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ANALYSIS OF TRAFFIC DISTRIBUTION IN THREE LANE UNI-DIRECTIONAL FREEWAY

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1. Introduction

The movement of vehicles within a freeway facility is a special area of traffic operation with several unique characteristics. One of such an area is analysis of traffic distribution behaviour in a multi-lane freeway. Here, traffic distribution is the distribution of the total traffic volume to the individual lanes of multi-lane unidirectional freeway. This is sometimes referred as lane utilization, lane traffic distribution or traffic split. The recent researches have recognised that the traffic distribution in each lane of a multi-lane freeway is not uniform among each other. Thus, identifying the phenomena of traffic distribution is very useful not only for application of new traffic operation strategies but also in freeway geometric design process. On the other hand, there are many factors affecting traffic distribution, such as speed and volume, traffic regulations, traffic composition, location of access points, flow direction, types of geometry configuration, light and weather condition, origin-destination patterns of drivers, local divers habits and so on(1). Because of these factors, so far there are no typical models or typical values for traffic distribution in a freeway segment. However, since location of access points highly influences the traffic distribution, in this study, only uninterrupted freeway segments were considered. Further, even though there are many factors affecting the traffic distribution, here it is decided to examine the effects due to directional flow, changes in freeway location, light condition, gradients, and segment's curvature by identifying a suitable model for traffic distribution. The objectives of this study have three parts. The first part is to develop analytical models for describing the traffic distribution and to provide some insights how these above mentioned factors might affect it. The second part is to develop a theoretical concept on traffic distribution to explain it's mechanism. Finally, it is to suggest the appropriate measures that can improve the capacity of freeway segment.

2. Site Selection and Data Collection

The study sites are segments of Tomei Expressway in Japan, and the details of selected nine sites are given in Table 1. Since this study considered only uninterrupted flow condition, the distance from detector to on/off ramps is considered significant during the site selection. As shown in Table 1, the sites A-I and A-II are considered as levelled and straight segments. Similarly, the sites B-I and B-II are considered as upgrade straight segments and the sites C-I and C-II are considered as downgrade straight segments. The site D-I is levelled curved segment with left hand turning movement, and sites D-II and D-III are levelled curved segment with right hand turning movement. Among this data set, sites A-II, B-II and C-II were selected for the analysis of the directional and locational effect on traffic distribution. Further, an upstream geometry effect also was observed at the sites D-I and D-III, which will be discussed under section 5(3).

Table 1: Detail of selected sites for traffic distribution analysis

Geometry		Site	Bound to	km Post	Grade(%)	Radius (m)	No of Data
Levelled and Straight		A-I	Nagoya	21.52	-0.06	2,800	1,429
		A-II	Tokyo	32.69	0.22	2,800	1,398
Upgrade and Straight		B-I	Tokyo	14.98	3.00	2,000	1,418
		B-II	Nagoya	16.35	2.83	3,000	1,429
Downgrade and Straight		C-I	Nagoya	12.50	-2.91	2,500	1,452
		C-II	Tokyo	16.77	-2.83	3,000	1,432
Levelled and Curved	LT	D-I°	Nagoya	2.49	0.00	900	1,370
	RT	D-II	Tokyo	2.47	0.00	900	1,413
	RT	D-III°	Tokyo	1.40	0.00	900	1,464

Note : RT means right turning movement, LT means left turning movement and ° indicates the sites with upstream effect

The total volume, total heavy vehicle, corresponding average speed, and percentage of occupancy in each lane for every 5 minute were obtained from detectors' data. In addition, nearly 25 hours headway data were collected by detectors at another three lane straight segment located at 30.51 km post towards Tokyo direction, on June 23, 1993 from 11:00 AM. The management of headway data for required analysis was explained by May(2). There are very few data on congested condition. Since the traffic distribution in congested region is not an objective of this paper, congested data were removed by identifying the critical speed and critical level of occupancy.

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* Keywords : Traffic distribution, Freeway, Traffic operation
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3. Analysis of Traffic distribution

In this study, traffic distribution P_i is defined as percentage of lane 'i' volume to total directional volume. As can seen from Figure 1, three lane freeway traffic distribution in a straight segment can be classified into three categories, such as, $P_2 > P_1 > P_3$, $P_2 > P_3 > P_1$ and $P_3 > P_2 > P_1$ for a flow rate ranging from 400 vph to 5,750 vph. Similar to the other studies[3,4], it is identified from these groups that the shoulder lane traffic distribution has never been highest, and middle traffic distribution has never been lowest for any flow condition. Further, under maximum flow condition, the difference in traffic distribution between shoulder lane and median lane is about 35%. This value is about 17% between shoulder lane and middle lane. Next step is to develop a suitable model that can describe the traffic distribution by suitable explanatory variables. From the visual inspection of these traffic distribution behaviour, together with the factors mentioned in Section 1, it was under-stood that either a function given by equation (1) which is similar to John[5] or a functional form of a second order model as given by equation (2) might be appropriate.

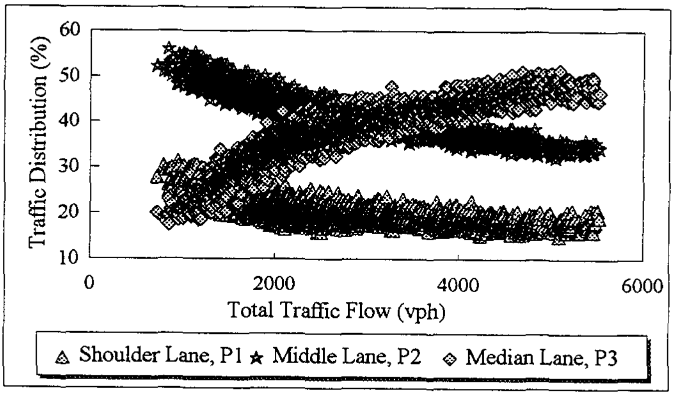

Figure 1 Traffic Distribution at Site A-I

Model I $P_i = a_{1i} + b_{1i} \ln Q + c_{1i} \ln Q_{hv} + d_{1i} \ln V$ (1)

Model II $P_i = a_{2i} + b_{2i}\, Q + c_{2i}\, Q^2$ (2)

Where; Q is the total traffic volume (vph), Q_{hv} is the amount of heavy vehicle (vph), V is the average speed of the traffic stream (kmph), a_{1i}, $a_{2i(i=1,2,3)}$ are constants $b_{ji\,((j-1,2)\,i=1,2,3)}$, $c_{ji\,((j-1,2)\,i=1,2,3)}$ and $d_{1i(i=1,2,3)}$ were coefficients. Here, j = 1,2 for Model I and Model II, and i = 1,2,3 for shoulder, middle and median lane, respectively. The next step was to calibrate the models for each station. A stepwise regression analysis method was used to calibrate the models from daytime data.

4. Result of Analytical Modelling

Three lane uni-directional freeway results of Model I such as the values of the R^2, the estimated constants and coefficients, the *'t'* values for each constant & coefficient and *'F'* values are given in Table 2. In addition, due to the limitation of the space, except value of R^2, other details of Model II were not given.

Table 2: Statistical results of three lane freeway (Model I)

Site	P_i	R^2	Coefficients				't' values				*F*	R^2 for
			a_{1i}	b_{1i}	c_{1i}	d_{1i}	t_a	t_b	t_c	t_d	value	Model II
A-I	P_2	0.78	84.49	-10.814	0.7479	8.158	13.51	-68.57	8.47	6.57	1,723	0.71
	P_3	0.87	-182.94	18.801	0.9942	14.735	-23.59	96.10	9.07	9.57	3,240	0.77
A-II	P_2	0.81	88.72	-11.364	1.3942	7.210	13.22	-58.27	17.97	6.10	2,913	0.75
	P_3	0.90	-166.66	18.374	1.5969	11.011	-23.22	85.13	18.60	8.42	3,848	0.67
B-I	P_2	0.85	146.59	-12.275	0.0596	-2.534	29.09	-64.85	6.90	-2.96	2,739	0.80
	P_3	0.88	-184.10	18.401	0.5441	16.258	-28.19	78.44	6.60	15.30	3,186	0.81
B-II	P_2	0.80	105.37	-11.372	0.1753	4.973	17.86	-68.30	2.12	4.34	1,865	0.80
	P_3	0.88	-172.18	18.528	1.4913	12.359	-25.35	96.51	15.68	9.37	3,594	0.87
C-I	P_2	0.79	89.23	-10.826	0.2295	7.439	14.11	-67.94	2.83	5.92	1,783	0.79
	P_3	0.86	-162.02	18.516	1.7357	9.921	-19.41	88.06	16.25	5.99	2,969	0.85
C-II	P_2	0.86	106.61	-11.231	0.5861	3.732	20.33	-69.70	8.95	4.00	3,106	0.84
	P_3	0.90	-181.83	18.291	0.4019	16.302	-28.99	94.94	5.13	14.61	4,234	0.89
D-I	P_2	0.79	168.28	-12.720	-0.2353	-6.496	25.84	-68.89	-2.91	-5.27	1,738	0.50
	P_3	0.68	-188.06	11.903	2.3845	24.749	-18.69	42.40	19.42	13.20	658	0.67
D-II	P_2	0.84	160.48	-10.902	-0.8813	-6.448	27.59	-80.21	-11.74	-5.59	2,589	0.83
	P_3	0.91	-256.28	18.424	1.1640	31.148	-38.24	117.64	13.46	23.42	5,095	0.88
D-III	P_2	0.75	150.39	-12.688	-0.2072	-2.988	19.42	-54.75	-2.21	-2.10	1364	0.61
	P_3	0.45	-185.04	11.846	2.4449	24.252	-14.07	30.10	15.37	10.06	368	0.38

Here, the values of R^2 and '*t*' test results were compared to select the suitable model for describing traffic distribution. This Table revealed that for each cases, the R^2 value for Model I is slightly higher than Model II values. Moreover, due to higher amount of data set from all sites as shown in Table 1, the '*t*' test characteristics show that the minimum required '*t*' value for 95 % significant level is about 1.65. As can be seen from this Table 2, '*t*' value for each parameter in Model I shows that all of them are statistically significant at 95% level, where some of the parameters in Model II fail to show significance. Thus, these results show that speed and amount of heavy vehicle should be used to estimate the traffic distribution in a three lane freeway. However, based on the knowledge of traffic flow characteristics, it may be said that the speed is not necessary to be considered for modelling because in a freeway the total traffic flow and the average speed have a strong relationship and similarly, the amount of heavy vehicle needs not to be weighed for modelling because the total traffic itself includes the amount of heavy vehicle. In order to answer these questions, this suggested model (Model I) statistically shows that for a particular flow condition, variations in both amounts of heavy vehicle and average speed have strongly influence on the traffic distribution in a three lane uni-directional freeway. More specifically, it can be said that when estimating traffic distribution in a three lane freeway, this suggested model has a capability for includings the variation in both amount of heavy vehicle and average speed for a particular flow condition. In addition, the calculated '*F*' values for the Model I was very high, which permits the rejection of the hypothesis that all parameters estimates are equal to zero, with high certainty. Thus, these results show that traffic distribution in a three lane uni-directional freeway can be more accurately expressed by Model I, i.e., by the explanatory variables such as total traffic flow, amount of heavy vehicles in the traffic and the average speed of the traffic stream.

Moreover, though the shoulder lane results (P_1) were not shown in Table 2, it was revealed that R^2 value for shoulder lane in every site is less than it for other two lanes. This may be due to the existence of higher percentage of heavy vehicle and their irregular vehicle movement in shoulder lane is higher than it for the other lanes. Therefore, in future, it is better to forecast the model for P_2 and P_3 and then P_1 can be obtained from $P_1 = 100 - P_2 - P_3$. This model is valid for a total flow rate ranging from 400 vph to 5,750 vph. However, this suggested model requires three explanatory variables such as total traffic flow, amount of heavy vehicles in the traffic and the average speed, for more accurately explaining the pattern of traffic distribution. Although in practical, sometimes it is difficult to obtain the average speed of the traffic stream. In such a circumference, it is also suggested here that one can develop his own model as given by the model II.

5. Analysis of the Factors Affecting Traffic Distribution

Understanding the degree of effect on traffic distribution pattern by various features is important for the designers and operators of freeway management system. Especially, in this study, in order to propose suitable capacity improvement measures, it is necessary to understand at least a tentative nature of traffic distribution with some features such as, effect due to directional flow, changes in location, light condition and geometry features; upgrade, downgrade and curvature. Thus, chi-square test was used to identify, whether any differences in lane traffic distribution exist due to these above mentioned factors. Here, randomly selected common samples were used to calculate the observed and estimated values based calibrated models.

(1) Effect due to Directional Flow and Changes in Location

The effects due to directional flow and changes in location on traffic distribution were compared between geometrically identical uninterrupted segments, such as between A-I and A-II, similarly B-I and B-II, C-I and C-II. These selected sites are located either sides of the Tomei expressway as can seen from Table 1, and bound to different directions. Thus, coincidentally, the testing between A-I and A-II will result the both interests such as effect due to the directional flow and effect due to the changes in freeway location. A similar identity could be observed between sites B-I & B-II and sites C-I & C-II. The chi-square test was carried out with 151 randomly selected sample set, which covers a total flow ranging from 400 vph to 5,750 vph. During the testing, for the sites between A-I and A-II, the calculated chi-square values for shoulder lanes, middle lanes and median lanes are 1.57, 1.46 and 11.31, respectively. Similar values for sites between B-I and B-II are 5.13, 4.63 and 26.58, and for the sites between C-I and C-II are 5.38, 1.66 and 15.26. All these calculated values are much lesser than the required value for rejecting the hypothesis for a level of 95% significance. Thus, it shows that there is no significant difference between the same geometry sites for a level of 95%. Also, during the comparison of these results, it shows that Chi-square (χ^2) value for middle lane is very much less than other two lanes. Thus, it can be said that, the middle lane traffic distribution is more identical for difference in directional flow and changes in freeway locations than the other lanes.

(2) Effect of Gradient

It is true that an upgrade segment causes uncongested flow occupancy to increase, subsequently reduce vehicle's speed, and vice versa for downgrade segment. Statistical tests for differences in traffic distribution in upgrade (about +3%) and downgrade (about -3%) freeway segment were made by comparing it with a straight level freeway segment. Thus, the differences in traffic distribution were calculated as, the traffic distribution in a lane at the site under consideration minus the same lane traffic distribution in a straight levelled segment, for a particular total traffic volume. Results show that, eventhough there are no differences in traffic distribution for 95% significant level for any flow condition, the trends in individual lane usage have unique differences in their behaviours, as shown in Figure 2.

This trend in differences was obtained by fitting second order linear regression, by considering flow as explanatory variable. Results show that, when gradient of a segment varies from level segment, regardless of up or down, the usage in shoulder lane and median lane is slightly increasing while the usage in middle lane is slightly decreasing. Further, under higher flow condition, the amounts of increases are more in shoulder lane than it in median lane, but for the lower range of total traffic flow the amount of increases in median lane is higher than it in shoulder lane. The reason for this phenomenon might be due to gravitational effect on the vehicle speed. However, due to the limitation of the availability of very steep upgrade and downgrade segments, these two sites C-I and C-II do not fit all criteria for steep grades segment. Therefore a relatively steep upgrade and downgrade segments have to be taken into consideration in future.

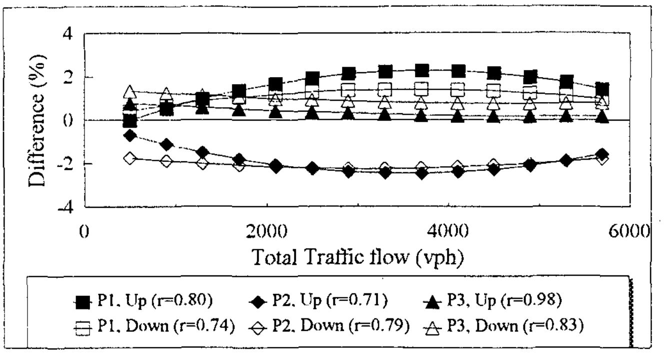

Figure 2 Differences in site B and site C with site A

(3) Effect of Curvature and Upstream Section

Analysis of effect of curvature on traffic distribution is essential for freeway design process. Thus, a statistical test was carried out to find the effect due to curved freeway segment. Here, the testing procedure as stated in the above Section (2) was repeated. Due to limitation on sites with reasonable radius of curvature, acceptable three existing sites that could satisfy the uninterrupted flow condition, were considered for this analysis. These selected segments have a radius of 900 m, as shown in Figure 3 and Table 1. In this Figure, line 1-1 shows the flow direction from Nagoya to Tokyo, and vice versa for line 2-2.

Results show, even though there are no differences in site D-II with straight segments for the level of 95% significant, the trends in individual lane usage have a unique variance in their behaviours, as can be seen from figure 4. This Figure shows, the value of P_1 increases for any flow condition, and the amount of P_2 decreases.

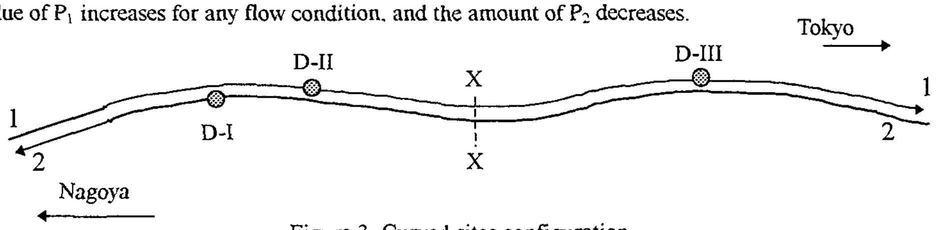

Figure 3 Curved sites configuration

On the other hand, when considering sites D-I and D-III, the traffic distribution widely differs from other sites. As an example, the pattern of traffic distribution in site D-I can be seen from Figure 5. The median traffic distribution is decreasing very much with increasing total traffic flow, while shoulder lane usage increases. The reason might be focused as effect due to upstream geometry condition. Because by looking the sites configuration, as shown in Figure 3, there is a 'U' type of segment (section X-X) within a distance from 400 m to 800 m, with a radius of 900m in the upstream section. Therefore, it can be said that even in uninterrupted freeway segment, a traffic distribution heavily depends on upstream profile. Thus, these two selected sites do not ideally represent the real interest of the curved segment due to the effect of upstream section (X-X).

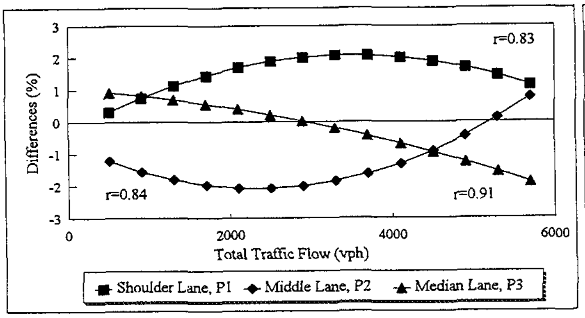

Figure 4 Differences in Site D-II with Site A-I

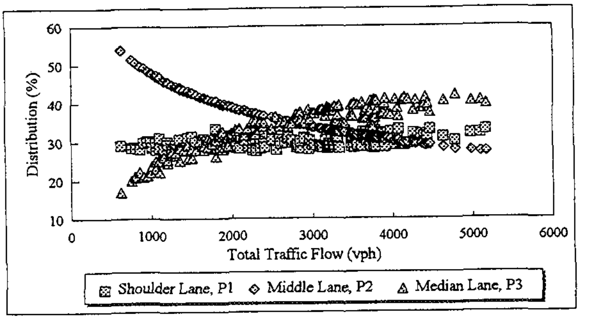

Figure 5 Traffic Distribution at Site D-I

(4) Effect due to Changes in Light Condition

Similarly, the effect due to changes in light condition was analysed for data set from levelled straight freeway segment (site A-I). The data was separated as daytime from morning 6:00 am to evening 5:00 pm and nighttime from 8:00 pm to 4:00 am. The typical differences in nighttime traffic distribution with respect to the daytime are shown in Figure 6. In night condition, the amount of usage in shoulder lane and middle lane is decreasing, while median lane usage is increasing. The usage reduction in middle lane is slightly less than it for shoulder lane. To identify the reasons, the differences in average speed in each lane were analysed between daytime and nighttime conditions. A straight line relationship was fitted, as shown in Figure 7, to have daytime and nighttime speed/flow relationship. It is obviously not safe to translate relationship in this way, but there is no objection to translating to have a tentative relationship when the speed falls above 70 kmph[6].

This showed that because of darkness, speeds were most often lower during the nighttime and this difference is the highest for median lane and the lowest for shoulder lane. Due to this, some drivers using middle lane in daytime try to use median lane in nighttime to gain the speed advantage, similarly daytime shoulder lane users try to use middle lane. Further, results also show that in nighttime heavy vehicle usage in middle lane increases. It seems that, though detailed explanation is not added here, there are two reasons for this behaviour; one is to gain the speed advantage and other one is due to a slight higher percentage of heavy vehicles in nighttime flow.

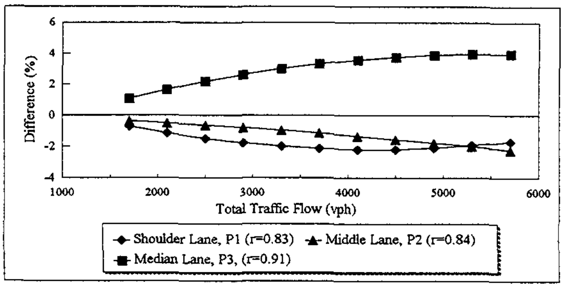

Figure 6 Differences in night traffic distribution with day

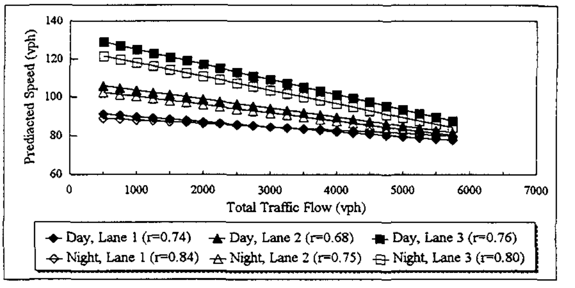

Figure 7 Speed flow relationship in day and night

6. Theoretical Concept for Traffic Distribution

The analyses carried out in the previous sections proved that the traffic distribution in an uninterrupted freeway segment has a unique nature in its behaviour, and shoulder lane and middle lane are urgently need capacity improvement measures under higher flow rate condition. In order to incorporate into the capacity improvement measures, it is very important to identify the theoretical concepts relating with the traffic distribution. Assume, $\underline{P}_i$ is the probability that a vehicle is in lane 'i' (i.e., the proportion of vehicles in lane 'i' to the volume Q, i.e., $\underline{P}_i = q_i/Q$). Therefore in three lane freeway the following expressions, as given by equation (4), should be satisfied.

$$\underline{P}_1 + \underline{P}_2 + \underline{P}_3 = 1 \tag{4}$$

Further, in three lane freeway, there are four possible lane changing movements: shoulder lane to middle lane, middle lane to median lane, median lane to middle lane and middle lane to shoulder lane. These vehicle changeovers between the adjacent lanes must be balanced at equilibrium state for a constant traffic volume (Q). Therefore, the following expression[7] given by equation (5) can be proved.

$$\underline{P}_i P_{ij} = \underline{P}_j P_{ji} \tag{5}$$

Where, $\underline{P}_{ij}$ is the transition probability that a vehicle in lane 'i' change it's lane to adjacent lane 'j' after a sufficiently long section of travels. From these two equations (4) and (5), expression for the probability that a vehicle in a lane can be written as given by equations (6), (7) and (8) for shoulder lane, middle lane and median lane, respectively.

$$\underline{P}_1 = 1/(1+\eta_{12}(1+\eta_{23})) \tag{6}$$
$$\underline{P}_2 = \eta_{12}/(1+\eta_{12}(1+\eta_{23})) \tag{7}$$
$$\underline{P}_3 = \eta_{12}\,\eta_{23}/(1+\eta_{12}(1+\eta_{23})) \tag{8}$$

Where, $\eta_{12} = P_{12}/P_{21}$ and $\eta_{23} = P_{23}/P_{32}$, i.e., η_{ij} means ratio of transition probability of lane changes between adjacent lanes. Similarly, for a 'n' lane freeway, the probability of traffic distribution in i^{th} lane can be written as given by equation (9).

$$\underline{P}_i = \eta_{01}\,\eta_{12}\,\eta_{23}\,\eta_{34} \dots \eta_{i-1,i} / \Omega \tag{9}$$

Where, $\Omega = (1+\eta_{12}(1+\eta_{23}(1+\eta_{34}(1+\dots+\eta_{n-2,n-1}(1+\eta_{n-1,n}))\dots))$ and η_{01} is equal to one, which is useful for describing two lane unidirectional freeway behaviour. Furthermore, by considering the flow equation, the average flow rate (Q) is the product of the average density (K) and average speed (V), the ratio of transition probability of lane changes between lane 'i' and lane 'j' can be written as given by equations (10).

$$\eta_{ij} = \frac{P_{ij}}{P_{ji}} = \frac{P_j}{P_i} = \frac{q_j/Q}{q_i/Q} = \frac{q_j}{q_i} = \left(\frac{k_j}{k_i}\right) * \left(\frac{V_j}{V_i}\right) \tag{10}$$

This equation (10) shows that, ratio of transition probability of lane changes between adjacent lanes (η_{ij}) is expressed by two defined traffic parameters such as ratio of average speed and ratio of average traffic density between those lanes. Meanwhile, the equations (6)-(8) show, ratio of lane changeovers between adjacent lane influences the probability of lane traffic distribution. Therefore, it can be concluded that changes in defined traffic parameters make lane changeovers between adjacent lanes and these lane changeovers make difference in traffic distribution. Since, this concept is very important for identifying freeway capacity improvement measures, a data set from site A-I was used to visualise the behaviour of these traffic parameters.

(1) Results of Lane Changeovers Analysis

A relationship between ratio of lane changeovers vs. flow curves was developed for site A-I, and shown in Figure 8. This Figure shows, the ratio of P_{12}/P_{21} ($=\eta_{12}$) is higher than one, and predicted trends show this ratio takes a value nearly two. It implies that at equilibrium condition, percentage of vehicle travelling in shoulder lane moving into middle lane is higher than it for middle lane to shoulder lane. Moreover, when comparing lane changeovers between middle lane and median lane, it has a steady and increasing relationship with increasing total flow, and when the flow rate is higher than about 3,000 vph, the ratio of changeovers from middle lane to median lane is higher than it for median lane to middle lane. Thus, this results show that at equilibrium state under higher flow rate condition, the percentage of vehicles travelling in a lower utilized lane change their position to adjacent lane is higher than the percentage of vehicles travelling in other lane change their position to lower utilised lane. Therefore from these results, one can guess that, under higher flow rate condition, restricting the vehicle changeovers from lower utilised lane to adjacent lane by road marking, might increase the traffic flow in lower utilised lane. Application of this capacity improvement measure will be discussed in section 8(1).

(2) Result of Ratio Analysis

Results from the analyses of defined traffic parameters such as; ratio of density between adjacent lanes vs. flow and ratio of speed between adjacent lanes vs. flow are shown in Figure 9. This results show that, the ratio of speed between adjacent lanes has an overlaying weaker relationship with total traffic flow. Examined results of this overlaying relationship in ratio of speed show; drivers are minimising the percentage of expected number of single or combination of drivers' constraints such as lane changeovers, overtaking or braking events. However, since this is irrelevant with this paper's aims, the full description not given here. Further, statistical results revealed that with the increasing total traffic flow, the changes in ratio of average density have very strong influence on traffic distribution. A subsequent analysis also shows that with the increasing total traffic flow, the rate of density increase is the highest in median lane and the lowest in shoulder lane, which was identified as the main reason for the lower flow rate in shoulder lane under higher total traffic flow condition. Therefore, it was understood that increasing the traffic density in a section of shoulder lane might improve the traffic capacity of a freeway section, and a simple methodology for increasing the traffic density will also be discussed under the section 8(2).

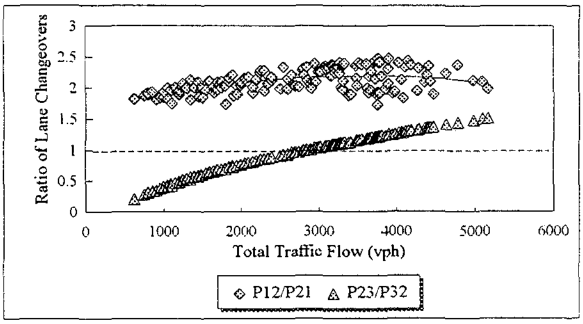

Figure 8 Ratio of lane changeovers between adjacent lanes

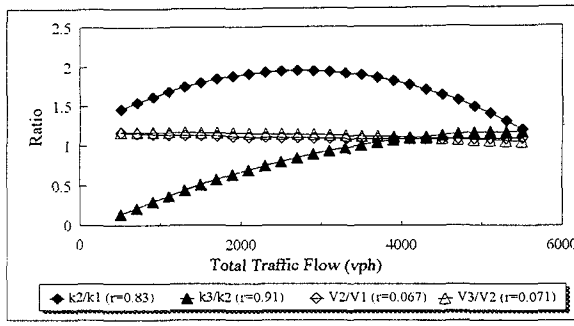

Figure 9 Result of ratio analysis

7. Result of Lane Utilisation Analysis

In this section, the collected headway data from a straight segment of a three lane freeway was used to examine the time and space utilisation between smaller size (passenger car) and larger size (heavy) vehicles. Since, this study's main interest is in the region where $\underline{P}_3 > \underline{P}_2 > \underline{P}_1$ for capacity improvement, a flow condition of approximately 4,000 vph was selected in this section, as a random data set. Further, here headway is defined as, time (h) or distance (d) between rear bumper to rear bumper of the vehicles (lagging headway). Next, headway data was categorised into four groups of headway such as passenger car following passenger car (PP), heavy vehicle following passenger car (TP), heavy vehicle following heavy vehicle (TT) and passenger car following heavy vehicle (PT). The shoulder lane results show that similar to the distance headway, the time headway for groups TP and TT were higher than it for PP group, two of them are shown in Figure 10.

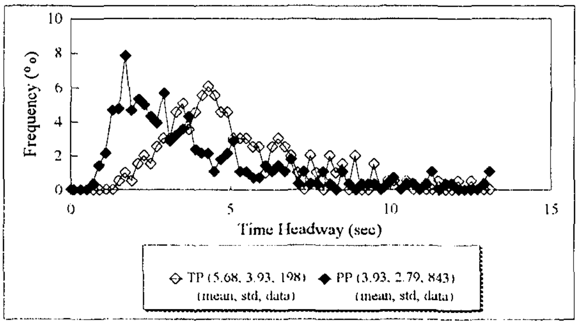

Figure 10 Time headway of TP and PP groups

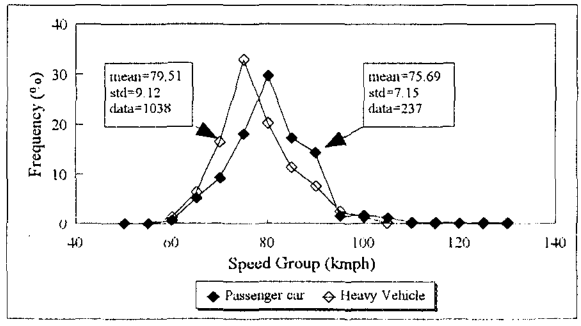

Figure 11 Speed distribution

There can be two reasons for this; one is heavy vehicles are longer than passenger car, and other one is heavy vehicles are keeping more gap from preceding vehicle for safety reason than it by passenger car. However, these results are for an uninterrupted freeway segment, where heavy vehicles' drivers have very lesser consideration on other vehicle. Moreover, result of shoulder lane's average speed difference between heavy vehicles and passenger cars revealed a slight lower value for heavy vehicle groups as shown in Figure 11, and the results have same features like SCHMIDT[8]. This had led a conclusion with the knowledge of HCM[1], that the available shoulder lane clearance may not adequate for the heavy vehicles' usage. Therefore, it can be said that, increase the width of the low utilised lane might be another way for improving the overall capacity of the unidirectional freeway. Due to the simplicity in field application of this proposed measure, detailed explanation of a methodology for increasing the width of lower utilised lane is not given in this paper.

8. Measures for Capacity Improvement

Compared with traffic control in other transport facilities, freeway control has difficulties in realising the measures for its capacity improvement. However, identifying the measures that can improve the freeway capacity is very useful for the system managers. Therefore, from the above results, the followings are considered as capacity improvement measures such as, restricting the lane changes from lower utilised lane to higher utilised lane by road marking, introducing a short passing lane with the shoulder lane and increasing the width of the low utilised lane. Applications of first two measures in the field are discussed below in Sections (1) and (2).

(1) Controlling Lane Changes by Road Marking

It has been proved that controlling lane changes from lower utilised lane to adjacent lane might improve the usage of lower utilised lane and subsequently improve the capacity of the freeway. Application of this method can be implemented as shown in Figure 12, by pre-installed changeable lighting arrangement, which can flash with the road surfaces as road marking. Typical lighting arrangement for two cases; $P_2 > P_3 > P_1$ and $P_3 > P_2 > P_1$ are given be lines A-A & B-B and A'-A' & B'-B', respectively. Allowable lane change movements are also shown by arcs. The lighting arrangement can be changed as shown in this Figure, with the changes in total flow condition.

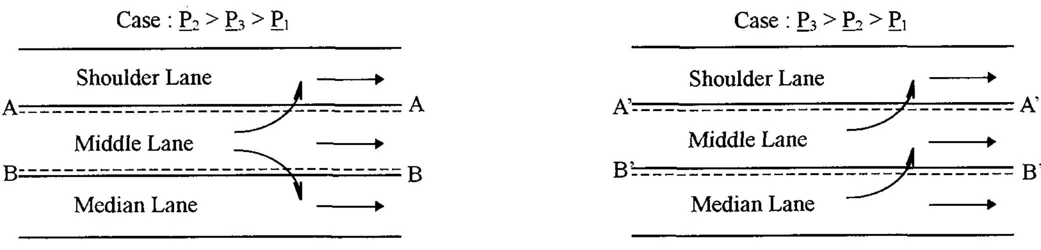

Figure 12 Controlling the lane changes by road markings

However, it is important that, if the flow rate reached the capacity then the lighting arrangement should turn to the normal condition. Because, speed and densities are relatively higher in freeway, and thus, disruptions in the traffic flow can rapidly propagate and increase in severity. Therefore, when imposing this suggested capacity improvement measure, care should be taken that it does not lead drivers to dangerous reactions.

(2) Introducing a Short Passing Lane

The section 6(2) discussed that increasing the traffic density in a lower utilized lane might improve its flow rate, and subsequently increase the freeway capacity. Therefore, here it is proposed that introducing a short passing lane, as shown in Figure 13, will increase the traffic density (K_i) in lower utilized lane in downstream section. Moreover, this measure might be not only better way for improving the freeway capacity in the downstream section but also adequate for a tunnel section capacity improvement. Because, by considering the downstream in this figure as a tunnel section one can accept that, a short lane can be added in the immediate upstream of tunnel's entrances without widening the tunnel. Subsequently, this introduced lane will definitely help to improve the traffic flow through the tunnel.

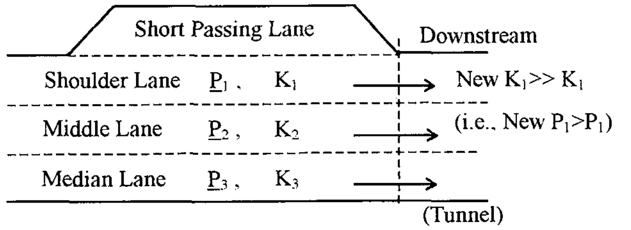

Figure 13 Adding a short lane to lower utilised lane

9. Conclusion

Analytical modelling for traffic distribution in an uninterrupted flow condition of three lane uni-directional freeways was carried out for data set from different locations with different geometrical characteristics in Tomei Expressway, Japan. The developed models revealed that, the traffic distribution can be well explained by explanatory variables such as total traffic flow, heavy traffic composition and average speed. Further, statistical tests show that between geometrically identical sites, there are no significant difference in traffic distribution due to either directional flow or changes in freeway location. Moreover, traffic distribution in up and down gradient of straight segments were tested against levelled straight segments. Results show when the grades vary between -3% to 3%, the traffic distribution in a grade segment is more identical with it for a levelled straight segment. Further, analyses show that upstream profile has influence on traffic distribution. In addition, it was found that, the lane usage in shoulder lane is slightly increasing for any changes in freeway geometry, i.e., if there is a small irregularity in geometry condition from a straight levelled segment, then shoulder lane traffic distribution is increasing. Moreover, result from the night flow condition shows that the traffic distribution in the shoulder lane is decreasing in nighttime, and reason for this nighttime behaviour also discussed. However, in this paper, these stated statistical testing for factors affecting the traffic distribution were investigated only between limited cases in macroscopic view, thus these conclusions must be considered as tentative.

Moreover, the developed theoretical model revealed that the amounts of lane changes between adjacent lanes in an uninterrupted flow highly influence the traffic distribution in an individual lane. Further, it shows that lane changeovers are influenced by two defined traffic parameters such as ratio of average speed and ratio of average traffic density between adjacent lanes. Analysed results revealed that with the increasing total traffic flow, the changes in ratio of average density have very strong influence on traffic distribution. Further, it was understood that increase the traffic density in lower utilized lane within an uncongested flow condition will improve the flow rate. Moreover, shoulder lane traffic utilisation analysis revealed that heavy vehicles' time and space usage are much higher than it for the smaller sized vehicles. In addition a speed analysis shows that in shoulder lane, the average speed of the heavy vehicle is slightly lower than smaller sized vehicles. It seems that the clearance in the shoulder lane is not adequate for the heavy vehicle.

Finally, based on these analyses, three measures that might increase the freeway capacity were suggested, such as restricting the lane changes from lower utilised lane to higher utilised lane by road marking, introducing a short passing lane with the lower utilised lane, and increasing the width of the lower utilised lane. The methodologies to implement first two measures at site also were discussed. However, these three proposed capacity improvement measures need field validation.

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高速道路片側３車線区間における交通量の車線分布に関する分析

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片側３車線区間における交通量の車線分布モデルを開発し、その現象構造を検討した結果、交通量・大型車交通量・平均速度による回帰モデルが説明力のあることが知られた。また、上り下り・幾何構造条件・昼夜等の条件による影響についても検討を加えた。さらに、車線変更に着目した理論モデルを開発して検討した結果、２つの状態量つまり隣接車線の平均速度比および密度比が寄与していることが推定された。これら２つの状態量についての分析を行いその特性を取りまとめた。最後にこれらの分析を通じて得られた知見をもとに、高速道路の交通容量を増加させるであろう３つの方策の提案を行った。

Analysis of Traffic Distribution in Three Lane Uni-Directional Freeway

Izumi OKURA and K. SOMASUNDARASWARAN

Developed analytical model for three lane uni-directional freeway revealed that, traffic distribution can be more accurately expressed by total traffic flow, heavy vehicle composition and average speed. Statistical tests were used to provide some insight to examine how location, geometry features and light condition might affect the traffic distribution. Moreover, developed theoretical concept revealed that amount of lane changeovers between adjacent lanes highly affects the traffic distribution in an uninterrupted freeway segment, and these lane changeovers are influenced by two defined traffic parameters; ratio of average speed and ratio of average traffic density between adjacent lanes. Analysed results revealed that, with the increasing total traffic flow, the changes in ratio of average density had very strong influence on traffic distribution. Finally, based on these results, three measures that might increase the freeway capacity were suggested.