【土木計画学研究・講演集 No.15(1) 1992年11月】

ESTIMATION OF EFFECT OF HEAVY VEHICLES ON MOTORWAY TRAFFIC CHARACTERISTICS.

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Measures to increase the efficiency of traffic operations has aroused increasing interest as the emphasis has shifted toward making the existing system work as well as it can. The diverse mixture of vehicular sizes, weights, and operating characteristics has become a potential limiting factor in trying to attain maximum efficiency from the motorway system. The estimation of effect of heavy vehicles in the traffic flow has thus become an important aspect in capacity analysis procedures. The mathematical model (HUBER, 1982)[2] to estimate the Passenger Car Equivalents (PCE) has been discussed. A new approach to estimate the PCE values has also been introduced with assumption of the straight line relationship between speed and density. Finally, a numerical example is presented and the results from the HUBER's approach and the proposed approach have been compared.

I. INTRODUCTION

The heavy vehicles in the traffic stream have some effect on the number of vehicles that can use the expressway. The heavy vehicles displaces several passenger cars in the flow and hence the concept of estimating "passenger car equivalent" (PCE) is to estimate the number of passenger cars that is displaced by each heavy vehicle. There have been many research works to estimate PCE values based on the microscopic as well as macroscopic behaviour of the traffic flow parameters, resulting in different numerical values. The importance of each result from the researches lies on the purpose of the application and the way the PCE value is used. But in the framework of traffic capacity procedures PCE values are employed as a device to convert a traffic stream composed of a mix of vehicle types into an equivalent traffic stream composed exclusively of passenger cars.

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The Highway Capacity Manual[3] used the relative number of passings of trucks by passenger cars in relation to the number of passings of passenger cars by passenger cars, the method, known as Walker Method. The equivalent delay method[4] considers the difference between the delay caused by heavy vehicles to standard passenger cars and the delay caused by slower passenger cars to standard passenger cars. CUNAGIN and MESSER (1982)[1] applied Walker method for lowest volume levels in free flow zone and equivalent delay method for highest volume levels. Constant volume-to-capacity ratio (V/C)[8] approach estimates the PCE by keeping the effective value of V/C constant for any given level of service for two flows.

A mathematical model was first introduced by HUBER (1982) to estimate PCE for multilane conditions with the deterministic (Greenshield's) model of traffic flow. The two traffic streams, one with passenger cars only (basic streams) and the other with heavy vehicles mixed with passenger cars (mixed stream) were related by using some measure of impedance as a function of flow. Three measures of impedance were introduced, the equal average travel time, the equal total travel time and the equal average travel time for the basic vehicles. Out of the three, the first two will be discussed which are more relevant to this study.

The two flow rates which will produce identical level of service can be equated such that,

$$q_B = (1-p)\, q_M + p\, q_M\, (PCE) \qquad ..eq.(1)$$

$$PCE = 1/p\, (q_B/q_M - 1) + 1 \qquad ..eq.(2)$$

where, q_B and q_M are the flow rates of basic vehicles only and mixed streams respectively and p is the percentage of heavy vehicles in the mixed stream.

The assumption of equal average travel time results in the equal average speeds for the two streams and as from Fig.1,

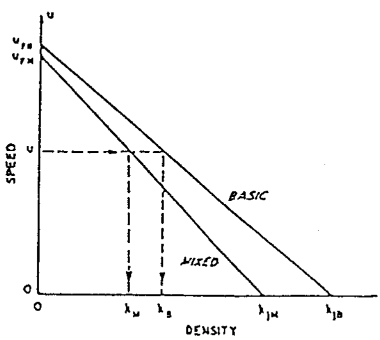

Fig. 1, PCE by equal average travel time

$$\frac{q_B}{q_M} = \frac{k_B}{k_M} = \frac{U_{FM}}{U_{FB}}\,\frac{k_{JB}}{k_{JM}}\,\frac{(U_{FB}-U)}{(U_{FM}-U)}$$

$$\therefore PCE = \frac{1}{p}\left[\frac{U_{FM}}{U_{FB}}\,\frac{k_{JB}}{k_{JM}}\,\frac{(U_{FB}-U)}{(U_{FM}-U)} - 1\right] + 1 \qquad ...eq.(3)$$

Similarly, the assumption of equal total travel time results in the equal density for the two streams and as from Fig. 2,

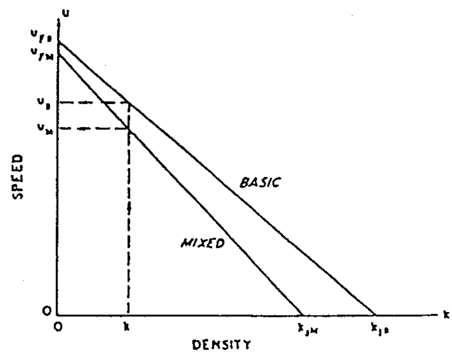

Fig.2, PCE by equal total travel time
(Refer- Huber, 1982)

$$\frac{q_B}{q_M} = \frac{U_B}{U_M} = \frac{U_{FB}}{U_{FM}}\,\frac{k_{JM}}{k_{JB}}\,\frac{(k_{JB}-k)}{(k_{JM}-k)}$$

$$\therefore PCE = \frac{1}{p}\left[\frac{U_{FB}}{U_{FM}}\,\frac{k_{JM}}{k_{JB}}\,\frac{(k_{JB}-k)}{(k_{JM}-k)} - 1\right] + 1 \qquad ...eq.(4)$$

II. INTERPRETATION OF THE ASSUMPTIONS

Calculation of PCE with the assumption of equal average travel time means to assume that the LOS (impedance) of a flow rate q_B of basic-vehicle-only-flow is equal to the LOS of a flow rate q_M of mixed-vehicle-flow at the point where these two flows correspond to the same average speed. Similar interpretation can be given for the assumption of equal total travel time (density) approach. But the more important fact is the way these PCE values will be used. For instance, a set of data is obtained from the vehicle detectors, with the data of flow rate, percentage of heavy vehicles and the average speed (from which density is mostly calculated as flow over speed). Let the set be [q_B, U_B, $k_B(=q_B/U_B)$] and [q_M, U_M, $k_M(=q_M/U_M)$] for arbitrary points in basic-vehicles-only-flow and the mixed flow with percent 'p' of heavy vehicles. The transformed basic vehicle flow rate q'_B of q_M would be,

$$q'_B = p\, q_M\, (PCE) + (1-p)\, q_M$$

If PCE was calculated from equal average speed assumption, and if in the two data sets $U_B = U_M$, then k'_B for transformed basic flow of the mixed flow has to be calculated as, $k'_B = q'_B/U_M$. By virtue of the assumptions the data set (q'_B, U_M, k'_B) should be equal to the data set (q_B, U_B, k_B) such that, $q_B=q'_B$, $U_B=U_M$, $k_B=k'_B$ and hence (q'_B, U_M, k'_B) lie on the same plane of basic vehicle flow curve.

For a similar case, if the PCE was calculated from equal average density assumption and if the two data sets were for the case at which $k_B=k_M$, then U'_B for transformed basic flow has to be calculated as $U'_B = q'_B / k_M$. Again, the set (q'_B, U'_B, k_M) should be equal to the set (q_B, U_B, k_B)and $q_B=q'_B$, $U_B=U'_B$, $k_B=k_M$.

III. DERIVATION OF NEW APPROACH

Although both the above mentioned approaches could estimate the PCE values for deterministic traffic flow model, the PCE values near the boundary conditions, where, free flow or jam occurs are undefined for equal speed and equal density approach respectively. The PCE value also changes sharply with respect to the change in flow, especially near the boundary when U approaches U_{FM} in eq.(3) and k approaches k_{JM} in eq.(4). As the concept is now to transform the mixed vehicle flow curve to the basic vehicle flow curve, such that the transformed curve overlaps exactly over the basic vehicle flow, an easier approach can be introduced, if the straight line relationship of speed and density is still considered valid.

The transformation of the mixed curve into basic curve is possible by transferring the three basic points; the free flow point, the capacity point and the jam condition point of the mixed curve to the basic curve. In more general words, it is to assume that the q_B and q_M in eq.(2), which produce identical measures of LOS (rather impedance as introduced by HUBER since LOS is a qualitative measure only), correspond to the same percentage capacity points of the respective curves. Then, for a straight line relationship of speed and density, and for same percentage capacity, as shown in Fig.3,

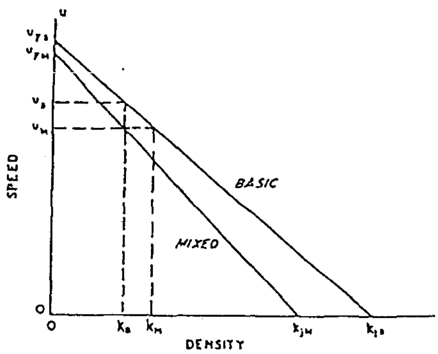

Fig.3, PCE by equal V/C ratio approach

$$k_B/k_{JB} = k_M/k_{JM};\ k_B/k_M = k_{JB}/k_{JM} = \text{const.}$$

because,

$$k_B = k_{JB}/2\ [1-(1-V/C)^{0.5}]$$
$$k_M = k_{JM}/2\ [1-(1-V/C)^{0.5}]$$

similarly,

$$U_B/U_{FB} = U_M/U_{FM};\ U_B/U_M = U_{FB}/U_{FM} = \text{const.}$$

hence,

$$q_B/q_M = q_{oB}/q_{oM} = (U_{FB}*k_{JB})/(U_{FM}*k_{JM})$$
$$q_B/q_M = \text{constant} \quad ..\text{eq.(6)}$$

where, q_B, U_B, k_B and q_M, U_M, k_M are any arbitrary set of points on basic and mixed flow curves for the same percentage capacity respectively and V/C is the percentage capacity ratio.

Thus, the PCE can be calculated by substituting the value of q_B/q_M from eq.(6) into eq.(2),

$$\therefore \ PCE = \frac{1}{p}\left[\frac{U_{FB}\,k_{JB}}{U_{FM}\,k_{JM}} - 1\right] + 1 \qquad ..eq.(7)$$

which is a constant for all range of flow for a given percentage of heavy vehicles. Moreover, it can also be argued that for the absolute boundary condition of free flow,

$$\frac{q_B}{q_M} = \frac{U_{FB}\,k_B}{U_{FM}\,k_M} = \frac{U_{FB}}{U_{FM}} \quad \text{where,} \ \lim_{\substack{q_M \to 0 \\ q_B \to 0}} \frac{k_B}{k_M} = 1$$

although at q_B=0, k_B=0 and q_M=0, k_M=0. Similarly, for absolute jam condition,

$$\frac{q_B}{q_M} = \frac{U_B\,k_{JB}}{U_M\,k_{JM}} = \frac{k_{JB}}{k_{JM}} \quad \text{where,} \ \lim_{\substack{q_M \to 0 \\ q_B \to 0}} \frac{U_B}{U_M} = 1$$

although at q_B=0, U_B=0 and q_M=0, U_M=0. Now, when the PCE values are calculated from eq.(7), and if the flow rate q_M is transformed to the equivalent flow rate q'_B, the corresponding speed and the density have to be calculated as, $U'_B = U_M*(U_{FB}/U_{FM})$ and $k'_B = k_M*(k_{JB}/k_{JM})$.

IV. NUMERICAL EXAMPLE

The vehicle detector data from the Tomei Expressway has been used to formulate a numerical example. However, the real traffic data defers from the assumed straight line relationship between speed and density. The free flow speeds and the jam densities were calculated from the real data observed in sections near Tsubura. But, however the data has been linearized by using the calculated density versus occupancy relationship, the jam densities for various percentage and hence obtaining the average effective lengths of the basic vehicle and the heavy vehicle. The free flow speed for basic vehicle and for heavy vehicle have been taken as 105 kmph and 96 kmph respectively. The effective lengths of basic and the heavy vehicle are taken to be about 10.7 m and 19.6 m respectively.

The PCE values have been calculated from eqs.(3),(4) and (7) for equal speed, equal density and the proposed approach respectively. Fig.4 is the comparison of PCE values for equal speed and equal density approaches calculated for the density/or speed corresponding to the basic vehicle flow per hour respectively. The plotted PCE values correspond to the results shown in Table 1 and Table 2 for the respective cases. The values entered as 999 in the tables represent the undefined infinite cases.

But in Fig. 5, the PCE values have been compared at same V/C ratio for each group of mixed vehicles. The PCE values are shown in Table 3, Table 4, and Table 5 for the respective cases.

Table 1. Estimation of PCE by equal average travel time corresponding to basic vehicle flow rate

			PCE at								
p	Kj	Uf	Qb =0	613	1227	1840	2453	1840	1227	613	0
			Ub=105	98	90	79	53	26	15	7	0
			Free Flow region				=>!<=	Jam region			
0	93	105									
0.1	86	104	999	3.31	2.41	2.12	1.93	1.86	1.85	1.84	1.83
0.25	77	103	999	3.95	2.54	2.17	1.94	1.87	1.85	1.84	1.83
0.5	66	101	999	6.52	2.83	2.27	1.96	1.87	1.85	1.84	1.83
0.75	58	98	999	49.8	3.28	2.39	1.99	1.88	1.86	1.84	1.83
1	51	96	999	999	4.04	2.55	2.02	1.89	1.86	1.84	1.83

Table 2. Estimation of PCE by equal total travel time corresponding to basic vehicle flow rate

			PCE at								
p	Kj	Uf	Qb =0	613	1227	1840	2453	1840	1227	613	0
			Kb =0	6.3	13.7	23.4	46.7	70.1	79.8	87.2	93.5
			Free Flow region				=>!<=	Jam region			
0	93	105									
0.1	86	104	1.09	1.15	1.23	1.37	2.00	4.44	10.6	999	999
0.25	77	103	1.09	1.15	1.24	1.39	2.16	7.86	999	999	999
0.5	66	101	1.09	1.15	1.25	1.43	2.58	999	999	999	999
0.75	58	98	1.09	1.16	1.26	1.47	3.45	999	999	999	999
1	51	96	1.09	1.16	1.28	1.51	6.50	999	999	999	999

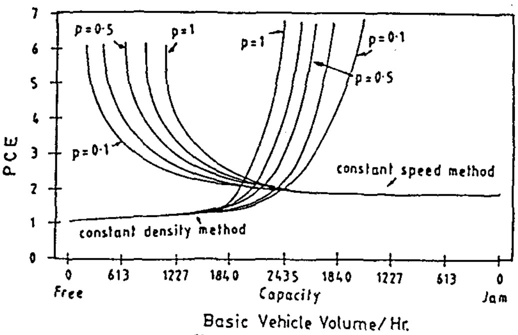

Fig. 4 Estimation of PCE Values

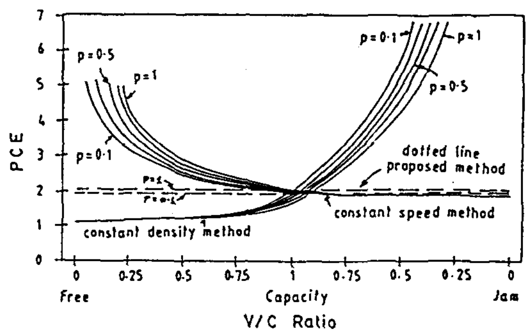

Fig. 5 Estimation of PCE Values

Table 3. PCE values at equal V/C ratio
Equal average travel time

p	Kj	Uf	PCE at V/C =								
			0	0.2	0.5	0.7	1	0.7	0.5	0.25	0
			Free Flow region=>				|<Jam region				
0	93	105									
0.1	86	104	99	3.1	2.4	2.1	1.9	1.9	1.8	1.8	1.8
0.25	77	103	99	3.3	2.4	2.1	1.9	1.9	1.8	1.8	1.8
0.5	66	101	99	3.5	2.5	2.2	2.0	1.9	1.9	1.8	1.8
0.75	58	98	99	3.8	2.6	2.2	2.0	1.9	1.9	1.8	1.8
1	51	96	99	4.0	2.7	2.3	2.0	1.9	1.9	1.8	1.8

Table 4. PCE values at equal V/C ratio
Equal total travel time

p	Kj	Uf	PCE at V/C =								
			0	0.2	0.5	0.7	1	0.7	0.5	0.25	0
			Free Flow region=>				|<Jam region				
0	93	105									
0.1	86	104	1.1	1.1	1.2	1.3	1.9	3.4	5.6	11.9	99
0.25	77	103	1.1	1.1	1.2	1.3	1.8	3.2	5.2	10.9	99
0.5	66	101	1.1	1.1	1.2	1.3	1.7	2.9	4.7	9.6	99
0.75	58	98	1.1	1.1	1.2	1.3	1.6	2.7	4.3	8.7	99
1	51	96	1.1	1.1	1.2	1.3	1.6	2.6	4.0	8.0	99

Table 5. PCE values from the
proposed approach

p	Kj	Uf	Qop	PCE
0	93.46	105	2453	
0.1	86.28	104	2245	1.93
0.25	77.37	103	1987	1.94
0.5	66.01	101	1658	1.96
0.75	57.55	98	1414	1.98
1	51.02	96	1224	2.00

It is to be clear that for Fig.5, the PCE value at a particular V/C ratio does not correspond to the same speed/or density (U/or k in eq.(3) and eq.(4) respectively) for groups with different percentage of heavy vehicles in equal speed and equal density approaches.

V. DISCUSSIONS

In the equal speed approach, when the PCE values are plotted against the basic vehicle flow rate (Fig.4), the PCE values decrease from free flow region to the jam region of basic flow and is the minimum at jam point. The PCE increases with the increase in percentage of heavy vehicles. The PCE values increase very sharply near free flow region and is undefined for the point at and beyond free flow of mixed stream.

In the equal density approach, Fig.4, PCE increases from free flow to the jam region of basic flow and is minimum at free flow point. In this case also PCE increases with the increase in percentage of heavy vehicle. The PCE values near the jam increase very sharply and is undefined for the point at and beyond jam of mixed stream.

But, when the PCE results are plotted against the V/C ratio of corresponding percentage of heavy vehicles, the PCE values decrease with the increase in percentage of heavy vehicles at particular V/C ratio for equal density approach. However, for equal speed approach, the PCE values increase with increase in percentage of heavy vehicles. For both the cases, the tendency of change in PCE from free flow to jam remains in the same direction as in Fig.4.

The PCE values from the proposed approach is shown in Fig.5 as dotted lines for comparison. The PCE values range from 1.93 for p=10% to 2.0 for p=100%. For this example, as the difference in free flow speed of basic vehicle and the truck is not large, the PCE values at capacity in equal speed approach (Fig.5) is almost equal to PCE values obtained from the proposed approach.

VI. CONCLUSIONS

The results from different approaches were compared and it was found that the proposed approach simplifies the concept of estimating PCE values. In case of equal speed concept, the PCE values near the free flow region varies very sharply. Similar is the case for equal density approach near jam condition, thus making numerical values of PCE very difficult to be used. The constant PCE values for all range of volume in particular percent group of heavy vehicle is in fact very easy to be applied. However, the PCE values obtained here are based on a numerical example only. Although this approach is based on the assumption of straight line relationship between speed and density, it is believed that the method could be used successfully for the cases with more than one regime flow model by considering straight line relation in different regions and hence is further planned to be studied.

VII. REFERENCES

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