ANALYSIS OF BOTTLENECK CAPACITY AND TRAFFIC SAFETY IN JAPANESE EXPRESSWAY WORK ZONES

Jian Xing, Dr. Eng.
Senior Researcher
Highway Research Department
Express Highway Research Foundation of Japan
4-17-5 Shiba Minato-ku Tokyo 108-0014 Japan
TEL: +81-3-6436-2089, FAX: +81-3-6436-2097
Email: jian-x@express-highway.or.jp

Hideki Takahashi
Senior Engineer
Engineering Department
Central Nippon Expressway Company Limited
2-18-19 Nishiki Naka-ku Nagoya 460-0003 Japan
TEL: +81-52-222-3632, FAX: +81-52-232-3713
E-Mail: h.takahashi.ai@c-nexco.co.jp

Kazuhiko Iida, Dr. Eng.
Associate Professor
The Graduate School of Engineering
Department of Civil Engineering
Osaka University
2-1 Yamadaoka Suita Osaka 565-0871 Japan
TEL: +81-6-6879-7611, FAX: +81-6-6879-7612
Email: iida@civil.eng.osaka-u.ac.jp

August 1, 2009

Word count: 4,528+2,750 (6 figures + 5 tables) =7,278 Corresponding Author: Jian Xing

ABSTRACT

This paper explores the characteristics of both bottleneck capacity and traffic safety in work zones of an 150km two-lane section on the Tomei Expressway in Japan. It is found that vertical sag in a work zone could be a major bottleneck in addition to the transition area of the work zone. The capacity of bottleneck sags tends to be smaller than that of the transition area. It also tends to decrease with the length of the one-lane section upstream of a bottleneck. The bottleneck capacity during closures of outer lane and inner lane is much the same in daytime and the former seems to be less than the latter in nighttime due to the negative effect of the narrow lateral spacing of the inner lane in nighttime.

The traffic accident analysis of work zones shows more than 70% of the total accidents and more than 90% of the total injury and fatal accidents occur during traffic congestion. Focusing on the injury and fatal accidents occurred in congested work zones, about half of them happen at the back of the queue and about 40% even in the section upstream of work zones. The accident rate in congested work zones is about 8 times as high as in non-congested ones. This study also highlights the locations of high accident rates in both congested and non-congested work zones.

Based the study results, some countermeasures are recommended to mitigate traffic congestion and improve traffic safety in work zones.

KEYWORDS: Work Zone, Lane Closure, Bottleneck Capacity, Accident Rate, Safety

INTRODUCTION

More than 40 years have passed since the inter-city Tomei Expressway was opened to traffic. It is the most important and heavily trafficked artery expressway in Japan. It is significant to introduce work zones to perform maintenance and rehabilitation activities. A work zone reduces the number of lanes available for traveling vehicles and therefore easily forms a bottleneck in capacity for traffic flow. Traffic congestion occurs behind the bottleneck of a work zone when traffic demand exceeds the bottleneck capacity of the work zone. During congestion, vehicles travel through the work zone at lower speeds enduring considerable delays in congested queue upstream of the bottleneck compared to uncongested flow condition. With the increase of frequency of the works in a year, total yearly delay caused by works related congestion tends to increase considerably, resulting in lower customer satisfaction for the services provided by expressway operators. Traffic safety, on the other hand, becomes a big problem for the travelers through work zones and also is a big challenge for traffic engineers.

To mitigate work zone related congestion, an intensive work period, in which approximately half of the yearly works are concentrated into two consequent weeks excluding weekends, has been introduced on some of Japanese heavily trafficked intercity expressways. It has been found from the past experience that, because large-scale publicity activities were performed via TV commercials, brochures and posters put in expressway rest areas every year prior to the intensive work period, traffic demand would decrease by about 30%. As a result, work zone related traffic congestion summed in a year would reduce by approximately 60% compared to that when works were dispersed in a year. Nevertheless, congestion still occurred in most of work zones, resulting in traffic accidents. It is, therefore, important and necessary to mitigate traffic congestion and to improve traffic safety in expressway work zones.

This paper focuses on analyzing the characteristics of both bottleneck capacity and traffic safety in work zones of a 150km four-lane section of the Tomei Expressway in Japan. Based the study results, some countermeasures are recommended to mitigate traffic congestion and improve traffic safety in work zones.

LITERATURE REVIEW

Most of studies related with capacity, safety and traffic control management in highway work zones have been conducted in the U.S. There are many ways to define and estimate the work-zone related capacity in related literature. They could mainly be divided into three types, i.e. a) the queue discharge rate during congested flow condition, b) the flow rate at which traffic flow quickly changes from uncongested flow condition to queued condition, and c) maximum value estimated from the basic Q-V-K diagram. The first definition was taken by the Highway Capacity Manual (HCM) (*1*) following the result of the research by Krammes and Lopez (*2*). They recommended a base capacity value of 1600 passenger cars per hour per lane (pcphpl) for all short-term freeway lane closure configurations, and suggested several adjustments that reflect the effects of the intensity of the work activity, the percentage of heavy vehicles and the presence of entrance ramps near the beginning of the lane closure. The second definition was taken in the researches made by Dixon and Hummer (*3*), Jiang (*4*) and Maze et al. (*5*). They define the capacity as the flow rate at which traffic flow quickly changes from uncongested to queued conditions, or immediately before queuing begins. Jiang (*4*) estimated the mean capacity of the partial closure of two-lane freeways as 1500-1550 pcph and the mean queue-discharge rate as 1200-1375 pcph from a study in Indiana. Maze et al. (*5*) obtained the approximate capacity of the Iowa rural work zone closures varying from 1400-1600 pcphpl. Racha et al. (*6*) examined the speed-density relationship from traffic data obtained from 22 work zone sites on South Carolina interstate highways, and by using it the capacity of a work zone was estimated to be 1550 pcph for 2-lane to 1-lane closure. However, the authors could not find relevant studies on the analysis of capacity of work zones on Japanese expressways.

On the other hand, numerous researchers in the U.S. have examined the influence of work zones on traffic safety since 1970s, primarily in terms of how accident rate changes when a work zone is introduced. It appears that accident rates increase in work zones compared with those in non-work zones although the amount of increases varies across studies (*7, 8*). However, there are no consistent agreement on the predominant type of crashes took place in work zones (*9*) and also on whether or not crashes occurred in work zones tend to be more severe, less severe, or as severe as in non-work zones (*10, 11*). It is also unclear whether or not crashes increase more significantly at night than in daytime (*11*). In summary, most accident studies have been conducted statewide and the findings vary with data sources because traffic control devices and traffic flow conditions may differ considerably across studies. Nevertheless, we could not find the analyses of the difference in characteristics of crashes by different locations within a work zone as well as by flow type, i.e. congested flow and uncongested flow. Since traffic congestion occurs frequently in the work zones on Japanese expressways, the effect of congestion on traffic safety in work zones has to be considered in our study. Unfortunately, no relevant researches on safety analysis of work zones have been conducted prior to our study.

ANALYSIS DATA

During the intensive work period, around-the-clock work zones were introduced if necessary. About half of the works needed in a whole year are almost concentrated into the intensive work period of about 9-10 weekdays usually in October or November. The data for work zone capacity analysis in this study is taken from an 150km two-lane section from Tokyo to Mikabi of the Tomei Expressway in the 9-day intensive work period conducted in 2007

(Table 1), i.e. from 0:00 am of October 9 (Monday) to 12:00 pm of October 12 (Friday), and from 0:00 am of October 15 (Monday) to 6:00 pm of October 19 (Friday). Altogether 132 work zones consisting of 72 closures of outer lane and 60 closures of inner lane were installed in the whole two-lane section in the 9-day intensive work period.

The data for analysis of injury and fatal accidents is taken from the same section as the work zone capacity analysis in a 5-year period from 2003 to 2007 including the intensive work period. The data for all accidents combined is only extracted in a 2-year period from 2003 to 2004 because the input accident data have been limited to severe and road damage only accidents since 2005.

Table 1 shows, as an example, a summary statistics of the work zones and traffic volumes of the intensive work period in 2007. It is seen from the table that traffic demand in the intensive work period was reduced by 30% due to the large-scale publicity activities such as TV commercials, brochures and posters put in expressway rest areas every year prior to the intensive work period. The average daily traffic (ADT) in the intensive work period was 45,500 vehicles per day, about 40% less than the annual average daily traffic (AADT) of 78,000 vehicles per day. Despite the reduced traffic demand, traffic congestion occurred frequently in the work zones during the intensive work period and it accounted for approximately 10% of the yearly congestion.

Table 1 Summary statistics of work zones and traffic volumes
in the intensive work period of 2007

Variable	Value
Total length (km)	150
Period	0:00 am Oct. 9 (Mon.) - 12:00 pm of Oct. 12 (Fri.) 0:00 am of Oct. 15 (Mon.) - 6:00 pm of Oct. 19 (Fri.)
No. of work zones	
Total	132
Closure of inner lane	72
Closure of outer lane	60
Work zone length (km)	
Average	7.3
Minimum / Maximum	0.7 / 21.6
ADT (vehicles per day)	
Average	45,500
Minimum / Maximum	36,000 / 65,000
AADT (vehicles per day)	78,000
No. of lanes	4
	3.6
Lateral clearance (left / right) (m)	3.0 / 1.25
Design speed (km/h)	80-100

BOTTLENECK LOCATION AND BOTTLENECK CAPACITY IN WORK ZONES

Considering the capacity drop from uncongested flow condition to congested flow condition when a queue forms behind a bottleneck, two types of capacity are adopted in our study, i.e. breakdown flow (capacity at the occurrence of congestion) and queue discharge flow (capacity during congestion). They are defined as follows:

- Breakdown flow: the 15-min flow rate immediately before the 5-min space mean speed decreases below 40km/h at a point immediately upstream of a bottleneck;
- Queue discharge flow: an average flow rate discharged from the bottleneck during congestion.

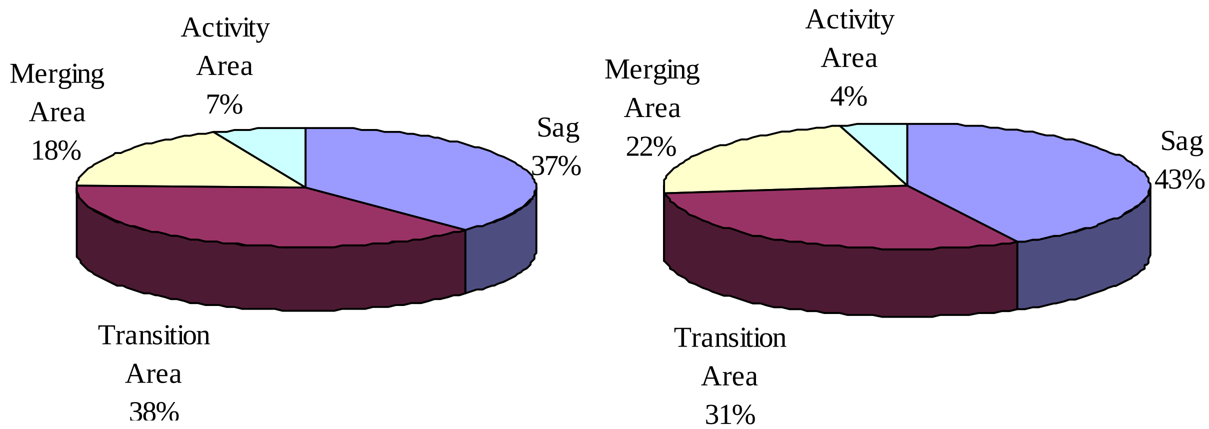
The location of bottlenecks was identified and their capacity was calculated from the data of vehicular detectors at a normal spacing of 2 km. If it was difficult to identify calculate the capacity from the detector data, then its capacity was not included in the study.

Bottleneck Location in Work Zones

Table 2 shows the number of bottlenecks in terms of both breakdown flow and queue discharge flow in the work zones of the intensive work period in 2007. The number is different because the bottleneck location during congestion i.e. the head of queue may stay at several bottlenecks for different time periods in addition to the initial bottleneck at the occurrence of congestion. Altogether there were 61 bottlenecks where congestion occurred, and 113 bottlenecks behind which queue formed. Figure 1 describes the percentage of the bottleneck locations for both the breakdown flow and the queue discharge flow. It is seen from Figure 1 that for the bottlenecks just at the occurrence of congestion and during congestion, sag or the change of vertical gradient within work zones, and the transition area of a work zone account for about 30%–40%, followed by the merging section for about 20% and the work activity area for less than 10%. The identified bottlenecks of sags within the work zones are actually identical with those when work zones are not applied. Certainly, the three types of bottleneck except the sag could sometimes also have an effect of the sag. In many cases, long queue behind a bottleneck of sag within a work zone tends to go upstream of the transition area.

Table 2 No. of bottlenecks of both breakdown flow
and discharge flow in intensive work period (2007)

Direction	Time Period	No. of Bottlenecks	
		Breakdown Flow	Discharge Flow
Eastbound	Daytime (7:00-17:00)	29	42
	Nighttime (17:00-7:00)	8	23
	Subtotal	37	65
Westbound	Daytime (7:00-17:00)	20	31
	Nighttime (17:00-7:00)	4	17
	Subtotal	24	48
Total	Daytime (7:00-17:00)	49	73
	Nighttime (17:00-7:00)	12	40
	Subtotal	61	113



Breakdown Flow Queue Discharge Flow

Figure 1 Percent of bottleneck locations in intensive work period (2007)

Bottleneck Capacity in Work Zones

In order to estimate bottleneck capacity, passenger car equivalents have to be estimated to take the effect of large vehicles into account. Here in this study, they are derived from the ratio of average tail-to-tail time headways of large vehicles to passenger cars. The time headway data were obtained from the pulse data recorded from vehicular detectors on a two-lane expressway. The large vehicles are defined here as those with its length more than 5.5m from the configuration of double loop detectors because the spacing of the loops is 5.5m. The percentage of large vehicles for the PCE estimation was observed less than 20%. The passenger car equivalents were estimated for both breakdown flow and queue discharge flow from one-hour data each before and after the occurrence of congestion. To remove extremely long spacing, the limit of car-following spacing was taken as 200m, which yields about 20 seconds in congested speed of 40km/h and 10 seconds in uncongested speed of 80km/h. The passenger car equivalents thus estimated are 1.6 for congested flow and 1.4 for uncongested flow for one-lane section. The passenger car equivalent for queue discharge flow is slightly larger than that for breakdown flow. These equivalents are used to convert the observed capacities into those in passenger car equivalents.

Table 3(a) describes the bottleneck capacities of both the breakdown flow and queue discharge flow of different locations, i.e. sag, transition area, merging area and activity area as shown in Figure 1. The breakdown flow is estimated around 1,400 – 1,500 pcph in daytime and 1,150 – 1,400 pcph in nighttime. The queue discharge flow is 1,200 – 1,400 pcph in daytime and 1,100 – 1,200 pcph in nighttime. It can be seen from Table 3(a) that for both daytime and nighttime breakdown flow and queue discharge flow, sag yields the least capacity value while the transition area of a work zone tends to give the highest value. Table 3(b) demonstrates the difference of bottleneck capacities between different closed lanes. For both the breakdown flow and queue discharge flow, the daytime bottleneck capacity does not differentiate between closures of outer lane and inner lane, the nighttime bottleneck capacity, however, tends to reduce more when outer lane is closed than closure of inner lane. This is partially due to the limited lateral clearances in the case of outer lane closure at night. This result suggests that it would be better to schedule the outer lane closure works in daytime rather than in nighttime in the intensive work period.

Table 3(a) Bottleneck capacities by bottleneck location

Bottleneck Location	Breakdown Flow (pcph)		Queue Dischage Flow (pcph)	
	Daytime	Nighttime	Daytime	Nighttime
Sag	1,433	1,165	1,208	1,091
Transition Area	1,520	1,399	1,429	1,201
Merging Area	1,425	1,343	1,356	1,158
Activity Area	1,481	-	1,233	-

Table 3(b) Bottleneck capacities by closed lane

Closed Lane	Breakdown Flow (pcph)		Queue Dischage Flow (pcph)	
	Daytime	Nighttime	Daytime	Nighttime
Inner Lane	1,459	1,348	1,332	1,166
Outer Lane	1,454	1,096	1,306	1,084

Figure 2 shows the relationship between bottleneck capacity and work zone length for both daytime and nighttime breakdown flow and queue discharge flow. Figure 3 depicts the similar relationship between bottleneck capacity and the length of one-lane section upstream of the bottleneck in a work zone. Here the zero length points mean the capacity for bottlenecks of transition areas. It seems from Figures 2 & 3 that both daytime and nighttime breakdown flow and queue discharge flow have a tendency to decrease slightly with the work zone length and the length of one-lane section upstream of the bottleneck although data scatters and the tendencies are less significant for short length work zones or one-lane sections. It was tested from the variation analysis that only the relationships between daytime breakdown flow and work zone length, nighttime breakdown flow and daytime queue discharge flow, and the length of one-lane section upstream of the bottleneck are statistically significant at 95% confidence level. The decrease in capacity might result from the speed drop in a long single-lane work zone. This result corresponds to the result of a previous study by Yoshikawa et al. (*12*, *13*) on capacity analysis of two-lane expressways that bottleneck capacity decreases with the length of one-lane section. This result recommends that both the work zone length and the length of 1-lane section upstream of the bottleneck be taken as short as possible in the short intensive work period to avoid the decrease in bottleneck capacity of a work zone. As seen from Table 1, the average work zone length in the intensive work period of 2007 is 7.3 km with a maximum length of 21.6 km.

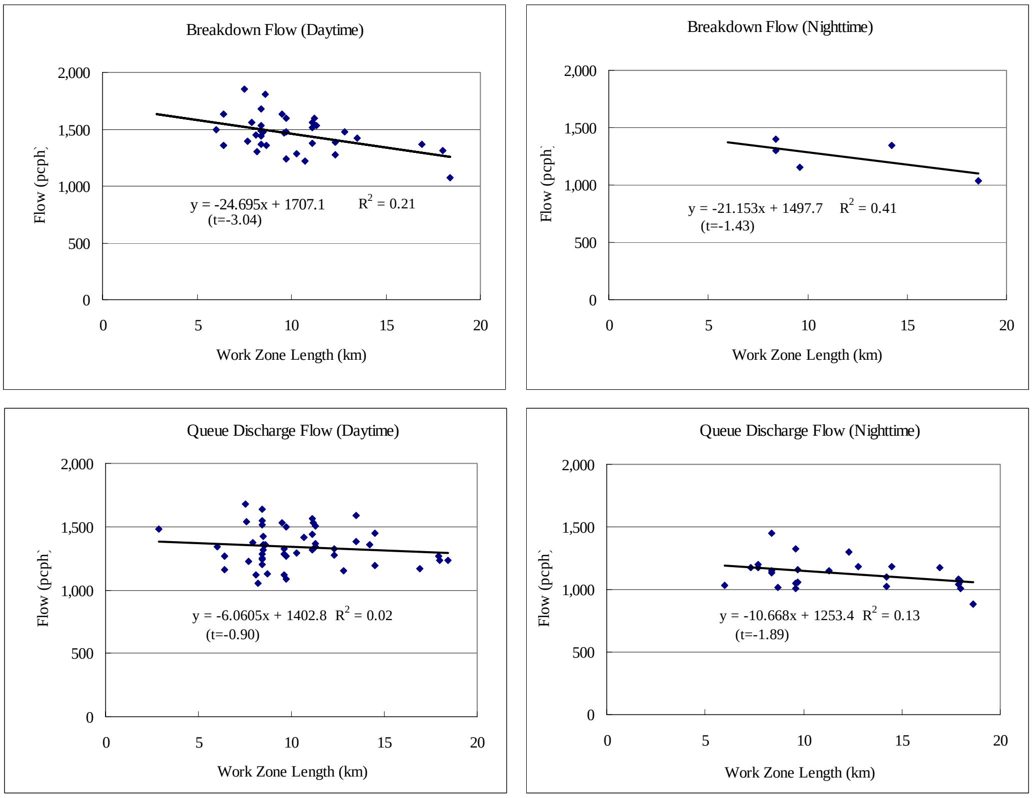


Figure 2 Relationship between bottleneck capacity and work zone length

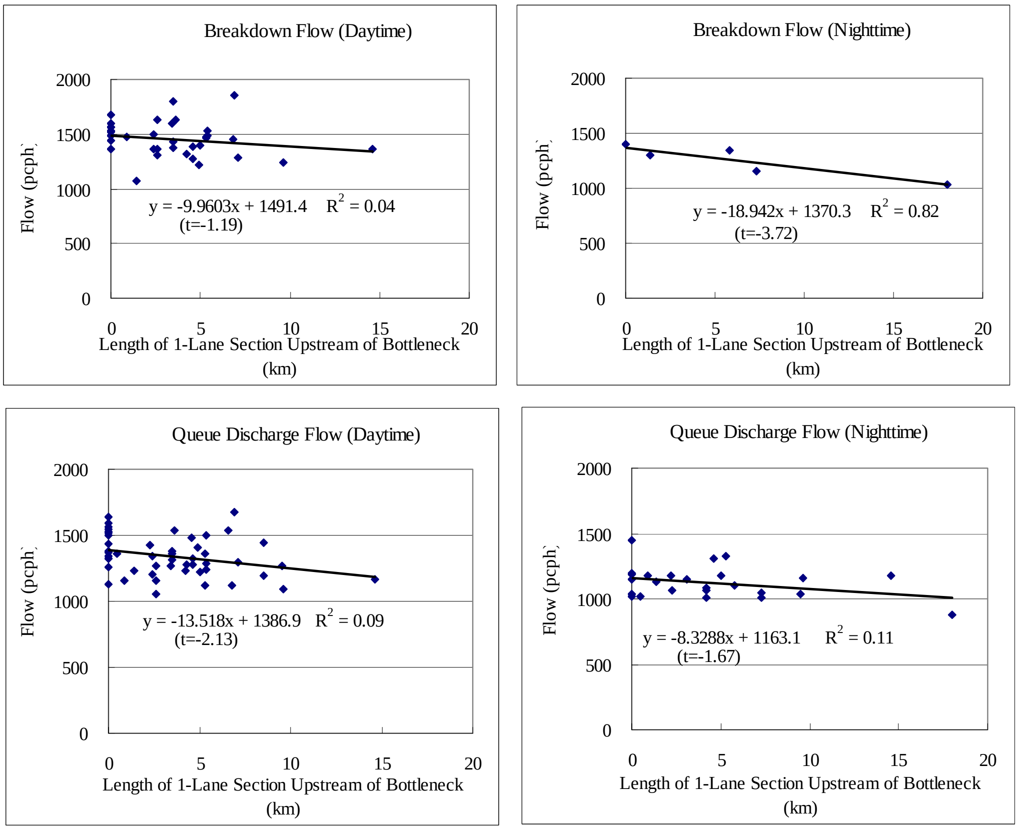


Figure 3 Relationship between bottleneck capacity and the length of one-lane section upstream of a bottleneck

TRAFFIC SAFETY IN WORK ZONES

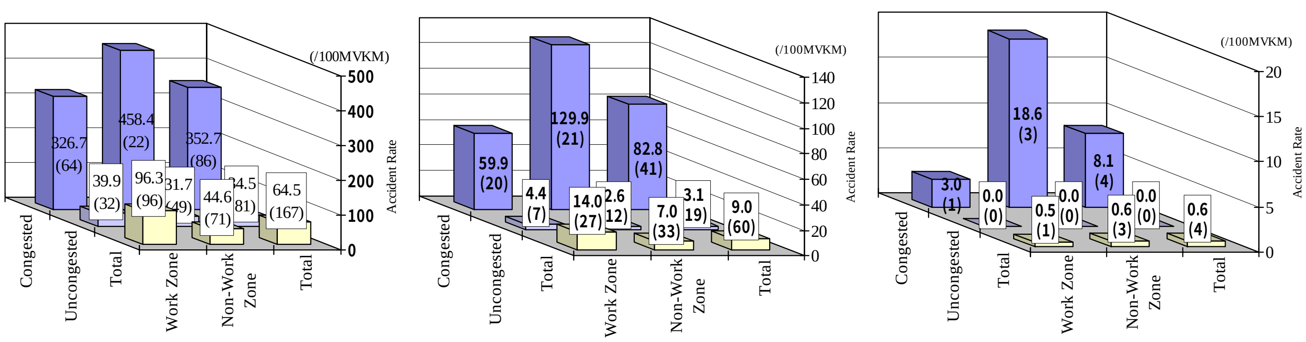
Comparison of Traffic Accidents between Intensive Work Period and Non-Work Period

Table 4 shows the number of accidents and accident rates of the intensive work period and the other non-work period for three different types of accidents, i.e. all crashes, severe (injury and fatal), and fatal only. As aforementioned, all crashes are summed in a two-year period from 2003-2004 and injury and fatal crashes in a five-year period from 2003-2007. Looking at the number of accidents occurred in the intensive work period of about 9-10 days, it accounts for only 2.7% of total crashes happened in a year for all crashes, 3.2% for severe ones and 4.2% for fatal ones. The average accident rates seem to be higher in the intensive work period than in non-work period for three severity types of crashes. The accident rates of the intensive work period are 64.5 crashes per 100 million vehicle kilometers traveled (100MVKM) for all accidents combined, 9.0 crashes/100MVKM for severe accidents and 0.6 crashes/100MVKM for fatal accidents, which are 50%, 70% and 2.0 times higher than those of non-work period respectively for three severity types of crashes.

Table 4 No. of accidents and accident rates of intensive work period and non-work period

Crash Severity	No. of Accidents			Accident Rate		
	Non-Work Period	Intensive Work Period	Whole Year	Non-Work Period	Intensive Work Period	Whole Year
All accidents Combined (2003-2004)	5942 (97.3%)	167 (2.7%)	6109 (100%)	42.7	64.5	43.1
Injury and Fatal (2003-2007)	1836 (96.8%)	60 (3.2%)	1896 (100%)	5.2	9.0	5.3
Fatal (2003-2007)	71 (94.8%)	4 (4.2%)	75 (100%)	0.2	0.6	0.2

Accident rate is expressed in accidents per 100 million vehicle kilometers traveled (1/100MVKM)



a) All accidents combined b) Injury and fatal accidents c) Fatal accidents

Figure 4 No. of accidents and accident rates by flow type and work/non-work zone for each crash severity in intensive work period

Looking into the accidents occurred in the intensive work period, they are divided by work/non-work zone and flow type (congested and uncongested) so as to compare some statistics of accidents. Here the work zone in this study is defined as a section from the location of 500m upstream of the transition area to the location of 500m downstream of the termination area taking into account the lane changing maneuvers immediately upstream and downstream of the work area from transition area to termination area. Figure 4 shows the number of accidents and accident rates featured by flow type and work/non-work zone for each crash severity in the intensive work period. Comparing the average accident rates between the work zone and non-work zone, the work zone accident rate for all crashes combined is 96.3 crashes/100MVKM, being 116% higher than the non-work zone accident rate of 44.6 crashes/100MVKM. It is also seen from Figure 4 that for each crash severity, the accident rates in congested flow condition are much higher than in uncongested flow condition in both the work zone and non-work zone. The average accident rate for all crashes combined in the work zone of congested flow condition is 326.7 crashes/100MVKM being approximately 8 times as high as that of uncongested flow condition of 39.9 crashes/100MVKM.

Severe accidents have similar results as all crashes combined. The work zone accident rate for severe crashes is 14.0 crashes/100MVKM, being 100% higher than that of non-work zone of 7.0 crashes/100MVKM. The accident rate in the work zone of congested flow condition is 59.9 crashes/100MVKM being nearly 14 times as high as that of uncongested flow condition of 4.4 crashes/100MVKM. For fatal crashes, only four crashes occurred in congested flow condition of the intensive work periods in a 5-year period, of which one happened in a work zone and the other three crashes took place upstream of the work zones. The highest values in non-work zone of congested flow condition for each crash severity result from the rear-end crashes occurred in the queue or at the back of the queue spilling backward from the bottleneck in the work zone, which is to be discussed in detail later in the paper.

Figure 5 describes the objects of collision for all crashes combined in both congested and uncongested flows and in both work zone and non-work zone in the intensive work zones of 2003-2004. As expected, the rear-end collision is the predominant crash type for both work zone and non-work zone in congested and uncongested flow conditions. It accounts for more than 95% for both work zone and non-work zone during congestion. In the work zone of uncongested flow condition, however, the rear-end collision accounts for 39% followed by 30% of collisions with the channelizing devices, 17% of crashes with falling objects and 13% of crashes with the objects at both sides of road. In the non-work zone of uncongested flow condition, rear-end collision accounts for 53% followed by 30% of crashes with the objects at both sides of road.

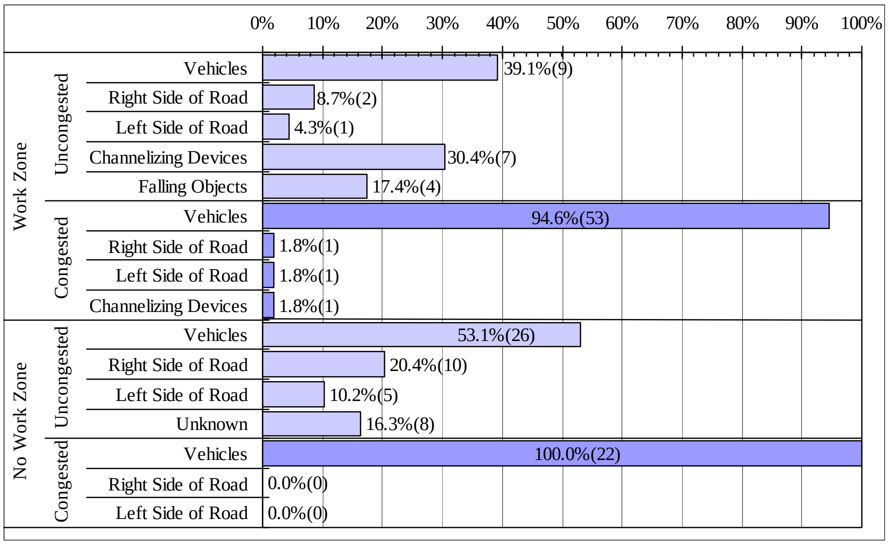


Figure 5 Objects of collision of work/non-work zone in intensive work periods (2003-2004)

Characteristics of Work Zone Related Traffic Accidents

This section analyzes the characteristics of work zone related accidents by partitioning the work zone into different areas, i.e. over and within 500m upstream of the transition area, the transition area, the merging and diverging areas, the normal section in a work zone, within 500m of the downstream taper. Figure 6 shows the number of accidents and accident rates by flow type and crash location for each crash severity. Here the range of over 500m upstream of transition area is as long as nearly 10 km corresponding to the farthest back of queue. For all accidents combined, about 70% of all the crashes occurred during congestion. The accident rate is higher at and upstream of the transition area in congested flow condition while it is higher only at the transition and diverging areas in the work zone of uncongested flow condition. For severe accidents, about 90% of injury and fatal crashes happened during congestion, and the accident rate is higher at and upstream of the transition area in congested flow condition and it is very low in the work zone of uncongested flow condition.

Since most of the accidents occur during congestion and the accident rates are much higher in congested flow condition than in uncongested flow condition for each crash severity, it is important to see how many accidents occur at the back of a queue, which tends to cause high severity crashes due to the large difference in relative speed of the vehicles involved in accidents. Table 5 shows the characteristics of work zone related accidents occurred during congestion, which are divided into the rear-end crashes within the queue and the read-end crashes at the back of the queue. Here the rear-end accidents are judged from the viewpoint of a) congestion related accident selected from the accident report data, b) speed contour obtained from speed data of vehicular detectors, and c) the relative speed of the two vehicles involved in a accident being more than 50 km/h. For all accidents combined, about 80% of total accidents occurred within the queue while only 20% happened at the back of the queue. For injury and fatal accidents, however, more than 60% of total severe accidents took place at the back of the queue and nearly 40% occurred within the queue. Looking into locations of the severe accidents in details, approximately half of the total severe accidents happened at the back of the queue where is upstream of the transition areas. All the four fatal accidents occurred at the back of the queue, of which three crashes happened upstream of the transition area. These accidents occurred even though warning of the back of queue was conducted with the LED vehicles. Therefore, to enhance traffic safety in work zones on Japanese heavily trafficked expressways, it is important and necessary to relieve traffic congestion that frequently occurs in work zones and also to consider automated warnings of the back of queue using recent ITS technologies when congestion occurs.

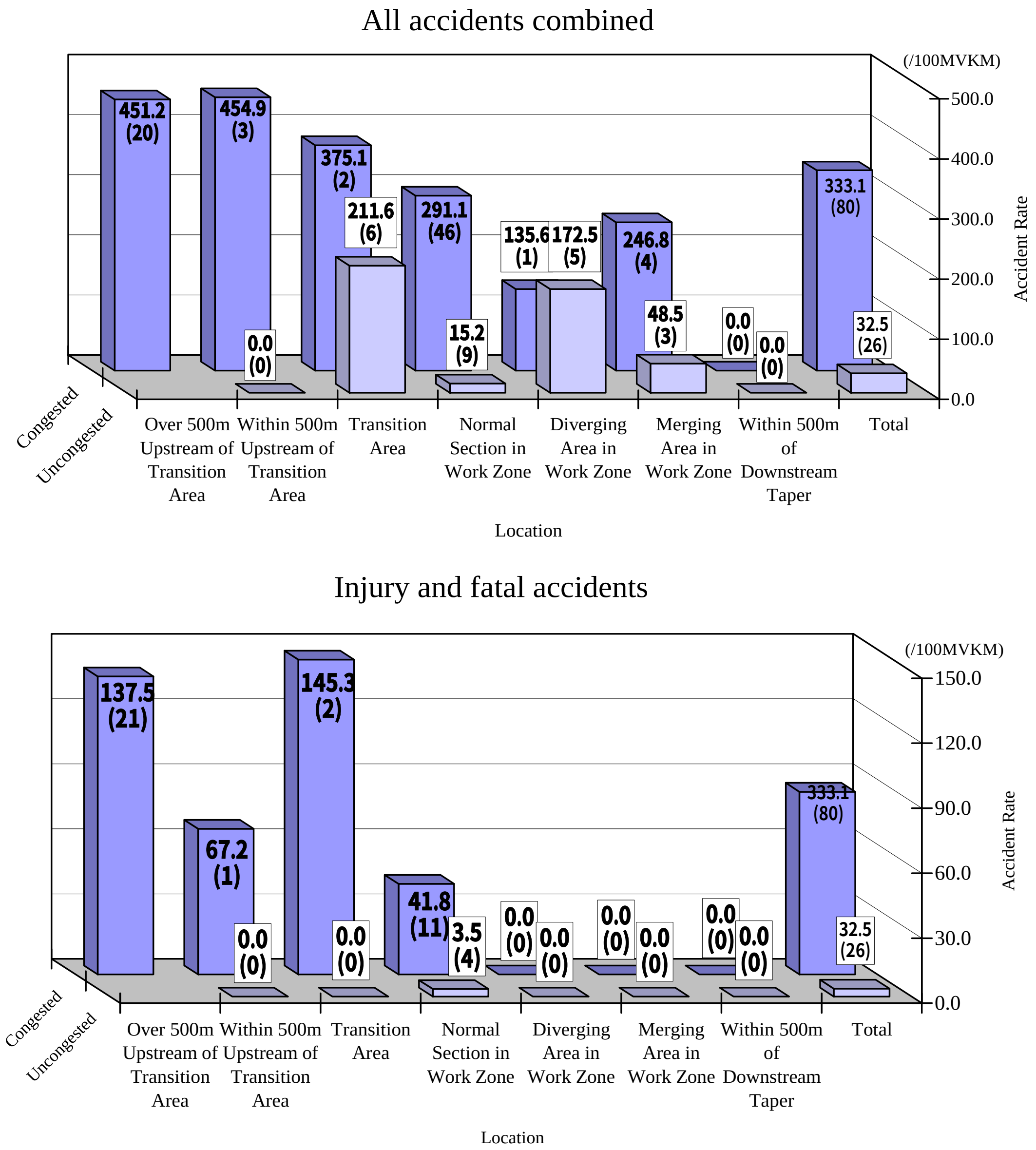


Figure 6 No. of accidents and accident rates by flow type and crash location
(Upper graph: All accidents combined; Lower graph: Injury and fatal accidents)

Table 5 Characteristics of work zone congestion related accidents by location of the queue and crash location and by crash severity

Crash Severity	Crash Location	Within the Queue		At the Back of the Queue	
		No. of Accidents	%	No. of Accidents	%
All Crashes Combined (2-Year)	Over 500m Upstream of Transition Area	10	13.5%	9	12.2%
	Within 500m Upstream of Transition Area	2	2.7%	1	1.4%
	Transition Area	2	2.7%	0	0.0%
	Normal Section in a Work Zone	41	55.4%	4	5.4%
	Diverging Area in Work Zone	1	1.4%	0	0.0%
	Merging Area in Work Zone	4	5.4%	0	0.0%
	Total	60	81.1%	14	18.9%
Injury and Fatal (5-Year)	Over 500m Upstream of Transition Area	5	14.3%	16	45.7%
	Within 500m Upstream of Transition Area	0	0.0%	1	2.9%
	Transition Area	0	0.0%	2	5.7%
	Normal Section in a Work Zone	8	22.9%	3	8.6%
	Total	13	37.1%	22	62.9%
Fatal (5-Year)	Over 500m Upstream of Transition Area	0	0.0%	3	75.0%
	Normal Section in a Work Zone	0	0.0%	1	25.0%
	Total	0	0.0%	4	100.0%

CONCLUSIONS AND RECOMMENDATIONS

This paper explores the characteristics of both bottleneck capacity and traffic safety in work zones of an 150km two-lane section on the Tomei Expressway in Japan. It is found that vertical sag in a work zone could be a major bottleneck in addition to the transition area of the work zone. Work zone capacity ranges for different conditions. The capacity of bottleneck sags tends to be smaller than that of the transition area. It also tends to decrease with the work zone length and the length of the one-lane section upstream of a bottleneck. The bottleneck capacity during closures of outer lane and inner lane is much the same in daytime and the former seems to be less than the latter in nighttime due to the negative effect of the narrow lateral spacing in nighttime.

The traffic accident analysis of work zones shows more than 70% of the total accidents and more than 90% of the total injury and fatal accidents occur during traffic congestion. Focusing on the injury and fatal accidents occurred in congested work zones, about half of them happen at the back of the queue and about 40% even in the section upstream of work zones. The accident rate in congested work zones is about 8 times as high as in non-congested ones. The study also highlights the locations of high accident rates in both congested and non-congested work zones.

Since work zone capacity tends to decrease with the work zone length and the length of single-lane section upstream of a bottleneck, shortening of the work zone length is considered as an effective measure to mitigate congestion in work planning, in particular, excluding the latent bottleneck from the work zone. Besides, it seems to be better to schedule the outer lane closure works in daytime rather than in nighttime because in nighttime the capacity in closed outer lane is less than in closed inner lane. The countermeasures against congestion are most effective to improve safety in work zones since most of the accidents for each crash severity occur during traffic congestion. It is also very important and necessary to introduce automated warnings of the back of queue using recent ITS technologies when congestion occurs. In uncongested flow condition, improvement of traffic control management such as channelizing devices should be considered to urge early merging in the advance warning area before the transition area to decrease the accident rate in the transition area.

REFERENCES

1. Transportation Research Board, *Highway Capacity Manual – 2000*, TRB, National Research Council, Washington, D.C., 2000.
2. Krammes, R. A., and G. O. Lopez. Updated Capacity values for Short-Term Freeway Work Zone Lane Closures. *Transportation Research Record*, No. 1442, TRB, National Research Council, Washington, D.C., 1994.
3. Dixon, K.K., and J. E. Hummer. *Capacity for North Carolina Freeway Work Zones*, Report No. 23241-94-8. prepared for the North Carolina Department of Transportation by the Center for Transportation Engineering Studies, North Carolina State University, 1995.
4. Jiang, Y. Traffic Capacity, Speed and Queue-Discharge Rate of Indiana Four-Lane Freeway Work Zones. *Transportation Research Record*, No. 1657, TRB, National Research Council, Washington, D.C., 1999.
5. Maze, T. H., Schrock, S. D., and A. Kamyab. Capacity of Freeway Work Zone Lane Closures. *Mid-Continent Transportation Symposium 2000 Proceedings*, Ames, IA: Center for Transportation Research and Education, Iowa State University, 2000.
6. Racha, S., Chowdhury, M., Sarasua, W., and Y. Ma. Analysis of Work Zone Traffic Behavior for Planning Applications. *Transportation Planning and Technology*, Vol. 31, No. 2, April 2008, pp. 183-199.
7. Khattak, A. J., Khattak, A. J., and F. M. Council. Effect of Work Zone Presence on Injury and Non-Injury Crashes. *Accident Analysis and Prevention*. Vol. 34, 2002, pp. 19-29.
8. Garber, N. J., and M. Zhao. Distribution and Characteristics of Crashes at Different Work Zone Locations in Virginia. *Transportation Research Record*, No. 1794, TRB, National Research Council, Washington, D.C., 2002, pp. 19-25.
9. Li, Y., and Y. Bai. Comparison of Characteristics Between Fatal and Injury Accidents in the Highway Construction Zones. *Safety Science 46*, 2008, pp.646-660.
10. Jin, T. G., Saito, M., and D. L. Eggett. Statistical Comparisons of the Crash Characteristics on Highways between Construction Time and Non-Construction Time. *Accident Analysis and Prevention*. Vol. 40, 2008, pp. 2015-2023.
11. Ullman, G. L., Finley, M., Bryden, J. E., Srinivasan, R., and F. M. Council. Traffic Safety

Evaluation of Nighttime and Daytime Work Zones. *NCHRP Report 627*. TRB of the National Academies. Washington, D.C., 2008.

12. Yoshikawa, R., Mizukami, H., Xing, J., Yoshii, T., and R. Kitamura. Bottleneck Capacity of Two-Lane Expressways. *Proceedings of the 5th International Symposium on Highway Capacity and Quality of Service*, Yokohama, Japan, July 2006.
13. Yoshikawa, R., Shiomi, Y., Yoshii, T., and R. Kitamura. A Study on Bottleneck Capacity of Two-Lane Expressways. Traffic Engineering, Vol. 43, No. 5, 2008, pp. 48-58.