Microscopic Modeling of Traffic Within Freeway Lanes

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Microscopic models provide an understanding of traffic operations at the level of passage of individual vehicles. Roadway performance can be ascertained by understanding how vehicles interact with each other. Cowan's M3 headway distribution models were calibrated for the curb and median lanes of two-lane mainline freeway segments, using data captured at 14 sites. Calibration of the relationship among Cowan's M3 parameters, proportion of headways greater than a minimum of 1 sec, and flow rate yielded exponential decay equations for each lane. The M3 models provide a source of vehicle arrivals for gap acceptance models, which may be used to quantify the ability of drivers to change lanes, for example. It was found that the parameters calibrated for each lane are suitable for use at any mainline site, independent of site-specific conditions. The proportion of small headways was found to be higher in the median lane than the curb, for all flow rates, and for both lanes lower than their respective equivalents on arterial roads with intersections. The largest bunched headway was considered to be between 2 and 3 sec. The models predicted bunching between 85 and 93 percent of median lane vehicles, and between 75 and 90 percent of curb lane vehicles, at capacity. The lesser amount of curb lane bunching reflects its use as a slower vehicle lane with greater stream friction.

Microscopic models provide a means of modeling traffic at the level of individual vehicles passing roadside observation points by describing the headways, or times between passage of vehicles. These models can be used as inputs to gap acceptance models, so that roadway performance can be quantified with capacity and delay estimates. Because of these attributes, microscopic models provide a greater level of understanding of the processes taking place than do macroscopic models.

This paper details an analysis of within-lane traffic flow on freeway mainline segments. It discusses a method of relating the proportion of headways greater than a minimum value to the lane flow rate, for each of the curb and median lanes on a two-lane, unidirectional element.

BACKGROUND

Headways are the time intervals between passage of successive vehicles past a roadside observation point. Figure 1 illustrates a typical cumulative distribution of freeway curb lane headways, measured over 15 min. The horizontal axis represents the size of headway, and the vertical axis represents the proportion of headways less than the corresponding horizontal axis ordinate. Knowledge of the headway distribution is necessary for the application of gap acceptance theory by which the ability of a stream to absorb vehicles can be quantified.

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Figure 1 shows the measured distribution and a theoretical Cowan's M3 distribution (*1*), which fits the data. This model has two components of headways: those assumed to be equal to a specified minimum, Δ, and those greater than the minimum. Those greater than the minimum are distributed exponentially. The proportion of those greater than the minimum is denoted as α. The two parameters, α and Δ, therefore are interrelated. Cowan's M3 model is given as a cumulative probability function by Equation 1:

$$F(t) = \begin{cases} 1 - \alpha e^{-\lambda(t-\Delta)} & t \geq \Delta \\ 0 & t < \Delta \end{cases} \tag{1}$$

where λ is a shape parameter, given by Equation 2:

$$\lambda = \frac{\alpha q}{1 - \Delta q} \tag{2}$$

and q is the lane flow rate, equal to the reciprocal of the mean headway.

Many headways of 1 sec, and even smaller, were observed. However, only freeway gaps greater than about 1.5 sec are useful for merging, so it was important to select parameters of Cowan's M3 model that consistently facilitate the accurate modeling of these headways. Headways less than this are not particularly useful, so they do not require accurate modeling.

For a particular data set, there is a particular set of α- and Δ-values that provide the best fit. Sullivan and Troutbeck (*2*) showed that α- and Δ-values can be varied slightly, but, by maintaining a relationship between them, the resulting distribution, $F(t)$, is not significantly affected. Consequently, the Δ-value was chosen to be a convenient constant, and α was reevaluated for each data set accordingly.

The minimum headway, Δ, was set to 2 sec for the study of arterial road operations, facilitating a maximum flow rate of 1Δ, or 1,800 veh/hr. Flow rates of up to 2,500 veh/hr were recorded in freeway lanes during this study, so a smaller value of Δ was necessary. A value of Δ equal to 1 sec was considered more appropriate for freeways, as it allows for theoretical flow rates up to 3,600 veh/hr, and accounts for a more realistic minimum headway.

Relationships between lane flow rate and proportion of headways greater than 1 sec need calibration to predict the arrival headway distributions in each lane on a two-lane unidirectional mainline freeway segment, for any lane flow rate. Headway distributions are required as input to merging and lane changing models, which quantify performance measures of capacity and delay.

Headway data were collected in 15-min observations, at mainline locations a minimum of 1 km from ramp junctions, to calibrate relationships between lane flow rate and proportion of headways greater

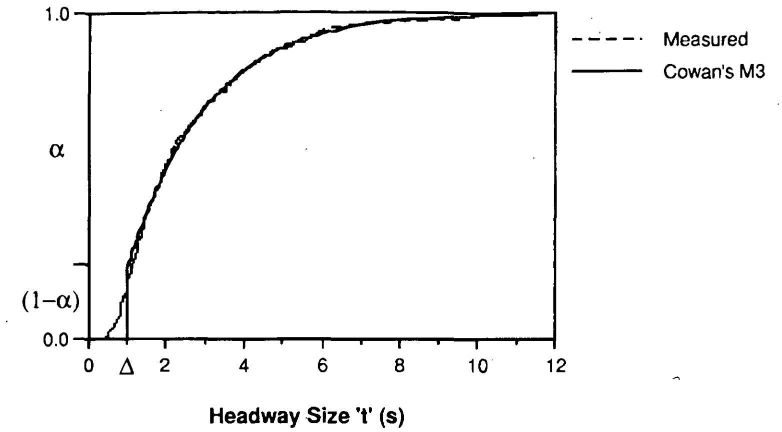

FIGURE 1 Measured distribution of headways, overlain by Cowan's M3 model representation.

than the minimum. With Δ set to 1 sec, the maximum likelihood technique (*3*) was used to find the best Cowan's M3 model fit to the measured distribution for each 15-min observation. The data acquisition led to a series of (α, *q*) data pairs for each lane at each site, for each observation period.

RELATING PROPORTION OF HEADWAYS GREATER THAN 1 SEC TO FLOW RATE

The analysis relating headway proportions to flow rate was limited to two-lane, unidirectional freeway mainline elements, where the lane nearest the edge of the road was denoted as the curb lane and the lane nearest the center of the road denoted as the median lane.

Curb Lane

Figure 2 illustrates the plots of the curb lane relationships between the proportion of headways greater than 1 sec, α, and flow rate, *q*, for all sites. For any given flow rate, there is a considerable spread of points occurring both within and between sites. The difference in environments between sites did not produce a marked effect on the overall relationship between α and *q*.

Although there is considerable spread in the data across all sites, postulating a single curve was considered reasonable, as there is a definite downward trend in α with increasing flow rate. This was expected, because more drivers would travel at small headways as flow rate increases, changing the shape of the headway distribution, so that there is a smaller proportion of the larger, exponentially distributed headways in the representative M3 model.

A model was sought between α and *q*, which would have common attributes to models representing other facilities. Current work by Sullivan and Troutbeck (*2*) showed that a negative exponential model is well suited to both lanes of an arterial road (one containing at-grade intersections). Relationships of this type were discussed and compared by Brilon (*4*) and Akçelic and Chung (*5*) and generally were found to be the best form of model.

Figure 2 shows that the data generally lie close to an α value of 1, up to a flow rate of about 0.2 veh/sec. This means that very few

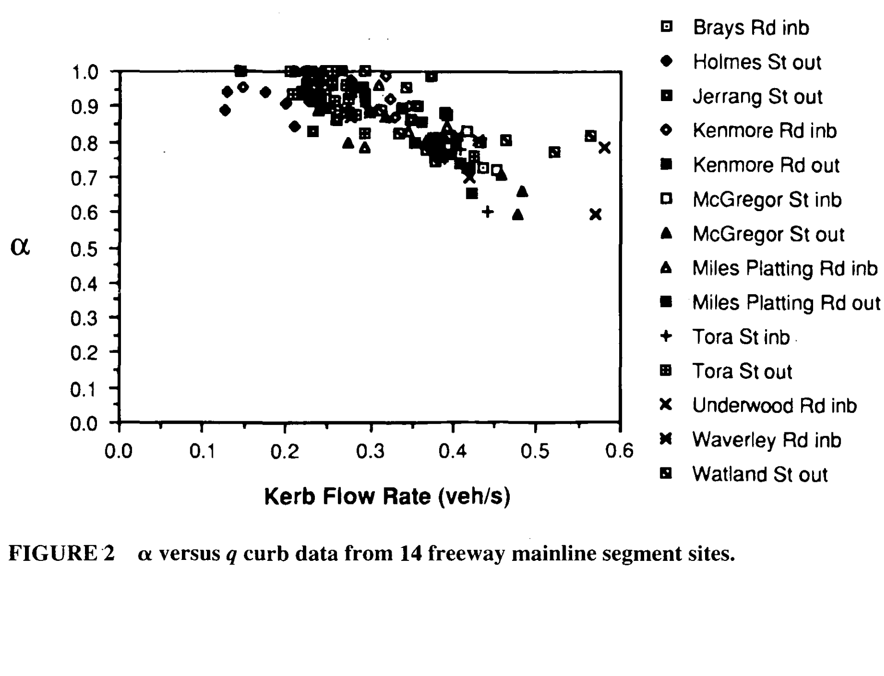

FIGURE 2 α versus *q* curb data from 14 freeway mainline segment sites.

drivers follow at the minimum headway, 1 sec, for low flow rates. Beyond this, the mass of data has a downward trend with flow rate. A constant value of α equal to 1 was considered adequate to reflect the conditions in the low flow regime. A downward trending relationship was considered for the higher flow rates.

This dichotomized relationship assumed that the turning point had the coordinates $(q_0, 1)$, where q_0 was to be found by regression analysis. The proposed relationship is given by Equation 3:

$$\alpha = \begin{cases} e^{-A(q-q_0)} & q \geq q_0 \\ 1 & q < q_0 \end{cases} \tag{3}$$

where q is the curb lane flow rate in vehicles per second, and q_0 is the curb lane flow at the turning point between the two states of headway distribution discussed earlier.

Note that for flow rates less than q_0, where α is equal to 1, Cowan's M3 model becomes a shifted negative exponential distribution, with a minimum headway, Δ, equal to 1 sec.

The values of q_0 and A providing the minimum standard error were found to be 0.1877 veh/sec and 1.0801 sec/veh, respectively; the standard error was 0.0586. A value of q_0 equal to 0.175 veh/sec produced a standard error only 0.597 percent larger than the best-fit value. The optimum value of A was found to be 1.0027, which was then rounded to 1.0, giving a standard error of 0.059—only 0.599 percent larger than the best-fit value. Equation 4 defines the regression equation found to predict the curb lane proportion of headways greater than 1 sec, α, for a given flow rate, q:

$$\alpha = \begin{cases} e^{-1.0(q-0.175)} & q \geq 0.175 \text{ veh/sec} \\ 1 & q < 0.175 \text{ veh/sec} \end{cases} \tag{4}$$

where Δ is equal to 1 sec.

An analysis of variance for Equation 4 yielded an F-value of 217, well exceeding the critical $F(1, 130, 0.05)$ value of 3.91, so the hypothesis that there is no relationship between α and q by Equation 4 was rejected at the 5 percent level.

Figure 3 illustrates the regression curve against the data. The dichotomized linear-exponential relationship fits the data well. A two-part linear relationship would have been equally acceptable within this range of flows. The exponential function selected for the downward trend decays very slightly, appearing almost linear anyway. The linear relationship was not chosen because it may predict negative α-values for some flow rates, which is not satisfactory. The function selected is also applicable to the median lane data, as will be discussed later. Consistency of functional form between both lanes is a positive attribute, as it is has greater flexibility in practical applications.

F-tests were used to establish whether the general relationship of Equation 4 was a suitable representation of the data for each individual site. The calculated F-values exceeding the critical $F(1, N - 2, 0.05)$ values in 10 of the 14 cases. The four sites found to bear no significant relationship by Equation 4 at the 5 percent level were Jerrang Street outbound (six points), Holmes Street outbound (six points), Underwood Road inbound (seven points), and Miles Platting Road inbound (eight points).

All of these sites had small sample sizes within narrow bands of flow rates. The data were not able to produce a strong enough trend for any relationship to be significant within each of these sites. The spread of data for each of the 4 sites, however, was not unusually high, compared with the data of all 14 sites. The generalized relationship was therefore considered to be acceptable for each of these locations.

Median Lane

As with the curb lane analysis, the median lane relationships between proportion of headways greater than 1 sec, α, and lane flow rate, q, were found to vary little between the 14 sites, for most flow rates. (Figure 4). For a given flow rate, data points lie within a band with depth of about 0.2 in terms of α, independent of site.

Two regimes of flow state can be seen in Figure 4 for flows above 0.6 veh/sec. A branch of data conforms to the trend of the lower flow data, below 0.6 veh/sec. However, there is also a branch where α-values are higher. Five or six data points that do not conform have α-values greater than 0.4 and result from the distribution's being relatively insensitive to α at these higher flow rates. For instance, if q is 0.65 veh/sec and α is 0.4 or 0.8, the pro-

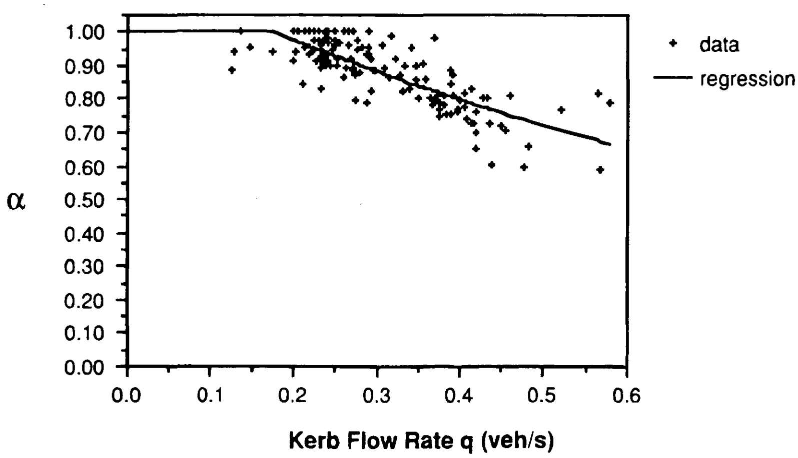

FIGURE 3 α versus q curb lane regression, using Equation 4 and data from 14 mainline sites; q_0 = 0.175 veh/sec, A = 1.0.

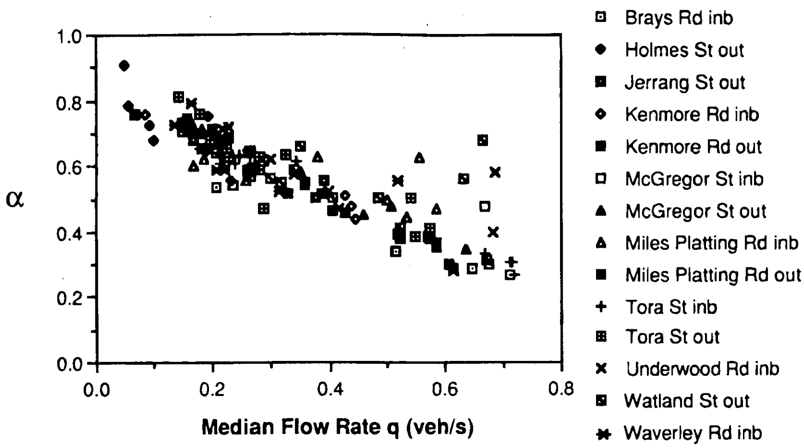

FIGURE 4 **α versus *q* median data from 14 freeway mainline sites.**

portions of headways greater than 2 sec are 19 and 18 percent, respectively. For purposes of modeling, operations were assumed to occur in the low state only, requiring only one curve for the entire flow regime.

In Equation 3, the exponential curve was shifted to the right to account for the low flow state in which practically all headways are greater than 1 sec. However, for the median lane data, a shift to the left was more appropriate, as the trend indicates that even for low flows the proportion of headways greater than 1 sec will not reach unity. When flow rate is 0, for an isolated vehicle, α must equal 1. A model incorporating these features is given by Equation 5.

$$\alpha = \begin{cases} e^{-A(q+q_0)} & q > 0 \\ 1 & q = 0 \end{cases} \tag{5}$$

Regression analysis using Equation 5 yielded optimum values of q_0 and A equal to 0.0869 veh/sec and 1.4070 sec/veh, respectively; the standard error in α was 0.0534. For q_0 rounded to 0.075 and A to 1.45, the standard error was 0.0535, compared with 0.0534 for the best-fit parameters. The difference is negligible. The regression curve for the relationship between α and q for the median lane is given by Equation 6:

$$\alpha = \begin{cases} e^{-1.45(q+0.075)} & q > 0 \text{ veh/sec} \\ 1 & q = 0 \text{ veh/sec} \end{cases} \tag{6}$$

where the minimum headway, Δ, is 1 sec.

Figure 5 illustrates the curve of Equation 6 against the field data. An analysis of variance for the equation gave an F-value of 723, compared with a critical F (1,125, 0.05) value of 3.91. The hypothesis that Equation 6 is unsuitable was rejected at the 5 percent level of significance.

F-tests were used to determine whether the common relationship of Equation 6 gives a reasonable representation to the data of each individual site. The calculated F-values exceeded the critical $F(1, N - 2, 0.05)$ values in all but 1 of the 14 cases. Again, insufficient data were available at this site to produce a strong enough trend for any relationship to hold.

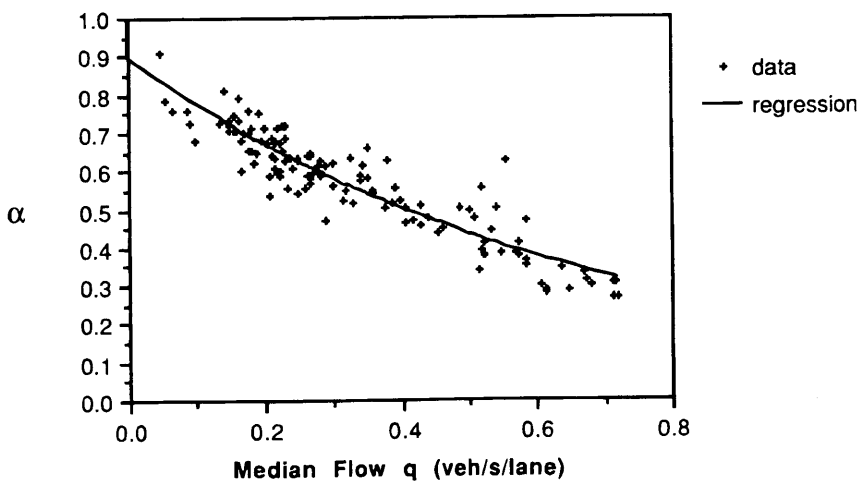

FIGURE 5 **α versus *q* median regression, using Equation 6 for data from 14 mainline sites; q_o = 0.075, A = 1.45.**

DISCUSSION OF RESULTS

Uses

The models for proportion of headways greater than 1 second, α, versus lane flow rate, q, have practical and theoretical applications in traffic engineering problems.

Bunker and Troutbeck (*6*) described relationships for estimating the flow rate in each of the curb and median lanes of a freeway mainline segment, given a total flow rate. Dichotomized linear models were selected to model the relationship between curb lane and total freeway flow rates. The relationships developed here may then be used to estimate the proportion of headways greater than 1 second in each lane, under the specified total demand. Using Equation 2, the decay constant of Cowan's M3 model may be calculated for each lane. All of the parameters necessary for using Cowan's M3 model for distribution of traffic within a lane, given in cumulative form as Equation 1, are then available. Thus, the amount of traffic in each lane and the distribution of headways within lanes may then be predicted for any freeway mainline segment, for any total flow demand.

This compound model has uses in prescribing the arrival of traffic on freeway mainline segments and estimating traffic inputs to gap acceptance models. Cases in which gap acceptance theory may be used for a mainline segment include merging and lane changing. Subsequent to the study described here, a gap acceptance model was established to predict delays and the distances required to perform lane changes, which are valuable performance measures. The model requires the distribution of headways in the target lane for the flow rate under consideration, as was calibrated here, and parameters for driver critical acceptance.

The models developed here may also be used to gain an understanding of the operation of a freeway and to compare it with other facilities. Comparisons are now made between the performance of freeway lanes and lanes on arterial roads with intersections.

Comparison of Curb and Median Lanes

Curb and median mainline freeway lanes do not operate in the same manner, as Figure 6 shows. For any given flow rate, the curb lane has a higher proportion of headways greater than 1 second and therefore would be expected to have fewer vehicles following at close headways.

The curb lane flow rates do not reach the high flows observed in the median lane. The maximum flow rate recorded in the curb lane at any site was approximately 0.58 veh/second, or 2,100 veh/hr, whereas in the median lane, the highest flow rate recorded was approximately 0.72 veh/sec, or 2600 veh/hr. This is consistent with the findings of Bunker and Troutbeck (*6*), who studied lane flows on freeway mainline segments. In those analyses they found that the curb lane is the dominant carrier under low total flows, and the median lane is the dominant carrier under high total flows, hence the discrepancy between maximum flows recorded in each lane.

The models for α versus q were not extended beyond the maximum flow rates recorded, as it is likely that they are close to capacity. The Cowan's M3 headway distribution model may not be applicable to congested operations. The relationship between α and q certainly would not be consistent with the model established earlier under those conditions.

The higher bunching in the median lane for any given lane flow rate relates to the apportioning of total flow between lanes (*6*). The median lane is reserved principally for overtaking on divided roads. Drivers using the median lane are likely to be more dissatisfied with their speeds than curb drivers, who tend to travel at more comfortable headways (of greater than 1 sec from the vehicle in front). Because the median lane is considered to be the fast lane, drivers might tend to be more alert and, as a result, travel closer to vehicles in front. This could be because a driver in a median platoon may intend to be in the median lane only until he or she passes the vehicle in the curb lane so is prepared to follow at a closer distance, or because the driver wishes to pressure the driver in front to speed up or move to the curb lane.

Drivers in the median lane may also be prepared to travel at close headways more often, as there is not as much stream friction created in the curb lane by merge and diverge areas.

If the proportion of vehicles following closely behind others can be considered to be a measure of the quality of service, then Figure 6 indicates that drivers in the curb lane have a better quality of service than those in the median lane. Of course, the driver elects to use a particular lane, so an improved speed that may be available,

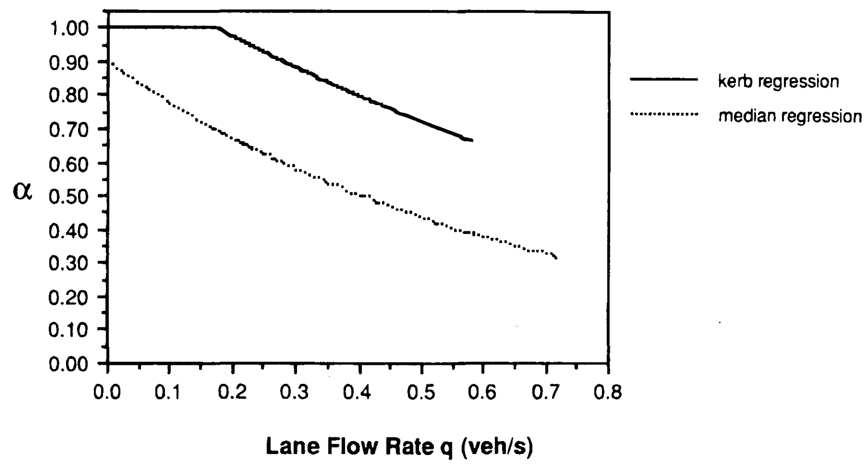

FIGURE 6 Models developed for α versus q in each lane, for freeway mainline segments. Differences show that each lane operates in a unique manner.

or perceived to be available, in using the median lane may be an offsetting quality-of-service measure.

Comparison of Freeway and Urban Arterial Facilities

Sullivan and Troutbeck (*2*) analyzed the behavior of traffic within lanes on urban arterial roads, classified as those with at-grade intersections, including traffic circles and unsignalized and signalized intersections. Cowan's M3 model was also used to model the distribution of flows within lanes for that analysis. However, the minimum headway, Δ, selected for that analysis was 2 seconds, the value recommended by road authorities for safe travel.

Sullivan and Troutbeck quantified the relationship between the proportion of "free" vehicles, having headways greater than 2 sec, and lane flow rate, *q,* for each lane on urban arterial link segments, away from intersections. Analyses were conducted for two- and three-lane segments; those for two-lane segments only are discussed here. Exponential models were selected for these relationships.

To compare freeway operations with arterial roads, it was necessary to establish relationships between the proportion of headways greater than 2 seconds and lane flow rate, *q,* for freeways. Using Equations 5 and 6 to predict α, the proportions of headways greater than 2 seconds were predicted by Equation 1. This proportion could then be compared directly with the equivalent quality for arterial roads. The results are plotted in Figure 7.

Figure 7 shows that for a given lane flow rate, a greater proportion of drivers closely follow others on an arterial road than on a freeway. This is partly due to the formation of platoons of vehicles at intersections on arterial roads. There are not as many opportunities to bunch vehicles together on freeways, where there are no interruptions in the uncongested state. The lower-speed environment of an urban arterial would also act to maintain a higher level of bunching. Vehicles on arterials are limited to the lower speeds necessary to maintain safety and order, which allows drivers to tolerate shorter headways.

Implications for Bunching

The development of the models for predicting the headway distribution in each lane, given the lane flow rate, helps in assessing the amount of bunching occurring. A bunched driver is considered to be one closely following a vehicle ahead. This assessment is most important at capacity conditions.

Figure 5 shows that the maximum flow rate recorded in the median lane at a site was approximately 0.7 veh/sec, or 2,500 veh/hr. It is postulated that this high flow rate is at, or very near to, capacity. Equation 6 gives the corresponding value of the proportion of headways greater than 1 sec, α, equal to 0.325. Equation 1 gives a proportion of headways less than or equal to 2 sec, of 85 percent. This can also be seen in Figure 7. The proportion less than or equal to 3 sec is 93 percent. If the largest headway in front of drivers who are bunched is between 2 and 3 sec, then between 85 and 93 percent of median lane vehicles are bunched at capacity, according to the model. This value appears to be reasonable.

Figure 3 shows that the maximum flow rate recorded in the curb lane was approximately 0.6 veh/sec, or 2,160 veh/hr. It is postulated that this value is also at or very near to capacity. The discrepancy between capacity flow rates in each lane is expected, as the median lane is usually the dominant carrier under such conditions. According to Equation 4, the value of α corresponding to capacity, is 0.65. The proportion of headways less than or equal to 2 sec is then 75 percent, and the proportion of headways less than or equal to 3 sec is 90 percent. If the largest bunching headway is between 2 and 3 sec, then between 75 and 90 percent of curb lane vehicles are bunched at capacity, according to the model. Again, this appears to be reasonable.

The lesser amount of bunching in the curb lane at capacity is to be expected because of the slower drivers who wish to travel at more relaxed headways, and the cautious drivers who expect vehicles to be merging into the curb lane from an on-ramp or the median lane. The result shows that it would be more difficult to move into the median lane at capacity than into the curb lane. This conclusion matches observations of capacity operations.

CONCLUSIONS

Headways are the times between passage of successive vehicles in a lane. Knowledge of the headway distribution is important when using gap acceptance theory to assess the ability of a lane to absorb merging vehicles. Cowan's M3 model was used to model the head-

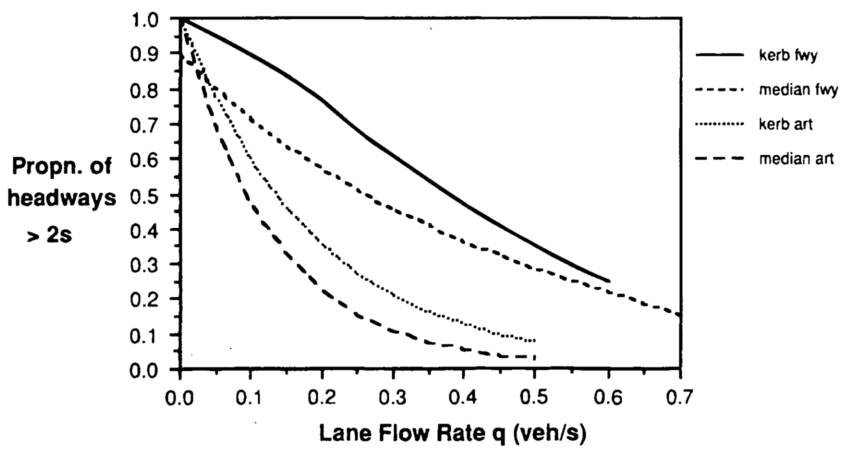

FIGURE 7 Proportion of headways greater than 2 sec versus lane flow rate, *q,* for curb and median lanes of freeway and arterial road types.

way distributions in the curb and median lanes on two-lane, unidirectional mainline segments, a minimum of 1 km from ramp terminals. Parameters of the M3 model include the minimum headway modeled, proportion of headways greater than the minimum, and a shape parameter, which is a function of the lane flow rate. Headways greater than the minimum are distributed exponentially.

A constant minimum headway of 1 sec was selected for convenience, as this value permits accurate modeling of all useful headways greater than about 1.5 sec. Small measured headways close to the minimum of 1 sec are poorly modeled; however, they are not considered useful to entering drivers so do not require specific attention.

Two relationships were found that relate the proportion of headways greater than 1 sec to flow rate, for each of the curb and median lanes. Both equations were based on exponential regression across 14 sites and were found to be significant at the 5 percent level, based on the results of F-tests. They were also shown to be suitable estimators of the relationships for individual sites. Although these empirical equations are recommended for estimating the value of α, given a lane flow rate, q, it must be emphasized that there was a considerable amount of spread in the data. The standard errors were 0.059 for the curb lane and 0.054 for the median lane, in terms of α.

The relationship may be used in conjunction with lane flow models to predict the distribution of vehicles in both lanes for any two-lane mainline location, given the total flow rate. Gap acceptance theory may then be used to predict delays, and subsequently distances required to change lanes, which are valuable performance measures.

Comparison of the relationships between proportion of headways greater than 1 sec and lane flow rate, for both lanes, shows that the proportion of small headways is greater in the median lane for any flow rate. This relates to its function as a fast or overtaking lane. Drivers in the median lane are more likely to be dissatisfied with their speeds, traveling at closer headways.

Relationships were compared with similar ones calibrated for arterial roads with at-grade intersections. The minimum headway modeled for these facilities was 2 sec. For any flow rate, and for both lanes, the proportion of headways greater than 2 sec is always greater for freeway traffic than for arterial traffic, because there are not as many opportunities to bunch traffic together on freeways.

The development of the models for prediction headway distributions in each lane enabled assessment of the amount of bunching. The largest bunched headway was expected to be between 2 and 3 sec. At capacity flow rates, between 85 and 93 percent of median vehicles and between 75 and 90 percent of curb vehicles are bunched, according to the models. These values match observations. The lesser amount of bunching is expected in the curb lane, as was the lesser amount of the very small 1-sec headways.

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