and OME perceptions.	Not accept	Not accept
not care	subject awareness	493	stay in a small space is comfortable	SME-1	SME-weak accepters
subject awareness	not care	314	only don't want personal space to be invaded, not care how much free space can be used.	SME-2	SME-strong accepters
subject awareness	subject awareness	316	fully want to stay in a small space.	SME-3	
not care	object awareness	49	want to use larger free space	OME-1	OME-weak accepters
subject awareness	object awareness	130	don't want personal space to be invaded, and have the willingness of larger free space.	OME-2	
object awareness	not care	164	only want to get protection by keeping far away from objects, not care how much free space can be used.	OME-3	OME-strong accepters
object awareness	object awareness	408	fully want to keep far away from the object.	OME-4	

** Total responses of SME: 1123*

** Total responses of OME: 751*

** Total responses of not accept: 369*

In the SME situations, SME-1 expressing the comfort of staying in small areas indicates the expression of space needs. SME-2 and SME-3 that reject road users outside personal spaces surrounding bodies of people show the expression of self-protection. In the OME situations, OME-1 and OME-2 presenting the willingness of receiving large spaces that can be freely used represent the expression of space needs. OME-3 and OME-4 describe the expression of self-protection through the expecting of restraining road users and keeping far away from them. The strength of SME and OME is also considered. based on the definition of ME, we think that the expression of ME in self-protection will be stronger than the expression in space needs (self-protection shows greater discomfort and vigilance to road users). Thus, responses are classified into five accepter groups. SME-1, OME-1, and OME-2 (the expression of space needs) are divided into SME-weak and OME-weak accepters. SME-2, SME-3, OME-3, and OME-4 (the expression of self-protection) are separated into SME-strong and OME-strong accepters. Responses that don't care about both SME and OME perceptions are classified as the not accept group.

4.3.3 Descriptive statistics for accepters of mental envelope

Descriptive statistics are utilized to observe differences in acceptance of SME and OME among responses of five feeling factors and eight scenarios. The results in table 4.6 are used to determine whether responses of feeling factors in accepter groups meet ME's definitions or not.

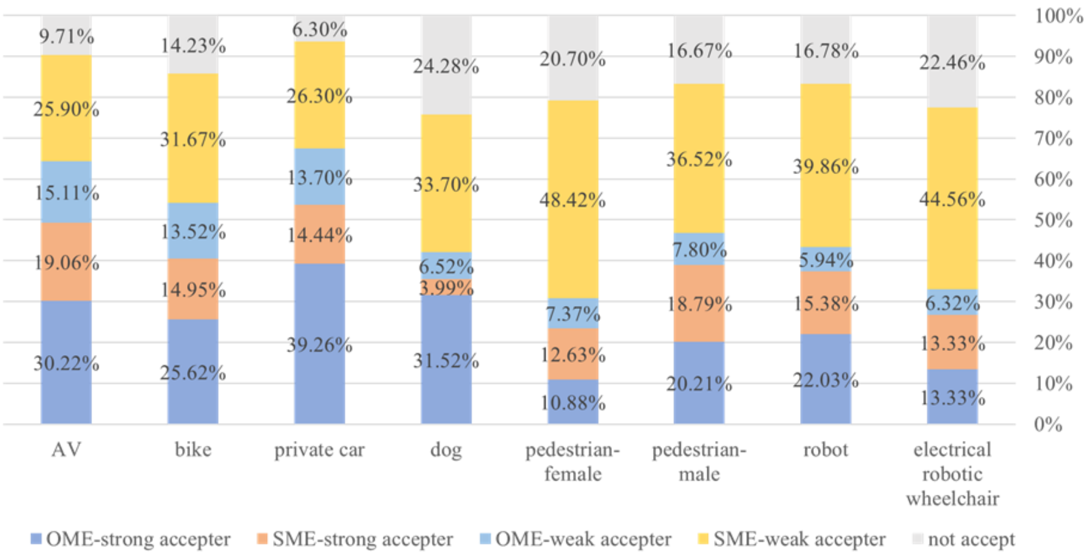
Table 4.6 Descriptive statistics of ME's acceptance in feelings

	stress		danger		friendly		body strength		attention	
	m	SD	m	SD	m	SD	m	SD	m	SD
not accept	2.08	0.90	2.51	0.99	2.38	1.07	2.70	1.24	3.28	0.96
OME-strong accepters	3.98	1.04	4.12	1.13	1.97	1.07	4.13	1.12	4.57	0.62
OME-weak accepters	3.15	1.09	3.29	1.07	2.30	1.08	3.40	1.32	3.99	0.94
SME-strong accepters	2.80	1.07	3.14	1.16	2.18	0.98	3.61	1.31	4.06	0.91
SME-weak accepters	1.75	0.88	2.38	1.01	2.73	1.31	2.46	1.26	3.38	1.08

** m: mean values; SD: standard deviation*

From the definition of ME, we assume that pedestrians would perceive more negative emotions if generating stronger MEs. They would have more discomfort if creating

OME than if creating SME. Table 4.6 shows that the mean values of stress and danger from OME-strong accepters (stress: 3.98, danger: 4.12) and SME-strong accepters (stress: 2.80, danger: 3.14) are respectively greater than that from OME-weak accepters (stress: 3.15, danger: 3.29) and SME-weak accepters (stress: 1.75, danger: 2.38). Also, scores of these negative emotions (stress and danger) in OME accepters are higher than that in SME accepters. In addition, the means of body strength and attention feelings related to negative emotions have a comparable tendency on outcomes. Therefore, the responses of five accepter groups are reasonable and consistent with the definition, which can be used in the following analyses.



**Chi-square test (no statistic significance if change of the percentage is less than the following data):*
OME-strong accepter: <8% (p>0.05); OME-weak accepter: <5%(p>0.05)
SME-strong accepter: <6.5% (p>0.05); SME-weak accepter: <9% (p>0.05); not accept: <7% (p>0.05)

Figure 4.3 Acceptance of SME and OME in eight scenarios

In order to determine the distribution of five accepter groups in eight scenarios, the counting statistics with chi-square tests are applied (figure 4.3). From the results of the chi-square test, the percentage difference (pd) among scenarios in each accepter group is not statistically significant if the following conditions occur: the group of OME-strong accepter: pd<8% (p>0.05); the group of OME-weak accepter: pd<5% (p>0.05); the group of SME-strong accepter: pd<6.5% (p>0.05); the group of SME-weak accepter: pd<9% (p>0.05); the group of not accept: pd:<7% (p>0.05). For instance, the percentage difference (pd) in OME-strong accepters between the bike scenario (25.62%) and the AV scenario (30.22%) is 4.6% (pd<8%, p>0.05). In this case, the difference in the number of OME-strong accepters between these two scenarios is not statistically significant. Figure 4.3 shows that the proportions of OME accepters among different scenarios change more dramatically than that of SME accepters. The proportions of five accepter groups of both SME and OME are similar in pairwise comparisons of some scenarios, such as scenarios between AV and bike, and scenarios between pedestrian (female, male) and electrical robotic wheelchair. Moreover, the responses from OME-strong accepters in the AV scenario and private car scenario are significantly different from most other scenarios. But their responses in the dog scenario are less different from theirs. In addition, the results of comparing scenarios between robot and male pedestrian (1.82%, $p>0.05$), and scenarios of robot and bike (3.59%, $p>0.05$) are not significantly different. And it is worth noting that although AVs and private cars share similar characteristics, the responses of OME-strong accepters differ significantly (9.04%, $p<0.05$). The responses from the SME-strong accepters in the bike, AV, and private car scenarios are not much different from that in other scenarios. However, their responses in the dog scenario have significant differences to them.

4.3.4 Subjective priority order

In order to explore the relationship between subjective priority order and ME, this survey ask participants for ranking road users depicted in pictures, including elder, child, adult, electrical robotic wheelchair, robot, AV, bike, and private car. Table 4.7 shows the means of ranking results of different road users from five accepter groups.

Table 4.7 Means of subjective priority orders in five accepter groups

	Pedestrians (elder, child, adult)	electrical robotic wheelchair	bike	robot	private car	AV
not accept	2.35	4.03	5.00	6.08	6.71	6.78
OME-strong accepters	2.31	4.61	4.88	6.65	6.75	6.97
OME-weak accepters	2.12	4.89	4.92	6.53	7.14	6.98
SME-strong accepters	2.49	3.84	4.76	6.66	6.80	7.10
SME-weak accepters	2.31	3.73	5.02	6.17	6.86	6.82
total	2.33	4.00	4.93	6.36	6.83	6.94

** The higher the score, the lower the ranking.*
**Statistical significance test($p<0.05$): pedestrian:>0.32; electrical robotic wheelchair >0.85; Bike: >0.51; robot: >0.81; private car: >0.85; AV:>0.63*

The results express that participants generally consider pedestrians (elder, child, adult) hold the highest priority, followed by electric robotic wheelchair, the bike, and finally the robot, private car, and AV. The result is are consistent with the descriptive statistics in section 4.3.1. In addition, the results of ranking the electrical robotic wheelchair expresses the statistical difference between SME and OME accepters according to the statistical significance test (differences >0.85, $p<0.05$). Compare with the SME accepters, OME accepters prefer to rank the electrical robotic wheelchair at a lower priority level. The differences in views of ranking electrical robotic wheelchair from participants may be due to this type of road users expressing characteristics of both human and machine. SME accepters may pay more attention to the female passenger without hostilities, while OME accepters may focus more on the mobility device of the electrical robotic wheelchair which shows a stronger body than that of pedestrians. Furthermore, bicycles and private cars is as road users with attributes of both humans and vehicles but their results from accepters of SME and OME do not present differences. We assume that people have already formed fixed cognitions of these existing vehicles that have been used for a long time in the human society.

Although the responses among accepter groups in other scenarios have less difference, the answers of electrical robotic wheelchair indicate that the subjective priority order is possibly related to MEs. This finding would assist to further explore the effects of priority on ME.

4.4 Analysis of influencing factors of mental envelope

4.4.1 Purpose and significance

In order to further explore the differences between SME and OME in different acceptance and the effects of influencing factors on them, the logistic regression model is considered. Binomial logistic regression is widely used in many situations, however, it is not applicable to analyzing the results of this survey. If we use binomial logistic regression, it will be difficult to observe differences among the five groups. Also, the analysis processes will become complicated and repetitive. Therefore, we finally choose the multiple logistic regression, which can acquire more explicit and clear results in the comparison.

4.4.2 The multinomial logistic regression model

In the extracted data, the total number of responses is 2243. The Five types of feelings (stress, danger, friendly, body strength, and attention), personal attributes of participants (age, gender, and body height), and the experience of walking with road users are used as independent variables. Five accepter groups of ME that are independent of each other are regarded as dependent variables. The not accept group is the reference group in this model. Table 4.8 shows the results.

Table 4.8 Estimation of multinomial logistic regression model

		Dependent variables (N=2243)			
		OME-strong accepters	OME-weak accepters	SME-strong accepters	SME-weak accepters
age	Coefficient	0.00	-0.02	0.00	0.01
	Odds ratio	1.00	0.98	1.00	1.01
	Std.error	0.01	0.01	0.01	0.01
	Pr (>|z|)	0.83	0.11	0.66	0.11
gender-male **(1: male, 0: female)**	Coefficient	-0.55***	-0.26	-0.33	-0.33**
	Odds ratio	0.57	0.77	0.72	0.72
	Std.error	0.21	0.24	0.21	0.17
	Pr (>|z|)	0.01	0.27	0.12	0.05
height	Coefficient	0.04***	0.03***	0.01	0.00
	Odds ratio	1.04	1.03	1.01	1.00
	Std.error	0.01	0.01	0.01	0.01
	Pr (>|z|)	0.00	0.05	0.32	0.96
stress	Coefficient	0.94***	0.79***	0.20**	-0.02
	Odds ratio	2.55	2.19	1.22	0.98
	Std.error	0.09	0.10	0.09	0.07
	Pr (>|z|)	0.00	0.00	0.02	0.82
friendly	Coefficient	-0.15**	0.02	-0.07	0.06
	Odds ratio	0.86	1.02	0.94	1.06
	Std.error	0.08	0.09	0.07	0.06
	Pr (>|z|)	0.04	0.83	0.37	0.31
body strength	Coefficient	0.11	0.28***	0.22***	0.04
	Odds ratio	1.12	1.32	1.24	1.04
	Std.error	0.07	0.09	0.07	0.06
	Pr (>|z|)	0.13	0.00	0.00	0.46
danger	Coefficient	0.37***	0.21**	-0.07	0.09
	Odds ratio	1.44	1.23	0.93	1.09

	Std.error	0.09	0.10	0.09	0.07
	Pr (>|z|)	0.00	0.04	0.41	0.20
attention	Coefficient	0.72***	0.44***	0.60***	0.31***
	Odds ratio	2.06	1.55	1.82	1.37
	Std.error	0.10	0.12	0.09	0.07
	Pr (>|z|)	0.00	0.00	0.00	0.00
experience	Coefficient	0.15***	0.10	0.14**	0.18***
	Odds ratio	1.16	1.10	1.15	1.20
	Std.error	0.06	0.06	0.05	0.05
	Pr (>|z|)	0.01	0.13	0.01	0.00
Akaike Inf. Crit.		5,810.40	5,810.40	5,810.40	5,810.40

*Note: *p<0.1; **p<0.05; ***p<0.01*

Results demonstrate the differences in the acceptance of SME and OME in terms of influencing factors. In table 4.8, the responses of OME-strong accepters are greatly affected by stress and danger, especially the OME-strong accepters (stress: coef: 0.94, danger: coef: 0.37, p< 0.01). However, the responses from SME accepters are not significantly affected by the danger. SME-strong accepters (coef: -0.07) even have lower relations on danger than the group of not accept have. Moreover, the perceived body strength of road users from participants affects the responses of both SME-strong (coef: 0.28, p<0.01) and OME-weak (coef: 0.22, p<0.01) accepters. And the attention has a larger impact on the responses of OME-strong (coef: 0.72, p<0.01) and SME-strong (coef: 0.60, p<0.01) accepters than on the responses of OME-weak (coef: 0.44, p<0.01) and SME-weak (coef: 0.31, p<0.01) accepters. Among the personal attributes, the responses of OME-strong and weak accepters (coef: 0.04/0.03, p<0.01) are influenced by body height of participants. The gender attribute affects OME-strong (coef: -0.55, p<0.01) and SME-weak accepters (coef: -0.33, p<0.01), which means that females prefer to accept the views of creating strong OME and weak SME. In addition, all the accepter groups are not affected by age. And the experience factor has slight affects on the responses of SME-strong (coef: 0.18, p<0.01), SME-weak (coef: 0.14, p<0.05), and OME-strong (coef: 0.15, p<0.01) accepters.

4.4.3 Discussion

The results of multinomial logistic regression present the different characteristics of SME and OME acceptance by evaluation from influencing factors. The negative emotions, including stress and danger, have a greater impact on OME accepters than

SME accepters, especially in the responses of OME-strong representing the ME's expression of self-protection. SME accepters are less influenced by these negative emotions, but are more affected by the attention and perceived body strength of road users than OME accepters. These differences reflect that SME and OME can represent distinct perspectives of pedestrian perceptions. SME as a fundamental comfortable range around bodies of pedestrians represents their vigilance and concerns to road users. OME expresses greater discomfort than SME by presenting rejecting feelings to road users far away. Therefore, the hypothesis of OME as another perspective of explaining pedestrian perception in this research is verified. The results of differences in SME and OME can lay the foundation for the application of ME as indicators to evaluate space quality.

Moreover, in the multinomial logistic regression, some minor impacts from several influencing factors are found. In the personal attributes, the factor of body height shows a great impact on the responses of OME accepters. Combined with the descriptive statistics in section 4.3.1, the effect of body height may be influenced by gender. It is because 97.8% of participants who are over 170cm are males, and 92.6% of participants who are under 160cm are females. Additionally, females are more inclined to accept the view of OME-strong and SME-weak expressions than males. This tendency is line with the results of previous studies showing that females are more vigilant than males and prefer to stay in small spaces (Iachini, et.al, 2014, Takayama and Pantofaru, 2009, Lauckner et al., 2014). Also, the factor of experience has a greater effect on SME-weak accepters than other groups. We consider that influence of experience is effective in road users without obvious threatening or hostile characteristics, such as pedestrians. The previous studies found similar results that people tend to maintain shorter distances with others or machines as their experience with them increases, but still keep far away from cars even their familiarity increases (Hayduk,1983, Edney, et al, 1976, Mead and Matarić, 2016).

4.5 The structural relationship between ME and influencing factors

4.5.1 Purpose and significance

In order to further explore the difference between SME and OME and the structural

relationship between ME and influencing factors, we consider structural equation modeling (SEM) as an effective method. SEM is a multivariate analytical approach, which is commonly used to examine the relationships between latent variables and observable indicator variables statistically (MacCallum and Austin, 2000, Wang and Wang, 2019). There are two parts in SEM used to comprehensively explain the relationship between different variables. The measurement model examines the adequacy of observed variables to their related latent variables, whereas the path model explains the causality among latent variables (Lei and Wu, 2007). As SME and OME are abstract concepts that cannot be analyzed directly asked by using a single observed question from the survey, using SEM to study them as latent variables is appropriate.
As SME and OME are abstract concepts that cannot be analyzed directly through a single question, latent variables have been used in SEM to analyze them. The results are expected to lay the foundation for further exploring the effects of ME's application of rule-making.

4.5.2 Hypothetical conceptual model

Before conducting the analysis of exploring the structural relationships between ME and its influencing factors, this research hypothesizes a conceptual model. In section 4.5.3 and section 4.5.4, we will test the reliability of both relationships between latent and observed variables and the relationships between latent variables in this hypothetical model by confirmatory factor analysis (CFA) and path analysis. Based on the test results, the model will be adjusted and used in the further analysis of SEM.

In the hypothetical model, some latent and observed variables are considered. Firstly, both SME and OME as abstract concepts are latent variables. Their observed variables are the four perception questions based on ME's expressions in the questionnaire. Secondly, among the influencing factors of ME mentioned in section 4.2.1, the factors of stress, danger, body strength, and attention would cause unease feeling of pedestrians in interactions, which may make ME become stronger. While the friendliness and people's experience with encountered road users would produce the closeness feeling of pedestrians in interactions, which may decrease the strength of ME. Hence, we consider unease and closeness as latent variables that are the main emotional effects on SME and OME. Here, the observed variables of unease are: stress, danger, body strength, and attention. The observed variables of closeness are: friendly and experience. Thirdly, the personal attributes (age, gender, and body height) and subjective priority order that can be directly asked are used as observed variables.

(1) Hypothetical effects on SME

Since this research considers SME as a substitution of interpersonal distance (IPS), the factors affecting IPS in the previous studies mentioned in section 4.2.1 will affect SME, including: unease, closeness, and personal attributes (age, gender, and body height). This research will reverify the factors in previous studies to ensure that SME can be used as a substitution of IPS in ME's definition. The hypotheses are as follows:

H1a: the perceived unease affects SME.

H2a: the perceived closeness affects SME.

H3a: the gender of the pedestrian affects SME.

H4a: the age of the pedestrian affects SME.

H5a: the body height of the pedestrian affects SME.

(2) Hypothetical effects on OME

In the definition of ME, OME as a novel idea is another perspective of expressing the pedestrian perceptions. We assume that main factors of the SME also affect OME, that are, unease, closeness, and personal attributes (age, gender, and body height). The effects will be verified in the SEM model.

Based on the definition of OME, this research assume that priority is highly correlated with OME. In previous studies, priority has been used to solve traffic congestion and coordinate the relationship between different transportation modes (section 2.3.3). The application of OME on rule-making has commonality with the application of priority, that is, giving someone the right to go first or freely use space on mixed public spaces. Moreover, the application of OME on rule-making requires more consideration of priority more than that of SME. The priority would be used to determine the road user who are constrained by rules, thus ensuring the safety travel of road users with high priority. Also, considering the vulnerable road users in priority orders can helps the application of OME on rule-making to be accepted by the public. Paschalidis, et.al (2016) found that people have less condemnation for vulnerable road users (such as pedestrians) in collisions than that for stronger ones (such as cars). Therefore, the relationship between OME and priority is a focus in the whole structure of ME and influencing factors. The results will be beneficial to further exploration of OME's applications. We assume that the priority can affects the strength of OME, that is, pedestrians will generate weaker OME when encountering the road users with higher priority, such as the weak.

The hypotheses are as follows:

H1b: perceived unease affects OME.

H2b: perceived closeness affects OME.

H3b: the gender of the pedestrian affects OME.
H4b: the age of the pedestrian affects OME.
H5b: the body height of the pedestrian affects OME.
H6: the priority considering vulnerable road users affects OME.

(3) Hypothetical relationship between SME and OME

This research also considers the relationships between SME and OME in the model. From the definitions of ME, although both SME and OME describe the pedestrian perception, OME a new idea proposed in this research may have not been realized by the public. Therefore, we initially assume that SME affects OME, which means that OME will be strengthened with the enhancement of SME. The hypothesis is:
H7: SME affects OME.

Based on above hypotheses and previous studies, the hypothetical conceptual model showing on the figure 4.4 is proposed.

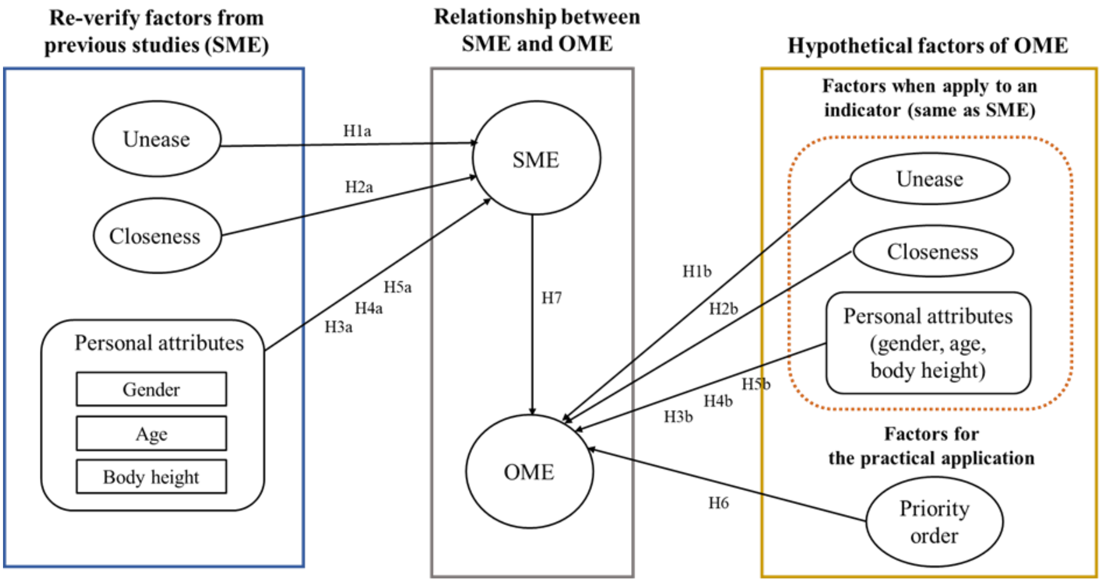


Figure 4.4 The hypothetical conceptual model

4.5.3 Model evaluation of the reliability

Based on the ME's expression, four perception questions of ME in the questionnaire are classified as the observed variables of SME and OME. QPS and QUS-small presenting the expressions of self-protection and space needs in SME are respectively renamed QSME1 and QSME2. QDO and QUS-large expressing these two types of

ME's expressions are retitled QOME1 and QOME2. In addition, the feeling questions of stress, danger, body strength, and attention are used as observed variables of unease. The questions about friendliness from road users and experience working with them are observed variables of closeness.

The reliability and validity of the observed variables explaining latent variables in the hypothetical conceptual model are tested prior to implementing the structural equation modeling (SEM). In the testing, we use the composite reliability (CR) values and average variance extracted (AVE) in confirmatory factor analysis (CFA). Generally, the CR value and AVE value are recommended to be greater than 0.70 and 0.50 respectively (Fornell and Larcker, 1981). Table 4.9 illustrates the results of the reliability and validity analysis. It is found that the latent variable of OME (CR: 0.91, AVE: 0.84) and unease (CR: 0.87, AVE: 0.63) meet the recommended test value. However, values of SME (CR: 0.55, AVE: 0.38) and closeness (CR: 0.61, AVE: 0.44) are lower than 0.7 and 0.5, due to the relatively low the factor loadings of QSME2 (-0.37) and experience (-0.22). Since all observed variables that closely related to the hypothesis and the ME's definitions meet the statistical significance ($p < 0.001$), the variables of QSME1 and experience will not be eliminated.

Table 4.9 Reliability and validity statistics in confirmatory factor analysis

Latent variables	Observed variables	Loadings	P-value	CR	AVE
SME				0.55	0.38
	QSME1	0.67	0.00***		
	QSME2	-0.37	0.00***		
OME				0.91	0.84
	QOME1	0.93	0.00***		
	QOME2	0.72	0.00***		
Unease				0.87	0.63
	stress	0.79	0.00***		
	danger	0.72	0.00***		
	attention	0.64	0.00***		
	body strength	0.65	0.00***		
Closeness				0.61	0.44
	friendliness	0.55	0.00***		
	experience	-0.22	0.00***		

CR: Composite Reliability; AVE: Average Variance Extracted.
Goodness of fit index (GFI):0.95 (>0.80)
Comparative Fit Index (CFI):0.93 (>0.90)
standardized root-mean-square residual (SRMR): 0.05 (<0.08)
Note: represents P < 0.05; ** represents P < 0.01; *** represents P < 0.001.*

In addition, the results of the goodness of fit index (GFI):0.95 (> 0.80), comparative fit index (CFI):0.93 (> 0.90), and the standardized root-mean-square residual (SRMR): 0.05 (< 0.08) confirm that variables in the hypothetical conceptual model fits well in the CFA model (Hu and Bentler, 1998, Doll, et.al, 1994). Despite certain limitations of this model, these four latent variables can be utilized to gain the preliminarily understanding of the relationship between the variables.

4.5.4 Hypothesis testing

All the relationship hypotheses in the hypothetical model are tested and verified through the pass analysis. The results in table 4.10 show that 9 of the 12 hypotheses are supported. SME is influenced by unease (1.04, $p < 0.001$), closeness (−0.40, $p < 0.001$), gender (0.10, $p < 0.01$), body height (0.13, $p < 0.001$), and age (−0.07, $p < 0.001$), which is in line with previous studies of IPS. In the passes of OME, unease (1.09, $p < 0.001$), closeness (−0.25, $p < 0.001$), body height (0.15, $p < 0.001$), and priority (−0.05, $p < 0.001$) have effects on OME, but three passes are not consistent with hypotheses, that are, age (−0.04, $p > 0.05$), gender (0.02, $p > 0.05$), and SME (−0.30, $p > 0.05$). these passes are rejected. Although SME does not affect OME, we still consider that SME is related to OME. Therefore, the effect of OME on SME will be examined in the following analysis of the SEM model.

Table 4.10 Hypothesis verification results in path analysis

path	path coefficient	p-value	status
H1a: unease → SME	1.04***	0.00	Supported
H2a: closeness → SME	-0.40***	0.00	Supported
H3a: gender → SME	0.10**	0.01	Supported
H4a: age → SME	-0.07***	0.00	Supported
H5a: body height → SME	0.13***	0.00	Supported
H1b: unease → OME	1.09***	0.00	Supported
H2b: closeness → OME	-0.25***	0.00	Supported
H3b: gender → OME	0.02	0.50	Rejected
H4b: age → OME	-0.04	0.07	Rejected
H5b: body height → OME	0.15***	0.00	Supported
H6: priority → OME	-0.05***	0.00	Supported
H7: SME → OME	-0.30	0.07	Rejected

*Note: * represents P < 0.05; ** represents P < 0.01; *** represents P < 0.001.*

4.5.5 The structural equation modeling (SEM)

Based on reliability and validity statistics and the hypothetical testing, the final SEM model is obtained by adjusting and examining relationships among variables repeatedly. Figure 4.5 shows the output of SEM with the standardized parameter estimate.

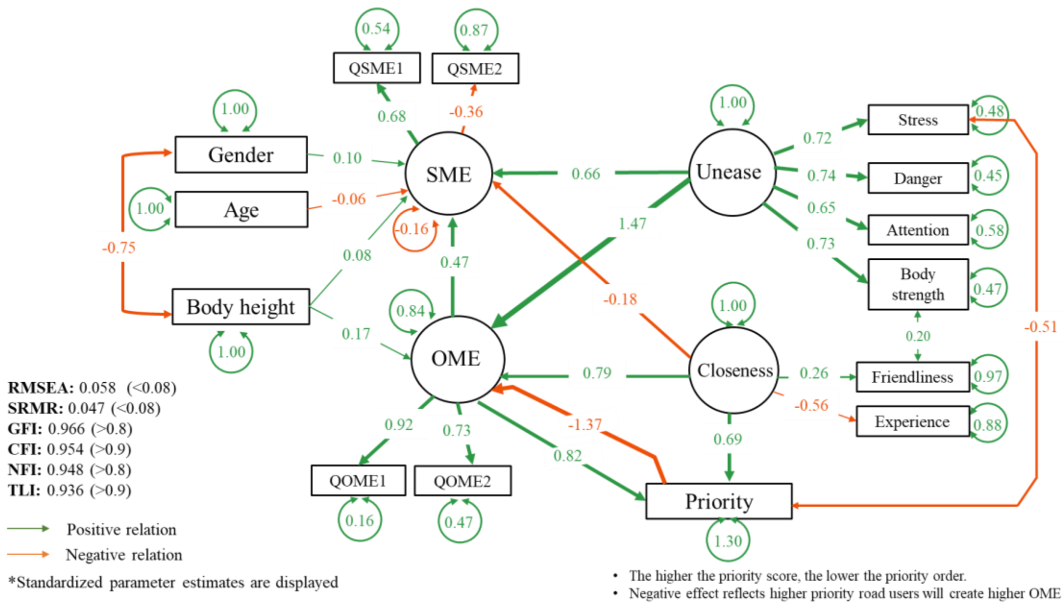


Figure 4.5 The output of structural equation modeling

The fitness of the SEM indicates the reliability of this model. Based on the recommendations from Hu and Bentler, (1998), Sinkovics, et.al, (2016), Hair, (2009), Kline, (2015), and Doll, et.al, (1994), results of the root-mean-square error of approximation (RMSEA = 0.06, < 0.08), standardized root-mean-square residual (SRMR = 0.05, <0.08), the goodness of fit index (GFI = 0.97, > 0.80), comparative fit index (CFI = 0.95, > 0.90), normed fit index (NFI = 0.95, > 0.80), and Tucker–Lewis index (TLI = 0.94, > 0.90) present a good fitness, meaning that this SEM model provides satisfactory results fitting the requirement.

Moreover, for the output of the SEM model, SME is influenced by unease ($\beta = 0.66$), closeness ($\beta = -0.18$), and personal attributes (gender: $\beta = 0.10$, positive: female; age: $\beta = -0.06$, body height: $\beta = 0.08$), showing that its main factor of is the unease feeling. Compared with SME, the unease ($\beta = 1.47$) and closeness ($\beta = 0.79$) have stronger effects on OME. For the personal attributes, OME is only affected by the body height ($\beta = 0.17$). Also, there are some new relationships in the final SEM model. OME has effect on SME ($\beta = 0.47$) and correlation with priority (priority→OME: $\beta = -1.37$, OME →priority: $\beta = 0.82$). These relationships are different from the hypothesis mentioned in 4.5.2. We also test the relationship between SME and priority to further verify the importance of priority to OME. The result shows that SME and priority are irrelevant. Additionally, priority has relationships with closeness ($\beta = 0.69$) and stress ($\lambda = -0.42$). And gender and height ($\lambda = -0.75$) shows the correlation in the model.

4.5.6 Discussion

The output of the SEM model further explores the difference between SME and OME and the structural relationships among ME and influencing factors. In the results of SME, the positive effect of unease ($\beta = 0.66$) as a main influence is in line with previous studies of IPS (Hall, 1966, Aiello, 1987, Iachini, et.al, 2014, 2016), that is, the greater the unease, the stronger the SME. Furthermore, the negative effect of closeness on SME ($\beta = -0.18$) corresponds with the results from Hayduk (1983), Edney, et al (1976), Mead and Matarić (2016), Takayama and Pantofaru (2009), showing that people prefer to generate less SME when encountering more familiar and friendly road users. For the effects of personal attributes, SME is affected by gender ($\beta = 0.10$), age ($\beta = -0.06$), and body height ($\beta = 0.08$). Results express that females prefer to generate stronger SME than males, while elders and shorter people generate weaker SME, which are in line with results from Aiello (1987), Uzzell and Horne (2006), Iachini, et.al (2014), Hecht, et.al (2019). Therefore, the relationships between SME and influencing factors reference from IPS verify the hypothesis that SME is as a substitution of IPS is proved.

Moreover, compared with factors of unease and closeness, the personal attributes (age, gender, and body height) have much lower effects on SME. This result differs from previous research findings that personal attributes have significant effect on IPS (Aiello, 1987, Iachini, et.al, 2014, 2016, D'Angelo, et.al, 2019). We assume that the difference between our results and previous studies might because of the effects of scenarios showing future road users in the questionnaire survey. Some previous studies in robotics proposed that age, gender, and body height did not have significant impacts on the IPS in human-machine interactions (Leichtmann and Nitsch, 2020, Kamide, et.al, 2014, Brandl, et.al, 2016), which illustrate our speculation.

As compared with SME, OME is much influenced by unease ($\beta = 1.47$) and closeness ($\beta = 0.79$). we assume that positive effects of unease and closeness on OME are related to impressions of people on road users. Participants generate strong OME to road users with obvious impressions of danger, such as automobiles and bikes, but generate weak OME to road users with ambiguous impressions, such as robots and electrical robotic wheelchairs. In addition, the reciprocal causation between priority and OME is discovered. In the questionnaire, road users ranked with high scores in the priority question are considered low priority. The results show that priority is positively affected by the OME ($\beta = 0.82$), which means that people who perceive stronger OME on road users prefer to rank them in lower priority order. Also, the negative effect from priority to OME ($\beta = -1.37$) means that road users who placed at a high level of priority will generate stronger OME. Combined with the descriptive statistics results mentioned in 4.3.1 (table 4.2), road users at high priority level can be identified for vulnerable road users. Therefore, the hypothesis that the priority has important effect on OME holds.

Furthermore, OME is positively affected by body height ($\beta = 0.17$) in factors of personal attributes. Two reasons are considered. One is that taller people have higher sightlines, making it easier for them to perceive road users at far distance and produce OME. Another is that taller people may like to express their needs for spaces directly. Some previous studies proposed that taller people prefer to show dominance in spaces (Stulp, et.al, 2015, Pazhoohi, et.al, 2019, Sell, et.al, 2009). These hypotheses require further exploration.

An unexpected result of the relationship between SME and OME is shown on the SEM model. In hypothesis 7 mentioned in section 4.5.2, we initially considered that OME as a novel idea of pedestrian perception is less realized by the public, and will be strengthened with the enhancement of SME. However, the results of SEM model show that SME is positively affected by OME. It may be because that unease has greater effect on OME than on SME, that is, strong unease feeling of people cause the generation of OME may increase the strength of SME (such as people generate strong OME when people meet fast automobiles, and their SME also become stronger). Hypothesis 7 fails to hold, probably because the unease feeling of generating the strong SME is not sufficient to increase OME (such as people may not create strong OME when encounter strong pedestrians, but when encounter fast cars). Additionally, the great impact of unease and closeness on OME indicate a higher level of public acceptance of OME than we expected. It reconfirms our hypothesis that OME is accepted by the public and can be used as another perspective of pedestrian perception (section 4.4.3). Consequently, OME contributes significantly to the description of pedestrian perception in the model construction. It is more appropriate to consider both SME and OME in pedestrian perception, instead of only the SME.

The findings in the SEM model will contribute to exploring the future application of SME and OME. The difference between SME and OME lays the foundation for evaluating road quality from multiple perspectives. And the relationship between OME and priority would be beneficial to OME's application of rule-making in future public spaces.

4.6 Limitations of the questionnaire survey

In the questionnaire survey, videos and pictures are used for guiding participants to imagine situations of walking with existing and future road users. And descriptions with simple and easy-to-understand words assist participants in answering questions even if they are unfamiliar with the definitions of ME. However, there are still limitations. First, biased responses of participants could be caused due to the differences in animations and videos depicting road environments. Second, given the complexity and difficulty of the questionnaire, scenarios only reflect differences of road users in types. If used road users present attributes in more detail (such as facial expressions, size, and speed), the responses from participants will change. Third, as this survey only preliminary investigates pedestrian perception in one-to-one situations where a pedestrian encounters a single road user in each scenario, multiple situations require to be further explored. Forth, in this survey, the pedestrian scenarios only show the appearance characteristics of the male and female, the psychological gender attributes are not considered. At this stage of this research, we focus more on observing the direct impressions from road users. Fifth, although the demographic question with only two options (male and female) fails to take gender diversity into account, it is helpful to simplify the classification of gender group in analysis.

Moreover, the scope of the investigation is limited. This research conducts a survey to the public in Japan, preliminarily exploring the existence of ME from participants' acceptance of ME. More precise proof of ME's existence will be needed in future studies from various aspects, such as considering participants from multicultural backgrounds and the influence of spatial environment. Also, the type of road users interacting with pedestrians in the questionnaire is limited. Considering the complexity and difficulty of the questionnaire, we choose road users that people can easily imagine as objects to preliminary understand the people's views of ME.

Despite these limitations, the results represent ME's acceptance, differences of SME and OME, and the structural relationships between ME and its influencing factors to a certain extent. These findings can help us to further explore the existence and future applications of ME.

4.7 Summary

This chapter focuses on preliminarily demonstrating the existence of ME and exploring the differences between SME and OME and the structural relationships among ME and influencing factors. An online questionnaire survey is used to investigate the acceptance of ME by the public. The questionnaire uses animations and pictures to reproduce interaction situations with existing and future road users to participants, and asks them questions about feelings they perceived in different situations using simple descriptions. For analyzing the results of the acceptance of SME and OME, we use cross-tabulation analysis to extract and categorize the responses based on the definitions and expressions of SME and OME. The results demonstrate that ME is accepted by most of the public (84%), indicating that OME can be used as another expression of pedestrian perception. For further exploring the differences between SME and OME and their structural relationships with influencing factors, we use the structural equation modeling. The result illustrates that OME is greater affected by unease and closeness feelings than SME, and its strength can positively influence the strength of SME, which is significant for describing pedestrian perception from a different perspective. The relationship between OME and priority is also beneficial to the future application of ME in rule-making. Despite some limitations of the questionnaire survey, the results still preliminary prove the conceptual hypotheses of envelope theorem, which will contribute to future exploration of applications of ME and utilization of envelope theorem.

Chapter 5. The utilization of envelope theorem for future public spaces

5.1 Introduction

When various kinds of mobilities share public spaces with people, many uncertainties in mixed traffic with multiple road users will be caused. In this case, how to ensure the safety and comfort of pedestrians and achieve the desired environment of human-machine coexistence is an important issue. This research regards that the envelope theorem can be further developed to consider the rule-making and forms of future public spaces, which can contribute to improving the human-machine coexistence. This chapter introduces the development of the envelope theorem and demonstrates the effects of applying the envelope in future public spaces through the simulation study. The simulator reproduces the actions of road users in the hypothetical forms of future public spaces, and expresses the application effects of each space form in the evaluation results. In the future, the simulator can be applied in society to observe and discuss public space utilization and management, and find possible problems for preparing in advance.

The following sections describe the simulation study in detail. Section 5.2 introduces the development of envelope theorem into envelope spaces and envelope analytical system, and its elements and relationships. Section 5.3 presents the contents of the simulation development, including the used materials and tools, factors for improving the simulation reality, space environment settings, evaluation indicators, algorithms for calculating ME and applying rules, and animation expressions in simulator. Section 5.4 presents the rationality test of the ME and rule algorithms used in simulator from different perspectives. Section 5.5 introduces the application effects of envelope in hypothetical future public space forms in the simulation model. The results show the performance of different space scenarios by evaluation indicators. Section 5.6 is the discussion of the simulation result and ideas of future public spaces. Section 5.7 explain the limitations of the simulator. Section 5.8 is the summary of this chapter.

The contents in chapter 5 have not been published, which will not be explained here.

5.8 Summary

This chapter introduces the development of the envelope theorem into the envelope spaces and envelope analytical system for considering future public space through the simulation study. We consider different types of envelope spaces as possible forms of future public spaces, and develop a simulator to reproduce them. The results clearly represent the movements of objects in different situations by animations, and show the effects of envelope spaces under different social goals through outputs of efficiency and safety/comfort evaluation indicators. For future applications, this simulator can be applied to help people directly observe and discuss public space utilization and management, and find possible problems for preparing in advance. In the future, the envelope theorem is expected to be improved and applied in various fields, which would spark more researchers to think out novel ideas for contributing to human-machine coexistence.

Chapter 6. Conclusion and recommendation

6.1 Conclusion

This research proposes and systematizes the envelope theorem to provide a theoretical basis and application methods for handling mixed traffic with various mobilities and ensuring pedestrians' safe and comfortable environment. The mental envelope (ME) explains the pedestrian perception from different perspectives. It is applied as the indicator to better evaluate the safety and comfort quality of public spaces, and as a basis of rules in future public spaces. The envelope theorem for realizing OME and related proof explain the idea of OME application in more detail. The envelope space and envelope analytical system is also used to explore the rule-making and forms of possible public space in the future.

The research process is as follows: First, the envelope theorem is proposed for explaining the human-machine spatial relationships in the mixed traffic. Second, a questionnaire survey is used to obtain empirical evidence to prove the existence of new ideas (ME) in the envelope theorem and to observe their relationships with relevant influencing factors. Third, the development of envelope theorem is used to considering the rule-making and space utilizations of future public spaces, which use the simulation study to demonstrate the application effects in different space forms.

6.1.1 Major findings

The important findings of this research are introduced from two aspects. The results from questionnaire survey verify conceptual hypotheses in envelope theorem. The questionnaire uses animations and pictures to show interaction scenarios to participants, and simple descriptions are used to ask them about perception questions. Through the analysis of cross-tabulation, multinomial logistic regression model, and structural equation model (SEM), the following findings are emerged.

1. **The existence of OME is proved.**
   The results show that the idea of OME expressions is accepted by participants, which is greater affected by feelings than SMEs, especially the negative emotions. It is in line with the definition of ME, that is, OME strongly represents the rejecting feeling that pedestrians want encountered road users to be far away, while SME as a basic comfortable range around bodies of pedestrians expresses their vigilance and concerns to encountered road users. The results verify the hypothesis that OME can serve as another perspective of pedestrian perception.

2. **The feasibility of SME as the substitution of IPS is demonstrated.**
   The results showed that SME is mainly affected by unease, closeness, and personal attributes (gender, age, and body height), which is consistent with previous studies (mentioned in section 2.3), including: SME increases as the unease increases, and decreases as the closeness increases; females are more likely to create stronger SME than males; elderly and children prefer to generate weaker SME. These results indicate that the influencing factors and characteristics of SME are consistent with that of IPS, so that SME can be described as a substitution of IPS in definition.

3. **The result of structural relationship between SME and OME is unexpected.**
   We hypothesize that OME as a new idea of pedestrian perception may be less recognized by the public, and positively affected by SME (OME increases as SME increases). However, in the results of SEM, OME positively affects SME, rather than being influenced by SME. It may be because OME is greater affected by unease feeling, meaning that strong unease feeling of people causes the generation of OME may increase the strength of SME, whereas the unease feeling of generating a strong SME may be not sufficient to increase OME (for example, people will generate strong SME when encountering a strong pedestrian, but will not produce OME). It can further verify the existence of OME which is in line with the definition.

4. **OME is related to the subjective priority order of people.**
   In the results of the SEM model, the reciprocal causation between OME and priority is found. People will rank specific types of road users at lower priority level if they generate strong OME for them. And the higher-priority road users are more likely to generate strong OME. However, SME has no relationship with subjective priority order. The relationship between subjective priority order and OME is important to explore the future application of OME.

The results of simulation study demonstrate the application effects of the envelope theorem. A simulator is developed to reproduce possible future public spaces (envelope spaces) and compare their characteristic differences by using the outputs of evaluation indicators.

6.1.2 Contributions

There are some contributions of this research. Firstly, the envelope theorem is a new perspective for explaining the spatial relationships among various road users. Its applications are helpful for dealing with the future mixed traffic with multiple mobilities. For one, the ME as a novel idea of explaining pedestrian perceptions can be applied to evaluate space comfort for pedestrians and the rule-making basis of public spaces. For another, the envelope space and envelope analytical system for explaining the relationship of the public space formation in society is used to consider the rule-making and utilization of future public spaces. Secondly, a simulator is developed for clearly expressing characteristics of future public space forms with different social goals and rules, which can be applied for directly observing and discussing future public space utilization and management, and finding possible problems for preparing in advance. Thirdly, this research discusses the expectation of future public spaces and provides recommendations for applying envelope. We hope our ideas in this research can inspire more discussions in future public spaces and more researchers to create novel ideas for contributing to the realization of human-machine coexistence.

6.1.3 Limitations

The limitations of this research are described in terms of questionnaire survey and simulation development. In the questionnaire survey, we use videos and pictures to guide participants to imagine interactions with various road users, and simple descriptions to support them to answer perception questions. However, there are still the following limitations. Differences in virtual animations and videos in the scenarios, and the specific appearances of road users showing in scenarios cause biased responses from participants. In addition, only one-to-one interactions are presented in scenarios. The pedestrian perception when encountering multiple road users need to be further explored. Furthermore, the binary gender group (male and female) is used in the questionnaire which is lack consideration for participants' psychological gender, but is beneficial to simplify the gender classification in the analysis. Despite these limitations, the results of statistical analysis still proved the existence of OME and verified the structural relationship between ME and influencing factors to some extent.

6.2 Recommendation for future works

Some important works of this research require to be further explored. Firstly, the concept of ME could be further expanded. At current research stage, we proposed SME and OME and four related expressions to explain pedestrian perceptions. In the future, as the social environment and values change, new types of perceptions may emerge. Further extensions of ME will contribute to a more comprehensive understanding of human perception, thereby helping to improve human-centered space design, urban planning, or robotics design in new situations. These would provide more comfortable environments for people.

Secondly, a more detailed and in-depth proof of the envelope theorem for realizing OME is necessary. This research only provides a simple proof of envelope theorem to further explain our idea of OME's application. Considering more comprehensive mathematical descriptions for multiple situations is important for future works.

Thirdly, the forms of ME and related applications need further exploration. The forms of ME showing pedestrian perception are still uncertain. Considering how to quantify the ME more precisely would be needed in the evaluation. Moreover, the application of ME needs to be expanded when considering the possible problems in future public spaces. The forms for showing the effect of ME application in actual spaces would vary because of application methods.

For the future outlook, we expect that the envelope theorem will not only be limited to solving traffic problems and human-machine relationships in physical space, but also various fields and applications, such as relationships in the information society, human-machine ethics, philosophy, etc. The Envelope theorem is also desired to inspire more consideration from researchers, which will pave the way for the coexistence of humans and machines or even new things in the future.

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