Empirical Analysis of Queue Discharge Flow by Merging Method During Lane Closure Caused by Road Works on Inter-Urban Expressways

Mitsuaki SAKURAI [a], Hiroyuki ONEYAMA [b], Yasuhiro NONAKA [c]

[a] *Central Nippon Highway Engineering Tokyo Co., Ltd., Tokyo, 160-0023, Japan*
[a] *E-mail: m.sakurai.aa@c-nexco-het.jp*
[b] *Graduate School of Civil and Environmental Engineering, Tokyo Metropolitan University, 192-0397, Japan; E-mail: oneyama@tmu.ac.jp*
[c] *Highway Planning Inc., 170-0013, Japan; E-mail: y_nonaka@doro.co.jp*

Abstract: Roadwork is commonly conducted on inter-urban expressways with lane closures in Japan. This often results in congestion, and there is a social demand for traffic control and guidance measures to minimize the impact of congestion. The zipper merge is considered to contribute to increasing the number of vehicles that can be cleared during congestion; however, the microscopic traffic behavior of individual vehicles in these merging methods have not been studied extensively in Japan. Therefore, in this study, we use multiple regression analysis to perform a macroscopic analysis of the relationship between lane utilization rates at the start of lane closures and traffic capacity during congestion, focusing on lane closures implemented on the Chuo Expressway. We also performed a microscopic analysis of the headways of individual vehicles depending on the merging method and proved the superiority of the zipper merge.

Keywords: Inter-urban Expressway, Construction Lane Closure, Traffic capacity, Headway, Camera survey, Zipper merge

1. INTRODUCTION

More than 50 years have passed since the first inter-urban expressway opened in Japan, and the number of deteriorated routes have is increasing. To operate and manage safe, secure, and comfortable expressways, concentrated work, such as repaving several stretches in a short period of time, and long-term renewal work, such as replacing bridge decks, are necessary, in addition to daily maintenance and repair work. Inter-urban expressways comprise important infrastructure that enable fast movement of people and goods between cities and regions. Thus, long-term road closures are detrimental to the Japanese economy. Therefore, it is common to perform roadwork while keeping some lanes open. Figure 1 shows examples of driving lane closures (top of Figure 1) and passing lane closures (bottom of Figure 1) on a two-lane section of an inter-urban expressway. Arrows and rubber cones are installed from the start of lane closure, and a lane reduction section of approximately 300 m (start of lane closure) is established, narrowing to a single lane. Particularly, considerable traffic congestion due to construction lane closures is observed in suburban areas. When the number of lanes is reduced owing to construction lane closures, congestion is unavoidable to some extent. However, even in such cases, there is a social demand for the implementation of traffic control and guidance measures that increase the number of vehicles that can be handled to the maximum and minimize the impact of congestion.

To this end, it is considered that alternate merging (hereafter referred to as zipper merge) contributes to increasing the queue discharge flow (QDF). For example, there have been reported cases in which zipper merges can alleviate congestion at highway interchanges (Minnesota Department of Transportation, 2025). In Japan, there have also been reported cases in which zipper merges have contributed to reducing congestion (Central Nippon Expressway Co., Ltd., 2020). However, few cases have been verified based on actual traffic data to determine whether zipper merges lead to increased QDF during congestion, considering the underlying factors.

In this study, we conducted a macroscopic analysis using multiple regression analysis to examine the lane utilization rate at the start and end of the lane closure section and QDF during congestion for lane closures at the roadwork implemented on the Chuo Expressway. We also conducted a microscopic analysis of the differences in the headways of individual vehicles depending on the merging method, and verified and discussed the advantages of zipper merge.

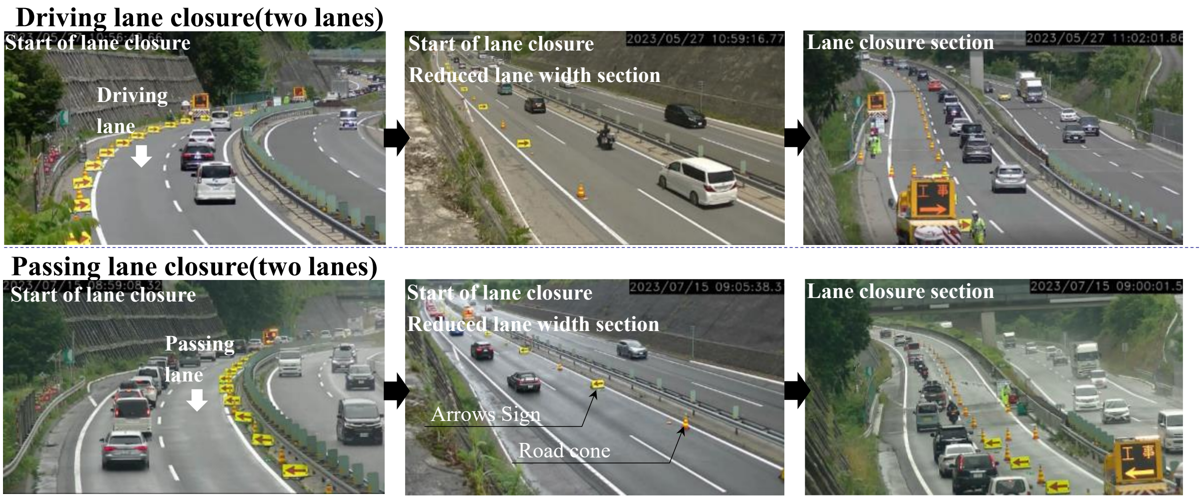


Figure 1. Example of construction closure.

2. LITERATURE REVIEW AND NOVELTY OF THIS RESEARCH

First, previous research on traffic capacity during lane closures during road work is summarized. The Highway Capacity Manual 7th Edition (TRB, 2022) presents a model formula for calculating the traffic capacity during lane closures due to roadwork as reported by Yeom et al. (2015), which sets the type of guardrail, area, lateral clearance, and day/night as explanatory variables. However, this analysis is based on data from the United States, where road and traffic conditions vary significantly compared to Japan.

Regarding the reports from Japan, the "Study on Road Traffic Capacity and Quality of Service (Japan Society of Traffic Engineers, 2021)," which summarizes previous research on traffic capacity in Japan, shows the traffic capacity when lanes are restricted due to road work. When restricting one lane in a two-lane section of an inter-urban expressway, the flow rate when congestion occurs is 1,100–1,520 pcu/h, and the flow rate during congestion is 1,080–1,430 pcu/h. In addition, when restricting one lane in a three-lane section, the traffic flow rate when congestion occurs is 3,820–3,860 pcu/h. These flow rates are a summary of the research results of Takahashi et al. (2008), Kato et al. (2017), and Yamashita et al. (2015), and traffic capacity includes the results over time. It has recently been shown that the yearly traffic capacity at bottlenecks on single-lane sections of expressways is decreasing. The factors contributing to this include longer inter-vehicle distances due to an increase in Adaptive Cruise Control (ACC) equipped vehicles and slower acceleration due to an increase in eco-driving and safe driving vehicles; therefore, it is important to understand traffic capacity using the latest data.

Regarding studies that considered recent changes in traffic conditions, Yamamoto et al. (2022) analyzed the traffic situation of two-way traffic restrictions during renovation work. They showed that the first points of congestion occurrence are the "starting point of the lane closure" and "within the restricted section (junction, single-lane section, lane shift section)," and that congestion mostly occurs at the starting point of the lane closure when the restricted section is short, and mostly occurs within the lane restricted section when the restricted section is long. They also clarified that the flow rate during congestion is the highest at the starting point of the closure and decreases in order for junction, single-lane section, and lane-shift section within the restricted section.

Sakurai et.al. (2024a) clarified the statistical relationship between the capacity and various factors that determine traffic congestion caused by lane closures at roadworks implemented on inter-urban expressways. For example, Sakurai et al. (2024b) conducted a flow analysis of driving lane closures and passing lane closures in two-lane sections, which are typical construction congestion on the Tomei and Chuo Expressways. Specifically, they used ETC2.0 probe data to create a time-space diagram, analyzed the behavior of individual vehicles before and after the occurrence of congestion, and inferred the mechanism of congestion. For example, Sakurai et al. (2023) analyzed the speed of individual vehicles, number of vehicles in the platoon, traffic capacity, lane utilization rate, speed difference between lanes, headway, etc. from ecamera data near the Otai Viaduct and the start of lane closure, but did not conduct a micro-analysis using the merging method during congestion.

Various research cases have been reported regarding the effectiveness of zipper merge. The Minnesota Department of Transportation reported cases where a zipper merge could reduce the speed difference between two lanes, reduce congestion by up to 40%, ease congestion at highway interchanges, and create fairness and equality by having all lanes travel at the same speed (Minnesota Department of Transportation, 2025). Lammers et al. (2017) analyzed two cases of zipper merge implemented in Kentucky, USA, and reported that in one case, zipper merge improved traffic flow and reduced congestion. In a simulation, Kang et al. (2011) reported that early merging is the best method when the traffic volume is low. Sensiba (2021) discussed a situation in New Mexico where both lanes were stopped despite signs encouraging zipper merge. In addition, he reported that Arkansas adopted a policy of installing a large electrician's signboard seven miles before merging and changing lanes. Galbraith (2021) reported that zipper merge is the optimal merging method; however, it is inefficient for drivers who are accustomed to merging early, and a behavioral science approach is required to promote zipper merges.

In Japan, the Central Nippon Expressway Company Limited (2020) showed that zipper merges contribute to reducing congestion; however, there are no findings that statistically analyze this at the micro level at the headway of individual vehicles. Japan's traffic conditions have been discussed in some studies, however, no analysis has been conducted that focuses on the micro differences in headways depending on the merging method during congestion.

Therefore, in this study, we focus on a lane closure case during a road work implemented on the Chuo Expressway and consider the differences in the QDF and headway depending on the merging method during congestion. By statistically analyzing the headway depending on the merging method, that is, zipper merge and non-zipper merge, it is possible to understand the QDF during congestion. Furthermore, we believe that this analysis is valuable because it allows for the creation of public relations plans that can reduce congestion.

3. TARGET ROAD SECTION

In this study, the Chuo Expressway (outbound) from the Suwa Interchange (Suwa IC) to the Okaya Junction (Okaya JCT) was the subject of the analysis. The Otai Viaduct is a main-line bridge located downstream of the Suwa Lake Service Area (Suwa Lake SA, outbound) and was undergoing renovation work to replace the deteriorated concrete deck (Figure 2).

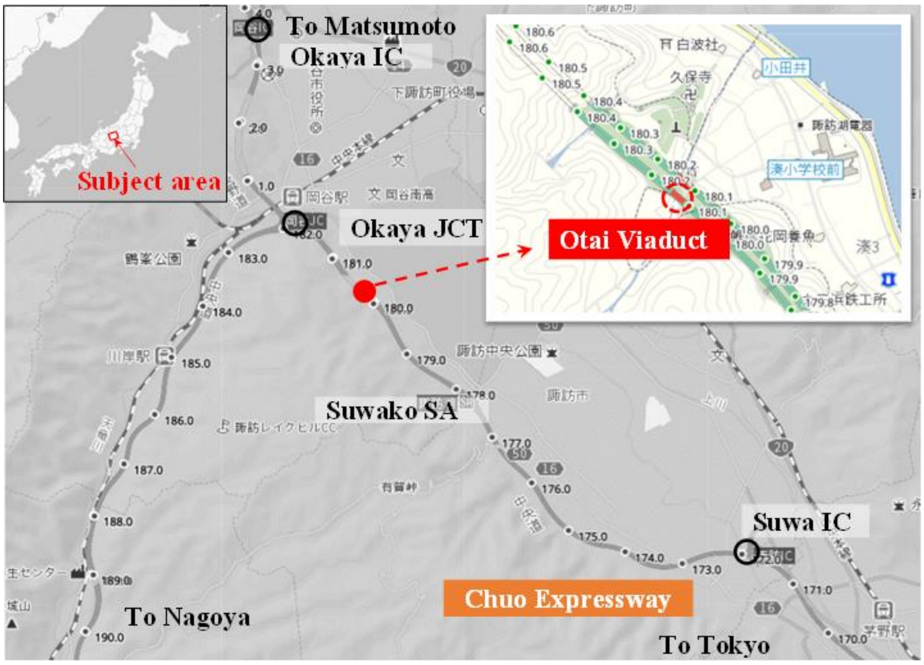


Figure 2. Location of Otai Viaduct.

The renewal work period was 72 days, from May 8, 2023, to July 19, 2023, with driving lane closures in place from May 8 to June 13, 2023, and passing lane closures in place from June 13 to July 19, 2023, continuously day and night.

A schematic of a lane-closed section is shown in Figure 3. The lane closure starts at 179.0 KP, and the lane width narrows 300 m from there, with the road structure being such that from 179.3 KP onwards, there is only one passable lane. The lane closure ends at 180.4 KP, just before the Hanaoka Tunnel, downstream of the Odai Viaduct. The total length of the lane closure, including the beginning of the closure, was 1.4 km.

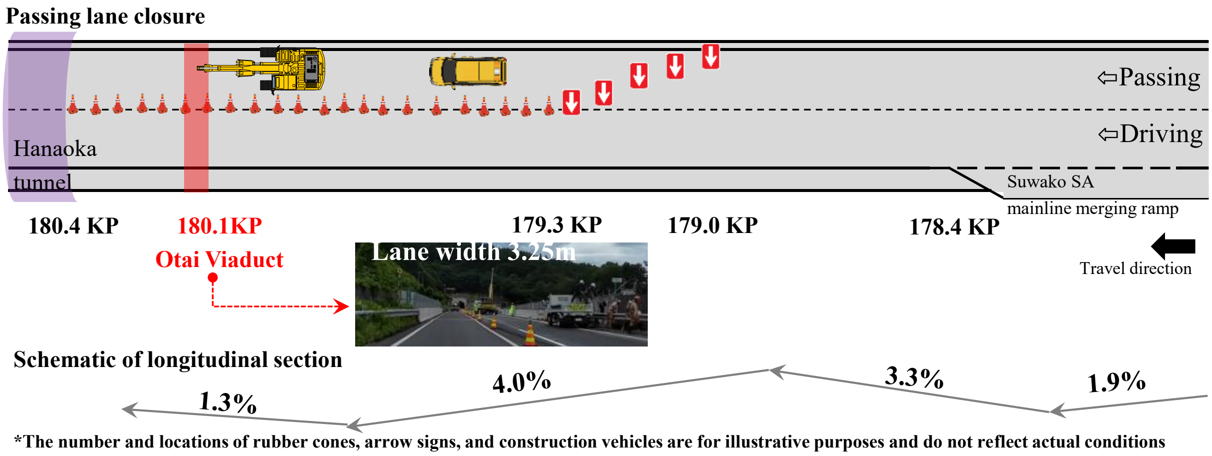


Figure 3. Schematic of construction lane closure section.

4. ANALYSIS DATA

4.1 Overview of Camera Observation

A camera observation survey was conducted to understand the traffic congestion from upstream to downstream during lane closures due to roadwork conducted on two days, from Friday, July 14 to Saturday, July 15, 2023, from 7:00 am to 4:00 pm, when the passing lane was restricted. Eighteen cameras were installed in the section between the junction with Lake Suwa SA (outbound) and the Otai Viaduct (Figure 4). Traffic congestion occurred on Saturday, July 15, 2023, and the cameras recorded the situation.

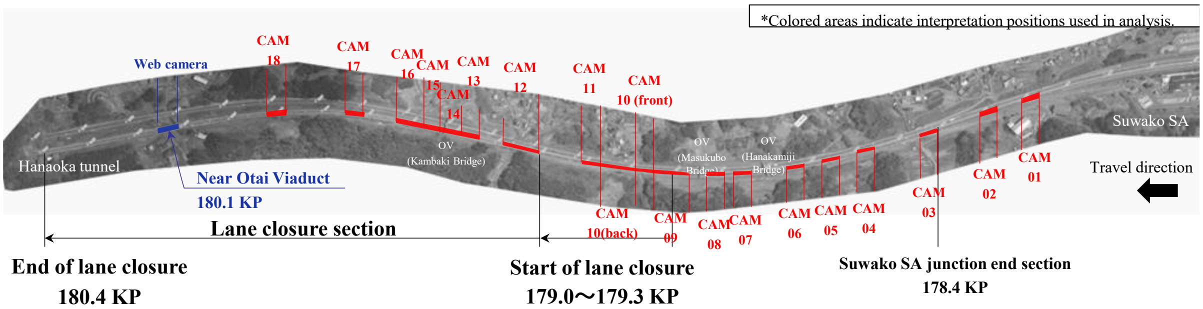


Figure 4. Collection locations of camera data.

4.2 Overview of Traffic Congestion on the Observed Date

Figure 5 shows a time-space speed contour map for the analyzed day. This time-space speed contour map shows the average speed of 1 min x 0.1 km from ETC 2.0 probe data, coloured by speed zone. Congestion occurs when speeds first decrease near the Otai Viaduct (near 180.1 KP), which then propagates upstream as a shock wave, resulting in a settling phenomenon where speeds decrease the most at the start of the lane closure. Note that the traffic volume from to 8:15-8:59, selected as the data processing time zone in the analysis that covers the period before and after the congestion, was 946 vehicles in total (108 large vehicles, large vehicle mix rate 11%) at the location of the web camera in Figure 4 (near 180.1 KP).

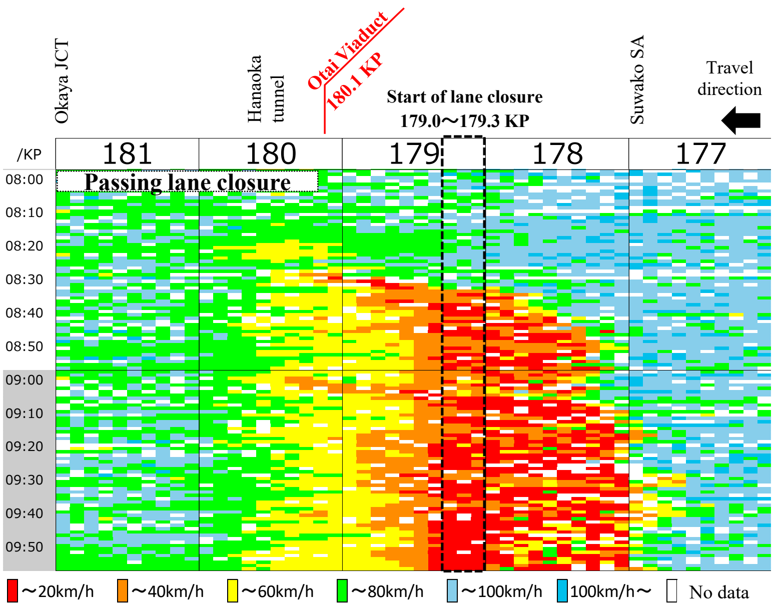


Figure 5. Time-space speed contour map.

4.3 Camera data reading methods and data conversion

The camera-reading positions and captured images used in this analysis are shown in Figure 6. The method of interpreting individual vehicles from camera data and converting them into data differs depending on the two analyses described in Section 5. First, for 5.1, the number of vehicles passing through reading points 1 (CAM09) and 2 (CAM12) were interpreted by lane and vehicle type (small or large) each minute. In Section 5.2, the passing times of individual vehicles passing reading points 1 (CAM09), 2 (CAM10), and 3 (CAM12) were interpreted. Individual vehicles were interpreted according to the lane and vehicle type (small or large). To identify the lane traveled by a vehicle passing CAM12 on the downstream side, matching was performed for the individual vehicles passing CAM09, CAM10, and CAM12. Additionally, the headway (tailway) was calculated as the passing time difference between the tail of the vehicle and that of the preceding vehicle.

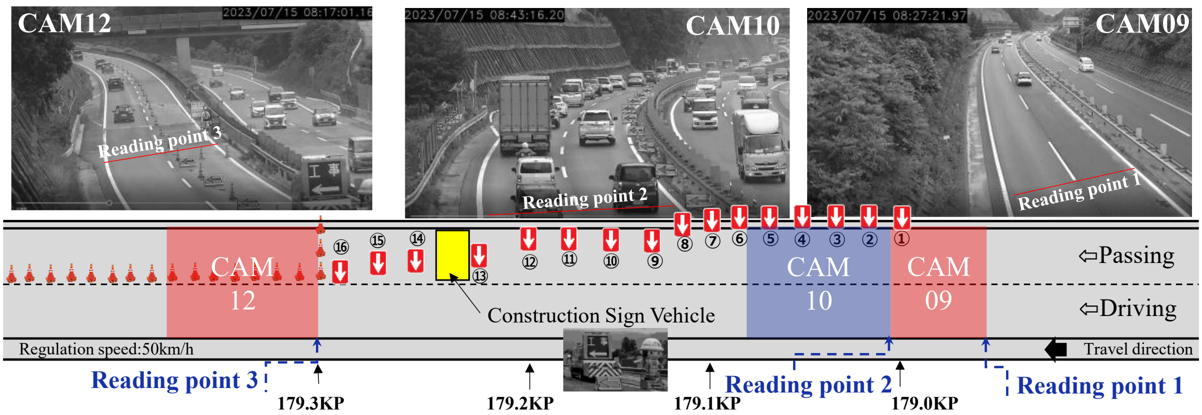


Figure 6. Camera reading point and captured image.

5. ANALYSIS METHOD

To understand the differences in traffic capacity and headways due to different merging methods during congestion on inter-urban expressways, we conducted two analyses: a macro analysis of the relationship between the lane utilization rate at the start of lane closure and QDF, and as a micro analysis, a comparison of headways by the merging method.

5.1 Analysis of the relationship between lane utilization rate at the start of traffic regulation and QDF

The lane utilization rate at the start of lane closure was calculated using CAM09, the QDF was calculated using CAM12, and the traffic volume was analyzed by lane and vehicle types each minute. In this analysis, the two items were analyzed using scatter plots and multiple regressions. The target time was a 32-min period during which the Otai Viaduct was not congested after the congestion had settled at the start of lane closure. In addition, CAM09 was located 300-m upstream of CAM12. The time required for the transition from CAM9 to CAM12 was approximately 90 s. Therefore, the lane utilization rate of CAM09, which was calculated each minute, and the QDF of CAM12 were shifted by one minute to analyze their relationship.

Conversely, congestion occurred repeatedly in the Otai Viaduct (Figure 5). Sakurai et.al. (2024a) used multiple regression analysis to show that "traffic capacity decreases when the distance from the start of the lane closure to the bottleneck is long" and "traffic capacity decreases when the rate of large vehicles is high." The objective of this analysis was to analyze the relationship between the QDF and differences in lane utilization rates at the start of lane closure. If we target both congestion within the lane closure section and at the start of lane closure, the QDF owing to differences in lane utilization rates at the start of lane closure may not be properly evaluated. Therefore, we analyzed the relationship between the lane utilization rate at the start of lane closure and the QDF for the period when there was no congestion on the Otai Viaduct. The congestion state judgment at Otai Viaduct was set using the results of Shiraishi et al. (2012). Specifically, they developed a method to calculate the critical speed using the Kittler method (1986) and judged congestion based on this method. This study also applied the same method to calculate the critical speed and judge congestion. The time period covered in the calculation of the critical speed was 8:15-8:59, before and after traffic congestion occurred. The calculation results are shown in Figure 7. The data show that the speed at 179.7 KP was ≥ 56 km/h, indicating that no traffic congestion occurred at the Odai Viaduct, that is, traffic congestion occurred at the start of lane closure. In addition, the proportion of large vehicles differs depending on the time of day, which affects the QDF size. In Japan, the passenger car equivalent (PCE) of large vehicles is determined as per the "Roads and Traffic Capacity (Japan Road Association, 1984);" however, this indicator is outdated. The acceleration performance of large vehicles has improved, and a calculation based on the actual situation would be desirable. Therefore, the PCE was calculated based on the research method adopted by Kuwahara et al. (1991) using data from 456 individual vehicles by type that traveled during traffic congestion at the start of traffic lane closure. As a result, the PCE was set to 1.7 when the large vehicle rate was ≤15%, and 1.8 when the large vehicle contamination rate was 15.1% - 25% or lower. The QDF was set to the passenger car unit (PCU) using these values. The maximum large vehicle rate during the period covered in this analysis was 19%.

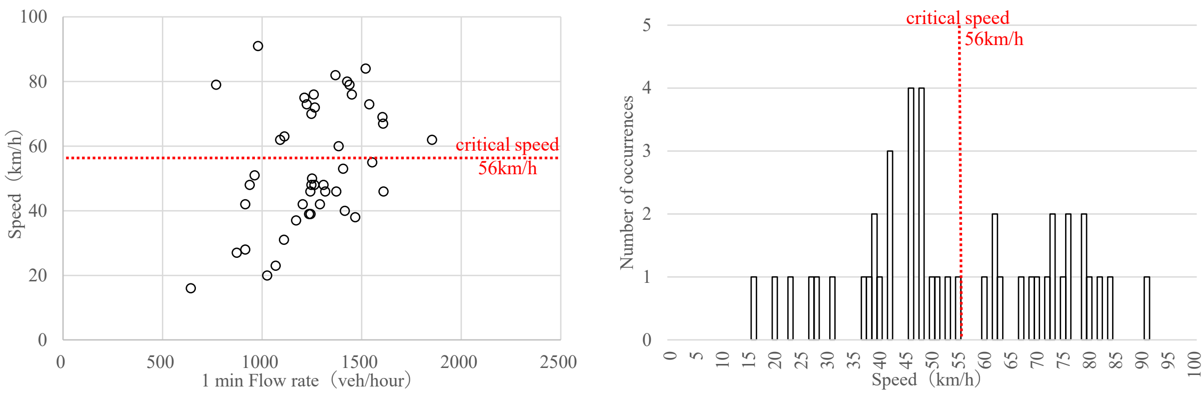


Figure 7. Critical speed threshold (179.7 KP data) .

5.2 Headway comparison analysis by merging method

An analysis was conducted for the vehicle headways that passed through CAM12, with the definition of target vehicles using the merging method, as shown in Figure 8, and the concepts of zipper merge and non-zipper merge, as shown in Figure 9. The target time period was a 15-min period during which the Otai Viaduct was not congested after the congestion settled at the start of lane closure. A zipper merge is defined as a case in which vehicles traveling in the driving lane and vehicles traveling in the passing lane merge alternately at the start of lane closure. The vehicles subjected to zipper merge (A) were classified as vehicles traveling in the driving lane (A1) and vehicles traveling in the passing lane (A2). Cases in which vehicles did not merge alternately were defined as non-zipper merge. Specifically, if the vehicle ahead was traveling in the same lane, it was considered a non-zipper merge vehicle. These were classified as vehicles traveling in the driving lane (B1) and vehicles traveling in the passing lane (B2). In addition, we classified the merged vehicles (B1) in a non-zipper merge into two cases: when there is a merging vehicle in the adjacent lane (B1-1) and when there is no merging vehicle (B1-2). This is because when there is a merging vehicle, it may mean that the vehicle may not give way to the merging vehicle, whereas when there is no merging vehicle, there is no vehicle eligible for a zipper merge in the first place; therefore, a zipper merge is not possible. In addition, a vehicle merges from the passing lane in a non-zipper merge (B2) when multiple vehicles merge between the same vehicles in the driving lane.

The headway of the large vehicle is excluded from the calculation; however, the headway of the small vehicle in front of the large vehicle is included.

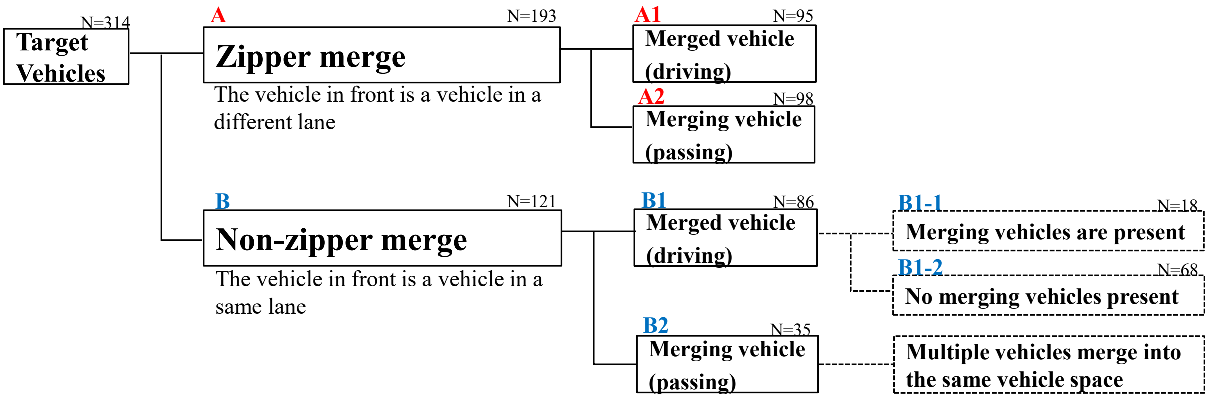


Figure 8. Definition of target vehicles by merging method.

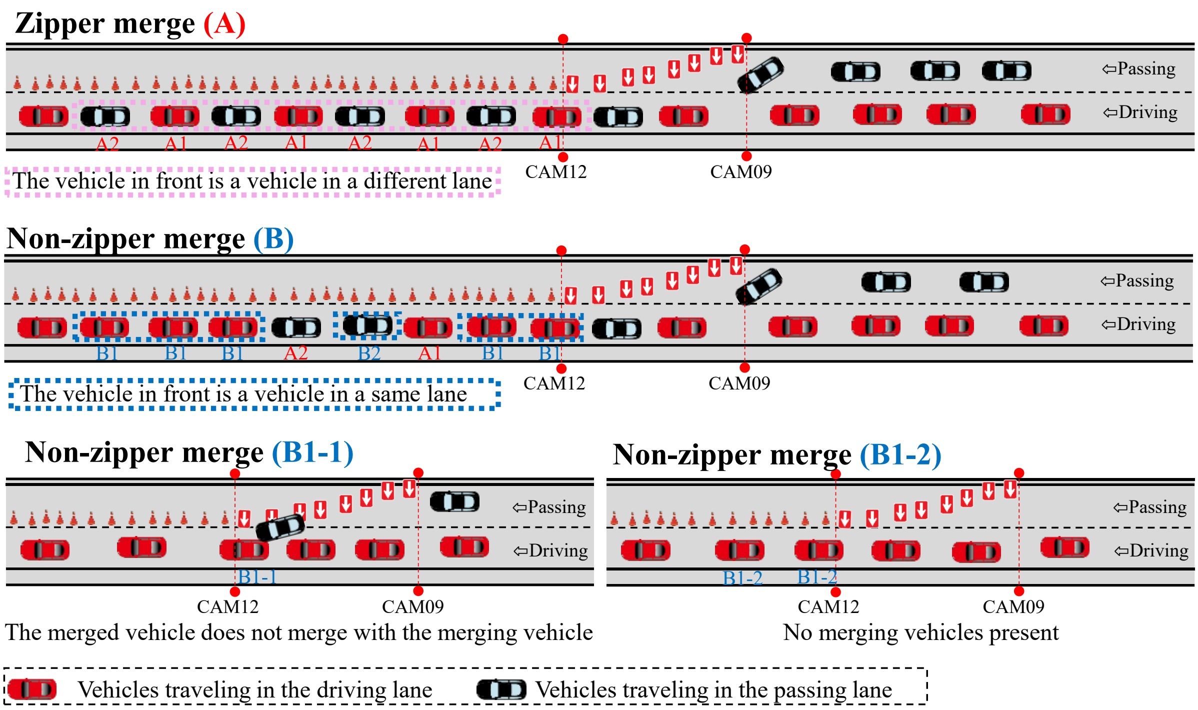


Figure 9. Conceptual image of zipper merge and non-zipper merge.

6. ANALYZED RESULTS

6.1 Analysis of the relationship between the lane utilization rate at the start of lane closure and QDF

Figure 10 shows a scatter plot of the passing lane utilization rate and the QDF at the start of lane closure. The passing-lane utilization rate at the start of lane closure was calculated using the CAM09 data, and the QDF was calculated using the CAM12 data. It can be seen that although there is variation in the data samples, the QDF is high when the passing lane utilization rate is approximately 50%. In passing lane closures, it is rare for the passing lane utilization rate to be significantly higher than 50%; therefore, the trend is not clear. However, from the data for rates below 50%, it can be seen that the QDF tends to decrease. This suggests that when there is traffic congestion, it may be possible to increase the QDF by entering the start of lane closure rather than changing lanes to the unrestricted lane (driving lane) in advance.

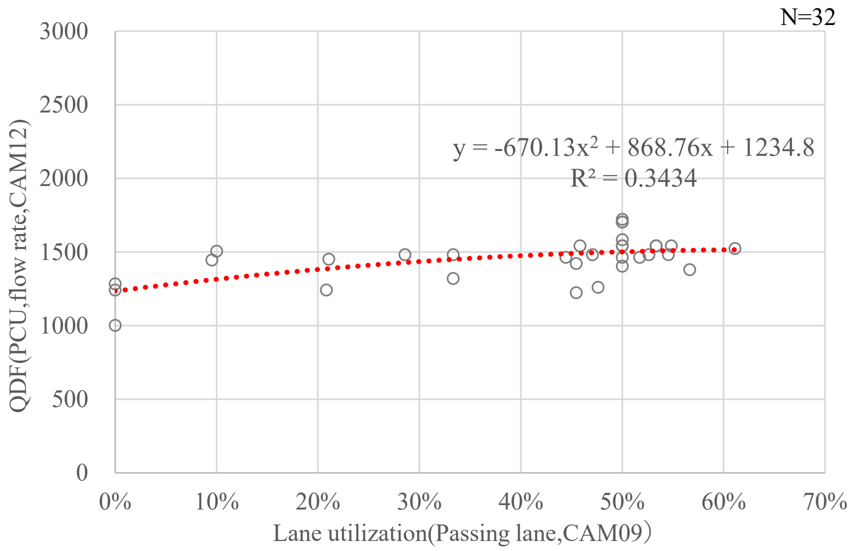


Figure 10. Lane utilization at the start of lane closure and QDF of the lane closure section.

Next, a multiple regression analysis was conducted with the QDF as the objective variable and the items shown in Table 1 as explanatory variables. The objective of this analysis is to determine whether there is a statistical relationship between the upstream merging lane utilization rate and the regulated QDF.

Table 1. List of influencing factors.

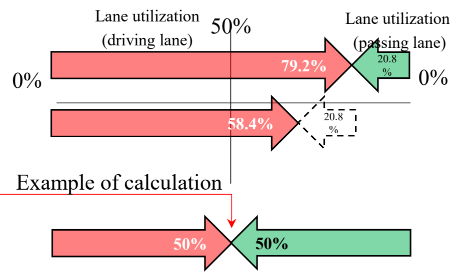
No.	Influencing factor (explanatory variable)	Input value
1	Upstream speed(179.0KP)	Numerical value(km/h)
2	Downstream speed(179.7KP)	Numerical value(km/h)
3	Lane utilization difference(driving lane)	Numerical value (%)
4	Lane utilization difference(passing lane)	Numerical value (%)

The upstream speed was set to 179.0 KP, which was the starting point of the regulation, and the downstream speed was set to 179.7 KP, which was the calculation position of the critical speed. Two items were set for the lane utilization rate difference: the driving lane and passing lane (merging lane). An image of the calculation method is shown in Figure 11.

No.	Time	Objective variable	Explanatory variable					
		QDF	Upstream speed (179.0KP)	Downstream speed (179.7KP)	Lane utilization difference (driving)	Lane utilization difference (passing)	Lane utilization (passing lane)	Lane utilization difference (passing-driving)
1	08:54	1,320	21	63	0.333	0.000	33.33%	-33.33%
2	08:55	1,242	19	60	0.583	0.000	20.83%	-58.33%
3	08:56	1,452	21	62	0.579	0.000	21.05%	-57.89%
4	09:01	1,446	21	60	0.810	0.000	9.52%	-80.95%
5	09:02	1,506	27	58	0.800	0.000	10.00%	-80.00%
6	09:03	1,482	51	57	0.429	0.000	28.57%	-42.86%
7	09:10	1,242	20	59	1.000	0.000	0.00%	-100.00%
8	09:11	1,002	11	58	1.000	0.000	0.00%	-100.00%
9	09:14	1,482	14	62	0.333	0.000	33.33%	-33.33%
10	09:15	1,284	13	60	1.000	0.000	0.00%	-100.00%
11	09:48	1,542	7	60	0.000	0.067	53.33%	6.67%
12	10:00	1,542	6	57	0.000	0.000	50.00%	0.00%
13	10:15	1,482	8	59	0.000	0.053	52.63%	5.26%
14	10:16	1,422	8	58	0.091	0.000	45.45%	-9.09%
15	10:19	1,260	14	66	0.048	0.000	47.62%	-4.76%
16	10:21	1,224	6	65	0.091	0.000	45.45%	-9.09%
17	10:57	1,482	12	56	0.000	0.091	54.55%	9.09%
18	10:58	1,542	11	58	0.083	0.000	45.83%	-8.33%
19	11:24	1,380	12	61	0.000	0.133	56.67%	13.33%
20	11:25	1,542	7	57	0.000	0.000	50.00%	0.00%
21	11:34	1,704	11	59	0.000	0.000	50.00%	0.00%
22	11:35	1,722	9	57	0.000	0.000	50.00%	0.00%
23	14:01	1,542	7	59	0.000	0.097	54.84%	9.68%
24	14:46	1,542	9	60	0.000	0.067	53.33%	6.67%
25	15:04	1,524	7	62	0.000	0.222	61.11%	22.22%
26	15:06	1,464	7	64	0.111	0.000	44.44%	-11.11%
27	15:07	1,482	10	58	0.059	0.000	47.06%	-5.88%
28	15:08	1,704	13	58	0.000	0.000	50.00%	0.00%
29	15:09	1,404	16	59	0.000	0.000	50.00%	0.00%
30	15:10	1,584	11	59	0.000	0.000	50.00%	0.00%
31	15:15	1,464	11	61	0.000	0.000	50.00%	0.00%
32	15:16	1,464	10	62	0.000	0.034	51.72%	3.45%

Example of calculation

Lane utilization (driving lane) : 79.17%
Lane utilization (passing lane) : 20.83%
Lane utilization difference=20.83-79.17=-58.34%
↓
Since the travel lane utilization is higher than the overtaking lane utilization, enter 0.583 for the travel lane utilization and 0 for the overtaking lane utilization.



☚In the case of 50-50, enter 0 for both driving lane and passing lane

Figure 11. Example of the explanatory variable calculation method.

The results of the multiple regression analysis are presented in Table 2. The speed at the start of lane closure on the upstream side was not statistically significant for the QDF. With the ETC2.0 probe data, it is not possible to classify the lanes in which the vehicle is driving. In addition, CAM09 is the average speed in both the driving and passing lanes, and there are cases in which the speed difference between the lanes is large. Therefore, the speed at the start of the lane closure may not accurately indicate the speed situation. In addition, when the speed on the downstream side was high, the QDF decreased. This is thought to be because vehicles are driven by a large gap between vehicles in low traffic density situations. The results showed that the QDF decreased when the driving lane utilization rate was 50% or higher. This result is consistent with the tendency shown in the scatter diagram in Figure 9. It is believed that the QDF increases by entering the start of lane closure and merging, rather than forming a line in advance in the driving lane. However, there was no significant difference in passing lane utilization rates. This is because the passing lane utilization rate was rarely 50% or higher, and the number of samples was small.

Table 2. Multiple regression analysis results.

No.	Explanatory variable		Partial regression coefficient	p-value
1	Upstream speed(179.0KP)	Numerical value(km/h)	2.6	0.348
2	Downstream speed(179.7KP)	Numerical value(km/h)	-22.3	0.014 *
3	Lane utilization difference(driving lane)	Numerical value (%)	-296.3	0.000 **
4	Lane utilization difference(passing lane)	Numerical value (%)	-60.3	0.890
-	Constant term	-	2819.8	0.000 **
-	Adjusted R^2(coefficient of determination corrected for degrees of freedom)		**0.434**	
-	Significance of regression equation (analysis of variance)		P < 0.001	
-	Valid cases		32	

** : P<0.01, * : P<0.05   [-] Item not highly correlated with objective variable (P>0.05)

6.2 Comparison of headways by the merging method

Figure 12 shows a comparison of the headways between the zipper and non-zipper merges. The graph on the left compares the zipper merge with the non-zipper merge, whereas the graph on the right classifies the number of vehicles in each lane into those with fewer than ten vehicles and those with more than ten vehicles. The number of vehicles in a merge indicates the number of vehicles in which zipper or non-zipper merges are formed in succession. An image of the number of vehicles in a merger is shown in Figure 13, considering the number of vehicles in the merger as platoons to obtain a macroscopic understanding of the differences in headway owing to the size of the platoon. The reason for setting the number of vehicles in the merge to ten was that an analysis of the individual numbers of vehicles in the merge showed that the headway tended to decrease when the number of vehicles was generally ≥ 10.

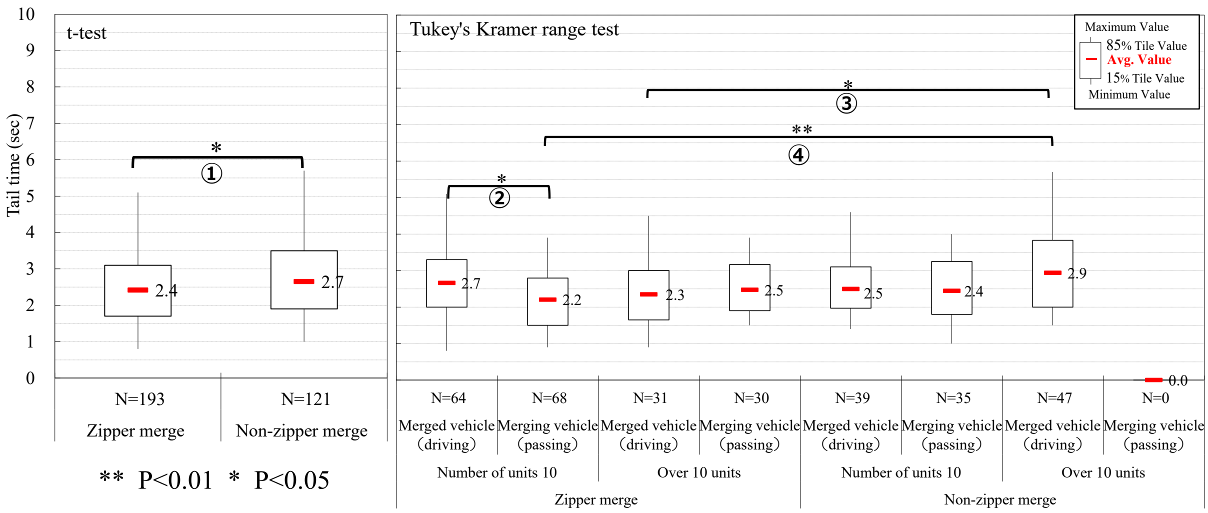


Figure 12. Comparison of headways.

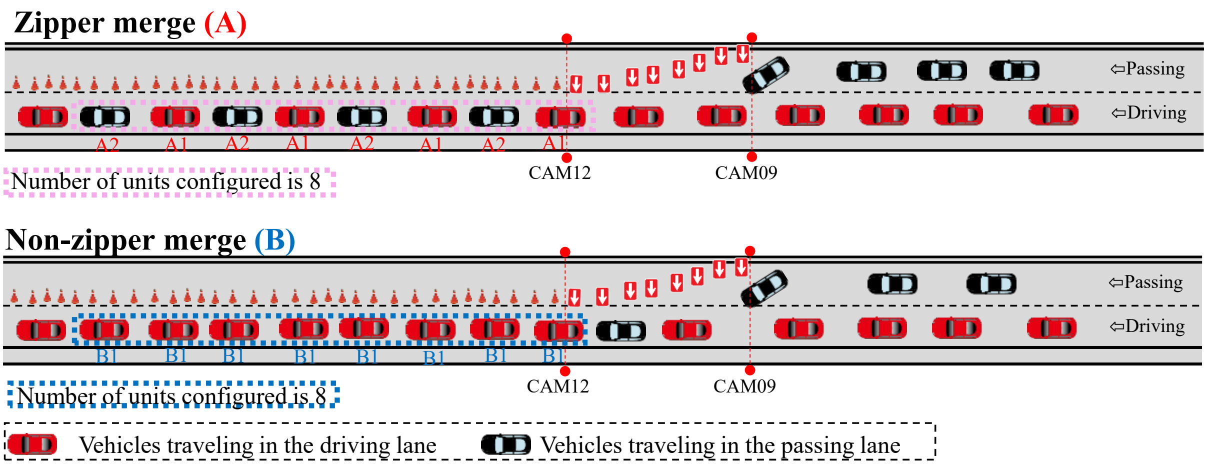


Figure 13. Image of the number of configured units.

The average headway for zipper merges was 2.4 s, whereas that for non-zipper merges was 2.7 s. The headway for zipper merges was 0.3 s shorter than that for non-zipper merges (①). When converted to QDF, the zipper merge was 1500 (vehicles/hour) and the non-zipper merge was 1333 (vehicles/hour), indicating that the zipper merge had a higher QDF. When the zipper merge had fewer than ten vehicles, the headway for the merging vehicle was 0.5 s shorter than that of the merged vehicle (②). This is thought to be because the merging vehicle has a strong desire to follow the vehicle in front of it. When the merged vehicle lane had ten or more vehicles, the headway for zipper merges was 2.3 s, while that for non-zipper merges was 2.9 s, making the zipper merge 0.6-s shorter (③). Furthermore, there was a 0.7 s difference in headway between merging vehicles with fewer than ten vehicles in a zipper merge and merged vehicles with ten or more vehicles in a non-zipper merge (④). We believe that when a platoon forms a long line on the driving lane side, the headway increases for several reasons, such as the absence of merging vehicles and a decreased desire to follow. We also speculate that this may be due to the driver characteristics of vehicles traveling in the passing lane, such as a strong desire to follow the vehicle in front.

Next, an analysis was conducted based on the number of passing vehicles. Figure 14 shows the number of vehicles passing through a zipper merge. The number of passing vehicles is defined as the order in which a zipper or non-zipper vehicle merge continues until the merging format changes. In the zipper merge example shown in Figure 14, numbers are assigned in order from the second vehicle, excluding the lead vehicle to the ninth vehicle before switching to a non-zipper merge. The aim of these analyses is to understand headways based on the number of vehicles comprising the merger.

The average headway of passing vehicles is shown in Figure 15, and the sample numbers of the average headway by the number of passing vehicles are listed in Table 3.

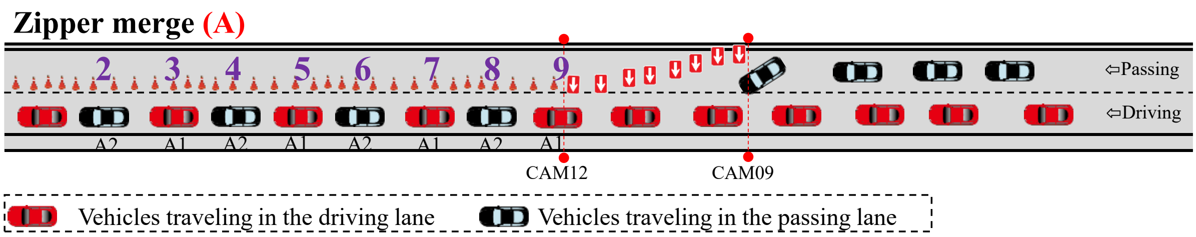


Figure 14. Image of the number of vehicles passed.

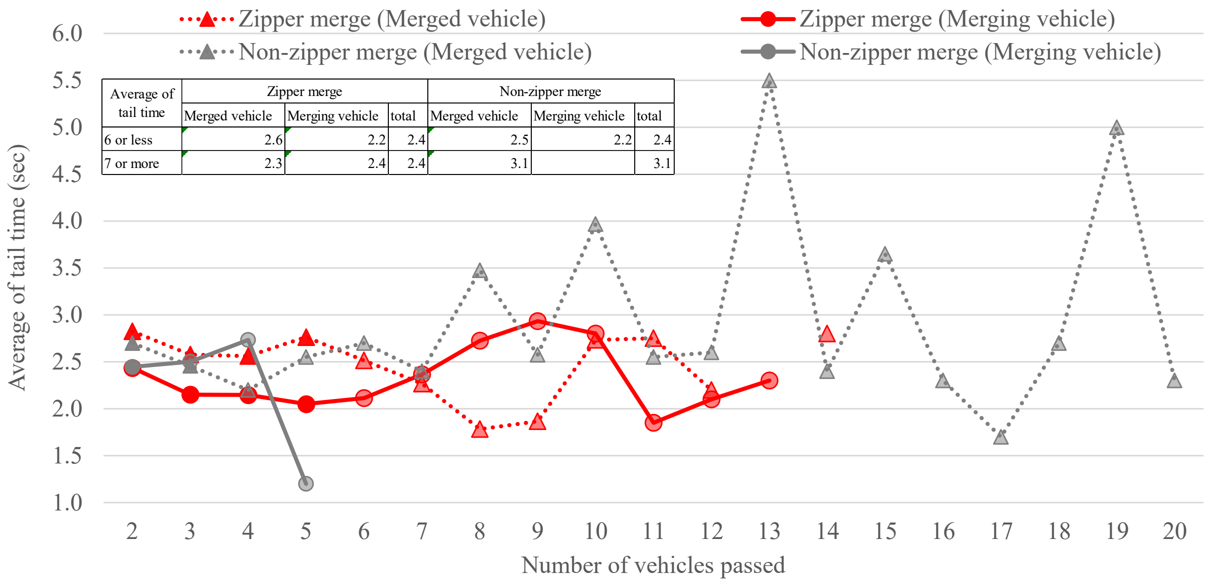


Figure 15. Average headway for passing units.

Table 3. Number of samples (average headway).

Number of samples		Number of vehicles passed																		
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Zipper merge	Merged vehicle	20	22	13	11	7	6	6	3	3	2	1	0	1	0	0	0	0	0	0
	Merging vehicle	28	20	13	10	8	6	4	3	2	2	1	1	0	0	0	0	0	0	0
Non-zipper merge	Merged vehicle	32	14	5	4	3	2	4	4	3	2	3	1	2	2	1	1	1	1	1
	Merging vehicle	24	7	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

First, we considered a zipper merge. Up to the sixth vehicle, the headway of the merged vehicles was shorter. We believe that as the merging vehicle line lengthens, the desire to follow decreases. From the seventh vehicle onwards, the headways of the vehicles being merged were shorter than those of the merging vehicle. We infer that this may be due to the psychology of the drivers of the vehicles being merged, not wanting to let other vehicles merge when there is an increasing number of merging vehicles; thus, they may be driving closer to the front. However, the number of samples from the sixth vehicle onwards is in single digits, and the relationship is reversed again from the eleventh vehicle onwards. Therefore, we consider psychology to be merely a hypothesis.

Next, we consider non-zipper merges. The headway tends to increase from the seventh vehicle onwards. Consider the zipper and non-zipper merges for all lanes without considering each lane (table in Figure 15), the headway is similar for up to that of the sixth vehicle, at 2.4 s. However, the headway for the seventh vehicle and beyond is 2.4 s for the zipper merge and 3.1 s for the non-zipper merge, indicating that the zipper merge has a shorter headway. We believe that with a zipper merge, in addition to the willingness of the merging vehicle to follow, the vehicle can physically close the gap. In contrast, non-zipper merges tended to have longer headways when platooned farther into the driving lane. We speculate that this is because of the driving characteristics of drivers in the driving lane who carefully maintain a safe distance between vehicles and because there are no merging vehicles at all, which results in a longer headway than that with a zipper merge.

Next, we compare the headway of the merging vehicle during non-zipper merges with and without merging vehicles (Figure 16). This indicates that the vehicles that do not allow merging vehicles to enter have a strong desire to follow. As mentioned above, this supports the result that the merging vehicle's "expression of not wanting to let the merging vehicle merge" leads to higher subsequent following behavior.

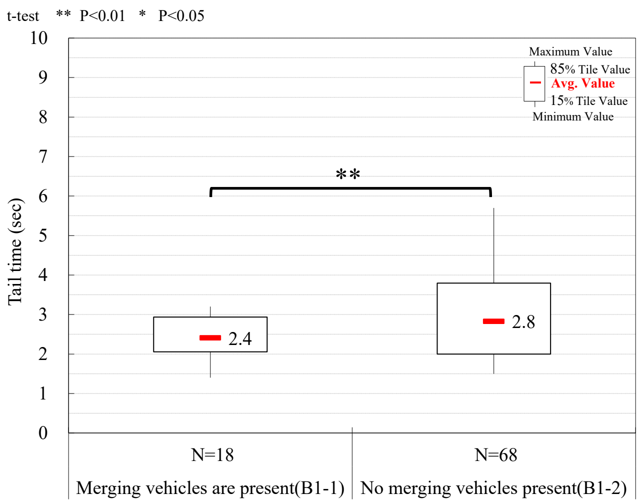


Figure 16. Comparison of headway with and without merging vehicles (non-zipper merge, merged vehicle).

7. CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

A camera survey was conducted on the passing lane closures implemented during the Otai Viaduct renewal work on the Chuo Expressway (outbound) to analyze and consider the differences in the QDF and headway during congestion, depending on the merging method. Two items were analyzed: a macro analysis of the relationship between the lane utilization rate at the start of lane closure and QDF, and a micro analysis of the headway depending on the merging method.

To analyze the relationship between the lane utilization rate at the start of lane closure and the QDF, the traffic volume was analyzed by lane and vehicle type every minute upstream of the bottleneck (CAM09) for the lane utilization rate at the start of lane closure and downstream of the bottleneck (CAM12) for the QDF. Two items were used in this analysis: a scatter plot and multiple regression analysis. In the scatterplot analysis, the QDF was high when the merging lane utilization rate was approximately 50%. Multiple regression analysis was performed to ascertain the reliability of the results. Multiple regression analysis also showed that the QDF decreased when the driving lane utilization rate exceeded 50%.

In the analysis of the headway using the merging method, we compared the headway of the zipper merges with that of the non-zipper merges. The average headway of zipper merges was 2.4 s, and the average headway of non-zipper merges was 2.7 s. The headway of the zipper merges was 0.3 s shorter than that of non-zipper merges. When converted into QDF, the zipper merge had a QDF of 1500 (vehicles/hour) and the non-zipper merge had a QDF of 1333 (vehicles/hour), indicating that the zipper merge had a higher QDF.

The QDF of the zipper merge was high because the headway of the merging vehicle was short, particularly when the number of vehicles in the lane was small and the number of passing vehicles was low. We speculate that this is due to the characteristics of drivers driving in the passing lane, that is, their desire to get ahead even slightly, and the fact that the headway is shortened as a result of merging and filling the physically empty gap between vehicles.

Non-zipper mergers tend to have longer headways when the platoons form a long line on the driving lane side. We speculate that this is because of the driving characteristics of drivers in the driving lane, who drive carefully while maintaining a safe distance between vehicles, resulting in a longer headway than that in zippered merges. However, we also found that some vehicles that were merged into a non-zipper merge had shorter headways because they did not allow the merging vehicle to pass. We believe that this analysis demonstrates that zippered merges have a shorter headway (that is, a higher QDF) than that of non-zipper merges.

7.2 Future Scope

Recommending zipper merge is important for fast congestion resolution. To promote this, it is essential to provide on-site information and promote understanding among drivers through various public relation media platforms. However, providing information recommending zipper merging in traffic conditions before congestion occurs could lead to a decrease in the QDF owing to merging friction and an increase in collision accidents at the start of lane closures. For this reason, we believe that it is necessary to consider providing information recommending zipper merge after the congestion has settled and stabilized at the start of lane closures.

ACKNOWLEDGEMENTS

The data used in this study were provided by NEXCO Central Nippon, and we express our appreciation to the NEXCO Central Nippon team.

REFERENCES

Minnesota Department of Transportation (2025) https://www.dot.state.mn.us/zippermerge/

Central Nippon Expressway Company Limited (2020) https://www.c-nexco.co.jp/corporate/pressroom/ news_release /4747.html. (in Japanese).

Japan Society of Traffic Engineers: Study on road traffic capacity and quality of service– Research report (Traffic capacity edition), 2021. (in Japanese).

Takahashi, H., Xing, J., Ito, H., and Iida, K. (2008) Bottleneck traffic capacity analysis of Tomei Expressway intensive construction section: *Proceedings of the 28th Conference of the Japan Society of Traffic Engineers,* pp. 97-100. (in Japanese).

Kato, D., Goto, A., and Nakmura, H. (2017) An analysis on stochastic of breakdown at a motorway lane-drop section, *Proceedings of Infrastructure Planning*, Vol. 55. CD-ROM (in Japanese).

Yamashita, K., Fukai, Y., Endo, S., Watanabe, T., and Asano, S. (2015) Analysis of factors effect on the traffic capacity at traffic restricted section in the metropolitan expressway when the road repair works with partial lane regulations, *Proceedings of Infrastructure Planning,* Vol. 51. CD-ROM (in Japanese).

Transportation Research Board: Highway Capacity Manual 7th Edition, 2022.

Yeom, C., Hajbabaie, A., Schroeder, BJ, Vaughan, C., Xuan, X., and Rouphail, NM (2015) Innovative work zone capacity models from nationwide field and archival sources. *Transportation Research Record: Journal of the Transportation Research Board, No. 2485, Transportation Research Board, Washington, DC,* 2015, pp. 51-60.

Yamamoto, T., Uemizu, K., Hanada, H., Tsuru, M., Nakabayashi, Y., and Shimokawa, S. (2022) Analysis of traffic capacity at the construction regulation on Inter-urban Expressway, *Proceedings of the 42nd Conference of the Japan Society of Traffic Engineers,* pp. 427-434. (in Japanese).

Sakurai, M., Oneyama, H., Uehata, J., and Aoki, T. (2024a) Research on factors influencing traffic capacity during lane closures on inter-urban expressways, *Journal of the Eastern Asia Society for Transportation Studies,* Vol.15, pp.2559-2574.

Sakurai, M. Uehata, J., Aoki, T., and Oneyama H. (2024b) Analysis of Traffic Capacity During Lane Closures on Inter-urban Expressways, *JSTE Journal of traffic engineering (special edition),* Vol. 10, pp. B_32-B_41. (in Japanese).

Sakurai, M., Uehata, J., Aoki, T., Nonaka, Y., and Oneyama H. (2023) Analysis of Traffic flow during Lane Closures on Inter-urban Expressways, *Proceedings of Infrastructure Planning,* Vol. 68. CD -ROM (in Japanese).

Shiraishi, T., Akahane, H., Oneyama, H., and Tanaka, S. (2012) Development of an Automatic Method for Setting Critical Speeds on Urban Expressways and Application to Bottleneck Capacity Analysis: *Proceedings of the 32nd Conference of the Japan Society of Traffic Engineers*, Vol. 32. CD-ROM (in Japanese).

Kittler J., and Illingworth, J. (1986) Minimum Error Thresholding, *Journal Pattern Recognition,* Vol.19, No.1, pp.41-47.

Japan Road Association (1984): Traffic capacity of roads, 1984 (in Japanese).

Kuwahara, M. and Chen, H. (1991) A Study on the Passenger Car Equivalents of Heavy Vehicles, *Institute of Industrial Science, the University of Tokyo,* Vol. 43, No. 12, pp. 606-609.