A New Envelope Theory for Multiple Subjects on Urban Road Spaces

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This paper proposed a new idea for solving conflicts among various subjects in road spaces. In the future, protecting the safety of weaker subjects and ensuring their spaces would be problematic when new mobilities such as low-speed autonomous vehicles and delivery robots enter future road spaces. This research considered the new conception of the envelope which can protect the safety of users and guide their moving actions in road spaces. Furthermore, this research briefly simulated moving conflicts among differently prioritized subjects on roads to explain the effects of the envelope.

Key Words : *envelope, coexistence, road spaces, multiple subjiects, rulemaking*

1. INTRODUCTION

With the development of human society, it is possible to have varieties of new mobilities such as autonomous vehicles, electric vehicles and delivery robots etc. so that road spaces can become chaotic and disordered. A large number of delivery robots use sidewalks to carry goods and occupy spaces of pedestrians. Those may hit people and cause accidents but there aren't any rules to restrict them. Moreover, attributes of human bodies may change such as elders with muscular bodies or pedestrians with equipment. Under this circumstance, the definition of the weak in road spaces can also be changed. For example, elders are now the weak on roads, but in the future, young people without any equipment may be weaker than muscular elders with high-tech suits. Under such conditions, sidewalks might be gradually occupied by machines and road spaces which originally belong to pedestrians will be gradually reduced and unsuitable for walking. As a result, people may change walking to other ways of traveling.

Now, the problem of mixed transportation gradually appears in people's life. For example, bicycles and pedestrians cause accidents on the share sidewalks; Amazon's delivery robots hit people to cause accidents, and monitoring robots suddenly sing a song on roads and obstruct people to move on. These problems are not far away from us.

To solve the problems, new rules and priorities in road spaces would be needed. On the one hand, it is necessary to ensure the safety of the weaker subjects on roads. On the other hand, it is significant to ensure road spaces for them. This research hypothesizes a new idea about the use of road spaces based on social norms and road priorities which would specify the low-speed autonomous vehicles.

This paper has been divided into several parts. Chapter two presents previous studies related to this research. Chapter three talks about a new conception of solving the problems mentioned in chapter one. Chapter four shows the effects of this conception by using the normative modeling. And chapter five is the conclusion.

2. PREVIOUS STUDIES

There is a concept called envelope in many fields. It is a physical method to isolate something or ensure security. For instance, the safety envelope in the maritime industry is a kind of ship domains that are used to identify safe areas around the ship [1]; flight envelope protection in the aviation a human-machine interface extension of an aircraft's control system that prevents the pilot from making control commands that would force the aircraft to exceed its structural and aerodynamic operating limits [2]; the building envelope in the architecture is the physical separator

between the conditioned and unconditioned environment of a building for resistance to air, heat, noise, light, and water to increase the energy-efficiency [3]; safe driving envelopes in the automobile industry are safe spatial areas where a predefined envelope of the vehicle and obstacles are used to set collision avoidance behavior [4]; the nuclear envelope in biology is a double membrane that maintains shape and size of the nucleus and is difficult to pass and maintain the separation of the intranuclear and intracytoplasmic compartments in cellular metabolism [5]. However, there aren't any related researches on traffic allocation and the use of road spaces in the study of the envelope.

The mental activities of people are important in the study of road spaces. Some conceptions about people's minds in psychology are as same as envelopes. For example, the social force model (SFM) presents psychological forces to drive pedestrians to move as well as keep a proper distance with others [6]; the interpersonal distance from Edward T. Hall explains the safety zone in people's mind during social interactions [7][8]; the psychological distance is defined as a fundamental dimension along which people organize their representation of the world [9]; the construal level theory (CLT) is used for explaining the abstract or concrete thinking of people[10]. These are some descriptive models and conceptions used for demonstrating the effects of psychological activities of human actions. This research refers to these psychological theories as a foundation and innovates new ideas of the pedestrian's mind.

Moreover, the priority on roads as a foundation of creating norms would affect people's views of others [11]. For example, Evangelos Paschalidis discussed the situations of blames from bike riders when they conflict with different road users based on the priority [12]; Iderlina Mateo-Babiano proposed the prioritization of pedestrians to explain the importance of their needs on roads based on the current traffic situation in Manila by using Analytic Hierarchy Process (AHP) [13].

This research hypothesized a new conception of the envelope in the transportation field based on previous studies. To explain the effects of envelopes, the conflicts among differently prioritized subjects on roads were simulated.

3. THE HYPOTHESIS OF ENVELOPE

(1) Definitions

The envelope in this research is used to protect the safety of users and guide their moving actions in road spaces. There are two types of envelopes: the physical envelope (PE) and the mental envelope (ME). The mental envelope included new ideas about people's mind in this research.

The physical envelope (PE) is a physical boundary to protect users and guide their moving actions in road spaces. Two types of indicators are used. The first one is facilities which are embodiments of traffic rules to guide users to use their moving spaces, such as yellow lines and guardrails etc. The second one is technologies used in machines, such as recognition and monitoring systems of autonomous vehicles, position detection systems in delivery robots, and intelligence analysis systems of AI. So, machines are totally guided by systems. Moreover, the enveloped space would explain the moving areas of users. For example, cars can be enveloped by guardrails, and the car lane is an enveloped space which limits cars to it.

There are some attributes of PE:

a) PE has a level of strength. For instance, guardrails are stronger than lines that divide pedestrians and cars.
b) PE is based on social norms. It is the embodiment of collective rules which formed over a long period of time.
c) PE attaches human will and purposes on roads. Their indicators are man-made structures so that big stone in the nature is not a PE, the guardrail made by stone is a PE.
d) For people, the utilizable PE requires understandings of people and identification. If not, people wouldn't follow PE.
e) For machines, they are controlled by PE at any time.

Moreover, people on sidewalks may feel safe or dangerous about guardrails that segregate people from car traffic on roads. In order to explain those feelings, it is possible to assume that people may have the mental envelope (ME), which is a psychological boundary of people in their minds to protect themselves and guide their decisions of moving actions on road spaces. It describes that people how to think about others on roads and make a kind of invisible boundary in their mind to distinguish their comfort zone from others.

Some attributes of ME are assumed:

a) Only people have ME that has individual difference;
b) ME is based on individual values and norms;
c) ME has the level of strength. People would have stronger ME when they meet high-speed bikes than when they meet children walking on sidewalks.

The ME is divided into two types. Road users may not realize those two concepts of MEs on moving. One type of ME is that subjects are enveloped in their

mind (SME). It is similar to previous psychological theory, such as the social force model and interpersonal distances from Edward T. Hall. This research internalized and illustrated them with the envelope theory. In Fig. 1, the enveloped space of SME is a kind of safety or comfort zone of *A* (subject) which doesn't want *B* (object) to enter into this area. If *B* close to *A* and intrudes into *A*'s comfort area, A may feel uneasy. In this case, *A* would move away or tolerate those uncomfortable feelings. When *A* meets many objects (*B, C, D*) on the road, the union of each enveloped space is the total comfort zone of *A*.

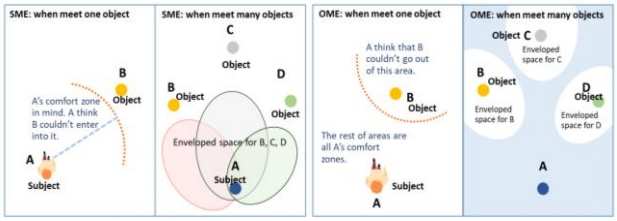


Fig.1 Mental envelope of SME and OME.

Another type of ME is that objects are enveloped in the subject's mind (OME). The enveloped spaces of OME is a restricted zone for objects in the subject's mind. In this sense, the subject in his/her mind is dominant on roads, and other objects may be virtually enveloped by the ME of the subject. In Fig. 1, *A* want *B* to only act in the enveloped space in his/her mind, and the rest of the spaces are *A*'s comfort zone. If B goes out of this area, *A* would feel uncomfortable. When *A* meets multiple objects, *A*'s comfort zone is the rest of the sum of each enveloped space. OME is a new idea in this research. This kind of exclusive spaces prevents objects from approaching subjects and protects their safety. It may happen when multiple new mobilities use roads with pedestrians in the future. It also depends on the innovation and development of technology. Although people now may not move according to this idea, OME would still exist. The existence, practical effects and application of OME would be considered in future works.

(2) The relationships of two types of envelopes

The concept of PE and ME is assumed to exist relatively. Envelopes will be generated when subjects meet objects on roads. Fig. 2 explained the relationship between PE and ME in a short time. PEs and specific situations are influential factors. The strength of PE would affect the strength of ME. For example, a sturdy guardrail would let people feel safer. While a sidewalk with a line to distinguish for a car lane would increase the pedestrian's ME so that they may want to have a stronger PE or leave this place quickly. Moreover, if there are some specific situations, such as having limited time to go, meeting big obstacles on paths, and moving with needless PEs, subjects may change their actions. But in general situations, subjects are more likely to follow PE and express usual actions. For example, bikers ignore bike lanes and run with the pedestrians because of the safe situations and week PEs.

In addition, there is a relationship between PE and ME in the long term. According to Fig. 3, people made PE like guardrails and yellow lines based on social norms at first. They got used to them for a long history. However, because of the real-life experiences of different individuals in the present age, there are many new perceptions and viewpoints. They would start to rethink about PE that have always been used. In this case, new social norms may be created and PE may be changed or adjusted. Finally, this structure would become a loop to continuously update norms and PE. For example, some European countries start to reduce the strength of guardrails to create shared road spaces. Because they found that those PEs are not necessary to their countries and other traffic rules can also achieve the same effects.

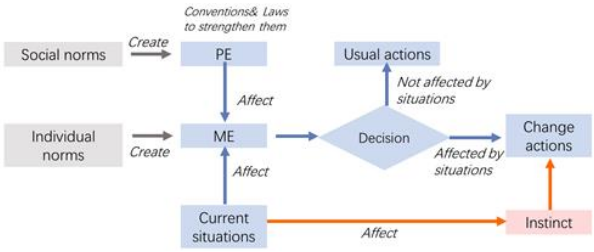


Fig.2 The relationship between PE and ME in the short term.

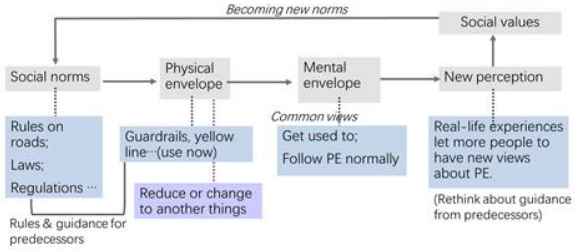


Fig.3 The relationship between PE and ME in the long term.

(3) The equations of the short-term relationship

This research used naive equations based on priority to explicate the relationship between PE and ME in short-term situations at the present stage. Equations reflect the effect of PE on the comfort zone produced by ME. Theoretically, PE will bring a certain sense of safety and weaken the subject's ME. In the SME, S_{ij}^{s} is the comfort space of subject *i* when meeting object *j*. P_k is the enveloped space of PE to *i*. *a* is used to measure the strength of PE that *i* feels. *b* is used to measure the strength of i's ME. M_{ij} is the enveloped space of *i*'s ME when meeting *j*. n is used to estimate the relative priority of *i* and *j*. The equation is:

$$S_{ij}^{s} = aP_k + b \cdot n \cdot M_{ij} \quad (1a)$$

$$(a, b \in [0,1];\ pr_i > pr_j, n = 1;\ pr_i \leq pr_j, n = 0)$$

According to Fig. 4, when subject *A* with higher priority meets object *B*, only *A*'s ME will work. The normative idea requires that higher-priority users can freely go in and out of ME of lower priority users. But someone with lower priority should comply with the ME of higher priority users. If there are PE on roads, *A* would have less vigilance for *B* and feel freer on roads.

There are specific situations of a+b=1. In this case, if a keeps getting closer to 1, the strength of PE that *A* feels is huge so that ME may not be required to limit *B*'s actions (only PE will work). If a keeps getting closer to 0, the strength of the PE is weak, the ME would protect *A*. *B* should follow *A*'s ME at this time.

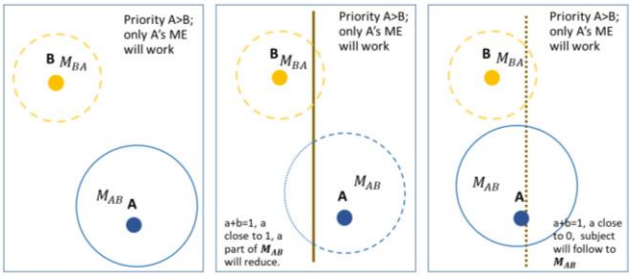


Fig.4 The relationship between PE and ME in the long term.

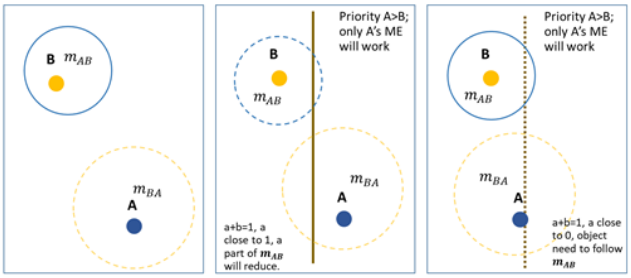


Fig.5 The relationship between PE and ME in the long term.

In the equation of OME, S_{ij}^{o} is the comfort space of subject *i* when it meets object *j*. *S* is the totally environmental space when the envelope happens. m_{ij} is the enveloped space of *i*'s ME for *j*. The meanings of P_k, *a* , *b* and *n* are same as that of in SME.

$$S_{ij}^{o} = aP_k + b \cdot n \cdot (S - m_{ij}) \quad (1b)$$

$$(a, b \in [0,1];\ pr_i > pr_j, n = 1;\ pr_i \leq pr_j, n = 0)$$

There are still situations that cannot be prevented in society even PE exists in the real life of human beings. For example, elderly drivers are accidentally rushing to the sidewalk and hurting pedestrians. Therefore, making the rules of ME might be an effective way of keeping orders on roads. These equations might be foundations for exploring the effects of setting a new rule for ME.

4. THE NORMATIVE MODELING

The purpose of the normative modeling in this research is to explain the effects of two types of ME based on the priority. Because the equations need to be improved, the effects from PE to ME wouldn't be estimated at this stage. Some descriptive models in psychology such as the social force model and interpersonal distances evidenced the psychological activities of a kind of ME in real life. However, the normative modeling hypothesized in this research explained the effects of normalized ME, rather than demonstrated people's behaviors.

ME will occur when the subject and the object get closer. It would happen once in a unit time Δ_t and be re-enveloped in the next unit timeΔ_t'. In this modeling, ME would appear when distances between subjects and objects are less than or equal to 5 meters. It would cause out of action when the one with higher priority couldn't percept the other with lower priority. This modeling just explained situations in one unit time.

A scenario is set to explain the hypothetical effects of SME and OME by observing the change of average speed, which is a method to measure the level of service (LOS) [14] [15]. The totally cost time of two users would be used for estimating the quality of roads. This scenario is a sidewalk with 10m long and 4m wide (Fig. 6). Five kinds of subjects and objects would be used for explaining the idea. Two different users would meet with each other in the same place. The speed without any interference of users is shown in Table 1:

Table 1 The speed of five types of users

	Child	Elder	Adult	Bike	E-scooter
speed	1m/s	1.16m/s	1.47m/s	3.3m/s	4.72m/s

The priority in the normative modeling is a foundation of rules of ME. This was set in the scenario as: child(*A5/B5*) > elder(*A4/B4*) > adult(*A3/B3*) > bike(*A2/B2*) > electric scooter(*A1/B1*). *A* refers to the subject and *B* denotes the object. The number 1 to 5 indicates the priority from low to high. The shape of ME is assumed as a circle. Its radius of different subjects in SME and OME is shown in Table 2 and Table 3. According to the priority, the ME of someone with a higher priority would work and the lower one has to follow his/her ME when they encounter on roads. In those cases, low-priority users would bypass or stop to wait for high priority users until they couldn't percept them (Fig. 6). If these users have the same level of priority, their ME all

wouldn't work. The yellow boxes in Table 2 and Table 3 show the effective ME of subjects when they meet objects.

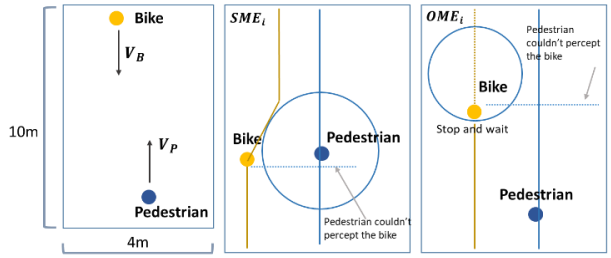


Fig.6 The scenario and illustrations of situations.

Table 2 The SME's radius of subjects

The SME's radius of subjects A_i (m)					
	A5: child	A4: elder	A3: adult	A2: bike	A1:e-scooter
B5: child	0.5	0.7	0.5	1.8	2.5
B4: elder	1	0.8	0.75	1.5	2
B3:adult	2	1.5	1	1.2	1.8
B2: bike	3	3	2	1	1.5
B1:e-scooter	3.5	3.5	3	1.5	1

Table 3 The OME's radius of subjects

The OME's radius of subjects A_i (m)					
	A5: child	A4: elder	A3: adult	A2: bike	A1:e-scooter
B5: child	3.5	3	3	3.5	3.5
B4: elder	2	2.5	2.3	2.8	3
B3: adult	1.5	1.8	2	2.3	2.5
B2: bike	1	1.5	1.7	2	2
B1:e-scooter	0.8	1	1.5	2	2

Fig. 7 and Fig. 8 can explain the changes of the average speed of two users in SME and OME when they meet on roads. The higher the subject's priority, the less the average speed changes. Because of the highest priority of a child in these five users, his/her average speed in every situation of SME and OME wouldn't be changed. However, the average speed of an electric scooter with the lowest priority fluctuates greatly. The requirement of the lowest level of priority enables it to avoid or wait for other types of users on roads. Moreover, it's easy to observe that ME would slow down the speed of low-priority users. Situations of different levels of priorities in OME vary more than that in SME. Because the subject can choose one of the paths to bypass the objects with higher priority in the SME. But in OME, the subject has to wait until the high-priority objects completely pass him/her. If the lower-priority users with much higher speed, the effects of OME would be more obvious. Because lower-priority users have to wait for a long time until higher-priority users couldn't percept them.

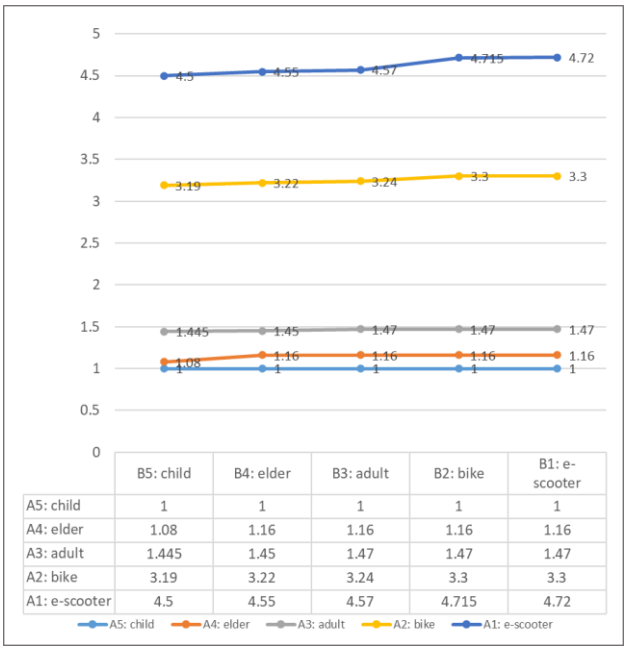


Fig.7 Changes of average speed in SME when Ai meet Bj.

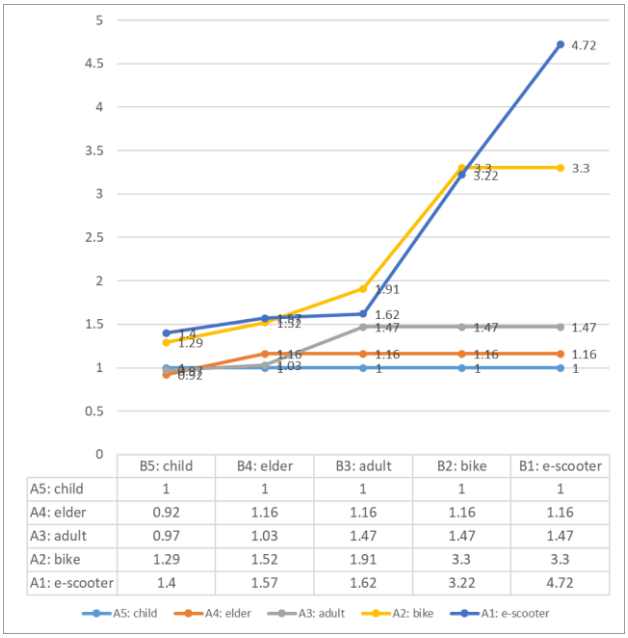
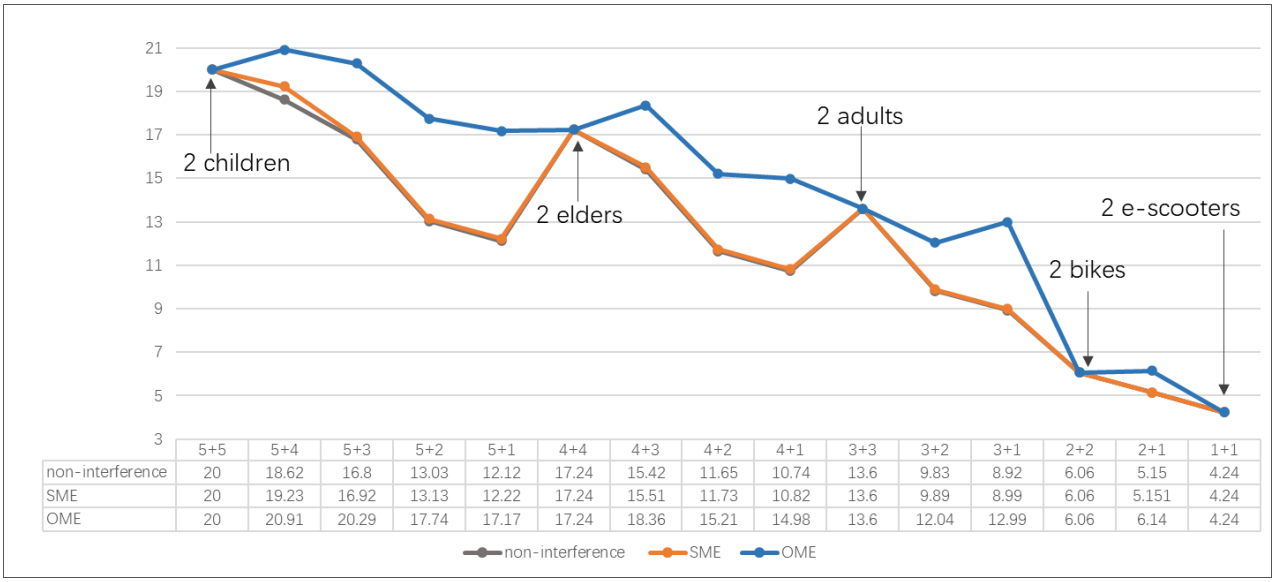


Fig.8 Changes of average speed in OME when Ai meet Bj.

Fig. 9 illustrates the overall performance of roads by using the total time of two users passing through simultaneously. This research calculated all combinations of users in SME and OME, and compared them with the total time when users without any restrictions. In the results, the total time in SME is not much different from the time when users under unconstrained conditions, but the total time in OME will increase too much.

To sum up, SME would not reduce efficiency of roads, but limit the range of movements of the higher-priority users. OME would ensure the safety of weaker subjects and their unimpeded movement, but



	5+5	5+4	5+3	5+2	5+1	4+4	4+3	4+2	4+1	3+3	3+2	3+1	2+2	2+1	1+1
non-interference	20	18.62	16.8	13.03	12.12	17.24	15.42	11.65	10.74	13.6	9.83	8.92	6.06	5.15	4.24
SME	20	19.23	16.92	13.13	12.22	17.24	15.51	11.73	10.82	13.6	9.89	8.99	6.06	5.151	4.24
OME	20	20.91	20.29	17.74	17.17	17.24	18.36	15.21	14.98	13.6	12.04	12.99	6.06	6.14	4.24

Fig.9 Changes of average speed in OME when Ai meet Bj.

the efficiency of low-priority users would be reduced greatly. If the difference in speed between subjects and objects is large, the effects of OME would be more obvious. Moreover, the effects of OME would have a greater impact on the overall road performance than that of SME.

5. CONCLUTION

(1) The conclusion of this research

In the future, new mobilities such as delivery robots and low-speed autonomous vehicles would enter road spaces. To solve the conflicts among various subjects in road spaces, this research considered the new conception of the envelope which can protect the safety of users or guide their moving actions in road spaces. The envelope was divided into the physical envelope (PE) and the mental envelope (ME). ME had two types, the SME and OME. The moving conflicts among differently prioritized subjects on roads were briefly simulated for explaining the effects of PE and ME. In conclusion, PE would improve a certain road performance from ME. SME would reduce less efficiency of roads, but limit the range of movements of the higher-priority users. OME would ensure the safety of weaker subjects and their unimpeded movement, but decrease the efficiency of low-priority users.

(2) The future works

Some tasks are considered as future works. First of all, the evidence of the existence of ME and the acceptance of using normalized ME from people need to be investigated. Also, the effects between ME and PE when multi-subjects use road spaces at same time would be demonstrated by doing experiments in the virtual region. Next, the clearer explanation of the relationship of PE and ME in the short term and long term need to be considered. Finally, the possibility of using rules of ME in the time-space allocation in the future would be studied.

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