A preliminary proposal of application of envelope theorem on mixed road spaces

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As machines gradually enter into people’s daily life to satisfy needs of travel and service, achieving human-machine coexistence becomes a significant issue. Previous studies explored its feasibility from the envelope concept and interpersonal distance (IPS). However, these two theorems are insufficient to satisfy needs of mixed road spaces among people and machines. This research redefines the envelope theorem and uses normative modeling to explain the effects of two mental envelopes (MEs). The conditions and rules are set based on the answers from the questionnaire survey. According to the results of the normative modeling, we hypothesized the suitable cases of using these two MEs, and proposed the plan of simulation in future works.

Key Words : *envelope, interpersonal distance, mental envelope, human-machine interaction, mixed road*

1. INTRODUCTION

With the development of advanced automated technology, low-speed electric mobility devices, personal mobility vehicles, robots, and autonomous driving will enter human society not only for satisfying people's travel and service needs, but also improving traffic safety[1),2),3)]. For example, robots could replace people to deliver goods, and autonomous driving systems will support distracted drivers to stop in time for avoiding traffic accidents with pedestrians. Under this development tendency, slow-speed electrical devices and robots will likely share sidewalks with pedestrians due to the increase of road users and the lack of spaces[4),5)]. In order to achieve the coexistence and road sharing of human and machines smoothly, allowing machines to understand human actions and emotions more sufficiently, and finding suitable distance required for human-machine interaction is particularly significant[1),6)].

For exploring the feasibility of human-machine coexistence, researchers tried to consider some theories and methodologies. Floridi[7),8)] proposed the definition of the envelope in the human-robot relationship. This is a boundary between robots and people divided by abilities and geographical locations to ensure their activities. For example, machines can only wash dishes or only can work in factories. Similar definitions have been found in the fields of artificial intelligence. Bostrom[9),10)], Daugherty and Wilson[11)] believed that there is limited scope for machines in physical spaces, division of labor, or social positions to ensure the coexistence and life activities with human beings. Also, the envelope in the research of autonomous-driving vehicles is a physical method of separating areas and restricting actions to ensure their normal operations and traffic safety[12),13),14)]. However, these definitions ignore people’s subjective perceptions and may impede interactions between humans and machines. Because of physical boundaries or information isolation, not only machines may ignore or misunderstand people’s feelings, but also people may gradually reduce their motivations to actively comprehend machines. It is insufficient to satisfy needs of mixed road spaces among humans and machines.

Researchers in the field of transportation and robotics also tried to apply the psychological knowledge to the research of human-machine interactions. The interpersonal space (IPS) in the proxemics is always used as a theoretical basis for estimating people's subjective perceptions[15)]. Many experiments are based on the critical distance when people begin to feel uncomfortable as the ideal point of interaction to avoid the negative impacts of space invasion[16], that is, people's vigilance and avoidance. For example, studies of interactions between people and personal mobility vehicles (PMVs) or robots analyzed the danger and discomfort that people perceived when these machines break into their interpersonal spaces[17),18),19),20),21)]. However, IPS has long been used to explore human interactions. It may be insufficient to adequately explain phenomena of people's perceptions as a theoretical basis when discovering human-machine interaction in the mixed road space. People will not only have distance needs for self-protection[2),22),23)], but also for willingness of obtaining more comfortable spaces, or confusions of judging appropriate distances at a close range. The experiment from Vassallo[24)] illustrates this point. People tend to avoid machines even if they know machines are safe and keep distances with them. The limitation of IPS may lead to a gap between people's true feelings and explanatory understanding in research.

Therefore, it is necessary to consider a new theorem applicable to mixed road spaces for people and machines. The purpose of this research is to redefine the envelope for dealing with the interaction among multiple road users. The normative modeling will be used to explain its effects as the first step, which will prepare for the simulation of proposals for the road allcations or usages in future research.

2. REDEFINITON OF ENVELOPE

(1) Defintions

In order to explain people's psychological phenomena more comprehensively and satisfy the needs of human-machine coexistence in the mixed road, we consider and redefine the envelope theorem. The envelope theorem in this research is composed of the physical envelope and the mental envelope. Physical envelope (PE) is described as a physical boundary that has effects to obstruct movements of road users, such as guardrails, yellow lines, or illuminant boundary made by high-tech monitoring system in the future. The mental envelope (ME) to explain the perception of people when meeting different road users. It is described as a psychological boundary used to distinguish the range of usable area and unpleasantness in people's minds. For example, people will feel nervous and uneasy when encountering a bicycle on mixed-traffic sidewalks. At this time, people will create a psychological line of defense against this bike.

Moreover, ME is divided into two types. There are definitions, and fig. 1 illustrates the imagines of SME and OME:

a) Subject mental envelope (SME):
It is a self-centered boundary at a close range in the subject's mind. SME has a similar definition to the IPS. Hall[15)] and Hecht[25)] described IPS surrounding a person forms circular space. It is more inclined to the protection and small usable areas.

b) Object mental envelope (OME):
It is an object-centered boundary from a greater distance in the subject's mind. It focuses more on keeping further distance and getting larger usable areas. For example, people feel strong anxiety about objects that are unpredictable in a mixed road space, such as dogs without ropes, and hope the actions of these objects to be restrained or even far away from themselves. Or pedestrians may want to constrain bicycles and obtain more usable road space on mixed sidewalks. OME is a new perspective of this research.

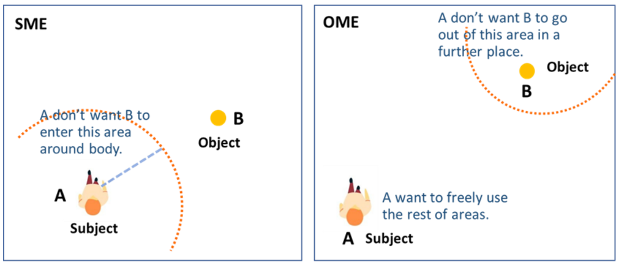


Fig.1 Subject mental envelope and object mental envelope.

(2) Application of envelope

This research assumed that the application of envelope will be expressed by their strength. In PE, the strength of physical defense will be different. For example, walls have strong strength, while the bicycle lanes drawn with lines are much weaker. In ME, the more people's discomfort and alertness of people, the stronger the ME. For instance, someone's ME when encountering cars will be stronger than that when meeting pedestrians.

However, ME not only needs the strength but also priority to produce actual effects. In previous studies, shared space is a mainstream way that enables multiple road users to use the same road spaces through a unified priority[26) 27)]. If all road users have the same priority, pedestrians will lose a lot of originally safe and comfortable walking spaces. Therefore, we consider that priority with different levels is important for using ME on mixed roads without physical separation. For example, pedestrians have higher priority than robots. Robots need to predict the ME of pedestrians to avoid or wait until they passes completely when they meet each other.

ME as a new concept has not been confirmed and quantified. This research will find the difference in the ME's strength of different people and influencing factors of ME through a questionnaire survey. The hypothetical normative modeling will be used to explain the effects of ME. These will be a basis of the simulation in future research.

3. QUESTIONNAIRE SURVEY

(1) Purposes

This questionnaire survey is to prepare for the simulation in future works. From previous studies, people's subjective perception is affected by negative emotions[18),28)], personal attributes(gender[16),29)], age[16),30)], body height[25),31)]), and familiarity with objects[32),33)]. This questionnaire will set related questions to explore the influencing factors of ME. Moreover, in order to understand the differences in perceptions of ME among different groups of people, this survey ask about SME and OME in different situations. The answers obtained will become the data basis of the simulation.

(2) Questionnaire survey

An online questionnaire survey was conducted on a website with the crowdsourcing service named Lancers (https://www.lancers.jp/). The survey was done from August 25th, 2020 to August 29th, 2020. Through the random sampling method, answers from 292 respondents were used as valid data. Every participant can get 200 JPY as the remuneration after answering and submitting the questionnaire. Respondents of the survey are Japanese who live in their native country in different age groups.

There are four parts of this questionnaire. The first part uses a video to introduce the background of future transportation and explain the idea of SME and OME in simply descriptive words. Definitions are not mentioned directly. This video allows participants to imagine an environment of human-machine coexistence before answering questions. The second part collects information regarding the demographic details including gender, age, region, body height, travel habits, and the type of sidewalks that they always used. The third part asks about the acceptance of SME and OME and perceptions of different feelings. Eight scenarios are designed in the questionnaire, including: robot, electrical robotic wheelchair, dog, autonomous-driving vehicle, pedestrians (female, male), bike, and private car. Videos are used to simulating scenes of walking with objects on mixed road spaces (Fig.2). Virtual scenes are used in specific situations, such as meeting robots and autonomous vehicles. And common situations are displayed by real imagines. The five-point Likert scale[34)] is used in the questionnaire. Participants answer four questions of ME's acceptance (1: disagree; 5: strongly agree). These questions are: (* *PS: personal space, DO: distant object, US: usable space*): Q_{PS}: Do you agree with this view: "I don't want this (objects in scenarios) to enter my personal space."? Q_{DO}: Do you agree with this view: "If it can be done, I hope this can keep away from me or stop after I go through."? $Q_{US\text{-}small}$: Do you agree with this view: "As long as my personal space is not occupied, this can use the rest of spaces."? $Q_{US\text{-}large}$: Do you agree with this view: " If it can be done, I hope this will be confined to a small space that far away from me, so that I can use the rest of spaces freely."? After that they rate their feelings about stress, danger, feeling of object's body strength (object is stronger than themselves or not), friendly (objects are friendly or not), attention (people will care about the object or not), and familiarity (having experience of walking with objects or not) (1: disagree; 5: strongly agree).

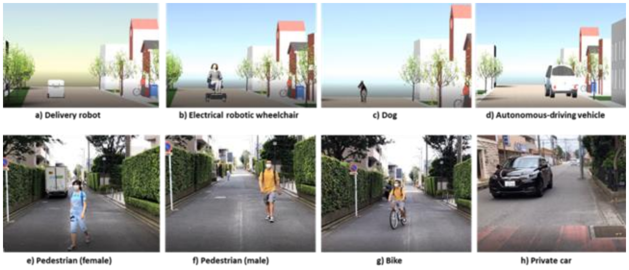


Fig.2 Scenarios in the questionnaire.

The fourth part is asked about the perspective of road priority. Participants rank the priority of eight types of road users shown in the picture according to their individual values. The eight road users are: elders, children, adults, robots, bikes, autonomous-driving vehicles, electrical wheelchairs, and private cars.

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

4. THE HYPOTHETICAL NORMATIVE MODELING

(1) Rules of the normative modeling

In order to explain the effects of ME and a simple attempt for the preparation of the simulation, this research use the hypothetical normative modeling based on parts of the responses and information of the questionnaire. We assumed that ME can take effects based on the order of priority and its strength. There are some rules of ME's application set in the modeling. First of all, the priority determines whether the subject's ME will be effective that change actions of objects or not. For example, pedestrians have higher priority than bicycles. ME from pedestrians will let bicycles move around them or stop and wait until they pass when they encounter. Since bicycles have lower priority, cyclist's ME cannot restrain actions of pedestrians. Secondly, effects of SME and OME are different. SME will determine ranges around bodies of subjects, so that objects cannot enter these spaces and need to avoid or change the path. OME will be generated as an object-centered boundary which is relatively far away from the subject. The object couldn't go out of this range until the subject cannot perceive them (see Fig.3). Thirdly, the strength of ME is also important. The stronger the ME, the greater the effects of it. For example, when pedestrians meet cars, the strength of ME will be stronger than that of meet bicycles. At this time, cars need to avoid pedestrians by changing longer paths or stop moving from greater distances than bycicles. Moreover, when subjects don't perceive ME on objects, even if their priority is higher, ME may not have effects, that is, objects can be close to subjects.

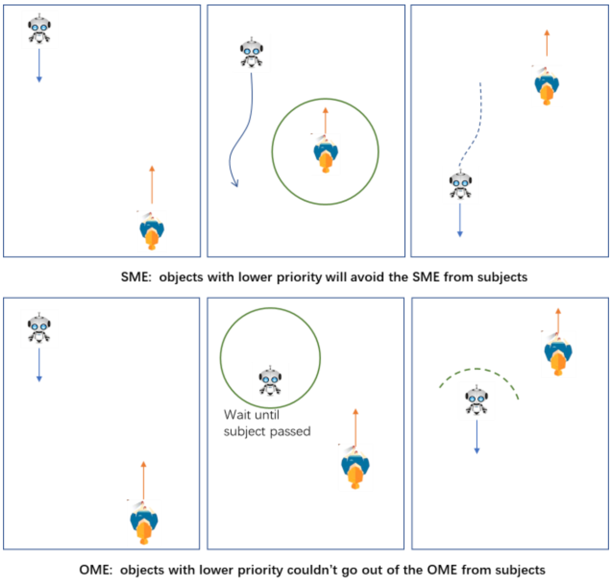


Fig.3 Illustration of how SME and OME work.

In order to determine the order of priority used in the normative modeling, the answers about road priority on participants' subjective perceptions in the questionnaire are used. Table 1 shows the road priority judging by participants (P1 is the highest priority and P8 is the lowest priority). Most of participants thought that pedestrians (elders, children, adults) have the highest priority, the second one is electrical wheelchairs, the third one is bikes, and then is robots, and finally are autonomous-driving vehicles (AVs) and cars. The normative modeling will use this priority to explain the effects of ME.

The strength of ME is expressed by the enveloped space of different radius in the normative modeling. Due to different objects, the performance of levels of ME's strength may be different. This normative modeling assumes the radius of the strength of ME for different objects according to the questionnaire (five-point likert scale). Table 2 shows the radius of five levels of strengths of SME and OME under six types of objects. In the questionnaire, level 1 means that the participants do not perceive SME or OME when meeting objects, so that ME wouldn't show the effects in the modeling.

Table 1 answers of eight level of priority for road users.

Count number of answers in eight level of priority								
	P1	P2	P3	P4	P5	P6	P7	P8
Robot	1	0	5	15	46	110	27	88
E-wheel	12	22	63	100	63	10	22	1
AV	2	7	1	2	4	43	161	72
Car	7	2	1	2	20	81	61	119
Bike	0	3	5	80	151	38	10	5
Elder	147	117	16	2	2	3	3	2
Adult	10	8	170	88	5	3	4	3
Child	113	133	31	3	1	4	4	2

** **priority order**: pedestrians (elder, child, adult) > electrical wheelchair > bike > robot > AV > car*

Table 2 ME's radius in 5 levels of strength for different objects.

Radius of SME and OME in 5 level of strength					
SME (radius)	1	2	3	4	5
Pedestrian	NA	0.5m	1m	1.5m	2m
E-wheel	NA	1.5m	2m	2.5m	3m
Bike	NA	1.5m	2m	2.5m	3m
Robot	NA	0.8m	1.3m	1.8m	2.3m
AV	NA	1.5m	2.5m	3.5m	4.5m
Car	NA	1.5m	3m	4.5m	6m
OME (radius)	1	2	3	4	5
Pedestrian	NA	5m	4.5m	4m	3.5m
E-wheel	NA	4m	3.5m	3m	2.5m
Bike	NA	4m	3.5m	3m	2.5m
Robot	NA	4m	3.5m	3m	2.5m
AV	NA	3.5m	3m	2.5m	2m
Car	NA	3m	2.5m	2m	1.5m

** five-point Likert scale (1: disagree; 5: strongly agree)*

(2) ME's effects in the normative modeling

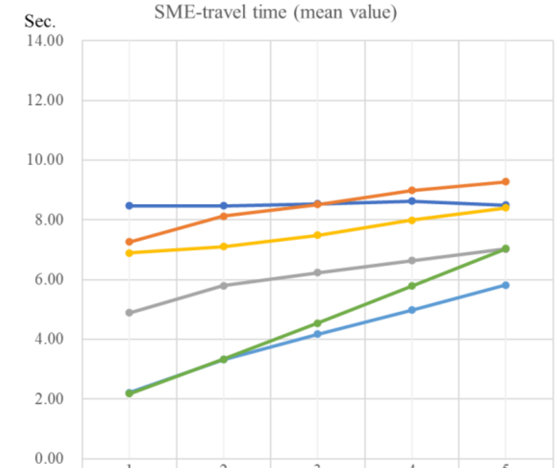
According to the rules set based on parts of informations in the questionnaire, situations of encounter between the subject and object in the questionnaire are reproduced. And changes of object's actions when ME is used as an effective ways rather than only kinds of perceptions are predicted. The modeling will compare effects of SME and OME based on conditions that are set. It is only used to explain the expected effects of ME in the concept, and the actual data will be used in the future simulation.

The scene of this modeling will be in a mixed road space with 10m long and 10m wide. The random number is set to simulate situations of road users walking or running freely in the road space. When subjects meet different objects, SME and OME will create effects according to the priority and the strength of ME, which will be reflected in the change of travel time of objects. There are six kinds of objects in the modeling. The initial average speed is set to: pedestrian: 1.4m/s, electrical wheelchair: 1.67m/s, bike: 2.5m/s, robot: 1,78m/s, AV: 5.5m/s, car: 5.5m/s. Due to the lack of information about the priority of the dog in the questionnaire, the dog is not considered as an object in this modeling.

This normative modeling only considers the cases that the subject is the pedestrian and meets different types of objects separately. Other cases of subjects such as bicycles and electrical wheelchairs also need to consider the attributes of both machines and people. The expression of ME needs further studies.

The change of object's travel time in different strengths of subject's ME are calculated. Each situation is calculated 100 times, and the change of travel time is reflected by the mean values. Fig.4 and Fig.5 show the mean value of travel time in five levels of strength of SME and OME when the six objects encounter the subject (pedestrian). If both subject and object are pedestrians, neither SME nor OME of suject has an effect on the object since they have the same priority. Also, travel time of the object pedestrian changes very small (8.49 seconds to 8.63 seconds). This fluctuation of travel time is because of the random pathes of the object. In addition, as the strength of ME increases, object's travel time changes more when it is affected by OME than that of SME. For example, the travel time of robot affected by the level 5 strength of SME is 1.5 seconds longer than that of not be affected (6.9 seconds to 8.4 seconds). However, its travel time affected by the level 5 strength of OME is 4.72 seconds longer than that of not be affected (6.82 seconds to 11.54 seconds). Moreoever, Fig.4 and Fig.5 show that the faster the average speed of objects, such as bikes, cars and AVs, the greater the impact of SME and OME. For instance, as the strength of OME increases, the travel time of the electrical wheelchair rise from 7.15 seconds to 11.33 seconds (increase 4.18 seconds), while the car increases from 2.18 seconds to 9.29 seconds (increase 7.11 seconds).

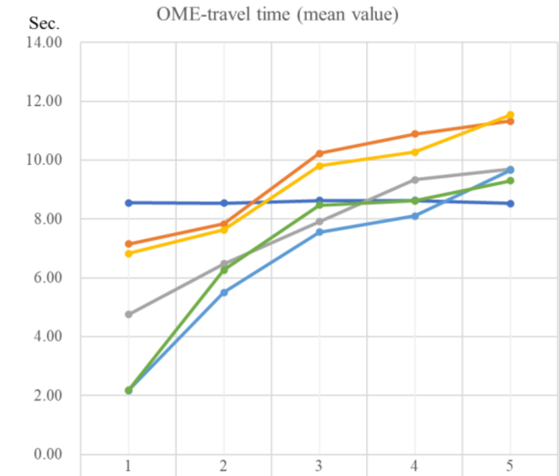
The different effects of SME and OME may because of the following reason. SME will create relatively short ranges around the bodies of subjects. Objects will avoid them by changing their paths. While OME will generate spaces that far away from subjects and surrounding objects. So that objects need to wait for subjects within the area of OME until they pass. At this time, objects will be restricted by the subject's speed, especially some objects with fast speed. Therefore, we suppose that SME is more suitable for objects with less danger, such as robots and electrical wheelchairs, to ensure the traffic flow. While OME is more suitable for objects that have potential safety hazards, such as private cars and AVs, to ensure safety as much as possible.



	1	2	3	4	5
Pedestrian	8.47	8.47	8.54	8.63	8.49
E-wheel	7.27	8.12	8.52	8.98	9.27
Bike	4.88	5.80	6.23	6.63	7.03
Robot	6.90	7.10	7.48	7.99	8.40
AV	2.21	3.32	4.17	4.98	5.82
Car	2.18	3.34	4.54	5.78	7.04

Pedestrian, E-wheel, Bike, Robot, AV, Car

Fig.4 Change of object's travel time on SME.



	1	2	3	4	5
Pedestrian	8.55	8.53	8.62	8.63	8.53
E-wheel	7.15	7.83	10.23	10.89	11.33
Bike	4.75	6.47	7.91	9.33	9.69
Robot	6.82	7.63	9.81	10.27	11.54
AV	2.17	5.51	7.55	8.10	9.65
Car	2.18	6.26	8.47	8.62	9.29

Pedestrian, E-wheel, Bike, Robot, AV, Car

Fig.5 Change of object's travel time on OME.

(3) Plan for the simulation

Since the normative modeling only explains the expected effects of ME, the verification of its effect also requires simulation by using actual data. In the future simulation, we plan to:

a) Quantitative calculation of SME and OME.

In the questionnaire survey, answers of SME and OME's perceptions and their influencing factors are received. The equations of the prediction model of SME and OME will be calculated by using the real data, which will be used in the simulation to predict the ME of pedestrians. Moreover, the situations of generating SME and OME, and whether these two ME can be occurred at the same time or not also need to be considered.

b) Consider SME and OME for cyclists or passengers of electrical wheelchairs.

Since the questionnaire only asked subjective perceptions of participants as pedestrians, how to judge the SME and OME of road users with both attributes of machines and people (such as cyclist and passengers of electrical wheelchairs) has not been understood. In future research, setting specific parameters to solve the problem will be considered. Some existing models are also referred to, such as the social force model. The additional questionnaire survey is also considered if it necessary.

c) Consider the situation of multiple road users in the mixed spaces, and propose a proposal of road allocation or road usage by using ME.

In the normative modeling, only the effects of SME and OME for different strengths when pedestrians as the subject meeting with one object separately are considered. In the future simulation, there will be multiple users with different levels of MEs in the mixed road space. New proposals for road allocations or usages based on ME will be considered by observing various situations and comparing some standards or indexes such as the level of service (LOS).

5. CONCLUSION

The envelope theorem is redefined for dealing with the interaction of multiple road users on mixed road spaces. The different interpretations of SME and OME in the mental envelope are key points of this research. This research uses hypothetical normative modeling to explain the expected effects of SME and OME, and suppose that SME is more suitable for objects with less danger to ensure the traffic flow. While OME is more suitable for objects that have potential safety hazards to ensure safety as much as possible. This modeling will serve as the basis for future simulations.

However, the normative modeling only considers the situation where the pedestrian is the subject and meets every object saperately, which has many limitations. How to explore the ME of a subject with attributes of both machine and human, such as bikes and electrical wheelchairs, needs to be considered. The situations where multiple road users appear in the mixed road space at the same time also needs to be thought about. In future works, we will propose new ideas for road allocation or usages based on envelope theorem through the simulation.

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