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# LANE UTILIZATION BEHAVIOUR IN A THREE-LANE UNI-DIRECTIONAL FREEWAY UNDER UNCONGESTED FLOW CONDITION

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## 1. Introduction

Lane utilization is the split of total traffic volume to the individual lanes of multi-lane uni-directional freeway. This is sometimes referred as traffic split, traffic distribution, lane distribution or lane traffic distribution. Previous studies on lane utilization analyses[1,2,3&4] in uninterrupted segments of three-lane uni-directional freeway show that lane utilization has a unique nature in its behaviour with varying total traffic flow. This unique behaviour in a straight three-lane uninterrupted freeway segment in Japan shows that the shoulder lane utilization has never been the highest and middle lane utilization has never been the lowest for total traffic flow ranging from 400 vph to 5,750 vph. Because of these inequalities in lane utilization, analysis of lane utilization becomes as an important research topic in the area of traffic operation. Although, at present a few works on lane utilization are available, still a theoretical mechanism which can show the behaviour of lane utilization in an uninterrupted flow is inadequate. Therefore, in this study an attempt is made to explain the mechanism of the lane utilization by both theoretically and analytically. Thus, the main objective of this study is to identify the mechanism of lane utilization by distinguishing the suitable explanatory traffic parameters.

## 2. Comparison of lane utilization in various countries

The Japanese models for lane utilization in percentage for straight segments of three-lane freeways are presented in Figure 1 together with the case studies in two countries: Germany (Heidemann, 1994) and United Kingdom (Yousif, 1996). This figure shows that when the total traffic flow rate is less than 4,000 vph, the Japanese shoulder lane usage is a little lower than that of the other two cases. Further, it shows that the use of the median lane is a little higher in Japan than in the other countries for a total flow rate ranging from 400 vph to 3,500 vph. Middle lane traffic usage shows an almost identical lane utilization behaviour in Japan and Germany, but a lower utilization tendency in the case of the United Kingdom. However, during the examination of the lane utilization behaviour between these three counties, it can be seen that the lane utilization has a noticeable nature in its behaviour.

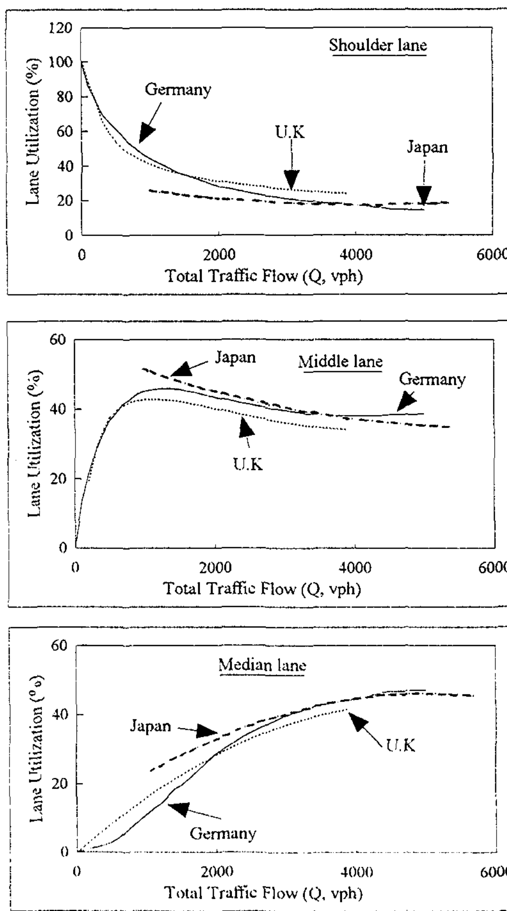


Figure 1 Lane Utilization in three-lane uni-directional freeway

## 3. Review of Existing Models

Okura and Somasundaraswaran[1] examined this unique nature in lane utilization by developing simplified models. Similar to Heidemann[4], the developed a model for lane utilization in a multi-lane uni-directional freeway shows that under a steady flow condition, the lane utilization is influenced by vehicles' lane changeovers between adjacent lanes. Moreover, the paper[1] shows that these vehicles' lane changeovers are influenced by two defined traffic parameters such as the ratio of average speeds and the ratio of average densities between adjacent lanes. If it is briefly reviewed, under an equilibrium condition, a relationship between the ratio of transition probability of the frequency of lane changes between adjacent lanes ($\eta_{ij}$) and these two defined traffic parameters, (i.e., these ratios) are shown in Equation (1). This equation was obtained as a result of balancing the number of vehicles' lane changeovers between adjacent lanes.

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

where,

- $P_{ij}$ - the transition probability that a vehicle travelling in lane '*i*' changes its position to adjacent lane '*j*'
- $P_{ji}$ - the transition probability that a vehicle travelling in lane '*j*' changes its position to adjacent lane '*i*'
- $P_i$ - lane utilization (in ratio) in lane '*i*' (similarly, $P_j$ for lane 'j')
- $k_i$ - traffic density (veh/km) lane '*i*' ($k_j$ for lane 'j')
- $\underline{v}_i$ - the average speed (kmph) in lane '*i*' ($\underline{v}_j$ for lane 'j')

Moreover, the relationship between the lane utilization ($P_i$) in lane '*i*' and the ratio of transition probabilities of vehicles' lane changes between adjacent lanes ($\eta_{ij}$) under an equilibrium condition is shown in Equation (2).

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

where,

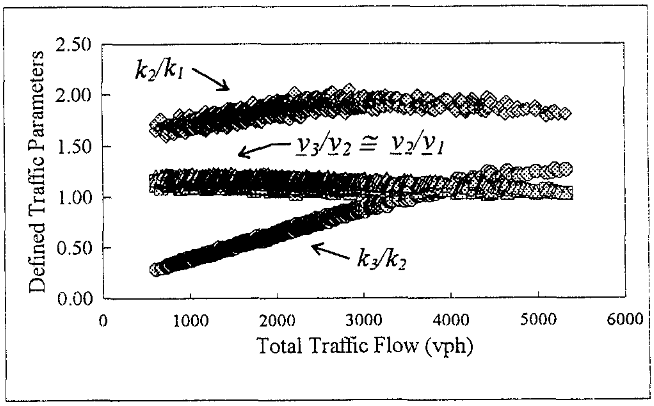
$\Omega$ = $(1+\eta_{12}\,(1+\eta_{23}\,(1+\ \eta_{34}\,(1+\ldots+\eta_{n-2,\,n-1}\,(1+\eta_{n-1,n}))\ldots))$ and

$\eta_{01}$ = 1.

Thus, it can be shown that the ratio of transition probabilities of vehicles' lane changes between adjacent lanes can be expressed by two defined traffic parameters such as the ratio of average speed and the ratio of average density between adjacent lanes of a multi-lane freeway. Further, Equation (2) shows that lane utilization is influenced by vehicles' lane changeovers between adjacent lanes. Therefore, it was concluded[1] that lane utilization is influenced by these two defined traffic parameters. 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 now to review these models in detail.

## 4. Traffic Parameters Analysis

The concluded remarks in the previous section is important for identifying the required lane utilization mechanism. Therefore, data sets from three-lane freeway segments were used to visualise the behaviour of these defined traffic parameters with varying total traffic flow. The study sites are segments of Tomei Expressway in Japan. Since, this study considered only uninterrupted flow condition, the distance between detector and on/off ramps was considered significant during the site selection, and these sites are as same as the sites given in Table 1 of Okura[1]. Developed relation-ships showed that the ratio of speeds between adjacent lanes in these sites have an identical overlaying behaviour with varying total traffic flow, and a typical result form a straight segment is also shown in Figure 2. The correlation among these defined parameters (i.e., the ratio of average densities and average speeds between adjacent lanes with varying total traffic flow) was also tested by multi-regression analyses.




Note : $k_i$ - density in lane '*i*' (veh/km) and $\underline{v}_i$ - average speed in lane '*i*' (kmph)
where, lane 1 - shoulder lane, lane 2 - middle lane, and lane 3 - median lane

Figure 2 Results of defined traffic parameters analysis

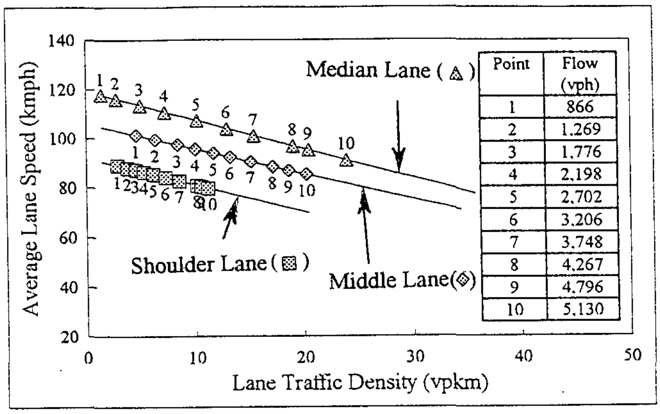
Results revealed that the ratio of average densities between adjacent lanes under uncongested conditions has a strong relationship with the total traffic flow. However, when the total flow rate increases, the rate of increase in traffic density varies widely among individual lanes.

This phenomenon was examined by considering a lane-by-lane speed-flow-density behaviour in an uninterrupted straight segment of a three-lane uni-directional freeway located at 21.52 kilometre post on Tomei expressway, and the results are shown in Figure 3. This Figure was obtained using two steps. First a linear model for the speed-density relationship was fitted for a flow rate ranging from 400 vph to about 5,750 vph. Lastly, ten different flow rates were considered to have a three dimensional relationship, as shown by the points from 1 to 10.

In this figure, the point marked by number '1' shows the speed-flow-density behaviour 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 speed is between these two lanes. Moreover, as can be seen from Figure 3, 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. That is, when the total traffic flow rate is lower than about 1,600 vph, the individual lane density classification shows $k_2 > k_1 > k_3$. Here, the densities in the shoulder, middle and median lanes were referred to as $k_1$, $k_2$ and

$k_3$ (in veh/km), respectively. Similarly, for a total traffic flow rate ranging between 1,600 vph to 3,600 vph, the lane density classification is $k_2 > k_3 > k_1$, and when the total traffic flow rate exceeds about 3,600 vph then the classification is $k_3 > k_2 > k_1$. Hence it can be notified that the shoulder lane density has never been the highest and middle lane density has never been the lowest for total traffic flow ranging from 400 vph to 5,750 vph. Thus, these results show that the rate of changes in the speed-density relationship with increasing total traffic flow varies widely between each lane. This rate of density increase was observed to be the highest in the median lane and lowest in the 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.

Moreover, the ratio of speed between adjacent lanes under uncongested conditions was found to have a weak correlation with increasing total traffic flow. That is, for a particular traffic flow condition, the ratio of speeds is almost equal. In this paper, this identical overlaying relationship of speed ratios was used as a key traffic parameter for describing the pattern of lane utilization.




Note : Number for each symbol point indicates the flow level

Figure 3 Lane-by-lane speed-flow-density relationship

## 5. Modified Form of Developed Constraints Models

In this section developed constraint models by Okura and Somasundaraswaran(2) are modified to derive a relationship among the results of the previous section and the pattern of lane utilization. It is a general understanding that in order to maintain a driver's desired speed, he has to optimise many constraints such as the frequency of overtaking, frequency of lane changes and the acceptable gaps for these overtaking or lane changes to occur (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 was observed that occurrences of these active constraints cause a nervous outburst for drivers in an uncongested flow condition. In practice, there are two types of constraints that 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 the opposite. In this paper, the occurrences of these constraints were considered for explaining the lane utilization mechanism in a multi-lane freeway. In this process, individual lane's drivers' behaviour was examined first, then it was concentrated on the speed differences between adjacent lanes.

### (1) Lane Speed Behaviour

The usual practice for describing the vehicle speeds in a lane is by deriving 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 behaviour in uncongested flow condition is examined by a simple model as follows. First, let the observed probability density function of speed $(v_j)$ in a lane '$j$' will be denoted as $f(v_j)$, the density of vehicles in this lane is '$k_j$' and a proportion $f(v_j)dv_j$ of vehicles has speeds in infinitesimal range from $v_j$ to $v_j+dv_j$. Next, assume an imaginary observer travelling 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 Equation (3).

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

Similarly, the 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, 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, $\underline{v}_j$ - the average speed of traffic stream in the lane '$j$'.

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. However, 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 a driver travelling with an average speed has to meet the equal amount of active and passive constraints, i.e., balancing the active and passive constraints. Moreover, it can be obtained from this Eq. (5) that if a driver travelling with a speed higher than the average speed of his traffic stream then he has to face some more excess active constraints. Here the excess active constraints mean the differences between the active and passive constraint for a driver. Normally, the excess active constraints make difficulties for faster drivers to reduce their speed. On the other hand, if a driver travelling with a speed lower than the average speed of his traffic stream then he will face a smaller amount of active constraints, but the rate of movement is lower for him when it is compared to others. Thus, based on these applications of the practical conditions on Eq. (5), it can be concluded that the drivers are maximising their faster movements by 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 lanes of a multi-lane freeway were examined by modifying the existing constraint models[2]. Here, two models are considered and given in sub-sections (a) and (b).

### a) Simple Constraint Model

Similar to Section (1), the occurrences of constraints and traffic characteristics were first examined by a simple constraints model. This was used to examine the reason for the identical relationship in the ratio of speed between adjacent lanes in three-lane freeway. Moreover, section (1) showed that an individual driver in a lane '$j$' maintains his speed closer to his lane average speed '$\underline{v}_j$' in order to balance the expected active and passive constraints. In this section, individual vehicle speeds are considered as their lane's average speeds. A time-distance diagram was used for a simple explanation, and is shown in Figure 4. Let, in a multi-lane freeway, the '$i$'th lane's traffic density be $k_i$, and all the vehicles travel with an average speed of $\underline{v}_i$ such that the 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 $\underline{v}_j$ ($>\underline{v}_i$). Figure 4 shows the intersections among lines representing 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 Eq. (6).

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

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

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

However, still there remains a question how the counting of this expected excess constraint should be evaluated, that is, in terms of proportion or probability or any other means. Because, for example if the value for $\underline{v}_j > 2\,\underline{v}_i$ then this proportion or probability term becomes more than one or more than 100 percentage, respectively. Therefore, since this study concentrate on only uninterrupted free flow condition, an analysis on the maximum and minimum values of the defined traffic parameters such as $\underline{v}_2/\underline{v}_1$ and $\underline{v}_3/\underline{v}_2$ were calculated. From these values it was understood that under uncongested flow conditions, speed differences between adjacent lanes are not more than 30.1% for a total flow rate ranging from 400 vph to 5,750 vph. This means that the maximum amount of expected 'drivers excess constraints' between two lanes is about 30%. Therefore in this study it is decided to scale the expected number of excess active

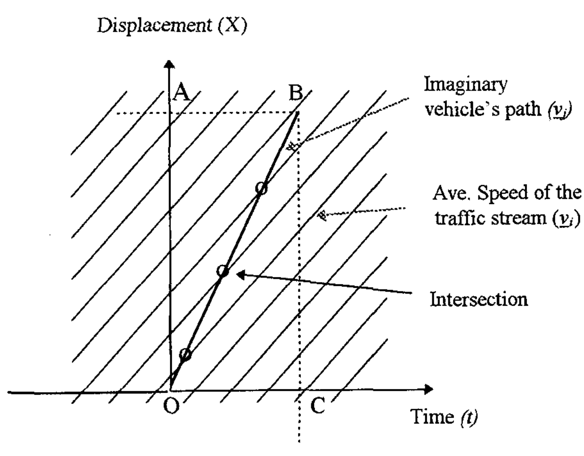



Figure 4 Vehicles movement on time-distance diagram

constraints by proportion.

Thus, this Equation (8) shows that the proportion of the excess active constraints which have to be encountered by an imaginary vehicle travelling with a speed of $\underline{v}_j$ in lane '$i$' is only a function of the speed ratio. (i.e., $\underline{v}_j/\underline{v}_i$). Further analysis revealed that the ratio of speed between adjacent lanes in a three-lane freeway is almost equal for a total traffic volume, and having an overlaying linear relationship with varying total traffic flow. Application of this speed behavior between adjacent lane in Equation (8) revealed that the proportion of expected number of excess active constraints along adjacent lanes is almost equal. Hence, it can be said that the drivers are balancing their expected excess active constraints between those lanes. However, this expression is for an average value rather than an integral form 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 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 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 in this traffic stream (lane '$i$') with a speed of '$\underline{v}_j$' (i.e., imaginary observer is travelling in lane '$i$'). From the knowledge of Equation (5), one can write that if this imaginary vehicle is travelling in lane '$i$', then the proportion of expected number of excess active constraints for this vehicle can be obtained by dividing Equation 5 by the lane traffic flow rate $(q_i=k_i\,\underline{v}_i)$, as given by Equation (9).

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

This result also shows that the proportion of the excess active constraints that will be encountered 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 speed ratio).

## 6. Mechanism of Lane utilization

By substituting $j=2$ (i.e., middle lane) and $i=1$ (i.e., shoulder lane) in either Equation (9) or Equation (8), the proportion of the expected number of excess active constraints between these two lanes can be theoretically obtained. A similar result can also be obtained by considering suitable values for the middle lane (i.e., $j=3$) and median lane (i.e., $i=2$).

On the other hand, the analytical results revealed that the ratio of speeds between adjacent lanes has an identical overlaying relationship. That is, the ratio of $\underline{v}_3/\underline{v}_2$ and $\underline{v}_2/\underline{v}_1$ are almost equal for a particular flow condition, as shown in Figure 2. Where, $\underline{v}_1$, $\underline{v}_2$ and $\underline{v}_3$ are the average speeds of the shoulder lane, middle lane and median lane, respectively.

These theoretical and analytical results revealed a climax that users of a three-lane freeway are balancing these expected excess active constraints between the lanes. In addition, it can be stated that this result is the reason for supporting the conclusion taken in Section 4: for a particular flow condition, there is a set of traffic densities which are ideally accepted by the drivers.

In addition to the previous statements, the overall average speed of a traffic stream represents the average rate of movement of a vehicle in distance per unit time interval. Analyses in uncongested flow conditions also show that with decreasing total traffic flow, the overall average speed tends to increase. This lead to the conclusion that most drivers in a freeway wish to move faster. Therefore, it can be stated that the existing pattern of lane utilization 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.: Eq. 5).

ii) drivers are balancing their expected drivers' excess active constraints between the lanes (ref.; Eq. 8 or 9).

## 7. Conclusion and Recommendation

It is true that if there are more than one lane available for traffic in a freeway, then the lane utilization varies widely among the individual lanes. There is no complete mechanism for explaining this collective behaviour of the traffic. Thus, in this paper, an attempt was made to discuss the lane utilization mechanism in a three-lane uni-directional freeway. In this process, an examination of an existing model showed that lane utilization is influenced by two defined traffic parameters, the ratio of average speeds and the ratio of average densities between adjacent lanes of a multi-lane freeway. The relationship among these identified traffic parameters with varying total traffic flow was examined using nine different uninterrupted three-lane uni-directional freeway segments. Results revealed that the ratio of speeds between adjacent lanes has an identical overlaying relationship with varying total traffic flow. Therefore, reasons for this relationship were then examined theoretically by considering the driver's behaviour in a lane as well as between the lanes of a freeway. It is a general understanding that in order to maintain a diver's desired speed, he has to optimise many constraints, such as the frequency of overtaking, the frequency of lane changes and the acceptable gaps for these overtaking or lane changes. These constraints were used to examine the driver's behaviour. Results showed that the existing pattern of lane utilization in a three-lane freeway can be guessed as 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. As stated in the previous study[1] the applications of this identified mechanism are enormous: as for example this three-lane results can be extended to multi-lane uni-directional freeway analysis and subsequently improvements on overall freeway capacity can be achieved.

Further, this paper mainly relays on the application of the models and results of previous study[1]. Importantly, Equation (1) was obtained as result of balancing the number of vehicles' lane changeovers between adjacent lanes. Therefore although it is very difficult to obtain the data for lane changing manoeuvres in a uninterrupted freeway segment, in future these behaviour should be observed at-least for a short period and compared with these models.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## 高速道路片側3車線区間・非渋滞時における車線利用挙動


ソマスンダラスワラン K.　・　大蔵　泉



交通量の車線分布について，運転者の挙動をベースにそのメカニズムを論じた。先ず、分析結果の知られた3カ国の状況を比較し、共通する特性について考察した。車線利用の現象的考察から、その要因は隣接車線間の速度比と密度比からなることを示した上で、これら2つの状態量の特性を踏まえた車線利用率推定モデルの提案をした。実測データで得られた結果を理論的に考察した結果から、運転者が交通流の中で受ける各種制約との関係から説明を試みた．つまり，現実の交通状態は，車線内では追いつきと追い越されがバランスし，車線間ではあるレベル差を持って挙動制約が生ずる結果として，実現するとの説明が可能であることを示した．


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## LANE UTILIZATION BEHAVIOUR IN A THREE-LANE UNI-DIRECTIONAL FREEWAY UNDER UNCONGESTED FLOW CONDITION


K. SOMASUNDARASWARAN and Izumi OKURA



In the process of analysing the unique nature of lane utilization behaviour, the examinations of existing models[1] showed that under uncongested flow conditions, lane utilization is influenced by two defined traffic parameters such as the ratio of average speed and the ratio of average density between adjacent lanes. Further, behaviour of identified traffic parameters is investigated by the occurrence of defined driver's constraints, such as number of overtaking, number of lane changes and acceptable gaps for these overtaking or lane changes (otherwise braking events). Results show that the existing pattern of lane utilization in a three-lane freeway is a result of maximising drivers' faster movements by balancing the expected drivers' excess active constraints between lanes as well as matching the active and passive constraint within a lane.


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