A SIMPLIFIED MECHANISM FOR TRAFFIC DISTRIBUTION IN A THREE LANE UNI-DIRECTIONAL FREEWAY

Izumi OKURA* ** and K. SOMASUNDARASWARAN***

1. Introduction

Traffic distribution is the split of total traffic volume to the individual lanes of multi-lane unidirectional freeway. This is sometimes referred as traffic split, lane utilization, lane distribution or lane traffic distribution. A previous study on traffic distribution analyses[1] in uninterrupted segments of three lane uni-directional freeway shows that traffic distribution has a unique nature in its behaviour with varying total traffic flow. This unique behaviour in a straight three lane uninterrupted freeway segment shows that the shoulder lane traffic distribution has never been highest and middle lane traffic distribution has never been lowest for total traffic flow ranging from 400 vph to 5,750 vph. Moreover, under a maximum traffic flow rate condition the median lane carries nearly half of the total traffic, while the shoulder lane carries only 1/6 of the total. Thus, when a straight three lane uninterrupted freeway segment is operating closer to its capacity, the median lane became three times efficient than the shoulder lane in terms of utilization. Because of these inequalities in lane utilization, analysis of traffic distribution becomes as an important research topic in the area of traffic operation. Although, at present a few works on traffic distribution are available, still a theoretical mechanism which can show the behaviour of traffic distribution in an uninterrupted flow is incomplete. Therefore, in this study an attempt is made to explain the mechanism of the traffic distribution by both analytically and theoretically. Thus, the main objective of this study is to identify the mechanism of traffic distribution by distinguishing the suitable explanatory traffic parameters.

2. Review of Existing Models

OKURA and SOMA[1] theoretically examined this unique nature in traffic distribution by developed simplified models. Their developed model for traffic distribution in a n^{th} lane uni-directional multi-lane freeway shows that under a steady flow condition the traffic distribution is influenced by vehicles' lane changeovers between adjacent lanes, and these vehicles' lane changeovers are influenced by two defined traffic parameters such as ratio of average speed and ratio of average density between adjacent lanes. Further, under an equilibrium condition, a relationship between the ratio of transition probability of lane changes between adjacent lanes (η_{ij}) and these two defined traffic parameters were given as shown in the following equation (1). This equation (1) was obtained as a result of balancing the number of vehicles' lane changeovers between adjacent lanes.

$$\eta_{ij} = P_{ij}/P_{ji} = P_j/P_i = (k_j/k_i)*(\underline{v}_j/\underline{v}_i) \qquad (1)$$

Here, P_{ij} is the transition probability that a vehicle travelling in lane '*i*' changes it's position to adjacent lane '*j*', further traffic distribution, traffic density and the average speed in the lane '*i*' are denoted by P_i, k_i and $\underline{v}_i$, and the similar values for lane '*j*' are denoted by P_j, k_j and $\underline{v}_j$, respectively. Moreover, the relationship between the traffic distribution (P_i) in the lane '*i*' and the ratio of transition probability of vehicles' lane changes between adjacent lanes (η_{ij}) under an equilibrium condition was given as shown in the following equation (2).

$$P_i = \eta_{01}\,\eta_{12}\,\eta_{23}\,\eta_{34}\,\ldots\,\eta_{i-1,i} / \Omega \qquad (2)$$

Where, $\Omega = (1+\eta_{12}(1+\eta_{23}(1+\eta_{34}(1+\ldots+\eta_{n-2,n-1}(1+\eta_{n-1,n}))\ldots))$ and $\eta_{01} = 1$. Thus, the equation (1) shows that ratio of transition probability of vehicles' lane changes between adjacent lanes can be expressed by two defined traffic parameters such as ratio of average speed and ratio of average density between adjacent lanes of a multi-lane freeway. Further, equation (2) shows that traffic distribution is influenced by vehicles' lane changeovers between adjacent lanes. Therefore, it was concluded[1] that traffic distribution is influenced by these two defined traffic parameters such as ratio of average speed and ratio of average density between adjacent lanes of a multi-lane freeway. Though, these concluded statements and given equations (1) and (2) are good enough to work towards the objective of this paper, no attempt has been made up to now to review these developed models in detail.

3. Traffic Parameters Analysis

Since stated conclusion in the above section 2 is important for identifying the required traffic distribution mechanism, data sets from nine different uninterrupted segments in three lane freeway with different geometric condition were used to visualise the behaviour of these defined traffic parameters with varying total traffic flow. Developed relationships show that ratio of speed between adjacent lane of these sites have an identical overlaying behaviour with varying total traffic flow. Since this developed relationship is useful to identify the required mechanism, one of such results from a straight segment is shown in Figure 1. The degree of relationship of these defined parameters such as ratio of average density and average speed between adjacent lanes with varying total traffic flow was also tested by multi-regression analyses. Results revealed that the

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** Member of JSCE, Prof. Dr. Eng., Dept. of Civil Eng., Yokohama National University.
(156 Tokiwadai Hodogaya-ku, Yokohama 240, Japan, Tel : 045-335-1451, Fax : 045-331-1707)
*** Student Member of JSCE and ITE, M. Eng., Dept. of Civil Eng., Yokohama National University.
(156 Tokiwadai Hodogaya-ku, Yokohama 240, Japan, Tel : 045-335-1451 Ext. 2738, Fax : 045-331-1707)

ratio of average density between adjacent lanes in uncongested condition has a strong relationship with total traffic flow. However, when the total flow rate increases, the rate of increases in traffic density varies widely between individual lanes. This phenomenon was examined by considering a lane-by-lane speed-flow-density behaviour in an uninterrupted straight segment of three lane uni-directional freeway, and results are shown in Figure 2.

This Figure 2 was obtained by two steps: first a straight line behavior for speed-density relationship was fitted for a flow rate ranging from 400 vph to about 5,750 vph, then ten different flow rates were considered to have a three dimensional relationship, as shown by the points from 1 to 10. In this figure point marked by number '1' shows the speed-flow-density behavior in each lane of a three lane freeway, for a total flow rate of 866 vph. Similarly, the points '2' to '10' represent the total flow rates of 1269, 1776, 2198, 2702, 3206, 3748, 4267, 4796 and 5130 vph, respectively. This three lane freeway speed-flow-density relationship shows that under uncongested flow rate condition, the median lane speed is always the highest, the shoulder lane speed is always the lowest and the middle lane is between these two lanes. Moreover, as can be seen from Figure 2, when the flow rate ranging from 400 vph to about 5,750 vph, traffic density in individual lanes of a three lane freeway can be classified into three categories, such as $k_2 > k_1 > k_3$, $k_2 > k_3 > k_1$ and $k_3 > k_2 > k_1$. Here, density in shoulder lane, middle lane and median lane was referred as k_1, k_2 and k_3, respectively. These results show the rate of changes in this speed-density relationship with increasing total traffic flow widely varies between each lane. This rate of density increase is the highest in median lane and it is the lowest in shoulder lane. This also shows that in a particular segment, for a particular flow condition, there is a set of traffic densities which are ideally accepted by the drivers. On the other hand the result of ratio of speed between adjacent lanes in uncongested condition shows almost an identical and overlaying weaker relationship with increasing total traffic flow. That is, for a particular traffic flow condition the ratio of speed between adjacent lane is almost equal. In this paper, this identical overlaying relationship of speed ratio was used as a key traffic parameter for describing the pattern of lane traffic distribution.

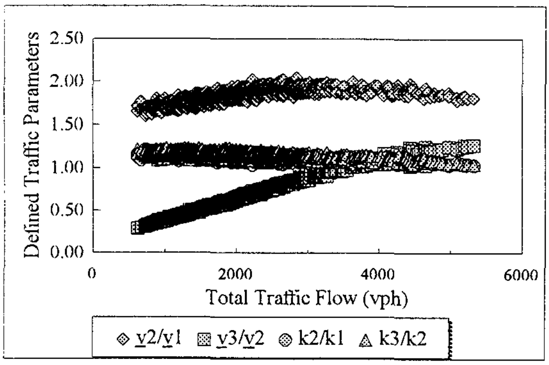

Figure 1 Results of defined traffic parameters analysis

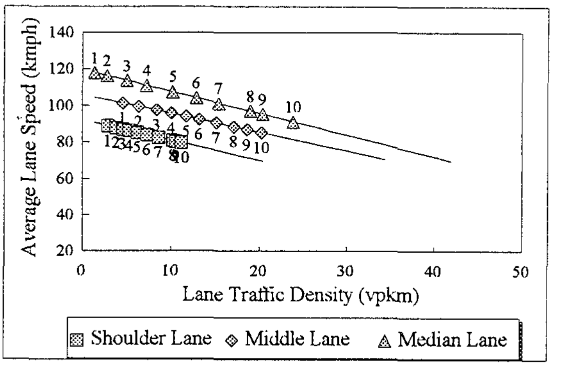

Figure 2 Lane-by-lane speed-flow-density relationship

4. Modified Form of Developed Constraints Models

In this section developed constraint models by OKURA and SOMA[2] are modified to have a relationship between the results of the above section 3 and the pattern of traffic distribution. It is a general understanding that in order to maintain a diver's desire speed, he has to optimise many constraints, such as number of overtaking, number of lane changes and acceptable gaps for these overtaking or lane changes (otherwise braking events). When a driver has to face these active constraints, his responses can be noticed by the application of brake pedal (illuminated brake light) or lane changes or overtaking and so on. Further, it is true that, occurrences of these active constraints cause a nervous outburst for drivers in an uncongested flow condition. Moreover, in practice, there are two types of constraints can be defined for drivers: active constraints and passive constraints. The active constraints can be expected by a follower, when he catches up with another vehicle travelling ahead of him in the same lane, and the passive constraint is a result of vice versa. Here, the occurrences of these constraints were considered for explaining traffic distribution mechanism in a multi-lane freeway. In this process first individual lane's drivers' behavior was examined, then it was concentrated on the speed differences between adjacent lanes.

(1) Lane's Speed Behaviour

The usual practices for describing the vehicles' speeds in a lane are the average value and the standard deviation. Analyses show that when the total traffic flow increases, then the standard deviation for the speed distribution becomes smaller, and almost all vehicles are travelling with a speed closer to the average speed. This vehicle's speed behavior in uncongested flow condition is examined by a simple model as follows. Let, the observed probability density function of speed (v_j) in a lane 'j' will be denoted as $f(v_j)$, the density of vehicle in this lane is 'k_j' and a proportion $f(v_j)dv_j$ of vehicle has speeds in infinitesimal range from v_j to v_j+dv_j. Further, assume an imaginary observer travel with a speed 'u_j' in this traffic stream. Hence, the rate at which this imaginary observer meets the active constraints per unit time interval, can be calculated for a vehicle having a speed 'u_j' by using the distribution of travel distance per unit time interval, as given by the equation (3).

$$\xi^{a}_{c,j} = k_j \int_{0}^{u_j} (u_j - v_j) f(v_j) dv_j \tag{3}$$

Similarly, total number of passive constraints can be calculated as given by equation (4).

$$\xi^{p}_{c,j} = k_j \int_{u_j}^{\infty} (v_j - u_j) f(v_j) dv_j \tag{4}$$

Further, from a simple re-arrangement of these two equations (3) and (4), the difference between active and passive constraints can be obtained as given by equation (5).

$$\xi^{a}_{c,j} - \xi^{p}_{c,j} = k_j (u_j - \underline{v}_j) \tag{5}$$

Where, $\underline{v}_j$ is the average speed of traffic stream in the lane 'j'. This equation (5) shows that if the imaginary vehicle is stationary. (i.e., $u_j = 0$ e.g., by accident), then all the vehicles travelling in lane 'j' ($q_j = k_j \underline{v}_j$) have to face the active constraints. Further, if the imaginary vehicle travels with the average speed of the traffic stream ($u_j = \underline{v}_j$), then the amount of active constraints he meets during a unit of time is exactly the same as the amount of passive constraints he meets. It means that, for a vehicle travelling with the average speed has to meet the equal amount of active and passive constraints, which is the highest under higher flow rate condition. Thus, based on the result from the equation (5), it can be concluded that, the drivers are balancing these active and passive constraints within a lane by maintaining their speed near to the average speed.

(2) Speed Differences between Adjacent Lanes

In this section, speed differences between individual lane of a multi-lane freeway were examined by modifying the existing constraint models[2]. Here, two models are considered as given in sub-sections (a) and (b).

a) Simple Constraint Model

Similar to the above section (1), the occurrences of constraints and traffic characteristics were first examined by a simple constraints model, which was used to examine the reason for the identical relationship in the ratio of speed between adjacent lane in a multi-lane freeway. Moreover, the above section (1) shows that an individual driver in a lane 'j' maintaining his speed closer to his lane average speed '$\underline{v}_j$' in order to balance the expected active and passive constraints. Therefore, in this section individual vehicle speeds are considered as their lanes' average speeds. The following time-distance diagram was used for a simple explanation as shown in Figure 3.

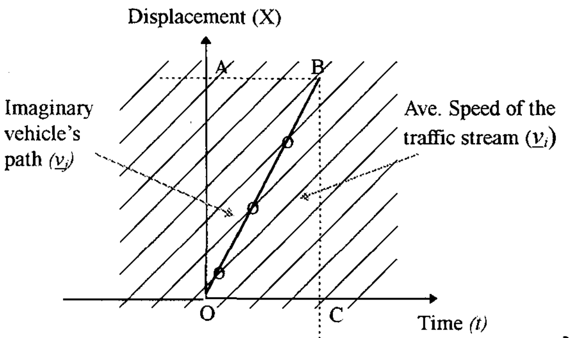

Figure 3 Vehicles' displacements by x-t diagram

Let, in a multi-lane freeway, the 'i'th lane's traffic density is k_i, all the vehicles are travelling with an average speed of $\underline{v}_i$ and total traffic flow is q_i ($=k_i\underline{v}_i$). Further, suppose an imaginary vehicle is travelling on this lane with a speed of $\underline{v}_j$ ($>\underline{v}_i$). This Figure 3 shows the occurrence of meeting points of vehicles' movements or in other words the occurrence of active constraints for the imaginary vehicle. By a simple procedure, the expected number of active constraints per unit time interval can be estimated as given by equation (6).

$$\xi^{a}_{c,i} = k_i (\underline{v}_j - \underline{v}_i) \tag{6}$$

Moreover, the amount of passive constraints per unit time interval can also be guessed as zero ($\xi^{p}_{c,i} = 0$). Hence, if this imaginary vehicle is travelling in this lane 'i', then the expected number of active constraints over the expected number of passive constraints (it will be referred in the following sections as excess active constraint and also denoted as $\xi_{i,j}$) for this imaginary vehicle can be obtained, as given by following equation (7).

$$\xi_{i,j} = \xi^{a}_{c,i} - \xi^{p}_{c,i} = k_i (\underline{v}_j - \underline{v}_i) \tag{7}$$

Therefore, if this imaginary vehicle is travelling in this lane 'i', then the probability of expected number of excess active constraints for this vehicle can be obtained from dividing $\xi_{i,j}$ by lane traffic flow rate ($q_i=k_i\underline{v}_i$), as given by equation (8).

$$P(\xi_{i,j}) = \left(\underline{v}_j / \underline{v}_i\right) - 1 \tag{8}$$

This result shows that the probability of the excess active constraints which have to be faced by an imaginary vehicle travelling with a speed of $\underline{v}_j$ in lane 'i' is only a function of speed ratio. (i.e., $\underline{v}_j/\underline{v}_i$). Further result of this model revealed that if the ratio of speed between adjacent lanes are equal then it means that the drivers are balancing their expected excess active constraints between those lanes. However, this expression is for an average value than a form of integral, because it was assumed that there is only a group of vehicles travelling in the lane 'i' with a speed of $\underline{v}_i$. Therefore, another integral constraints model is necessary for describing the differences in speeds.

b) Integral Constraints Model

Similar to the above section (1), assume that the observed probability density function of speed (v_i) in a lane 'i' will be denoted as $f(v_i)$, the density of vehicle in this lane is 'k_i' and a proportion $f(v_i)dv_i$ of vehicle has speeds in infinitesimal range from v_i to v_i+dv_i. Further, assume an imaginary observer, who has a traffic characteristic of lane 'j' is travelling with a speed '$\underline{v}_j$' in this traffic stream (i.e., in lane 'i'). From the knowledge of the above equation (5), one can write that if this imaginary vehicle is travelling in this lane 'i', then the probability (proportion) of expected number of excess active constraints for this vehicle can be obtained from dividing it (equation 5) by lane traffic flow rate $(q_i=k_i\,\underline{v}_i)$, as given by equation (9).

$$P(\xi_{i,j}) = P(\xi^{a}_{c,i} - \xi^{p}_{c,i}) = \left(\underline{v}_j / \underline{v}_i\right) - 1 \tag{9}$$

This result also shows that the probability of the excess active constraints that have to faced by an imaginary vehicle travelling with a speed of $\underline{v}_j$ in lane 'i' is only a function of $\underline{v}_j/\underline{v}_i$ (i.e., the ratio speed).

5. Mechanism of Traffic Distribution

By substituting $j=2$ (i.e., middle lane) and $i=1$ (i.e., shoulder lane) in this equation (9) or in the equation (8), the probability of expected number of excess active constraints between these two lanes can be obtained. A similar result can be obtained by considering the middle lane $(j=3)$ and median lane $(i=2)$. But, the analytical results show that ratio of speed between adjacent lanes has an identical overlaying relationship, i.e., the ratio of $\underline{v}_3/\underline{v}_2$ and $\underline{v}_2/\underline{v}_1$ are almost equal for a particular flow condition. Here, $\underline{v}_1$, $\underline{v}_2$ and $\underline{v}_3$ are the average speed of the shoulder lane, middle lane and median lane, respectively. Thus, these results show that users in a three lane freeway are balancing these expected excess active constraints between the lanes. Further, one can accept that this result is the reason for the conclusion taken in the section 3, i.e., for a particular flow condition, there is a set of traffic densities which are ideally accepted by the drivers.

Moreover, overall average speed of a traffic stream represents an average rate movement of a vehicle in distance per unit time interval. It can be guessed and analyses in uncongested flow conditions [i.e., for a total flow rate ranging from the maximum value (capacity) to a minimum value (free flow rate)] also show that with the decreasing total traffic flow, the overall average speed is increasing. This can be lead a climax that the drivers in a freeway are maximising their faster movement, too. Therefore, it is concluded that the existing pattern of traffic distribution in a three lane freeway is a result of maximising drivers' faster movements by minimising the expected active constraints in the following manner.

i) drivers are balancing their active and passive constraint with in a lane (ref.; equation 5).
ii) drivers are balancing their expected drivers' excess active constraints between the lanes (ref.; equation 8 or 9).

6. Conclusion

It is true that if there are more than one lane available for a traffic in a multi-lane freeway then the traffic distribution varies widely between individual lanes, and still there is no complete mechanism for explaining this collective behaviour of the traffic. Thus, in this paper, an attempt was made to discuss the traffic distribution mechanism in a three lane uni-directional freeway. In this process, first an examination of an existing model shows that traffic distribution is influenced by two defined traffic parameters such as ratio of average speed and ratio of average density between adjacent lanes of a multi-lane freeway. Therefore, relationship of these identified traffic parameters with varying total traffic flow was examined in nine different uninterrupted three lane unidirectional freeway segments. Results revealed that ratio of speed between adjacent lane has an identical overlaying relationship with varying total traffic flow. Therefore, reasons for this relationship were then examined theoretically by considering the driver's behavior in a lane as well as between the lanes of a freeway. Because, it is a general understanding that in order to maintain a diver's desire speed, he has to optimise many constraints, such as number of overtaking, number of lane changes and acceptable gaps for these overtaking or lane changes (otherwise braking events), thus, these constraints were used for examining the driver's behavior. Results show that the existing pattern of traffic distribution in a three lane freeway is a result of maximising drivers faster movements by balancing their expected drivers' excess active constraints between lanes as well as matching their active and passive constraint within a lane.

Moreover, as stated in the previous study[1] the application of this identified mechanism are innumerous. In addition, an ongoing research by these authors shows that this identified mechanism is useful tool for suggesting a new control strategy for individual lane speed regulation, by which existing patterns of traffic distribution in a multi-lane freeway can be balanced, and subsequently improvements on overall freeway capacity can be achieved.

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