A Comparative Study on Crash Rate Characteristics at Different Intercity Expressway Facility Types

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For investigating methods of geometry design and traffic operation for safer expressways, this study aims to identify differences of crash rate (CR) characteristics at various expressway facility types. The test bed is a section of Tomei-Meishin Expressway, and it was segmented into six facility types. Furthermore, basic segment was divided into 2-lane and 3-lane sections based on the number of lanes per direction. Basic/merge/diverge/service-area segments were analyzed due to the limitation of crash samples. Then relationships between traffic density and CR were compared among these expressway facility types, as well as between 2-lane/3-lane basic segments. The results reveal that merge/service-area segments have significantly higher CR compared to basic/diverge segments for uncongested flow. For congested flow, diverge segment has significantly higher CR compared to basic/service-area segments. Regarding basic segment, 3-lane basic segment has higher CR than 2-lane basic segment for uncongested flow, while significantly higher CR exists at 2-lane basic segment for congested flow.

Key Words: *crash rates, traffic density, facility type, quadratic function, traffic control strategy*

1. INTRODUCTION

Several studies have shown that crash rate characteristics are associated with traffic flow conditions, while most of them focused on discrete uniform segments[1,2] or analyzed the whole routes without classifying facility types[3]. Meanwhile, some papers such as Wu *et al.*[4] considered the impacts of facility types along with traffic density on crash rates at various urban expressway segments. However, the differences of crash characteristics at various segments of other expressways which have different geometric and traffic characteristics from urban expressway have not been identified well.

Intercity expressway is a common type of separated highway with full control of access in Japan. Generally, it is composed of various facility types such as basic and merge segments, and geometric and traffic characteristics at those facility types are often different. Even for the same facility type, vehicle behaviors at sections with altered number of lanes are possibly not similar as well. Thus, crash characteristics at the segments of various facility types or multiform cross-section types may be different from each other. For investigating methods of geometry design and traffic operation for safer expressways, it is necessary to identify differences of crash characteristics caused by variation in geometric and traffic characteristics. Therefore, this paper aims to quantify relationships between crash rates and traffic flow conditions at various intercity expressway facility types. The rest of this paper is organized as follows. In Section 2, the feature of the study site, the methods to process crash and detector data, and the formula to calculate crash rates are presented. Crash rates-traffic density relationships for various facility types are compared in section 3. Section 4 identifies crash rates-traffic density relationships between 2-lane and 3-lane basic segments. Section 5 offers conclusions and suggestions for future research.

2. METHODOLOGY

(1) Study site and data bases

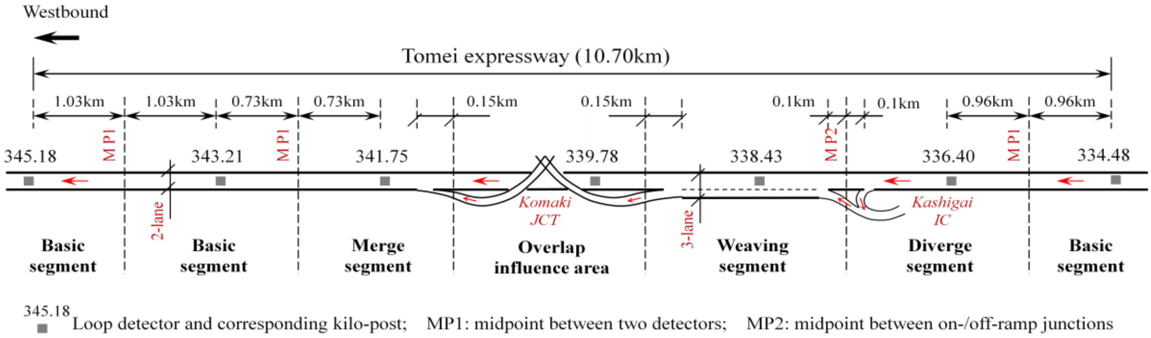

Fig.1 Segmentation of expressway facility types

The test bed of this study is the section of Tomei-Meishin Expressway from Mikkabi Interchange (IC) to Yokaichi Interchange (IC). The total length of this section is 183.6km, with a design speed of 80~120 km/h. Along the mainline, there are usually 2 lanes per direction, except the area in which an auxiliary lane is designed. Most of IC are formed by a combination of on-ramp and off-ramp that is located immediately upstream of the on-ramp (Fig.1). Nearly 180 loop detectors (2 directions) are installed in approximately 2 km intervals.

Four databases were used for the following analysis; 1) crash record with occurrence time in minute and locations in km; 2) lane-based detector data collected traffic flow, speed and occupancy per 5 minutes; 3) geometry design data and locations of detectors in km; 4) locations and periods of lane or section closure. The period of the data above is three years from January 1, 2007 to December 31, 2009.

(2) Segmentation of facility types

Expressway sections were segmented into five facility types as shown as the example in Fig.1. Other than these segments, there are service/parking areas with vehicle-passenger interaction, and their acceleration/deceleration lanes are often shorter than the lanes at merge/diverge segments. Hence the areas were regarded as another distinct segment type, and named as service area in unity. The informatory sign for service area is usually located in 1km upstream of entrance, and most of acceleration/deceleration lanes in the test bed are shorter than 0.4km. This study defined the section from 1km upstream of entrance to 0.5km downstream of exit as one service-area segment due to the limited number of detectors.

There are only six tunnels in the test bed, and the total length is just 3.1 km. Therefore, tunnel section was not analyzed in this study. For basic segment, sections of 2-lane/3-lane per direction were regarded as different cross-section types. Most of other facility types are sections of 2-lane per direction. Since crash samples at weaving segment and in overlap area are limited, only basic/merge/diverge/service-area segments were analyzed. Statistical results of geometry for those facility types were shown in section 3.

(3) Extraction of detector data

Loop detector measures traffic conditions at location of detector. For collecting detector date for each crash, this study divided influence area of detector. The area was bounded by the midpoint between neighboring detectors at basic segment (Fig.1). Other facility types can be regarded as one single influence area. Then, traffic condition preceding a given crash may be represented by data collected at the corresponding detector. Meanwhile, the time of crash was recorded by road administrators after crash occurrence, and it is not the exact occurrence time. In such case, detector data within small time before crashes should be rejected to avoid “cause and effect” ambiguity as explained by Abdel-Aty and Pande[5]. So this study chose the last detector data within 5 minutes at least before the recorded time. Invalid data with unreasonable values such as aberrant values (e.g., speed>200km/h or traffic flow>400veh/5-min) or negative values, and the data in lane/section closure were excluded in advance.

Note that, detector data in original databases is lane-based, while existing related results were developed according to cross section-based data. Considering relativity with existing analyses, this study was also conducted based on cross section-based data that can be converted by the following formulas.

$$q_S = \sum q_i \tag{1}$$

$$v_S = \frac{\sum q_i \times v_i}{\sum q_i} \tag{2}$$

$$k_S = \frac{12 \times q_S}{v_S} \tag{3}$$

Where, q_i and v_i are traffic flow and average speed on individual lane, respectively; q_s, v_s and k_s are the estimated traffic flow, average speed and traffic density for the whole cross-section, respectively.

(4) Classification of traffic flow conditions

Fig.2 explains traffic flow-speed diagram at a sag section of Tomei Expressway (272.65 KP), one typ-

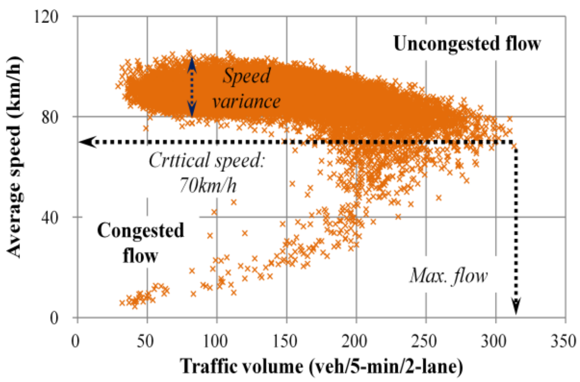

Fig.2 Traffic flow-speed diagram of a bottleneck

ical bottleneck in the test bed. As used in Wu *et al.*[2,4], the speed at maximum flow was defined as the critical speed that was used for classifying uncongested and congested flow regimes. According to Fig.2, 70 km/h can be selected to be the critical speed. Furthermore, corresponding values of other bottlenecks were found to be around 70 km/h.

Average speed often has a high variance in the conditions of same traffic flow (Fig. 2). Occupancy isn't a commonly used variable. So estimated density calculated by formula (3) was regarded as the measure of effectiveness for classifying traffic flow conditions. Based on the number of crash samples available, the aggregation intervals of traffic density were set as 10 veh/km and 30 veh/km for uncongested and congested flow regimes, respectively.

(5) Data matching

Related facility type and traffic flow condition for individual crash can be matched as shown in Table 1. Meantime, crashes matched with invalid detector data and in the intervals of lane/section closure were also excluded. As a result, a total of 3716 crashes were remained for the following analysis.

(6) Calculation of crash rates

Crash rate for traffic flow condition *j* (CR_j) can be calculated by the following formula.

$$CR_j = \frac{NOC_j \times 10^6}{\sum Q_{jk} L_k} \qquad (4)$$

Where, *j* is the ID of traffic flow condition; *k* is the ID of detector; NOC_j is the number of crashes for traffic flow condition *j*, and $Q_{jk}L_k$ is the value of vehicle-km of traveled (VKMT) in the influence area of detector *k* for traffic flow condition *j*.

3. CRASH RATE CHARACTERISTICS AT VARIOUS FACILITY TYPES

(1) Uncongested flow regime

Fig.3 describes tendencies of total crash rates (CR) following traffic density at basic, merge, diverge, and service-area segments for uncongested flow. Due to the limitation of available number of segments, only sections with 2-lane per direction were compared. Generally, CR is convex downward to traffic density for the four facility types. This study employed quadratic functions to model those tendencies as demonstrated in Table 2. The model formulations can generally fit to the relationships between CR and traffic density. Furthermore, all of the models and variables are of statistical significance (95% confidence interval). Considering the model formulations above, it is clear that CR at merge segment is most sensitive to the increase in traffic density, about 2.5 times of CR increases as that at diverge segment by increase of one unit of traffic density.

Regarding differences among those facility types, CR at service-area segment is obviously higher than the values at other facility types in low density conditions (<30 veh/km). It may be induced by that vehicles entering or exiting service areas can't decelerate or accelerate adequately, due to the impacts of vehicle-passenger interaction and shorter deceleration and acceleration lanes. Because the mainline flow is not strongly interrupted, CR at basic segment is relatively smaller compared to merge/diverge segments in low density conditions. With the increase in traffic density, CR tend to increase at all segment types. For merge/service-area segments, the value increases rapidly, while for diverge segment, it increases relatively mild. For basic segment, CR also gets much higher than the value at diverge segment, but it is smaller compared to merge and service-area segments. The characteristics above may be related to vehicle behaviors at various facility types; with the

Table 1 Example of data matching for individual crash

Crash ID	Detector ID [a]	Facility type	Number of lane	Traffic flow condition preceding crashes: Traffic flow (veh/5-min)	Speed (km/h)	Density (veh/km)	Flow condition	Flow regime
1	1-253.20	Diverge segment	2-lane	133	88.70	18	10~20	Uncongested
2	1-255.59	Basic segment	2-lane	157	52.07	81	60~90	Congested
3	2-260.09	Service-area segment	2-lane	58	89.98	8	0~10	Uncongested
4	1-267.60	Merge segment	2-lane	62	103.16	7	0~10	Uncongested

[a] Detector ID: 1- means eastbound direction, 2- means westbound direction, 253.2 stands for Kilo-post of detector.

increase in traffic density, it gets difficult to take safe merging behavior due to more frequent interaction between merging and mainline vehicles. Compared to merging vehicle, diverging vehicle can utilize longer space at diverge segment. Therefore, the chance to seek an adequate gap for safe lane changing maneuver is higher than that at merge segment. At service-area segment, lane changing maneuver also gets difficult with the increase in traffic density, and negatively impacts on safety. A paired t-test was applied as shown in Table 3, and the results prove that there isn't significant difference between basic and diverge segments as well as between merge and service-area segments, while CR at merge and service-area segments are significantly higher than CR at basic and diverge segments. So safety at merge and service-area segments deserves more attention.

(2) Congested flow regime

Fig.4 explains distributions of CR with the increase in traffic density at the four facility types for congested flow. Likewise, only sections of 2-lane per direction were compared. In general, CR follows increasing tendencies to traffic density. Since crash samples for congested flow are limited, no regression model was developed in this study. Fig.4 shows that CR at diverge segment is clearly higher than the values at basic/service-area segments. T-test in Table 4 also confirms such differences. For merge segment, CR is very low during the transition to congested flow; with the increase in traffic density, CR can increase most rapidly, and gets the highest in heavily congested conditions. CR characteristics above may be also induced by different vehicle behaviors. For relatively low density conditions for congested flow, diverging vehicle can strongly interrupt mainline flow in the process of lane changing from median lane to deceleration lane. In contrast, the interruption of merging vehicle on mainline flow is not so strong, because only mainline flow near to acceleration lane can be significantly impacted. With the increase in traffic density, CR at merge segment increase rapidly since the limited length of acceleration lane provides less chance to seek adequate gap for safe merging. Regarding service-area segment, drivers may give up entering and still follow mainline flow, or put off exiting and stay in service area, if an adequate gap can't be found out for congested flow.

4. CRASH RATE CHARACTERISTICS AT 2-LANE AND 3-LANE BASIC SEGMENTS

(1) Uncongested flow regime

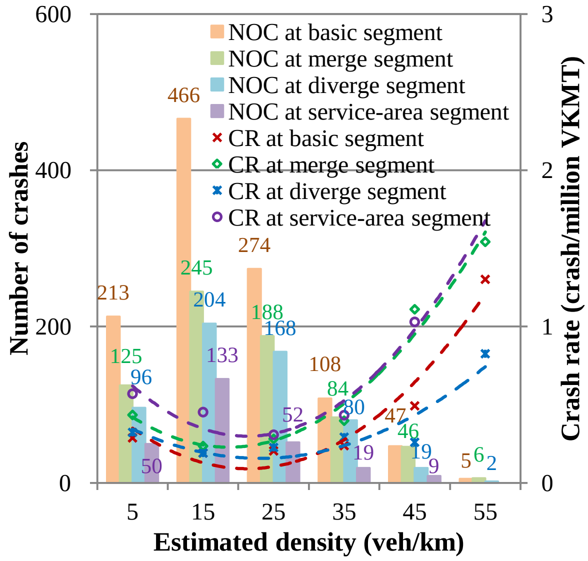

Fig.3 Crash rate-density for uncongested flow

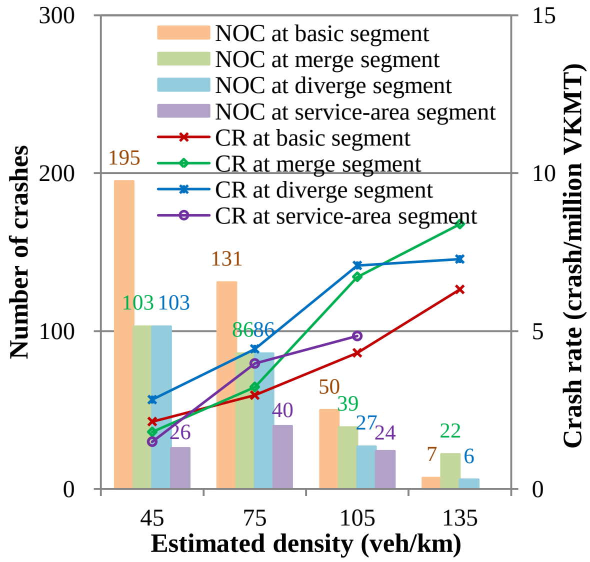

Fig.4 Crash rate-density for congested flow

Table 3 t-test of crash rate for uncongested flow

Paired	t-value	df	Sig.
Basic/merge segment	-2.819	5	0.045
Basic/diverge segment	1.149	5	0.303
Basic/service-area segment	-3.812	4	0.019
Merge/diverge segment	2.905	5	0.042
Merge/service-area segment	-1.719	4	0.161
Diverge/service-area segment	-3.460	4	0.020

Table 4 t-test of crash rate for congested flow

Paired	t-value	df	Sig.
Basic/merge segment	-1.645	3	0.199
Basic/diverge segment	-3.196	3	0.049
Basic/ service-area segment	-0.616	2	0.601
Merge/diverge segment	-0.702	3	0.533
Merge/service-area segment	0.631	2	0.592
Diverge/service-area segment	3.162	2	0.050

Table 2 Crash rate regression model for uncongested flow

Facility type	Segment size	Total length	Number of crashes	Item		Modeling result	
Basic segment (2-lane)	92	154.9 km	1113 crashes	Function		$CR=0.001k^2-0.042k+0.534$	$R^2=0.945$
				F-test		F=25.774	Sig.-0.013
				t-test	k^2	t=4.601	Sig.-0.019
					k	t=-3.267	Sig.-0.050
					Con.	t=3.266	Sig.-0.050
Merge segment	33	67.6 km	694 crashes	Function		$CR=0.0015k^2-0.059k+0.743$	$R^2=0.990$
				F-test		F=142.389	Sig.-0.001
				t-test	k^2	t=9.859	Sig.-0.002
					k	t=-6.340	Sig.-0.008
					Con.	t=6.149	Sig.-0.009
Diverge segment	34	67.4 km	569 crashes	Function		$CR=0.0006k^2-0.027k+0.463$	$R^2=0.839$
				F-test		F=8.830	Sig.-0.044
				t-test	k^2	t=3.871	Sig.-0.044
					k	t=-3.345	Sig.-0.048
					Con.	t=3.927	Sig.-0.041
Service area segment	24	34.3 km	263 crashes	Function		$CR=0.0012k^2-0.052k+0.849$	$R^2=0.920$
				F-test		F-18.382	Sig.-0.026
				t-test	k^2	t=4.897	Sig.-0.046
					k	t=-4.368	Sig.-0.049
					Con.	t=5.222	Sig.-0.035
Basic segment (3-lane)	10	9.7 km	95 crashes	Function		$CR=0.002k^2-0.076k+0.819$	$R^2=0.930$
				F-test		F-12.773	Sig.-0.043
				t-test	k^2	t=3.516	Sig.-0.048
					k	t=-3.586	Sig.-0.046
					Con.	t=3.626	Sig.-0.045

Fig.5 gives tendencies of CR following traffic density at 2-lane/3-lane basic segments. As the trend at 2-lane section, CR at 3-lane section also takes the shape of convex downward to traffic density. A quadratic function was employed again to model the tendency as shown in Table 2. The regression model indicates that CR at 3-lane section is more sensitive to the increase in traffic density compared to 2-lane section, and twice of CR increases as that at 2-lane section by increase of one unit of traffic density. Based on Fig.5, 3-lane section has relatively higher CR than 2-lane section in low density conditions. With the increase in traffic density, CR at 3-lane section increases more rapidly, and gets to be much higher than the value at 2-lane section. The result of t-test in Table 5 also implies CR at 3-lane section is significantly higher than the value at 2-lane section. Such characteristics may be related to the variation in vehicle behaviors between the two section types. In low density conditions, vehicles with low running speed may diverge from mainline flow, and move to the auxiliary lane at the beginning of 3-lane section, or merge into mainline flow at the end of 3-lane section. With the increase in traffic density, more and more vehicles may utilize the median lane according to the tendency of lane flow distribution analyzed by Duret *et al.*[6]. Due to wider cross-section at 3-lane section, effects of lane changing maneuver interrupting through vehicle may be much stronger than those at 2-lane section, adverse to road safety.

The findings above imply the negative impacts of a wider cross-section on road safety for uncongested flow due to the discretionary lane-changing behavior. So it is important to reduce the demand of the behavior above. As suggested by Duret *et al.*[6], measures such as variable speed limits (VSLs) and driving ban for trucks (DBTs) are effective in achieving speed harmonization during various lanes. It may demonstrate the direction of traffic control strategy for the improvement of road safety at multiple-lane expressway sections.

(2) Congested flow regime

Fig.6 illustrates distributions of CR with increase in traffic density at both section types for congested flow. Similar to 2-lane section, CR at 3-lane section follows an increasing tendency to traffic density. However, the value at 3-lane section gets lower than CR at 2-lane section for congested flow. The t-test in Table 5 also suggests CR at 2-lane section is significantly higher than CR at 3-lane section.

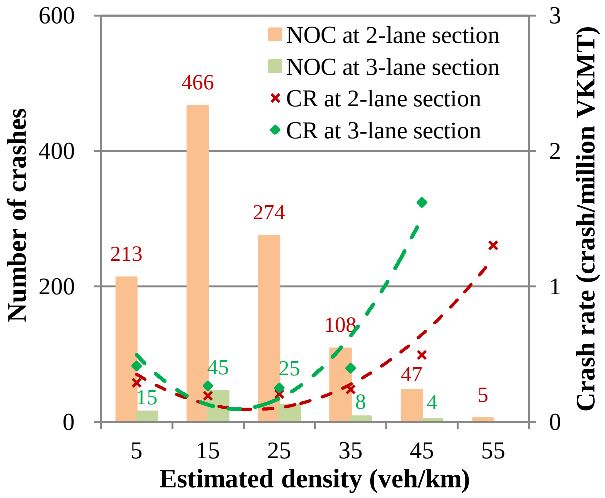

Fig.5 Crash rate-density at basic segment (uncongested flow)

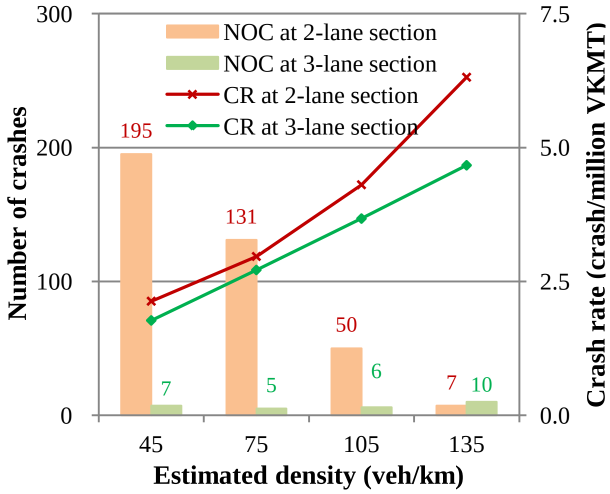

Fig.6 Crash rate-density at basic segment (congested flow)

Table 5 t-test of crash rate at basic segment

Paired	t-value	df	Sig.
2-lane/3-lane (uncongested flow)	-2.397	4	0.040
2-lane/3-lane (congested flow)	3.741	3	0.028

For congested flow, differences of operating speed during various lanes may gradually fade away, and the reduced spacing may limit lane changing maneuver. Then, vehicle behavior on individual lane is important for CR characteristics. Under the same traffic demand, driving conditions at 3-lane section, such as spacing and drivers' loading, may be better than conditions at 2-lane section in terms of safety. Such findings may imply the advantage to make full use of cross-section space available for congested flow, such as to open the shoulder of road as a traffic lane during peak hours.

5. CONCLUSIONS AND SUGGESTIONS

From the above analyses, the following conclusions can be provided; CR for uncongested flow at the four facility types is convex downward to traffic density. CR at merge/service-area segments is significantly higher than the values at basic/diverge segments. There isn't significant difference of CR between basic and diverge segments as well as between merge and service-area segments. For congested flow, CR follows increasing tendencies to traffic density at those facility types. Diverge segment has significantly higher CR compared to basic and service-area segments. CR at merge segment is much low during the transition to congested flow, while it can increase most rapidly with the increase of traffic density and gets the highest in heavily congested conditions. CR at 3-lane basic segment is also convex downward to traffic density for uncongested flow, and the value is significantly higher than CR at 2-lane basic segment. For congested flow, CR at 3-lane basic segment still increases with the increase in traffic density, while the value is significantly lower than CR at 2-lane basic segment.

The findings from this study suggest benefits of crash rate analysis for investigating existing methods of geometry design and traffic control strategy. On the other hand, for the reliable application, further studies are required by using high-sample-size data and crash type-dependent analysis. Meanwhile, for better understanding of crash mechanisms, a microscopic analysis on vehicle behavior is necessary at merge, diverge, and service-area segments.

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