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PASSENGER CAR EQUIVALENTS OF HEAVY VEHICLES FOR UNCONGESTED MOTORWAY TRAFFIC FROM MACROSCOPIC APPROACH

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Different macroscopic approaches of estimating Passenger Car Equivalents (PCE) are evaluated first. Another approach is then introduced in which PCE is estimated by comparing flow rates at same percentage of capacity. Data from Tomei expressway (two lanes in each direction) are divided into various percentage of heavy vehicle class and PCE is estimated for each lane first. Unified PCE for both lanes is then calculated from distributions of total volume and heavy vehicle volume by lane. Results for different geometric conditions and direction of flow are also compared. PCE increases with increase in percentage of heavy vehicle to some maximum and decreases or remains almost constant afterwards.

Key Words *: heavy vehicles, passenger car equivalents, level of service*

1. INTRODUCTION

The concept of estimating *passenger car equivalent* (PCE) is to estimate the number of passenger cars displaced by each heavy vehicle in the flow. There have been many researches to estimate PCE based on microscopic as well as macroscopic behavior of traffic flow, giving different numerical results. Importance of each result lies on the purpose of application and the way PCE value is used. In capacity analysis procedures, PCE value is used to convert a mixed traffic stream into an equivalent traffic stream composed of passenger cars only. Examined is the method of estimating passenger car equivalents from macroscopic approach for capacity analysis procedures. The necessity for additional investigation arises mainly due to the existence of different approaches, and also due to the fact that level of service criteria for different percentage of heavy vehicle is presently unclear.

2. MICROSCOPIC METHODS

The Highway Capacity Manual1) used Walker Method to estimate PCE values, which compares the relative number of passings of trucks by passenger cars in relation to number of passings of passenger cars by passenger cars. On the other hand, equivalent delay method2) considers the difference between delay caused by heavy vehicle to standard passenger cars and delay caused by slower passenger car to standard passenger cars. Cunagin and Messer3) applied Walker method for lower volume level and equivalent delay method for higher volume level. The equivalent headway method4),5) considers the ratio of headways involving truck and headways involving passenger cars to calculate PCE. Werner and Morrall6) used Walker method in rolling terrain and equivalent headway method in level terrain. McShane and Roess5) discussed that PCE estimated from Walker method or equivalent delay method may not have direct relevance to capacity analysis. As capacity analysis procedures are based on *Level of Service* (LOS) concept, many researchers4),7) suggested that PCE estimation should also be based on this concept.

3. MACROSCOPIC METHODS IN PCE

From macroscopic approach of traffic flow, PCE can be estimated by comparing flow rate without heavy vehicles (basic flow) and flow rate with heavy vehicles (mixed flow) at similar traffic flow conditions. As the capacity analysis procedures are based on LOS concept, the traffic flow conditions are considered to be similar at same LOS. The basic equation for service flow rate given in the Highway Capacity Manual[8)] (HCM, 1985) is rewritten as,

$$SF_i = MSF_i \times N \times f_w \times f_{HV} \times f_p \qquad (1)$$

The factors f_w (for lane width), f_p (for driver population) and N (number of lanes) can be omitted for a particular lane of a particular freeway. If SF_i and MSF_i, the service flow rates under prevailing and ideal conditions with same LOS *i,* are represented by q_M and q_B, then, $q_M = q_B \times f_{HV}$, where, f_{HV} is the adjustment factor for heavy vehicle, q_M and q_B are flow rates per lane with same LOS *i* for mixed flow condition (with percentage 'p' of heavy vehicles) and ideal condition (without any heavy vehicle) respectively. If f_{HV}, is calculated as defined in HCM;

$$f_{HV} = \frac{1}{1+p(PCE-1)};\ PCE = \frac{1}{p}\left(\frac{q_B}{q_M}-1\right)+1 \qquad (2)$$

The macroscopic estimation of PCE from Eq.(2) is generally accepted, but there seem to be different approaches concerning the criteria to be used which produce the same LOS for both flows.

Linzer etal[9)] estimated PCE based on Midwest Research Institute (MRI) simulation model. Truck equivalents were based on keeping effective value of V/C constant for given LOS. PCE values in Circular 212[10)] were also based on MRI studies. Roess and Messer[7)] revised Circular 212 values by using performance curves of speed on extended upgrades. However, the PCE values were based on simulation results on trucks with certain assumed weight-to-horsepower ratio. It had been of many debate on what should be the most representative weight-to-horsepower ratio, because, results of different studies varied considerably and produced different curves.

A mathematical model to estimate PCE was introduced by Huber[11)] with the Greenshield's model of traffic flow. Three different approaches were used to correlate traffic flow parameters to LOS and hence the definition of PCE becomes different in all three approaches. Two of the approaches will be discussed which have more relevance to this study.

In one of the approaches, **Fig.1**, it was assumed that flow rates q_B and q_M will produce identical LOS when total travel time (consequently density) for both the flows is equal. In another approach, **Fig.2**, it was assumed that q_B and q_M will produce identical LOS when the average travel time[12)] (consequently speed) for two flows is same.

(1) Equal density approach

Huber[11)] derived the following equation for PCE by equal density approach, after substitution in Eq.(2) from Greenshield s model of traffic flow;

$$PCE = \frac{1}{p}\left[\frac{v_{FB}}{v_{FM}}\frac{k_{jM}}{k_{jB}}\frac{(k_{jB}-k)}{(k_{jM}-k)}-1\right]+1 \qquad (3)$$

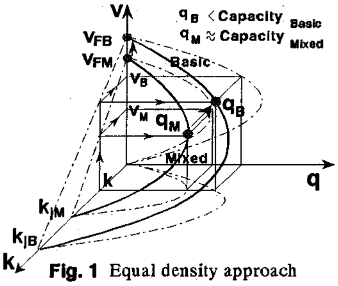

Fig. 1 Equal density approach

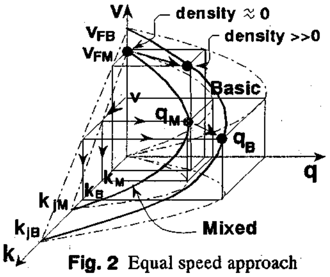

Fig. 2 Equal speed approach

In this approach, the idea is to see the difference in speeds for q_B and q_M when these flows correspond to same density. This approach may be practical at complete free flow region when density is very low, but for higher flow rates, LOS for mixed flow will be lower than that for basic flow, if density and speed both are considered as criteria for LOS. It is because, mixed flow will have same density (but with larger vehicles) and also lower speed. PCE near capacity from this approach may be inadequate because, although equivalent basic flow (q_B in **Fig.1**) will still show occurring below capacity, actual mixed flow (q_M in **Fig.1**) could be near capacity or even in congested regime for same density.

The 1985 HCM, revised Chapter 7 (1992)[13)] on Multilane Rural and Suburban Highways, considered density to be the governing parameter for LOS, although it is defined both by density and speed. It explains, *density is a measure that quantifies the proximity of vehicles to each other within the traffic stream and indicates the degree of maneuverability within the traffic stream* . For these reasons McShane and Roess[5)] stated that equal density approach will be more appropriate since density is the primary parameter for LOS. Density could be an indication of degree of maneuverability if we consider a single flow relationship. In other words, various points in same flow relationship at different density will give different degree of maneuverability without any doubt. But, this may not necessarily be true that same density in two different flow relationships (basic and mixed) will still produce the same degree of maneuverability. If the degree of maneuverability in basic stream and in mixed stream (with heavy vehicles) is considered equal at equal density, it means that the maneuvering situation for a heavy vehicle and for a passenger car is the same.

(2) Equal speed approach

Similarly, Huber[11)] has derived following equation for PCE by equal speed approach;

$$PCE = \frac{1}{p}\left[\frac{v_{FM}}{v_{FB}}\frac{k_{jB}}{k_{jM}}\frac{(v_{FB}-v)}{(v_{FM}-v)}-1\right]+1 \qquad (4)$$

Kuwahara and Iryo[14)] also used equal speed approach to evaluate the effects of heavy vehicles. To avoid the deficiency of this approach, a 3–dimensional regression of flow, speed, and percentage of heavy vehicles as a function of the alignment and visibility, was proposed.

The equal speed approach may be practical at highest flow and congested conditions. But, at free flow condition, the speed of the passenger car in mixed stream is hardly interrupted by heavy vehicles. Even if a free moving passenger car is interrupted by a heavy vehicle, free overtaking will be possible.

The free flow point in mixed stream, when transformed to basic stream at same speed, will have some higher density as shown in **Fig.2**. In such condition, it will practically mean that certain highest LOS will never exist for mixed stream. To some extent, if some heavy vehicles are present, a freeway with a very high quality of geometric design will not be able to give the highest LOS even at the free flow condition. Conceptually from the road planner's point of view, it will be preferable to assume that, with a certain geometric condition of any particular freeway and for a certain range of LOS for basic flow condition, there should exist equivalent range of LOS for mixed flow condition also. Then, Eq.(1) will be applicable for all possible values of i.

Generally, the two curves for basic and the mixed stream are imagined as shown in **Figs.1 or 2.** However, to get a consistent relationship as appearing in the figures from the real data for different percentage of heavy vehicle is not easy. Besides, if the speed-density relationship is to be obtained by regression analysis from the scatter data, whether speed, or, density shall be considered as independent variable, should be made clear. Either of the cases will fit the data well but with different relationships. From the statistical considerations, speed should be considered as the independent variable for equal speed approach in order to minimize the error in estimating density whereas, the case is opposite and density should be considered as the independent variable for equal density approach.

Moreover, when PCE is calculated from Eq.(3), as k approaches k_{jM} (or for Eq.(4) as v approaches v_{FM}), PCE becomes very large and becomes undefined when $k = k_{jM}$ (or $v = v_{FM}$ for equal speed approach).

4. ANOTHER APPROACH IN ESTIMATING PCE

If density is held constant then speed and V/C ratio will not be the same and if speed is held constant, density and V/C ratio will not. Then how will it be possible to estimate PCE for similar LOS and why such situation occurs? Such situations will always occur if level of service is defined in terms of a single absolute value, either of density or of speed alone for basic and the mixed stream both.

At complete free flow region, *speed chosen by individual driver is the choice of their own even in mixed stream and should correspond to the highest LOS as that of basic stream*, although macroscopic speed for mixed stream may be lower than that of basic stream. Thus, defining LOS in terms of density alone may be appropriate, but defining LOS in terms of speed alone will not be suitable at free flow region. On the other hand, near highest flow region, density will no longer be of major concern to drivers (although may still be of some importance) because a small difference in density will not change their freedom to maneuver significantly.

Thus an assumption is required which could be valid for all the regions of traffic flow and this assumption should consider both density and speed as parameters for defining LOS. It is true that mixed stream can never attain a free flow speed as high as that of basic stream. It is also true that mixed stream will have relatively lower jam density than that of basic stream. So a relative evaluation approach is necessary while comparing the LOS for two different flow situations, although LOS is defined in absolute terms for the respective prevailing conditions.

In such a relative evaluation approach, the first consideration is; for a full range of LOS in basic stream, there should exist a full range of LOS in mixed stream also. In other words, as shown in **Fig.3**, PCE value should transform the free flow point, the capacity point and the jam point on mixed curve to free flow point, capacity point and jam point of basic curve respectively. For macroscopic traffic data, it is assumed that the average LOS felt by all the driver population in the mixed stream at free flow condition (or capacity or jam) is same as the LOS felt by basic vehicles in basic stream at free flow condition (or capacity or jam), *although the LOS felt* *by a passenger car in mixed stream and a passenger car in basic stream can not be compared directly.*

Absolute evaluation with absolute equal density or absolute equal speed criteria will try to correlate the LOS felt by passenger cars in mixed stream and LOS felt by passenger cars in basic stream. A relative evaluation approach is needed because the flow conditions and the meaning of LOS for all the vehicles as a whole system in basic stream and all the vehicles as a whole system in mixed stream may differ. In macroscopic approach, it is very important that PCE estimation should be based on estimating the effect of heavy vehicle to the whole system instead of analyzing the effect of heavy vehicle to passenger cars alone. This is true especially in view of planners who have to design the motorway system not only for passenger cars but for a mixed system.

This approach implies that LOS in basic stream and in mixed stream can be compared when the normalized density and normalized speed of two flows are equal, as in Eq.(5). Consequently, same normalized density or normalized speed corresponds to same volume-to-capacity (V/C) ratio. This assumption supports the basic definition of PCE given in HCM (page 3-11) which states, *"PCE represents the number of passenger cars that would consume the same percentage of freeway's capacity as one truck..* Roess and Messer[7] pointed out that the proportion of capacity used and the proportion still available are critical pieces of information. They continued; *..constant V/C values may be relevant, but the interpretation of level of service criteria, when applied to mixed traffic streams, is unclear* . However, this assumption does not imply that LOS should be defined in terms of V/C ratio. Level of service for ideal condition or for any particular percentage of heavy vehicle class, should still be defined in terms of density and speed both, for that prevailing condition. What can be the interpretation of LOS by equal V/C ratio approach then?

Considering Greenshield s model of traffic flow with straight line relation between speed and density, if a boundary of density (k_B) and speed (v_B) is fixed for LOS i for basic stream, the boundary of density and speed to produce same LOS under mixed condition can be fixed at same normalized values **(Figs.3 and 4)**, such that,

$$\frac{k_M}{k_{jM}} = \frac{k_B}{k_{jB}};\ and,\ \frac{v_M}{v_{FM}} = \frac{v_B}{v_{FB}} \qquad (5)$$

$$\therefore\ k_M = k_B \times \frac{k_{jM}}{k_{jB}};\ and,\ v_M = v_B \times \frac{v_{FM}}{v_{FB}}$$

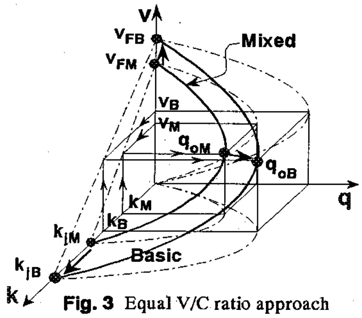

Fig. 3 Equal V/C ratio approach

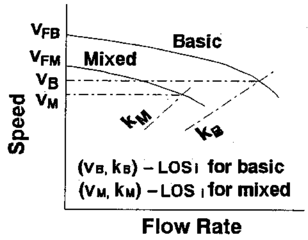

Fig. 4 Interpretation of LOS

It is assumed that the possible decrease in LOS in mixed stream due to the decrease in speed is compensated by the possible increase in LOS due to the lesser density in mixed stream. Thus, for straight line relation between k and v and for the same V/C ratio of two traffic streams,

$$\frac{q_B}{q_{oB}} = \frac{q_M}{q_{oM}},\ \therefore\ \frac{q_B}{q_M} = \frac{q_{oB}}{q_{oM}} = constant$$

$$\boxed{\therefore PCE = \frac{1}{p}\left(\frac{q_{oB}}{q_{oM}} - 1\right) + 1} \qquad (6)$$

where, q_{oB} and q_{oM} are the capacity for basic and mixed flow respectively. As a result, PCE for each lane remains constant for all range of lane volume from this approach. The assumed straight line k-v relation also fitted the analysed data well and hence Eqs.(5) and (6) will be valid for all volume range in uncongested regime. Some errors may arise if there exists a flat or some other relation near complete free flow region. However, due to the constant PCE for all volume, the magnitude of the error will be very less. Considering the application of PCE in such complete free flow region, it should not affect the capacity analysis considerably.

5. DATA USED

Vehicle detector data of Tomei expressway with two lanes in each direction have been used. Data (24 hrs) used are from July to September in 1990. The data include 5 min average of flow, percentage of heavy vehicle (vehicles longer than 5.5 m as descriminated by twin loop detector), occupancy and speed. Data of 5 min average were used because a longer averaging time will be less practical in terms of percentage of heavy vehicle. Weekends and holidays data were not included. Although there may be some effect due to weather and a detail analysis will be needed, the effect has not been included in this study assuming equal effect to all vehicle population. Considerable difference was observed between day and nighttime condition as well as by lane (the scatter plots have been given elsewhere[15]). So, the data for each site were divided into four groups; median lane day (will be named 'lane2 day'), shoulder lane day (lane1 day), median lane night (lane2 night) and shoulder lane night (lane1 night).

The data for each group were divided into several classes (12 to 15) according to percentage of heavy vehicle. Data include maximum up to 50-60% of heavy vehicle for daytime and 85-90% for nighttime. Interval of each class is not uniform and is chosen such that the number of data in each class does not differ much. Proper critical speed and critical occupancy values are chosen to separate uncongested and congested flow regime, after examining scatter plots of speed-flow-density/occupancy. *Only data lying above the critical speed and below the critical occupancy were taken for analysis.*

6. DATA ANALYSIS AND RESULTS

(1) Comparison of different approaches

The results are first compared for a site and lane2 daytime condition for different approaches; the equal speed, the equal density and the proposed V/C ratio approach. Detailed analysis will then succeed for the proposed V/C ratio approach for various conditions.

As stated earlier, although it would be preferable to regress speed against density for equal density approach and vice versa for equal speed approach, density was regressed against speed (linear) to get the speed-density relationship in order to compare the results for same relationship. Besides, decrease in estimated free flow speeds and jam densities with increase in percentage of heavy vehicle, were more consistent when speed was considered as independent variable. However, estimated free flow speeds were relatively higher for higher percentage of heavy vehicle (although lower than for near-to-basic condition) than those estimated by considering density as independent variable. Capacity to be used in proposed equal V/C ratio approach was also calculated from the same speed-density relationships. Comparisons of results are shown in **Fig.5**.

As seen in **Fig.5**, PCE values obtained from equal speed approach are not very practical, because the values change very sharply with flow rate and very high up to V/C as high as 0.5 for higher percentage of heavy vehicle class. PCE values from equal density seem to be relatively stable for lower flow rates, but increase sharply near capacity. These values near capacity do not seem to be very high for this example. This is because, the difference in free flow speed between basic condition and the higher percentage of heavy vehicle class, was not much. However the difference would have been larger if speed were regressed against density taking density as independent variable. PCE values estimated from equal speed and the equal V/C ratio approach, were very similar near capacity, but were relatively larger from equal density approach, especially for higher percentage of heavy vehicle classes.

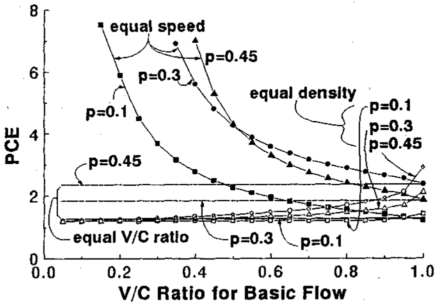

Fig. 5 Comparison of results

(2) PCE by lane

The detailed estimation of PCE is first done for a site with almost ideal geometry and the results will be compared for other geometric conditions. The site selected is for inbound traffic (to Tokyo), which is at 43.95 kilo-post. The horizontal curvature is of radius 5000 m and no vertical grade at the station. More detail has been given elsewhere[15]. Koshi et al[16] have indicated this site as sag section for congested flow analysis. It is considered that, under uncongested flow, -0.3% grade, which is at about 500 m upstream of the site, will not have larger effect.

In order to calculate the PCE values from Eq.(6), the optimum flow rates (capacity) for different percentage of heavy vehicle classes have to be estimated. In real, the capacity flow is difficult to be observed for all different percentage of heavy vehicle classes. So, the capacity values are estimated from the basic traffic flow relationships. The word capacity will be used to mean the estimated capacity and should not be confused with the observed capacity or observed maximum flow.

Firstly, capacity values were estimated from flow rate and speed relationships for each percentage of heavy vehicle class. Flow rate was regressed against speed to minimize the error in estimating flow rate. The relationship is of the form, $q = A \times v + B \times v^2$, where, A and B are coefficients and, q and v are flow rate and speed respectively. Capacity was estimated as the optimum of this relationship as shown in **Fig.6**. These values should not be considered as absolute capacity for the respective percentage of heavy vehicle class. There may be some difference between real and estimated capacity. Since the ratio of two capacity values will be used in Eq.(6), the residual error in the estimated ratio will be much lesser compared to the error in each capacity value.

When the percentage of heavy vehicle increases, lesser data were available near capacity region and become more scattered. This could result in higher error in estimation. So, another method to estimate capacity was also investigated for comparison.

After examining the data for various spots, both for inbound as well as outbound traffic, it was observed that maximum flow always occurred around the same critical occupancy (**Fig.7**) for all percentage of heavy vehicle class. The value of this critical occupancy was different for two different sites even for the same direction of flow and it depends on the geometric condition of the site. From these observations of data for all sites it was presumed that highest flow occurs nearly at the same occupancy (but not same density; density at this occupancy decreases as percentage of heavy vehicle increases), although there was no theoretical basis yet available. Hall and Barrow[17] and, Persaud and Hall[18] have also discussed about using occupancy to separate and analyze uncongested data.

Flow-occupancy scatter seemed more stable. Less data near high flow condition was found to give very little error in estimated relationships. Besides, the ratio of two flow rates at same occupancy for two different percentage of heavy vehicle class was found to be nearly constant after certain value of occupancy (for example, at occupancy 11 or 12 or 13% in **Fig.7**). Thus, some error in defining the exact critical occupancy value will not account for much error in estimating PCE. For these advantages, the capacity values were re-estimated from flow–occupancy relationship. The function used was of the form, $q = \alpha \times O_c + \beta \times O_c^2 + \gamma$, where, α and β are coefficients, γ is constant, q is the flow rate and O_c is the occupancy. The estimated capacity values for various conditions have been given in **Fig.8**. Regarding the adequecy of the type of function to be used for estimating capacity, three things can be considered; (a) analytical stability for various traffic conditions, (b) explanatory power based on theoretical evidence, and (c) purpose or application. As discussed earlier, although there were less theoretical evidence on flow-occupancy relationship, this relationship and the function was applied due to its higher analytical stability. Besides, the purpose was not to calibrate the exact capacity for each percentage of heavy vehicle but to calculate the relative value (ratio) as will be used in Eq.(6).

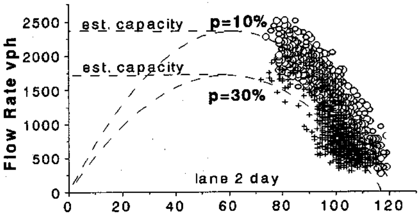

Fig. 6 Speed-Flow relationship

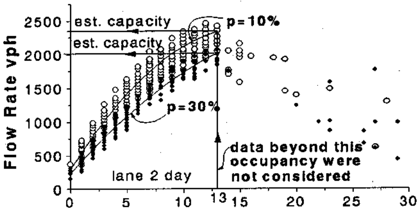

Fig. 7 Flow-Occupancy relationship

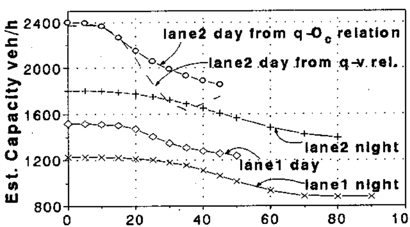

Fig. 8 Est. capacity from q-Oc relation

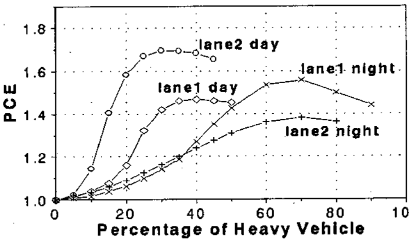

Fig. 9 PCE values

A considerable difference was observed between the capacity values estimated from speed-flow and the occupancy-flow relationships for higher percentage of heavy vehicle classes in lane 2 daytime condition. A very little difference was observed between two regression results in the case of lane1 daytime and also in the cases of both lanes nighttime conditions. For the reasons explained above, the values calculated from occupancy-flow relationships have been used throughout this analysis. PCE values are then estimated from Eq.(6) for both lanes and day and nighttime separately.

Capacity for basic condition corresponds to capacity at p=0% for the respective cases in **Fig.8**. Data around p<5-10% were very few, so the values were assumed constant below these percentages as observed from the nature of result. Due to this fact PCE values shown in **Fig.9** converge towards 0% of heavy vehicle. Whereas, actual PCE values could be little higher than shown in **Fig.9** for p<10% by considering the tendency. PCE increases with the increase in percentage of heavy vehicle to some maximum and decreases or remains almost constant afterwards. Discussion on results will follow later.

(3) PCE for whole roadway section

When the directional total volume (Q) and the total percentage of heavy vehicle (P) are known, the unified PCE for both lanes (whole roadway section) should be estimated as follows, instead of simply taking mean of two PCE values for each lane;

$$Q \times P \times PCE_d = q_1 \times p_1 \times PCE_1 + q_2 \times p_2 \times PCE_2$$

$$PCE_d = \frac{1}{P}\left[\frac{q_1}{Q} \times p_1 \times PCE_1 + \frac{q_2}{Q} \times p_2 \times PCE_2\right] \qquad (7)$$

where, PCE_d is the unified passenger car equivalent for whole direction of roadway. Suffixes 1 and 2 are for lane1 and lane2 respectively; such that, $Q = q_1 + q_2$, and $P \times Q = p_1 \times q_1 + p_2 \times q_2$. So, q_1 , q_2 and p_1, p_2 are the respective lane volumes and percentage of heavy vehicle. Q and P are the total volume and the total percentage of heavy vehicle for both lanes.

In order to calculate directional PCE_d from Eq.(7) for known values of Q and P, the values of q_1, p_1 and q_2, p_2 have to be estimated first. If p_1 and p_2 are known, PCE_1 for p_1 and PCE_2 for p_2 can be estimated from **Fig.9**.

Values of p_1 and p_2 for a known value of P can be calculated from distribution of heavy vehicle by lane. Plot between P against p_1 for nighttime is shown in **Fig.10**, which gave the following equation,

$$p_1 = 1.516 \times P - 0.00556 \times P^2 \qquad (8)$$

$R^2 = 0.95$, $F = 2243.4$

This distribution was found to be same for daytime condition also. Only difference is that the maximum percentage of heavy vehicle available during the daytime condition was little less.

Similarly, values of q_1/Q and q_2/Q for a known value of Q can be obtained from the distribution of total volume by lane. The distribution of total volume by lane for daytime condition has been presented in **Fig.11**, which results the following equation,

$$100 \times \frac{q_1}{Q} = 87.2 - 0.032 \times Q + 0.000005 \times Q^2 \qquad (9)$$

$R^2 = 0.84$, $F = 1423.4$

This distribution was found to be unaffected by percentage of heavy vehicle class. The detail has been given elsewhere[19]. However, some difference for nighttime condition was observed and separate relationship was used. Eqs.(8) and (9) were statistically significant by F-test for $\alpha = 0.005$.

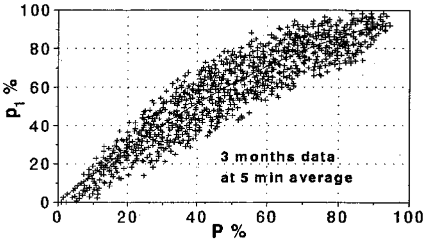

Fig. 10 P vs p1, night time

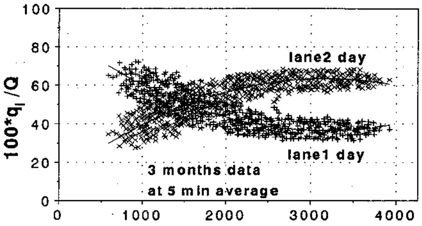

Fig. 11 Distribution of volume by lane

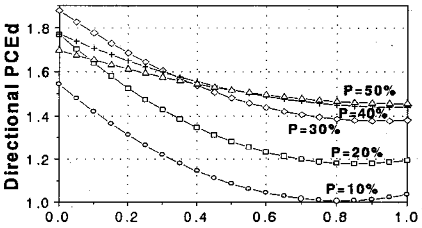

Fig. 12 Directional PCE day

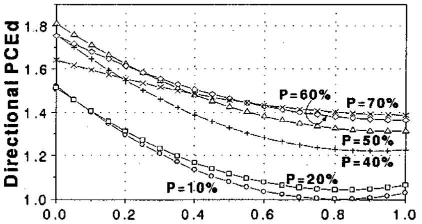

Fig. 13 Directional PCE night

Finally, PCE_d for the whole roadway direction is calculated from Eq.(7) for daytime and nighttime separately and are presented in **Figs.12 and 13** respectively. The directional PCE_d for the same percentage of heavy vehicle decreases with the increase in volume or V/C ratio. It becomes almost constant after V/C greater than about 0.5. The discussion on results will follow later at the end.

7. PCE FOR DIFFERENT GEOMETRIC CONDITIONS

The estimated capacity and the PCE values were examined for several other sites both for inbound as well as for outbound traffic. Results are first compared for three typical cases; positive upgrade, negative downgrade and almost flat (discussed earlier), all three sites for inbound traffic. The site selected for upgrade is at 60.1 kilopost and is just after +3.3%. The site for downgrade is at 47.95 kilopost and is just after -1.3%. No sharp horizontal curves can be observed near all three sites.

Results of estimated capacities for lane2 daytime condition have been given in **Fig.14** for comparison. When PCE values were calculated independently for each site from Eq.(6), PCE for the same percentage of heavy vehicle class were sometimes lesser for upgrade section than for level section. So, to reflect the effect of grades on PCE directly, PCE values were estimated as follows,

$$PCE_g = \frac{1}{p}\left(\frac{q_{oBi}}{q_{oMg}} - 1\right) + 1 \qquad (10)$$

where, q_{oBi} is the capacity of site with ideal geometry (level section) for basic condition (0% heavy vehicle) and q_{oMg} is the capacity of the site concerned, with percentage of heavy vehicle, p. The estimated PCE_g values have been given in **Figs.15 and 16** for lane1 day and lane2 daytime condition respectively. PCE_g for upgrade is unique and decreases with increase in percentage of heavy vehicle.

Capacity values for downgrade section and lane1 day were estimated almost equal to (slightly less than) the capacity for ideal section for all percentage classes, resulting little high PCE values in **Fig.15.** But, PCE in downgrades for p<15% in lane2 day are less than unity **(Fig.16)**. Meaning of PCE from Eq.(10) should be clear which accounts for the effect of geometry directly. PCE less than unity is because the capacities for p<15% were higher than capacity for basic condition in ideal site. When heavy vehicles are low, passenger cars on downgrades especially in faster lane can travel faster than in level section, thus giving little higher capacity. But, when heavy vehicles increase, the capacity is almost same as that in level section or, may be even lower if the downgrade is steeper. So, PCE less than one should not be considered for practical purposes. However, further analytical works and the detail comparison of capacity between downgrade and level section for lower percentage of heavy vehicle will be needed to explain the mechanism of this tendency.

8. INBOUND AND OUTBOUND TRAFFIC

To increase the number of sites in the analysis some sites in outbound direction were also analysed, but an unexpected difference in the result was observed. Past researches[12),14),20)] based on data from Tomei expressway, have usually used the data from both directions of flow. The behavior of traffic may differ between inbound and outbound direction and hence were checked further. It is quite difficult to match several sites with similar geometric conditions in both directions. So, comparisons will be made for almost ideal sites in both directions. The site selected for inbound traffic is the same as discussed earlier. The site for outbound traffic is at 45.95 kilopost, about 2 km apart from the site in inbound direction. There is no vertical grade at this site and the radius of horizontal curvature is 4000 m. So the geometric conditions of these two sites were very similar.

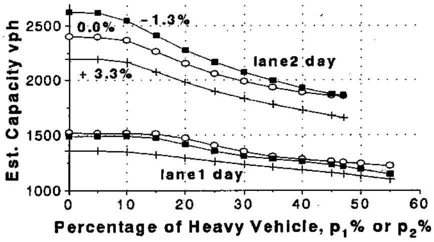

Fig. 14 Capacity for different grades

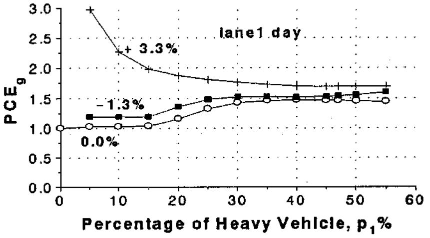

Fig. 15 PCE for different grades

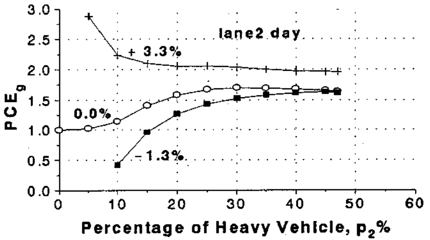

Fig. 16 PCE for different grades

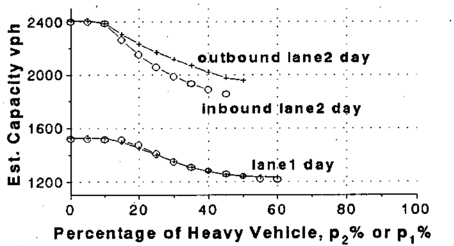

Fig. 17 Inbound and outbound traffic

The results of the estimated capacity have been presented in **Fig.17**. No significant difference was found for lane1 daytime condition. However, considerable difference was observed for lane2 daytime condition, only for higher percentage classes. No difference was observed below p<10%. So, further investigations were required to explain the cause of this difference.

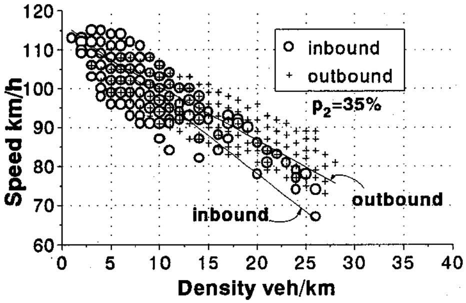

Fig. 18 Speed-density relationships

Firstly, the distributions of total volume by lane were checked, but gave no significant difference, except for sites very close to merging and diverging sections. Then, the distributions of heavy vehicle by lane were checked. There was no difference in the distribution for sites in same direction of flow, but some difference was observed between inbound and outbound flow. After about P>20%, the percentage of heavy vehicle in lane2 (p_2), for the same total percentage of heavy vehicle (P), was little higher for outbound traffic than for inbound. Which means, more heavy vehicles in outbound direction chose faster lane. This led to the question of vehicle loading condition. Trucks in inbound direction could be heavily loaded, carrying cargo to Tokyo. Since no quantitative data were available for loading condition, k-v and q-v relationships were examined. An example for lane2 daytime condition is shown in **Fig.18** (k-v relation) at p_2 =35% (32-38% class) for both directions. This relationship for lower percentage class was very similar.

The relationship for inbound flow is steeper such that, with the increase in density decrease in speed is higher. Again, at lower density, scatter seems larger for inbound traffic indicating that vehicle population has different characteristics among themselves. These characteristics were similar for other sites also, but direct quantitative comparison was not possible for other geometric conditions due to the unavailability of similar sites in both directions. So, it seems that loading condition of vehicles will have significant impact on the estimated values of PCE.

9. CONCLUSIONS AND DISCUSSIONS

Some conclusions and the possible explanations on the results obtained have been listed below.

1) Comparison of results for different approaches shows that the proposed V/C ratio approach simplifies the PCE values and the PCE values are defined for all range of flow.

2) From the results of PCE for each lane, **Fig.9**, PCE increases with the increase in percentage of heavy vehicle to some maximum and decreases or remains almost constant afterwards. PCE close to unity for lower percentage of heavy vehicle is due to the assumed constant capacity below certain percentage as explained earlier. Least PCE values for lowest p may be explained from the fact that, in level section large difference in speed will not be observed when the heavy vehicles are very few in number. The decrease or almost constant PCE in later part of p is because capacity becomes less sensitive to percentage of heavy vehicle after certain value. This may be due to the platooning effect where trucks can travel closer to each other as percentage becomes very high. Maximum PCE occurs at around 25-30% for daytime and 60-70% for nighttime condition.

3) The directional PCE_d for the same percentage of heavy vehicle class **(Figs.12, 13)** decreases with the increase in total volume. Holding the percentage of heavy vehicle constant, at lower flow rate (lesser density), higher difference in speed between passenger car and truck is expected. This will increase the number of maneuver requirements and hence, larger effect is observed near lower flow rate. As the flow rate increases, the difference in speed gradually diminishes and so is the number of maneuvers also. Although the total number of interactions between passenger car and truck increases as volume increases, the average number of passenger cars influenced by each truck decreases.

4) PCE is relatively higher for upgrade sections, mainly at lower percentage of heavy vehicles. When percentage of heavy vehicle is low, effect of heavy vehicle on upgrades is more serious. HCM chapter 7 (revised 1992) also shows a decrease in PCE with increase in percentage of heavy vehicle for upgrades, which is similar to the results obtained. However, HCM shows constant PCE for level section, which may have resulted from the simulation model or the reason of which is not very clear otherwise.

5) Although mild downgrade sections may not have any adverse effect on capacity directly (especially for lower percentage of heavy vehicle), for steeper downgrades, the effect may be serious when percentage of heavy vehicle is high.

6) The distribution of total volume by lane seems to be unaffected by the percentage of heavy vehicle.

7) Separate traffic flow relationships may be required for different direction of flow, if the vehicle loading conditions are different. Thus, difference may occur even in same direction of flow. Possible effects should be studied first before using data from both directions or from different sites for analysis.

10. FURTHER STUDIES

1) The loaded and unloaded condition of heavy vehicle should be considered seriously as it may have different impacts on basic flow relationships and hence to PCE. Further investigation is required in this field before drawing any definite quantitative conclusions. Since the effect is not uniform throughout all the percentage of heavy vehicle classes, adequate method to consider such effects should be developed adequately.

2) PCE values for various other geometric conditions must be analyzed and updated in detail. A quantitative relationship between PCE and geometric elements is desirable to be used in practice. Weather conditions are also important factors which will affect capacity and should be considered in detail.

3) Similar concept can be applied for estimating the effect of lane width and lateral clearances and should be investigated further.

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高速道路の自由流における大型車の乗用車換算係数に関する巨視的分析

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道路交通流に対する車線別の大型車の影響を定量的に把握する方法については，種々の推定規準による提案がなされてきた．本研究においては，先ず，これらの各種アプローチについての現象論的妥当性について論じて後，都市間高速道路の自動車交通流を対象にして，論理的説得性の観点から比較的欠陥の少ない推定規準である，交通量・容量比規準による分析を行い，その結果について考察した．次いで，車線別に得られた推定結果をもとに，複数車線から成る方向別交通流における大型車の影響度を統括する推定方法について提案し，その現象論的特性について実証的な分析結果に基づく考察を行い，道路断面における大型車の影響度の定量的な把握を行った．