IN-ADVANCE LANE CHANGING AND TRAFFIC VOLUME DISTRIBUTION OVER LANES AT EXPRESSWAY ON-RAMP SECTIONS

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Abstract

The distribution of the volume of incoming through traffic over lanes at the upstream-side end of on-ramp merging section is a key factor in designing the geometry of on-ramp junctions. This distribution may be affected by the merging traffic volume and the geometric design of the junction. However, the mechanism how the geometric and traffic conditions affect the incoming traffic distribution over lanes is not sufficiently clarified. This study analyses the behavior so-called "in-advance lane changing", and develops a model that illustrates how "the distribution of traffic over lanes at the upstream-side end of the on ramp merging" is formed under the influence of "traffic phenomena that take place at the on-ramp merging sections." The proposed model shows rather good capability for reproducing observed traffic phenomena.

Keywords: Estimation model; Traffic volume distribution over lanes; On-ramp merging section; In-advance lane changing
Topic area: C3 Traffic Control

1. Introduction

The distribution of the volume of incoming through traffic over lanes at the upstream-side end of on-ramp merging section is a key factor in designing the geometry of on-ramp junctions. This distribution may be affected by the merging traffic volume and the geometric design of the junction. It is necessary to estimate this distribution, understanding in-advance lane-changing behavior of through-traffic drivers, i.e. anticipatory lane changing at a point far enough from the junction to avoid possible conflict with merging cars. However, very few studies can be found that deal with in-advance lane changing, because observation of driving behavior over a long distance up-stream of a merging section is not an easy task.

This study develops a model that illustrates how "the distribution of traffic over lanes at the upstream-side end of the on ramp merging" is formed under the influence of "traffic phenomena that take place at the on-ramp merging sections." It proposes a method to estimate "the distribution of incoming traffic over lanes into the on-ramp merging section" under various traffic conditions.

In Chapter 2, the survey results from observing in-advance lane changing are detailed, and in Chapter 3, modeling of the in-advance lane-changing behavior as a utility maximization action is carried out, and a resultant model to be used for lane occupancy ratio estimating is proposed. In Chapter 4, the validity of the model is examined by case analysis.

2. Actual state of in-advance lane changing upstream of on-ramp merging sections

2.1 Outline of Observation

For analyzing the traffic of the on-ramp merging sections, the relationship between the traffic conditions and in-advance lane changing is an element that cannot be overlooked. Data showing the actual state of traffic at the merging sections that also include in-advance lane changing, however, is hardly available due to the fact that it requires a large scale survey, including macroscopic observation from the air. To the authors' knowledge, Japan Society of Traffic Engineers (1987) observation data is the only available data of this kind. The current status is that although Kita, Maeda and Shiotani (2001) did publish a report on the analysis of in-advance lane-changing behavior at the upstream end of on-ramp merging sections, there is little accumulation of detailed behavior analysis.

In order to assess the reality of lane changing taking place upstream of on-ramp merging sections, we carried out an observation using a radio controlled model helicopter (see Kita, Shiotani and Maeda, 2001). The model helicopter is an industrial type one of 60cc displacement and about 2m in total length, generally used for aerial photography for geographical surveys and for crop dusting. Two digital video cameras were mounted to the helicopter, which we had hover above and film the merging sections of the Toyota and Okazaki I.C. of the Tomei Expressway in Aichi Prefecture, which were chosen as our observation site. The area videotaped is a 750-meter-long section including the on-ramp area, i.e. 500 m upstream of the on-ramp nose, and 250 m downstream of the on-ramp nose. Video image filmed was used to measure traffic volume by lane, traffic volume entering at the on-ramp merging section, and the positions where in-advance lane changes were made in the following sections along the 5 observation lines: at the merging nose, 50 m upstream, 100 m upstream, 150 m upstream and 200 m upstream. Results from the above were compiled in the data to assess the in-advance lane-changing behavior. This enabled us to obtain the across-the-board data of the entering traffic at the on-ramp merging section, traffic at the upstream end of the merging sections, in-advance lane changing and the like, and as a result we were able to assess the actual state of in-advance lane changing and its impact on traffic.

2.2 Location and quantity of in-advance lane changing

The percentage of merging traffic volume to the total traffic volume after merging (hereafter referred to as the "merging traffic ratio") was around 20 to 30%. An example of the traffic volume by lane and the number of lane-changing vehicles in each section are shown in Table 1. In all the cases analyzed, the volumes of traffic on the through-traffic lanes and passing lanes began to change at a location about 200 m upstream of the on-ramp nose, and this tendency became prominent at a location about 150m upstream of the on-ramp nose. Fig. 1 shows a comparison between the traffic volumes on the through lane and the passing lane. Despite the fact that the traffic volume on the through lane at the location of 200 m upstream of the on-ramp nose was by far greater than the traffic volume on the passing lane, at the locations of 100 m and 150 m upstream of the on-ramp nose, the traffic volume on the through-traffic lane and passing lane was roughly at the same level. And at the on-ramp nose (0 m), in more than a few cases, the traffic volume on the passing lane was greater by far than the traffic volume on the through-traffic lane. Judging from the fact that the number of vehicles that changed lanes from the passing lane to the through lane was very small, it is likely that almost all vehicles that changed lanes in this 200 m section upstream of the on-ramp nose made in-advance lane changes to avoid conflict with merging vehicles.

Table 1 Occurrence of in-advanced lane changing behavior

	Case 1	Case 2	Case 3	Case 4	Case 5
0-50m	21	22	15	22	17
50-100m	16	25	21	12	14
100-150m	17	19	23	16	12
150-200m	3	1	9	14	5
Total	58	67	68	64	48
Ratio *	0.241	0.275	0.219	0.211	0.182

* In- advance lane changing ratio

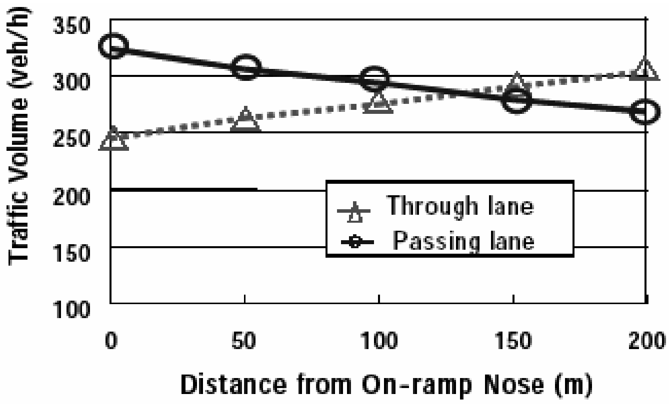

Fig. 1: Traffic volume on through and passing lanes at different locations

Define the percentage of vehicles that changed lanes from the through-traffic lane to the passing lane in all vehicles that passed the location 200 m upstream of the on-ramp nose as the in-advance lane change ratio. The ratio obtained was as high as 18 to 27%. This implies that a considerable number of drivers empirically anticipated the traffic conflict likely to occur at the merging section and deliberately made a lane change in advance to avoid it.

2.3 Volume of Merging Traffic and In-Advance Lane Changing

Noting the relationship between the merging traffic volume ratio and the in-advance lane change ratio, a correlation as shown in Fig. 2 was identified (R=0.764). This implies that drivers who, while upstream of the on-ramp merging section, were unaware of the existence of merging vehicles, made lane changes in advance to avoid possible traffic conflict in the merging section, by making the experience-based prediction of the volume of merging traffic, which we found very interesting.

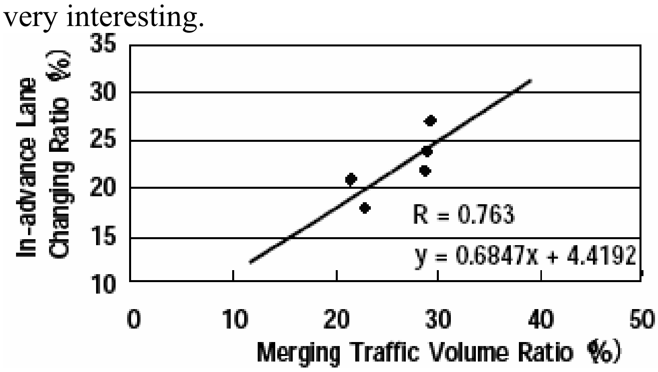

Fig. 2: Merging traffic volume ratio vs. in-advance lane-changing ratio

3. Estimation model

3.1 Study review on lane-changing behavior and the traffic volume distribution

Kita and Kubozono (1994) focused on drivers' decision-making in merging in onto through lane and in giving-way for merging traffic, of which traffic phenomena at the merging sections are mainly composed. They developed a model of drivers' behavior at the expressway on-ramp merging sections by using non-cooperative game theory, which enables implicit consideration of the decision-making of these two interacting drivers. Kita, Fukuyama and Tanimoto (1999) adhering to the approach made by Kita and Kubozono (1994), analytically obtained realized solution of merging-giveway behaviors from multiple equilibria, and examined the validity of the model by using the observed data.

Kita, Tanimoto and Fukuyama (2002) gave an estimation method of equilibrium selection among multiple equilibria. In these studies, it was indicated that in-advance lane-changing behavior (from the through-traffic lane to passing lane), anticipating the entering traffic at the merging section, was also a dominant factor in understanding traffic phenomena in the vicinity of merging section. The observation by Kita, Shiotani and Maeda (2001) were conducted under such a background. Kita, Kousaka and Fukuyma (2001) was an attempt to develop a model for estimating traffic conditions including traffic volume distribution over lanes with taking the interaction between merging and through traffic into consideration.

3.2 Modeling approach

In order to derive the traffic volume ratio of through traffic over lanes at the merging section, we assume that the merging vehicles and the through lane vehicles at the merging sections make their decisions in merging and giveway, considering their own utility consisting of safety and delay, i.e. risk reduction from facing traffic conflict with merging vehicle and increasing travel time due to driving in the heavier traffic.

The location of each lane and each vehicle at the expressway merging section shown in Figure 3 is taken into consideration. The vehicle **s,** which will make the in-advance lane-changing decision, is currently moving in the through-traffic lane toward the merging section. Suppose that driver of this vehicle, who makes the in-advance lane-changing decision, has the prior knowledge that the merging section is coming up, that s/he makes a prediction of the driving condition in the merging section, prior to reaching the merging section, and is about to make the in-advance lane-changing decision now. If the driver of the vehicle engaged in in-advance lane changing makes the decision by considering safety only, it would be desirable to make an in-advance lane change to the passing lane. The objective of the drivers on the expressway, however, may be to arrive at the destination as quickly as possible, in addition to safety, which leads us to the need to consider driving amenity. Consequently, safety and driving amenity, both essential to decision making for in-advance lane changing, are considered concurrently, and then the model to estimate traffic volume distribution over lanes will be developed.

In relation to safety and driving amenity, the increase and decrease of traffic volume caused by in-advance lane changing must be taken into consideration. Suppose the total through traffic volume is λ, and the traffic volume of the through-traffic lane and of the passing lane prior to the in-advance lane-changing decision is $\lambda 2$ and $\lambda 3$ ($\bar{\lambda}=\lambda 2+\lambda 3$) respectively. Probability of lane changing is expressed as in-advance lane-changing probability p . Suppose the traffic volume of the through-traffic lane and the traffic volume of the passing lane after the in-advance lane-changing decision is made are dependent on the above probability and each is expressed as $\lambda_2$and λ^* respectively, then they are obtained by using the following equations.

$$\lambda_2^* = (1-p)\lambda_2 \qquad (1)$$
$$\lambda_3^* = p\lambda_2 + \lambda_3 \qquad (2)$$

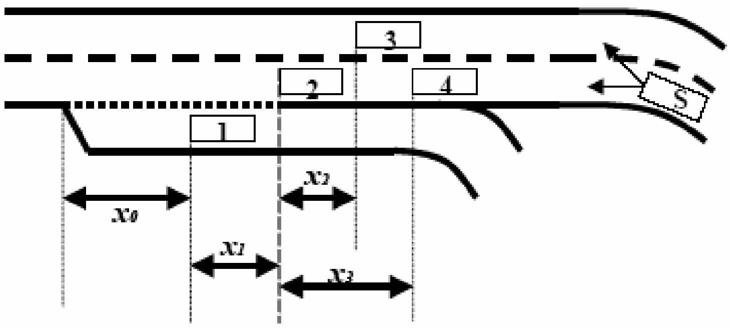

Fig.3 Lane Configuration and Vehicle Locations

3.3 Safety

3.3.1 Potential accident risk from merging vehicles

In order to explain factors relating safety, the earlier version of this model developed in Kita, Kousaka and Fukuyama (2001) will be used after modifying it. As shown in Fig. 3, the vehicles that will be making the merging and giveway decisions at the on-ramp merging section will be called the merging vehicle[1] and the through vehicle[2]. The merging vehicle[1] and the through vehicle[2] move while taking their own safety into consideration. As an indicator expressing safety, TTC between vehicles is used. TTC stands for "Time To Collision" and indicates how many seconds it will be before a collision takes place if this vehicle and the other vehicle continue moving while maintaining the same speed. It can be used as an indicator to show the degree of potential accident risk, in the sense that it expresses the extent of how imminent the danger is. TTC of the vehicle *a* and vehicle *b* is shown in the following equation.

$$TTC = \frac{X_a - X_b}{V_b - V_a} \qquad (3)$$

X_i shows the location of the vehicle i i =ba) on the expressway. V_i is the speed of the vehicle i i = ba) . The denominator of this equation expresses the relative speed of vehicles moving in tandem, and the numerator expresses the space headway between the two vehicles. Here, the payoff matrix is defined by using TTC. Each driver's payoff is compiled in Table 2; thus the payoff values are specified. The location of the through vehicle[2] at the time when it reaches the entrance of the merging section, which

Table 2 Payoff Matrix of Merging and Through Vehicles

		Through Vehicle	
	Action	A_1^2	A_2^2
Merging Vehicle	A_1^1	(F_{11}, G_{11})	(F_{12}, G_{12})
	A_2^1	(F_{21}, G_{21})	(F_{22}, G_{22})

A_1^1 : Merge A_1^2 : Go with giveway

A_2^1 : Pass A_2^2 : Go without giveway we have referred to as the on-ramp nose, is used as the datum point. The positional relationship between each vehicle is established as shown in Fig. 3, and the speed of the vehicle[1], [2], [3] and [4] are represented as v_1, v_2^{2} , v_3 and $v2$(= $v2$) , respectively. Each driver's payoff is sorted out below.

$$F_{11} = \frac{v_1 t_m + x_1 - (v_2^4 t_m - x_3)}{v_2^4 - v_1} \tag{4}$$

$$F_{01} = \frac{(x_0 - x_1) - v_1 t_m}{v_1} \tag{5}$$

$$F_{10} = \frac{v_1 t_m + x_1 - v_2^2 t_m}{v_2^2 - v_1} \tag{6}$$

$$F_{00} = \frac{(x_0 - x_1) - v_1 t_m}{v_1} \tag{7}$$

$$G_{11} = \frac{v_2^2 t_g - (v_3 t_g - x_2)}{v_3 - v_2^2} \tag{8}$$

$$G_{01} = \frac{v_2^2 t_g - (v_3 t_g - x_2)}{v_3 - v_2^2} \tag{9}$$

$$G_{10} = \frac{v_1 t_g + x_1 - v_3 t_g}{v_3 - v_2^2} \tag{10}$$

$$G_{00} = 0 \tag{11}$$

Payoff values of the merging vehicle[1] and through vehicle[2], F_{ij} , G_{ij} respectively, are a function of t with the speed of each vehicle v being constant. M represents the time between the beginning of the *non-cooperative game* and the moment the merging vehicle[1] merges in onto the through lane. t_g represents the time between the beginning of the game and the moment the through vehicle[2] makes a giveway onto the passing lane. To simplify the model, it is interpreted that the merging or giveway takes place at the same instance specified in Figure 1 and thus tm = ,0 tg = 0 . Thedrivers of the merging vehicle[1] and the through vehicle[2] both select the optimum strategy, meaning a behavior of high safety, by comparing the payoff functions.

When the decision made by the merging vehicle[1] is to "merge", the risk of an accident with the vehicle(s) moving in the through-traffic lane will arise. And if the decision made by the through vehicle[2] is to "giveway", an accident risk with the vehicles on the passing lane will arise. This kind of accident risk has a great effect on the vehicles moving in the through-traffic lane. In this study, therefore, the effect of merging and giveway behavior on each lane is considered a "loss" of safe driving, or a negative payoff function. In order to simplify the model, it is assumed here that the through vehicle does not make giveway unless the merging vehicle merges in onto the through-traffic lane.

3.3.2 Combinations of behavior of merging and through vehicles

The following 4 cases can occur as combinations of the behavior of through and merging vehicles.

Case 1: If no merging vehicle exists in the acceleration lane, merging behavior cannot take place. Through vehicle, therefore, makes no giveway. This case is categorized as "No merging and no giveway", and is called Case 1.

Case 2: When a merging vehicle is present in the acceleration lane, and the merging vehicle [1] recognizes that the distance to the through vehicle [2] is long enough to merge in, it merges in in front of the vehicle [2], and through vehicle [2] finds enough distance to the through vehicle [3], it changes lanes onto the passing lane. This case is categorized as "merge and giveway", and is called Case 2.

Case 3: When a merging vehicle is present in the acceleration lane, and the merging vehicle [1] finds enough distance to the through vehicle [2], it merges in onto the through lane. Because through vehicle [2] does not find enough distance to the through vehicle [3], it does not change lanes. This case is categorized as "merge and no giveway", and is called Case 3.

Case 4: When merging vehicle is present in the acceleration lane, and the merging vehicle [1] does not find enough distance to the through vehicle [2], it does not merge in onto the through lane. At this time, the through vehicle [2] does not make giveway. This case is categorized as "pass and no giveway", and is called Case 4.

Based on the above 4 cases, the payoff functions of through and merging vehicles under conflict can be formulated as follows. Loss function is expressed as t_j^i (through lane $i = 2$, passing lane $i = 3$, and j expressing the case number) and in case there is no influence from the vehicles on other lanes, the value is 0.

(a) Payoff function of the through vehicle when affected by the merging vehicle

Case 1: Because of no merging vehicle trying to merge, the through vehicle is not affected.

$$t_1^2 = 0 \qquad (12)$$

Case 2: In case the merging vehicle [1] merges and the through vehicle [2] makes giveway, the through vehicle [4] is influenced by the merging vehicle [1]. By using the equation (6), the negative payoff in case 2 is expressed in the following equation.

$$t_2^2 = -\frac{x_1 + x_3}{v_4^2 - v_1} \qquad (13)$$

Case 3: In case the merging vehicle [1] merges and the through vehicle [2] does not make giveway, the through vehicle [4] is affected by the merging vehicle [1]. By using the equation (6), the negative payoff in case 3 is expressed as follows.

$$t_3^2 = -\frac{x_1}{v_2^2 - v_1} \qquad (14)$$

Case 4: In case the merging vehicle [1] does not merge in, and the through vehicle [2] does not make giveway because there is no entering vehicle, the through-traffic lane is not affected.

$$t_4^2 = 0 \qquad (15)$$

(b) Payoff function on the passing lane when affected by the through vehicle [2]

Case 1: No effect on the passing lane.

$$t_1^3 = 0 \qquad (16)$$

Case 2: The through vehicle [2] has an effect on the through vehicle[3]. This is expressed in the following equation, by using the equation (8) to obtain the negative payoff.

$$t_2^3 = -\frac{x_2}{v_3 - v_2} \qquad (17)$$

Case 3: No effect on the passing lane.

$$f_3^3 = 0 \quad (18)$$

Case 4: No effect on the through lane.

$$f_4^3 = 0 \quad (19)$$

Using the above equations, the payoff functions of each lane were obtained. Now, using these obtained payoff functions, the probability of the occurrence of each phenomenon detailed in the combinations of merging and giveway behavior will be derived.

In Fig.3, headway between each vehicle x_1, x_2, $x3$ is assumed to follow the probability distributions. Here, the assumption is that it follows the shifted exponential distributions shown in equations (20) through (22). The combinations of entering and giveway behavior are given as the equilibrium solutions of the game, and the probability of the occurrence of each equilibrium solution is derived by specifying the distribution of headway for each lane.

$$f_{X_1}(x_1) = \lambda_1 \exp[-\lambda_1 x_1] \quad (20)$$

$$f_{X_2}(x_2) = \lambda_2^* \exp[-\lambda_2^*(x_2 - \alpha_2)] \quad (21)$$

$$f_{X_3}(x_3) = \lambda_3^* \exp[-\lambda_3^*(x_3 - \alpha_3)] \quad (22)$$

$\lambda 1\ \lambda 2\ \lambda 3^*$ represent the traffic volume of each lane. α_2 and α_3 represent the minimum headway between consecutive vehicles in the through and passing lane, respectively.

Using the above equations, the payoffs determined by the location and relative speed of surrounding vehicles per each combination of merging and giveway behaviors are derived. As indicated in Table 3, in the equilibrium solution (0,0)at (x*) *, , the merging vehicle will eventually merge in onto the through-traffic lane. From the magnitude relation of these payoff values, ($F11 - F01 >$ (<),0 $F10 - F00 >$ (<),0 (G11 − $G10$ < >)0), the equilibrium solutions, (x, y) , of the merging and the through vehicles in each situation of encounter illustrated above are derived.

3.3.3 Probability of occurrence of each case of encounter

The probability of occurrence of each case is estimated as follows.

Case 1:

$$P_1 = \int_{\alpha_3}^{\infty}\int_{x_0}^{\infty}\int_{\alpha_2}^{\infty} f_1(x_1) f_2(x_2) f_3(x_3)\, dx_2\, dx_1\, dx_3 \quad (23)$$

Case 2:

$$P_2 = \int_{\alpha_3}^{\infty}\int_{\frac{v_2-v_1}{v_2}x_0}^{x_0}\int_{\frac{v_3-v_2}{v_2-v_1}x_1}^{\infty} f_1(x_1) f_2(x_2) f_3(x_3)\, dx_2\, dx_1\, dx_3 \quad (24)$$

Case 3:

$$P_3 = \int_{\alpha_3}^{\infty}\int_{\frac{v_2-v_1}{v_2}x_0}^{x_0}\int_{\alpha_2}^{\frac{v_3-v_2}{v_2-v_1}x_1} f_1(x_1) f_2(x_2) f_3(x_3)\, dx_2\, dx_1\, dx_3 \quad (25)$$

Case 4:

$$P_4 = \int_{\alpha_3}^{\infty}\int_{0}^{\frac{v_2-v_1}{v_2}x_0}\int_{\alpha_2}^{\infty} f_1(x_1) f_2(x_2) f_3(x_3)\, dx_2\, dx_1\, dx_3 \quad (26)$$

Table 3 Equilibria of the Merging-Giveway Game

Equilibria	(x^*, y^*)	$F_{11} - F_{01}$	$F_{10} - F_{00}$	$G_{11} - G_{10}$	$(\bar{x}, \bar{y})$
I	(1,1)	$x_3 > \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 > \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 > \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,1)
II	(1,0)	$x_3 > \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 > \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 < \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,0)
III	(1,1)(0,0)(G,F)	$x_3 > \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 < \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 > \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,1)*
IV	(0,0)	$x_3 > \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 < \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 < \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,0)*
V	(G,F)	$x_3 < \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 > \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 > \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	—
VI	(1,0)	$x_3 < \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 > \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 < \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	—
VII	(0,0)	$x_3 < \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 < \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 > \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,1)*
VII	(0,0)	$x_3 < \frac{(v_2^4 - v_1)x_0}{v_1} - \frac{v_2^4}{v_1}x_1$	$x_1 < \frac{(v_2^2 - v_1)x_0}{v_2^2}$	$x_2 < \frac{(v_1 - v_2^2)}{(v_2^2 - v_1)}x_1$	(1,0)*

3.3.4 Expected payoffs for each lane

From the combinations of these probabilities of occurrence, the expected payoff EU when in-advance lane changing is not carried out, and EU the expected payoff when in-advance lane changing is carried out, can be derived. The change in expected payoffs for each lane, when in-advance lane-changing probability p fluctuates, is obtained.

The expected payoff for the through lane is expressed as follows,

$$EU_2(p) = t_1^2 P_1 + t_2^2 P_2 + t_3^2 P_3 + t_4^2 P_4 \qquad (27)$$

and expected payoff for the passing lane is expressed as follows,

$$EU_3(p) = t_1^3 P_1 + t_2^3 P_2 + t_3^3 P_3 + t_4^3 P_4 \qquad (28)$$

As shown above, the expected payoffs for safety in each lane can be derived.

3.4 Driving amenity

In order to explain the driving amenity, suppose that the in-advance lane-changing vehicle to be treated here is 200m upstream of the on-ramp nose, and the driver is currently making a decision whether to make an in-advance lane change or not. The in-advance lane-changing vehicle is trying to move at the desired speed to quickly reach its destination. In other words, the in-advance lane-changing vehicle, while taking other vehicles in through traffic into consideration, predicts which lane would make the quickest arrival possible at the merging zone, before acting. Let us suppose here that a certain level of traffic volume is carrying out in-advance lane changing. Because of the increase in the traffic volume on the passing lane, the desired speed cannot be achieved there. Due to this speed change, the loss of distance, from the total distance required before reaching the on-ramp nose, which should have been achieved if the driver had been able to move at the desired speed, takes place. If this loss of distance is smaller in the through lane than in the passing lane, driving in the through lane will be more "agreeable".

The loss in distance at the on-ramp nose is 0 m, and at any location upstream of the on-ramp nose the values are positive. Many studies on the average speed have been conducted so far. In this study, it is assumed that the average speed is derived from Underwood's equations (Underwood, 1961).

$$V_i = Vf_i \cdot e^{-\frac{k}{kc}} \quad (29)$$

$$k = \frac{\lambda_i^*(p)}{V_i} \quad (30)$$

V_i : average speed on each lane
Vf_i : desired speed on each lane
i : through-traffic lane $i = 2$ and passing lane $i = 3$
k_C : critical density
Q : traffic flow rate per hour

As the assumption is that the in-advance lane-changing vehicle is making the lane-changing decision at 200 m upstream of the on-ramp nose, the times required to drive the 200-m distance at the desired speed and at the average speed are expressed respectively in the equations

$$tf_i = \frac{0.2}{Vf_i} \quad (31)$$

$$t_i = \frac{0.2}{V_i(p)} \quad (32)$$

Time loss is expressed as,

$$T_i = t_i(p) - tf_i \quad (33)$$

and speed loss is expressed in the following equation.

$$v_i = Vf_i - V_i(p) \quad (34)$$

Using the equations (33) and (34), payoff S_i of loss in distance is expressed as follows.

$$S_i = -v_i(p)T_i(p) \quad (35)$$

Thus, the loss in distance in each lane in relation to driving amenity can be derived.

3.5 Model for estimating traffic volume ratio over lanes

From the equations (27), (28) and (35), the expected payoffs for safety and for driving amenity were derived. If the weight of driving amenity against safety is expressed in parameter β , the expected payoff for the through lane, U_2 , and the expected payoff for the passing lane, $U_3(p)$, will be shown as below.

$$U_2(p) = EU_2(p) + \beta S_2(p) \quad (36)$$

$$U_3(p) = EU_3(p) + \beta S_3(p) \quad (37)$$

On the road with two lanes in each direction, the more the one lane is congested, the less effective it would be to drive in this lane, and the more effective it would be to drive in the other lane. If the effectiveness of one of the two lanes is higher than the other, drivers will change lanes to reduce the loss. Thus the traffic volume of each lane shall reach an equilibrium condition, where the expected payoff for the passing lane and that of the through lane are equal. By simultaneously obtaining the solutions of the following equations,

$$U_2(\lambda_2^*(p), \lambda_3^*(p)) = U_3(\lambda_2^*(p), \lambda_3^*(p)) \quad (38)$$

$$(\bar{\lambda} = \lambda_2^*(p) + \lambda_3^*(p)) \quad (39)$$

The traffic volume ratio of the through lane, ψ_0 , and that of the passing lane, ψ_1, are obtained as,

$$\psi_0 = \frac{\lambda_3^*}{\lambda} \tag{40}$$

$$\psi_1 = \frac{\lambda_2^*}{\lambda} \tag{41}$$

The traffic volume ratio, ψ_0 , derived from the above equations, therefore, becomes the traffic volume ratio $p^* = \psi 0$ at the on-ramp nose.

4. Case analysis

4.1 Established conditions

In order to examine the validity of the model, we conducted a case analysis how the proposed model can explain the phenomena, by using the observed data detailed in Chapter 2 was attempted.

The traffic flow rate identified in the observation was 518 (veh/h) on the entering lane at a point 200 m upstream of the on-ramp nose, 749 (veh/h) on the through lane, and 806 (veh/h) on the passing lane. Comparable figures at the on-ramp nose were 391 (veh/h) on the through lane and 1,164 (veh/h) on the passing lane. The length of the acceleration lane was 200 m, and the average speed of the acceleration lane, the through lane, and the passing lane vehicles was 82.8km/h, 85.8km/h, and 95.7km/h respectively. Critical density, kC, is approximately 40 to 50 vehicles/km/lane in general based on the observed results in Japan, a figure of 50 vehicles/km/lane is used here. The desired is set at 100 km/h, which is the speed limit of expressway.

4.2 Results of the analysis

Using the hypothesis that the in-advance lane-changing vehicle makes the decision whether to make in-advance lane changes or not, while anticipating the potential accident risk with the entering vehicles at the merging zone, as well as taking into consideration the driving amenity; a value for the parameter β that appropriately replicates the phenomena was estimated and $\beta = -0.0321$ was obtained. By incorporating this in the model, the lane occupancy ratio was calculated from the established conditions for calculation.

The expected payoff when safety and driving amenity are taken into consideration, U_2 and U_3 , at the merging zone, of the through-traffic lane and passing lane respectively are shown in Fig. 4. Calculated traffic volume ratio at the on-ramp nose was 0.218. Compared with the actual lane occupancy ratio 0.251 of the through-traffic lane, it was somewhat underestimated, but we believe the estimated value obtained was close enough.

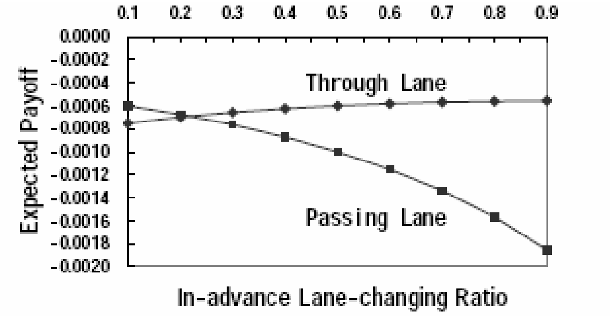

Fig. 4 In-advance lane-changing ratio and expected payoff of each lane

5. Conclusion

In this study, modeling of the in-advance anticipatory lane-changing behavior upstream of the expressway on-ramp's merging zone was conducted. The in-advance anticipatory lane-changing behavior upstream is viewed as a utility maximization action, and a model to be used for estimating the traffic volume ratio over lanes at the on-ramp nose of the merging zone was proposed. Through case analysis, it was verified that the points of this study do explain the phenomena to a certain extent, but as the scope of the study was limited, there still remain more than a few points to be further studied. By using the models proposed here, the authors have developed separately a model to be used for determining the length of the acceleration lane. The traffic volume ratio over lanes at the on-ramp nose of the merging zone, which had traditionally been given exogenously despite the fact that it is dependent on the geometric design and traffic characteristics of the merging zone, is provided endogenously, instead. This model, however, will be presented at another occasion.

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