Congestion Analysis of Metropolitan Expressway No. 3 at Interchange Inflow Section

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Abstract: Traffic flow problems have affected to various field and we have established various policies for the reduction of traffic congestion. But these policies are not perfect and occasionally cause a traffic jam in another place. Therefore, in this study, we analyzed the mechanism of traffic jams on the outbound line of Metropolitan Expressway No.3 using a statistical model analysis. The result indicated that the increase in traffic volume and decrease in speed due to traffic convergence cannot be ignored as contributing factors for congestions that occur on the outbound traffic. And it was also indicated that the required time for resolving a congestion could be reduced by implementing measures for prompting drivers to take detours for avoiding most congested sectors, while keeping in mind the issue of equilibrium arising from differences in the traffic inflow routes when the vehicles head into applicable locations. (143 words)

Keywords: Traffic congestion, Statistical model analysis, Metropolitan Expressway No.3, Sag, Interflow

1. INTRODUCTION

Since decades, traffic flow problems have have affected to various field. In particular, in the Tokyo Metropolitan area, Metropolitan Expressway No.3, a very important route from the metropolitan area to Tomei Expressway, is very well known for the frequent traffic congestion it encounters, and this problem became extremely serious when Ohashi Junction was bulit in 2010.
We have the various policies for the reduction of traffic congestion, such as the expansion of road networks, development of new lanes, efficiency strategies of toll collection, information supplement for drivers, and caution sign or something in the speed degradation area. These policies have been effective to some extent, but they are not perfect and occasionally cause a traffic jam in another place.
Therefore, in this study, we investigated and analyzed the mechanism of traffic jams on the outbound line of Metropolitan Expressway No.3 using a statistical model analysis.

2. LITERATURE REVIEW

Many studies have reported the traffic congestion in Japan. With respect to its analysis, many studies used the traffic volume data detected by the ultrasonic wave or the loop coils or the one collected at the ETC gates. Nakamura et al.[1)] analyzed the effect of regulations on the inflow at the tollgates on the Metropolitan Expressway or the Metropolitan Ring Road and reported that it was effective in decreasing the traffic congestion at the downstream bottleneck.
Further, regarding the policies for resolving the bottleneck, many studies also have reported rate inhibition or traffic flow control, i.e., the development of additional lanes[2)], regulations on the inflow to freeways, signal operations[3)], and improvement of signs[4)]. Yoshikawa et al.[2)] compared the mechanism and the traffic capacity between a two-lane highway and a four-lane highway and showed that the traffic volume per lane

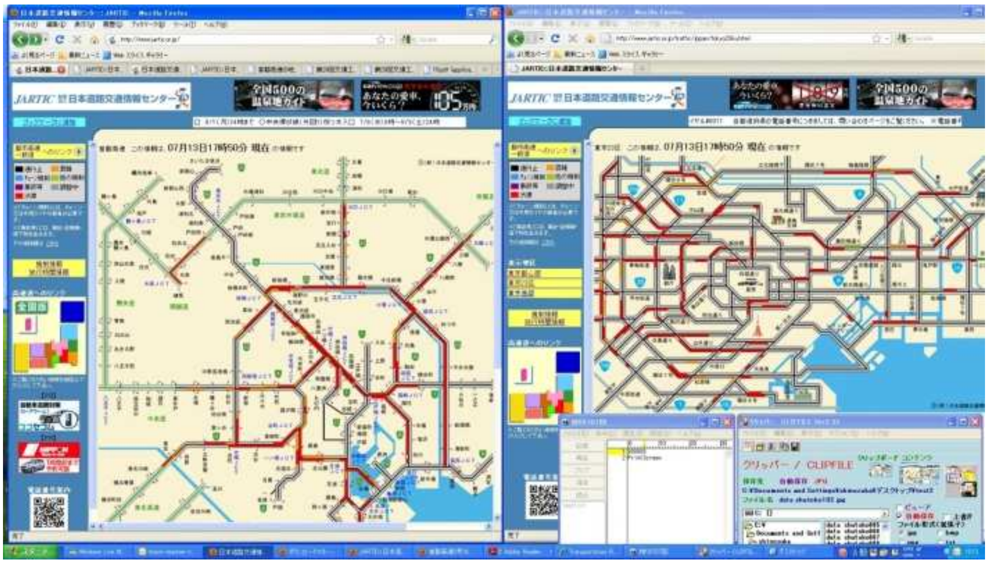

Figure 1 Situation map of traffic congestion byJapan Road Traffic Information Center

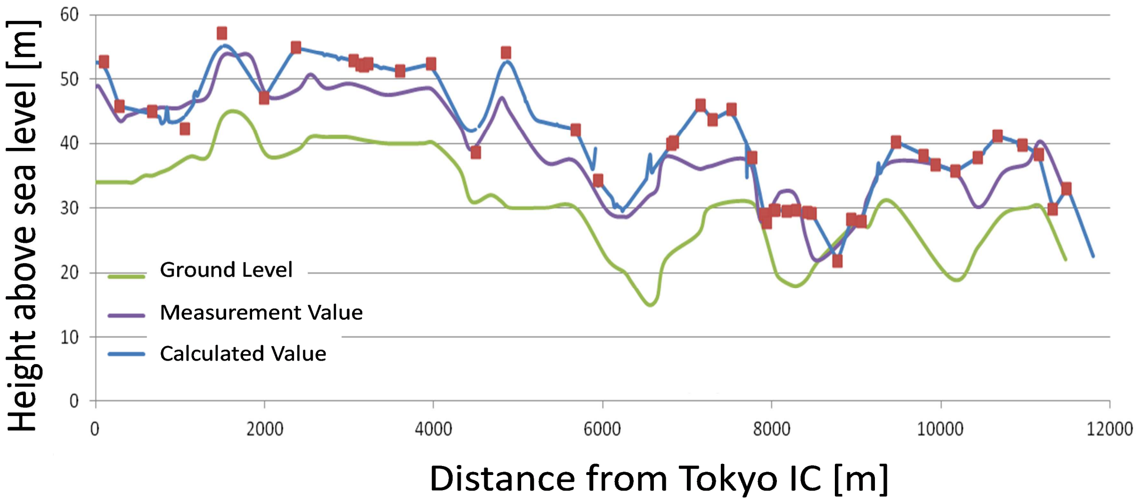

Figure 2 Height above sea level of the Metropolitan Expressway No.3 (Tokyo IC – Tanimachi IC)

Figure 3 Video images of fixed-point observation
(Left; the Metropolitan Expressway, Right; local roads)

of the two-lane section of the Tokai-Hokuriku Expressway was 30% lower than that of the four-lane section when the traffic congestion generated and disappeared. Moreover, they introduced the case example for reducing the frequency of traffic congestion by building an additional lane upstream of the two-lane bottleneck section. Kato et al.[3] investigated the methodology and the effect of regulations on the inflow at the interchange, service area, rest area, or tollgate at the upper stream of the bottleneck using a simulation. Further, they showed that three approaches, namely, ramp metering, regulation of the inflow at a tollgate with ETC, and one with a signal operation, could considerably reduce the queue length and the duration of the traffic congestion at a low cost.

Congestion, however, is not a homogeneous condition; rather, it is a phenomenon composed some of stages. Although it would be considered necessary to understand each stage of this phenomenon in order to have a detailed information of the mechanism of congestion, not many studies have focused on.

Therefore, in this research, we analyzed the phenomena and contributing factors for specific sectors that have sag sections or traffic inflow segments, by considering congestion into 3 stages of occurrence, extension, and clearance. Furthermore, since it is necessary to gain an understanding of the traffic conditions in the vicinity of both the traffic inflow and the outflow segments, as well as between nodes in order to analyze the phenomenon of congestion. We obtain the data obtained from vehicle detectors were used, since such data enable us to gain an understanding from both the abovementioned perspectives.

3. ANALYSIS OF CONGESTION PHENOMENON USING DATA ANALYSIS

3.1 Summary of data

We firstly gained the detailed understanding of the congestion phenomenon of the outbound traffic on Metropolitan Expressway Route No. 3, by using the vehicle detector data, road condition data of ordinary roads in the vicinity, and data on the structure of the Metropolitan Expressway. The following data were used:

- ◆Vehicle detector data of the targeted road from June 5 (Monday) to 11 (Sunday), 2006, acquired from the International Traffic Database (ITDb)[7], as well as vehicle detector data of the targeted road from September 1 (Wednesday) to October 19 (Tuesday), 2010, acquired from the Metropolitan Expressway Company Limited: These were data on the average traffic volume at 5-min intervals and the average traffic speed at 5-min intervals, with the observation sectors that span approximately 600 to 1,000 m, except at segments where a considerable amount of traffic divergence or convergence occurs.
- ◆Road traffic information data on open roads, which was parallel to expressways from July 15 (Friday) to July 29 (Friday), 2011, acquired from the website of the Japan Road Traffic Information Center[8]: The data were collected for the period starting at 17:30 on July 12 (Tuesday), 2011, and ending at 17:10 on August 2 (Tuesday), 2011, with an update occurring every 5 min. We could obtain information on the chronological changes in the traffic on the expressway that roughly indicated the occurrence and clearing of congestions, including situations on ordinary roads in the vicinity, since the traffic velocity of 40 km/h and under was indicated in orange (congestion) and the traffic velocity of 20 km/h and under was indicated in red (high congestion) for the Metropolitan Expressway, whereas on ordinary roads, the traffic velocity of 20 km/h and under was indicated in orange (congestion) and the traffic velocity of 10 km/h was indicated in red (high congestion).
- ◆Video data recorded the conditions under which vehicles and how congestions occurred at the converging segment of the traffic at Ohashi Junction: The date of observation was December 7, 2011 (Wednesday), from 14:00 to 16:00. A fixed-point video observation at the converging segment and a tracking observation at the converging segment during congestion were conducted, with no accidents occurring and no restrictions imposed on the traffic.

Table 1 Comparison of the vehicle volume from 6pm to 1am

	Sangen-Jaya Exit ~ Ikejiri Entrance		Ikejiri Entrance ~ Ohashi Junction	
	2006	2010	2006	2010
Average	231.2	236.5	201.9	204.5
Variance	682.0	349.9	531.5	437.2
T-test	0.0130***		0.219	

*** differ significantly between groups using a level of significance of 0.01

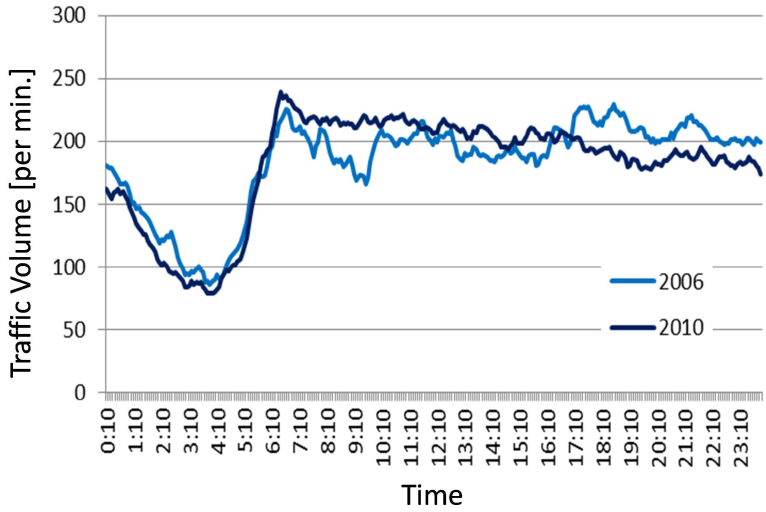

Figure 4　15 minutes-moving-average traffic volume (Weekday, per 5 minutes)

Table 2　Analysis of variance for the sag point and the merging point

	Dispersion	Dispersion Ration	P-Value
Sag Point	7.70×10^{4}	2.23×10^{2}	2.91×10^{-45}
Merging Point	9.49×10^{4}	2.75×10^{2}	3.74×10^{-54}
interaction	4.07×10^{4}	1.18×10^{2}	6.72×10^{-26}

◆Altitude data on the entire zone of Metropolitan Expressway Route No. 3: A distance meter was used at locations that were passable on foot under the overpass on November 26 (Saturday), 2011, and compared with the measurements of height from the ground surface taken against the elevation of the ground surface acquired from the Internet to gain a rough transition of the elevation (Figure 2).

3.2 Fundamental analysis of traffic flow

(1)　Change in traffic flow due to completion of Ohashi Junction

Data on the average and the dispersed traffic conditions from 2006 and 2010 were compared to understand the change in traffic phenomena before and after the placed in service of Ohashi Junction. Figures 4 and 5 show the average transition of the traffic volume and speed (15-min average and daily average) for the sector from Ohashi Junction to Ikejiri Exit. This revealed that the traffic volume between Ikejiri Entrance and Sangenjaya Exit increased and that the speed of the traffic decreased between Ikejiri Entrance and Sangenjaya Exit. Since the speed of the traffic from Ohashi Junction to Ikejiri Entrance decreased even though the traffic volume in the segment was not considered and it is inferred that the convergence of the traffic at Ohashi Junction has had some impact to cause the decrease in the traffic speed.
Therefore, the effect of the traffic convergence on congestion was investigated in the next section.

(2)　Analysis of effects of sag sections and traffic convergences on congestion

The intensity of the effects of the sag sections and traffic convergences, which were considered to have a particularly strong impact, among a number of contributing factors, on the decrease in the traffic speed, was analyzed. We categorized the targeted road section according to whether they had some sag sections or traffic convergences on the basis of the data from 2010. An analysis of variance was performed on the data from 6:00 on one day to 1:00 on the next day, using two-way classification with repetitions. The results of this analysis are given in Table 2, which revealed that the traffic convergences contributed more to the occurrence of the decrease in traffic speed than the sag sections.

Table 3　Comparison of the vehicle speed from 6pm to 1am

	Sangen-Jaya Exit ~ Ikejiri Entrance		Ikejiri Entrance ~ Ohashi Junction	
	2006	2010	2006	2010
Average	59.48	43.83	66.53	36.84
Variance	179.8	120.7	388.8	407.5
T-test	1.41×10^{-35}***		1.02×10^{-45}***	

*** differ significantly between groups using a level of significance of 0.01

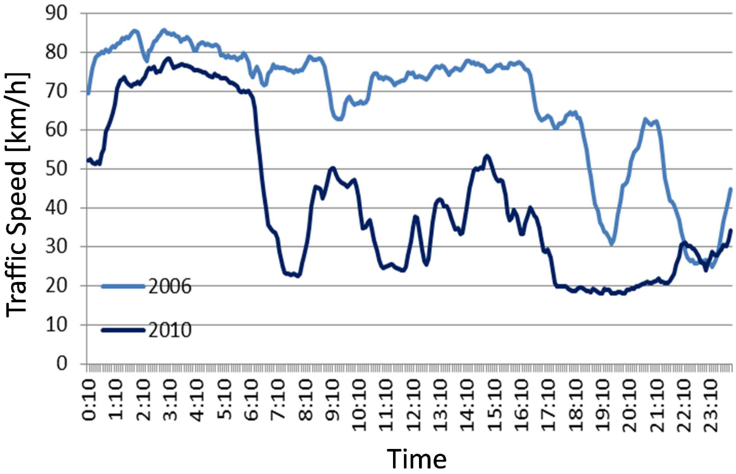

Figure 5　15 minutes-moving-average vehicle speed (Weekday, km/h)

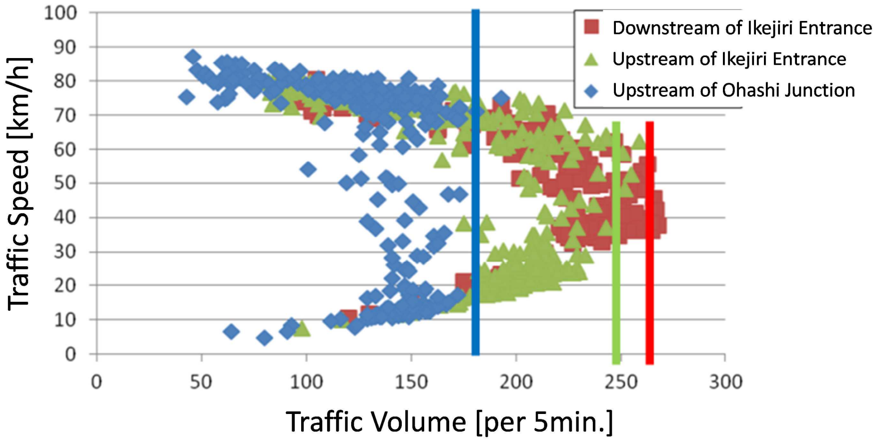

Figure 6　Q-V Curve at Ikejiri Entrance and Ohashi Junction

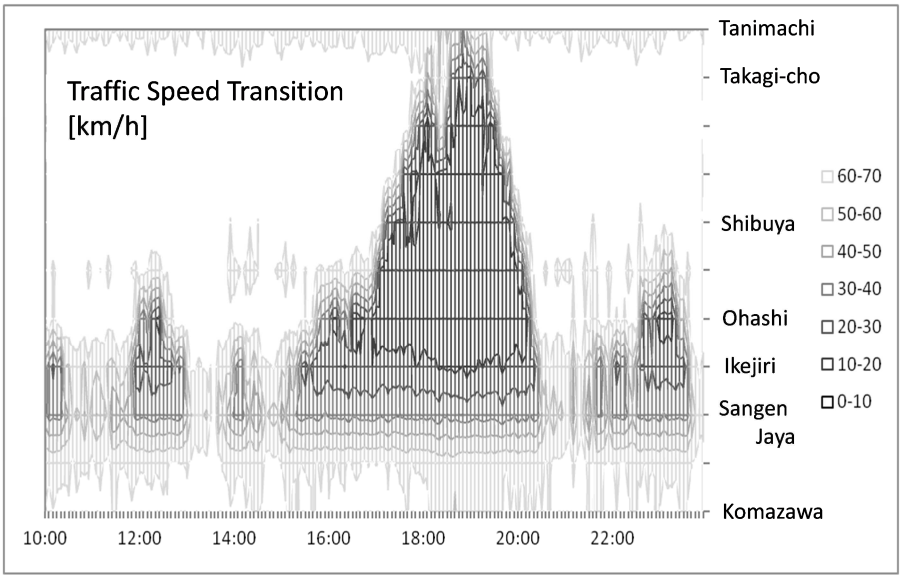

Figure 7 Traffic speed transition in the afternoon

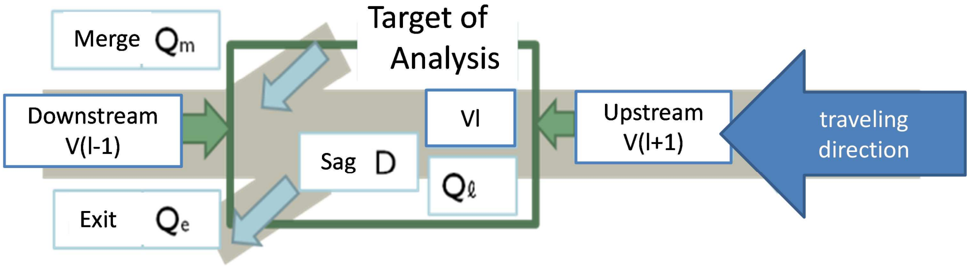

Figure 8 Setting up the parameters

Furthermore, in order to understand the congestion phenomenon from 2010, congestions in the afternoon were sorted according to the speed range (Figure 7), which revealed the following:

・Traffic congestions occurred in the vicinity of Sangenjaya Exit;

・At the locations which the traffic speed decreased mostly when congestions were in the vicinity of Ohashi Junction, with the speed gradually recovered from Ohashi Junction to the vicinity of Ikejiri Entrance, as well as to the vicinity of Sangenjaya Exit.

Moreover, the relationship between the traffic speed and volume before and after the converging segments is shown in Figure 6. There was a significant difference in the shapes of the curves before and after the traffic convergence, indicating that the traffic speeds and volumes differed as the traffic transitioned from a free-flowing condition to the congested condition. This indicated that the contributing factors to the extension of congestion were not only the sag sections but also the decrease in the traffic speed due to traffic convergence.
The most significant factor of speeddown was considered to be the “timing at which vehicles of the through traffic met with vehicles entering the traffic from the converging lane.” Therefore, in order to analyze the phenomenon of traffic congestion (considered the condition where the traffic flow is at 40 km/h or less), the phenomenon was divided into the three stages of “occurrence,” “extension,” and “clearance” for analyzing these phenomena individually.

(3) Factors for occurrence, extension, and clearance of congestions

First, we attempted to clarify the contributing factors of congestions by a discriminant analysis. Velocity V (km/h) was used as the objective variable that was converted into variable y, which is negative in the case of congestion and positive in the case of a free-flowing condition. The explanatory variables were selected from the following: sag section (dummy), traffic convergence, downstream velocity, traffic volume Q (unit

Table 4 Prediction rate of discriminant for generating congestion

Total	Sangenjaya	Upstream of Ikejiri	Ohashi JCT	Downstream of Shibuya
84.4%	80.4%	82.2%	89.9%	85.3%

Table 5 Parameter estimation in the extention of traffic jam

R2=0.869

		coefficient	standardized regression coefficient	t-value
Intercept	a6	-0.0651	-0.0881	-0.869
Speed at Upstream	a1	0.412**	0.393	21.7
Speed at Downstream	a2	0.609**	0.566	37.1
Product parameter	a3	-0.0315**	-0.174	-10.1
Volume at Exit	a4	0.0391**	0.0681	4.64
Sag	a5	-0.00680	-0.00456	-0.335

** differ significantly between groups using a level of significance of 0.05

Table 6 Parameter estimation in the convergence of traffic jam

R2=0.868

		coefficient	standardized regression coefficient	t-value
Intercept	b6	0.571	0.744	1.22
Speed at Upstream	B1	0.589**	0.597	30.3
Speed at Downstream	B2	0.520**	0.469	31.4
Product parameter	B3	-0.0161**	-0.0847	-4.60
Volume at Upstream	B4	-0.191**	-0.0276	-2.09
Sag	b5	0.0944**	0.0609	4.76

** differ significantly between groups using a level of significance of 0.05

per 5 min), inclination (dummy), curve (dummy), and tunnel (dummy); these were considered to be contributing factors, and each of these terms was multiplied by the traffic volume as the impact on the decrease in velocity was considered to occur only when the traffic volume was large for both the sag sections and the traffic convergence. Variables were set as shown in Figure 8 in order to ensure that the prediction rate exceeded 80% in the four sectors between Shibuya and Sangenjaya, and then, a regression analysis was conducted, which provided the following linear discriminant equation (the coefficient is a standardized regression coefficient):

$$y_{\ell} = 0.53V_{\ell+1} - 0.18DQ_{\ell} - 0.08Q_{\ell}Q_{m} - 0.19Q_{\ell} - 0.62 \quad (1)$$

The prediction rate according to this equation, based on the data for 1 month, which excluded accidents in the respective sectors, is as shown in Table 4. It revealed that more traffic congestions occurred because of the sag sections than because of traffic convergence.

Next, statistical modeling using a multiple linear regression analysis was conducted in order to clarify the factors for the extension and clearance of traffic congestions. The targeted time slot was limited to the peak hours in the evening over a 3-day period and parameters for the model were estimated by using data from the seven sectors between Tanimachi and Ikejiri, where traffic congestion conditions with the traffic speeds of 20 km/h or less occurred. It was believed that the decrease in speeds in the targeted sectors, as well as the recovery time, could be understood by comparing the traffic speed acquired from a detector located just downstream from the targeted sector with that acquired from a detector located just upstream. Furthermore, since traffic convergences or exits that exist downstream from a targeted sector can affect the traffic speed within the targeted sector and as the traffic speed was considered to decrease when the sag sections existed within the targeted sector, exponential-type statistical models as expressed by equations (2) and (3) were prepared with consideration of these factors.

$$V_\ell = {V_{\ell-1}}^{a_1} {V_{\ell+1}}^{a_2} (Q_\ell Q_m)^{a_3} {Q_e}^{a_4} \exp(a_5 D + a_6) (2)$$
$$V_\ell = {V_{\ell-1}}^{b_1} {V_{\ell+1}}^{b_2} (Q_\ell Q_m)^{b_3} {Q_{\ell-1}}^{b_4} \exp(b_5) (3)$$

The respective parametric estimation results are presented in Tables 5 and 6.
The fact that the impact of a traffic convergence was stronger than that of a sag section was apparent in cases where the traffic congestion followed equation (2). The clearance of traffic congestions, on the other hand, was impacted only slightly by the traffic convergence or the traffic volume.
Therefore, the impact and the clearance of a traffic congestion were considered simultaneously, and a linear statistical model was prepared by combining the explanatory variables used in equations (2) and (3) in order to obtain a coefficient, which led to equation (4). Substitution of this equation into the data of the traffic congestion phenomenon gave a result that fitted well, as shown in Figure 10, making it possible for us to consider that we could formulate an equation for obtaining the traffic speed in the targeted sector on the basis of the data on speed just before the sector as well as the traffic volume data and road conditions.

(4) Speed model using traffic volume

The model described in the previous section had a problem in that it required repeated calculation of speed when examining operational measures, which led to a broadening of the error. A statistical model that does not rely on past traffic speed data and that can be expressed on the basis of only the traffic volume data and road conditions was prepared. Road conditions that can be considered include road sag, inclination, tunnel, and curve. However, it was decided that the sag section, which is considered to have a strong impact, as well as road inclination, which is similar to the sag section and is a quantitative data element, should be taken into consideration, while a new item, the cumulative traffic volume Q' (the difference in traffic volume since the start of measurement), was also included.

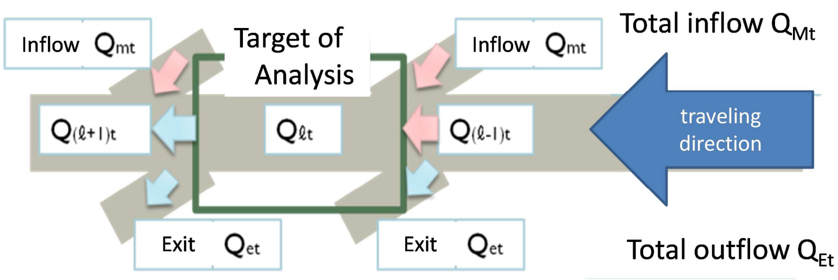

Figure 9 Definition of Q’

Table 7 Parameter estimation of speed model

R2=0.476

		coefficient	standardized regression coefficient	t-value
Intercept	c6	85.2**	3.10	29.1
Integrated volume “Q’ ”	c1	-0.307**	-0.486	-26.7
Product parameter	c2	-0.00364**	-0.481	-26.1
Volume at exit	c3	0.846**	0.263	9.81
Upgrade dummy * volume	c4	-6.66**	-0.232	-8.22
volume	c5	-0.131**	-0.162	-7.63

** differ significantly between groups using a level of significance of 0.05

The outflow and inflow of traffic as shown in Figure 9 can be considered for the targeted sector. The amounts of inflow and outflow do not match, and the difference thereof affects the targeted sector as a density variation. The cumulative traffic volume Q' was therefore considered in the following manner:

$$Q'_{\ell t} = Q'_{\ell(t-1)} + \Delta Q'_{\ell t} \quad \left(Q'_t = 0, \text{if } Q'_t < 0\right)$$
$$\Delta Q'_{\ell t} = Q_{(\ell-1)t} + Q_{Mt} - Q_{(\ell+1)t} - Q_{Et}$$

where the linear equation that replaces the term of sag section with the uphill inclination S is expressed as

$$V_\ell = -c_1 Q'_\ell + c_2 Q_\ell Q_m + c_3 Q_e + c_4 DQ_\ell + c_5 Q_\ell + c_6 \tag{5}$$

This parameter was estimated to obtain the data shown in Table 7. Further, equation (5) was used for calculating the required time to drive from Tanimachi to Sangenjaya; this led to the outcome shown in Figure 11, which indicated that while some error in timing for the start and the end of the congestion did occur, there was no significant difference of 5% from the source data and the error for the total required time was also within 10%.

4. SENSIVITY ANALYSIS OF CONGESTION PHENOMENON

Results discussed in the previous section have led us to the understanding that the increased traffic volume resulted in the decrease in traffic speed, which occurred because of the sag section in the sector just before Sangenjaya Entrance. When the traffic volume increased even further, the traffic congestions started at the

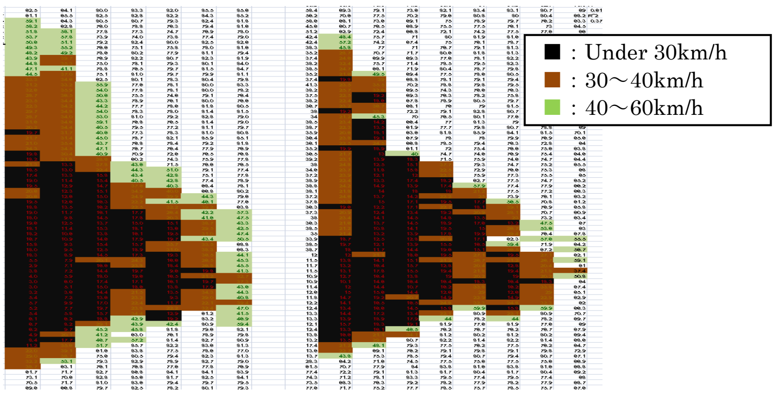

Figure 10 Vehicle speed (Left; model data, Right; real data)

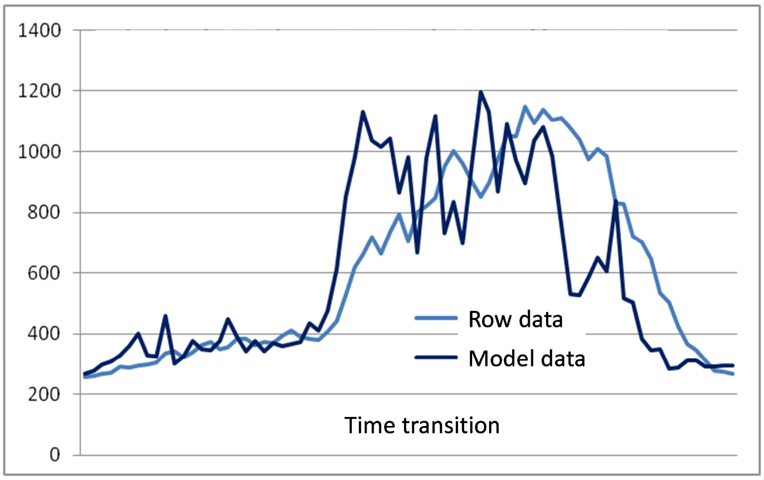

Figure 11 Transition of total travel time

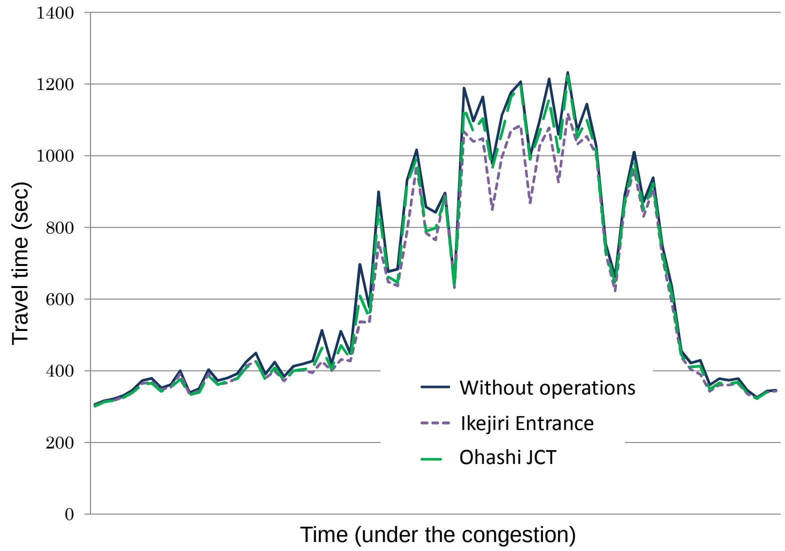

Figure 12 Reduction of the total travel time with the operation

two locations with traffic convergence, Ikejiri Entrance and Ohashi Junction. With these points in mind, the change in the traffic congestion phenomenon, which is caused by the increase and decrease in the traffic volume that occur when some measures are implemented or new routes are created, was compared on the basis of the total required time. This research limited the focus to the vehicles that transit all sectors between Tanimachi Junction and Sangenjaya Exit in particular, to calculate the total required time. Since the traffic convergence within the targeted sector occurred at the two locations of Ohashi Junction and Ikejiri Entrance, the traffic volume was increased and decreased at both the locations in order to observe the changes. Calculations of the changes in all inflow traffic volumes were also performed with an assumption that the measures are implemented for the data for the peak time slot during the evening over a 3-day period.

First, the transition of the required time when the inflow traffic volume of each single day was set to 80% is shown in Figure 12. Furthermore, the total required time for the case where the each inflow traffic volume was set to 80% over the 3-day period was similarly compared (Figure 13). In comparison with the cases where no measures were implemented, the result was such that some reduction did occur.

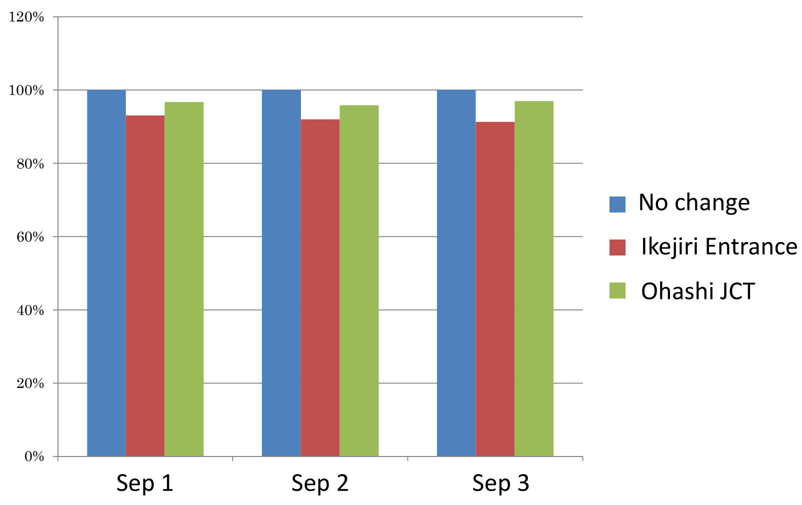

Figure 13 Comparison of the total travel time (horizontal axis)
in the condition of 20% reduction of inflow traffic volume

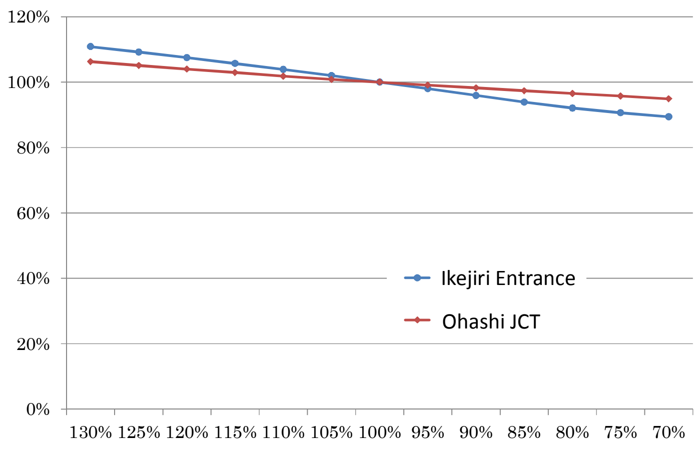

Figure 14　Comparison of total travel time (horizontal axis) under the condition of different traffic volume (vertical axis)

The effect was greater particularly when the inflow traffic volume from Ikejiri Entrance was reduced than when the inflow traffic volume at Ohashi Junction was reduced. The reason why such a result was achieved was considered to be the manifestation of the more significant effectiveness when even just a little traffic convergence that increased the traffic volume was reduced than when a major traffic inflow was reduced. Thus, a greater impact on the required time was achieved with this model when a recovery of speed was conducted in the sector with slower traffic speed.

Furthermore, the transition of the total required time when the inflow traffic volume transitioned from 70% to 130% is shown in Figure 14. The change in the inflow traffic volume at the traffic convergence sections was revealed to linearly affect the total required time.

5. CONSIDERATIONS FOR CONTRIBUTING FACTORS OF TRAFFIC CONGESTION

The traffic congestion data were modeled in this research on the basis of a statistical model. Items that are typically assumed for the regression analysis employed for this purpose, as well as the relevant model equations used in this research, will be considered here.

◆Correlations between explanatory variables

The positive coefficient of 0.537 for the upstream speed and the downstream speed, as well as the negative coefficient of -0.539 for the upstream speed and the product of traffic convergence can be cited as the coefficients with a relatively strong correlation value. We believe that the contributing factors for traffic congestions can be resolved by examining such explanatory variables in more detail.

◆No serial correlation was assumed to exist with the disturbance term.

DW was 0.52 for the model considered in this research, which is significantly lower than standard DW of 2. The coefficient was therefore corrected by using the Cochrane–Orcutt method.

◆The dispersion of the error term was assumed to be uniform.

White correction was performed in this research, and its validity was verified by confirming that no significant change in the t-value occurred.

Furthermore, in this research, different models were used as the statistical model used for performing the phenomenal analysis from the model used for future predictions. A reason that can be cited for this is the fact that the statistical model used for performing the phenomenal analysis used actual speed data from 5 min prior to the target time point, and hence, if the prediction data were to be used continuously for future predictions, errors could be multiplied or dispersed so that it would not have been possible to explain the phenomenon appropriately, as shown in Figure 15. In reality, however, it is considered that it may be possible to perform a phenomenal analysis and future predictions from data that use a unified model by

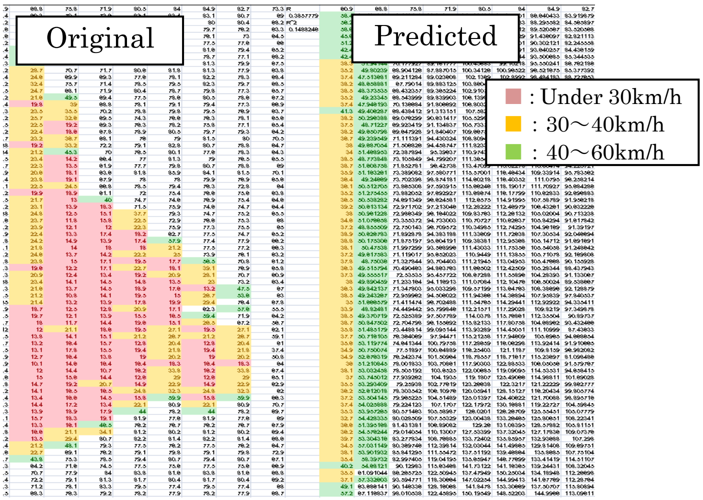

Figure 15 Real and Predicted speed

using the chronological data dynamically. Furthermore, while the acquired vehicle detector data were the average data for 5-min intervals and modeling was performed on the basis of these data, by comparing the span of individual sectors and speed of the traffic, we found that multiple sectors were passed by the traffic within the 5-min interval. The data of 1-min intervals would represent the traffic passing through about one sector, which is considered to increase the compatibility of the data with the model. Since the actual data of 1-min intervals are anticipated to have great fluctuations, however, it is considered possible to use the 1-min-interval data by employing a differential concept to estimate the 1-min-interval data based on the average data, as well as the relationships with the data that precede and follow the considered data.

6. CONCLUSIONS

This research indicated that the increase in traffic volume and decrease in speed due to traffic convergence cannot be ignored as contributing factors for congestions that occur in the case of the outbound traffic on Metropolitan Expressway Route No. 3, which in the past were considered to occur because of the sag sections and uphill climbs that exist in the vicinity of Sangenjaya. Furthermore, by conducting a statistical model analysis by dividing congestions into the three stages of occurrence, extension, and convergence, the sag sections when a congestion occurs and the traffic convergence when a congestion is spreading were revealed to have a strong impact. It was also possible to indicate that the required time for resolving a congestion could be reduced by implementing measures for prompting drivers to take detours for avoiding most congested sectors as a fundamental analysis result, while keeping in mind the issue of equilibrium arising from differences in the traffic inflow routes when the vehicles head into applicable locations.

Providing an even more general clarification of the traffic congestion phenomenon by increasing the number of locations targeted for analysis, as well as performing a more detailed analysis with considerations of impact on ordinary roads in relation to operational measures, can be cited as topics for future work.

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