SPEED AND DELAY ON SIGNALIZED ARTERIALS

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(Reviewed by the Highway Division)

ABSTRACT: This paper presents a model to predict the influence of traffic flow on the running speed of signalized arterials in Montgomery County, Maryland, while controlling for link length, the number of lanes, and route type. The model separates the changes to link running speed due to same-direction traffic and intersection approach delay from cross-traffic. It is found that flow has a small impact on link speed, each 1,000 v/l/h reduces speed by 4–8 k/h. Longer links have higher speeds, indicating that they more closely approximate free-flow conditions. Measures of intersection and link travel times are also compared. Although link running times exceed intersection stopped delay in general, total intersection delay (stopped and approach) exceeds the delay caused by same-direction traffic. This information can inform investment decision makers about roadway and intersection improvements.

INTRODUCTION

Estimates of average travel and running speed on signalized arterials from transportation models are inadequate to meet the many demands being placed on them. Link travel time determines the choice of route, and, in the long term, the number of vehicle trips. Similarly, the efficient timing of traffic signals depends on the accurate estimation of the time it takes to travel between them. Metropolitan areas, to meet air quality standards, must forecast the speed-dependent emissions from vehicles. Lastly, travel speed and delay define level of service, which is used for infrastructure planning, land regulation, and development exactions.

As many needs as there are for good speed estimates, there are approaches to obtain these numbers, including both macroscopic and microscopic methods. Among the macroscopic methods are theoretical and practical approaches. In macroscopic theory, traffic is modeled as a stream (Gerlough and Huber 1975; Pensaud and Hurdle 1991; Ross 1991; Hall et al. 1992; Banks 1992; Gilchrist and Hall 1992; Disbro and Frame 1992; Daganzo 1995). For intersections, queuing models have been developed (Webster and Cobbe 1966; Hurdle 1985; Hagen and Courage 1992; Teply 1992). Signalized arterials comprise a complex state in between idealized traffic streams and intersections. While they are streamlike in some respects, there are many slow downs, accelerations, and a great deal of side friction which cannot be ignored. Furthermore, rarely is the link itself the capacity constraint, but rather the downstream intersection. Although theory is well developed for idealized cases, signalized arterials are hybrids, and theory needs to be combined with an empirical approach.

Approaches used in practice include methods from the Highway Capacity Manual (HCM) [Transportation Research Board (TRB) 1985] and volume-delay functions used in route assignment models (Spiess 1988). However, as might be expected, the approaches emphasize different things, engineering references focusing on intersection delay, and planning models on same-direction traffic.

Engineering references such as the HCM (TRB 1985) posit capacities on signalized arterials, and estimate running speeds, but in the HCM arterial running speed is not a function of traffic flow (though travel speed is, through the measure of delay at signalized intersections). These sources acknowledge a relationship between stopped delay at the downstream intersection on a roadway segment and an approach delay, suggesting that approach delay equals 1.3 times stopped delay. McShane and Roess (1990), while acknowledging that, in principle, arterial running time is a function of flow, argue that calculating arterial travel speed at different flows is unnecessary because the changes in arterial travel speed would be dominated by stopped delay.

Transportation planning models developed initially to plan the interstate highway system have since been applied at more detailed scales (Boyce et al. 1988). The route assignment component of these models determines the paths that travelers take on the network as a function of travel time, solving for a network equilibrium. Each link has a function which relates the flow on the link to the travel time on the link, an inverse supply curve. Typically, however, these functions either assume a fixed intersection delay or only allow intersection delay to vary with the flow on the approach link, rather than explicitly considering cross-traffic. This is done despite the fact that intersection delay depends on the amount of green time given to a specific approach, and the proportion of green time bears some resemblance to the approach flow relative to the flows approaching from other legs (cross-traffic) as well as the turn capacity.

Neither approach is complete, and each misses important influences on travel time. The research objectives of this paper are:

- To estimate a model of peak hour running speed on signalized arterials as a function of same-direction traffic, cross-traffic, and physical characteristics of the roadway (length, number of lanes, and route type)
- To use the model to quantify the amount of delay caused by same-direction traffic and by cross-traffic in the observed data.

The database for this study merges traffic counts with travel and multiple running speed observations collected from a floating car study on 941 different road segments in Montgomery County, Maryland, during 1987, for the morning peak hour. The data are used to estimate the speed curve for three classes of road. While the data and analyses here are necessarily limited to Montgomery County, the general results from the estimated model can be compared with other areas. Furthermore, the approach taken to measure the proportion of de-

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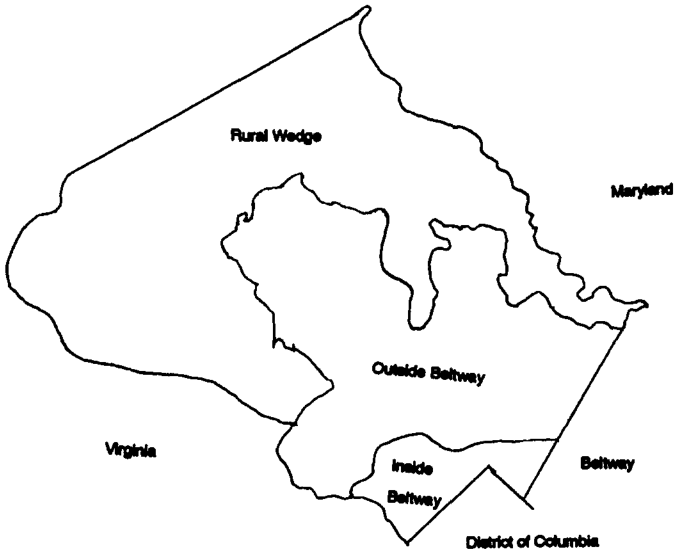

FIG. 1. Map of Montgomery County, Maryland

lay due to same-direction traffic and cross-traffic can be applied to other networks.

A brief description of the region of study, Montgomery County, is presented in the following section. This paper then discusses the data sets used in the analysis. The specific hypotheses for the speed model are subsequently presented. Subsequent are the results from an ordinary least-squares regression. The estimated model is applied to determine the proportion of delay on signalized arterials due to other same-directional traffic and due to cross-traffic.

REGION OF STUDY

Montgomery County, Maryland, the geographic focus of this study, had 750,000 residents and 415,000 jobs in 1990. For purposes of this analysis, the county is divided into three areas: inner suburbs (the area between the District of Columbia and the Capital Beltway), outer suburbs (the suburban areas outside the beltway), and the rural "wedge" area, shown in Fig. 1. These areas were identified because the nature of the transportation network differs. The inner suburbs are older and mostly built prior to World War II, with somewhat narrower roads and driveways opening onto major arterials. The outer suburbs have been built mostly since World War II, with highways designed to higher engineering standards. The rural areas have old farm-to-market roads, which have been paved and widened since their original construction, but most are considered substandard.

DATA

Three primary data and information sources were used for this analysis. The first is the Montgomery County traffic counts database, developed from periodic collection of intersection turning movement counts. The traffic counts used in this study were taken during the morning peak hour throughout 1987 and adjusted using day-of-week and month-of-year factors to obtain annual average weekday traffic in the morning peak hour (Greenhorne and O'Mara 1988).

The second data source was a floating car study conducted in 1987 (Douglas 1992). Running time and intersection delay on major routes in Montgomery County were collected for the morning and afternoon peak and off-peak periods. Multiple runs were made in each time period; they were then averaged to give morning peak period trip (and running) times and speeds. The highest all day running speed was also extracted from the data. Intersection stopped delay was defined by the point after the vehicle first came to a complete stop when approaching an intersection, and was defined to end when the driver reached the center of the intersection. While attempts were made to measure approach (non-stopped) delay directly, they were not consistent between the test drivers and not carried forward to the final data set for analysis. Therefore, only two direct time measures are used in this study; (1) time in motion, which includes deceleration and acceleration; and (2) time stopped.

The third data source is the road network database used in the county's transportation planning model. The 1987 network database with its length, lanes, and geographical coding was combined with the traffic count and speed data. Directional links which had both morning peak hour (running and travel) speed and flow data in 1987 were selected for this study, totaling 941 data points.

The speed and downstream delay were collected at different times from the flow data. The effect of the time disparity on the model should have less correlation between speed and flow, than if the data were collected together. To the extent that the results are statistically significant despite the imperfections of the data, they suggest that an even stronger relationship would appear had the data been collected together. In the aggregate analysis, if the results are significant, then there is confidence that the coefficient values are different from zero in the direction suggested by the sign. Nevertheless, it is recognized that the variance is larger than in the ideal case of simultaneous data collection. Ideally, more observations would be obtained for all variables using more accurate measurement techniques, including, particularly, downstream approach and stopped delay, but any variable's significance, despite few observations and high variance, indicate its importance.

METHODOLOGY

In this model, morning peak hour running speed is the dependent variable. Independent variables include flow per lane (Q) and several physical characteristics of the link. They are highest all day speed [V_H (in kilometers per hour)]; dummy (1, 0) variables for whether the directional (one-way) link is two lanes ($N2$), three lanes ($N3$), or four or more lanes ($N4$); the classification of the highway [major highway ($R2$), primary arterial ($R3$), secondary arterial ($R4$)]; and downstream intersection stopped delay [T_s (in minutes)]. Further, the link length [L (in kilometers)], which indicates to what extent the road segment approximates a limited access facility, should also be a factor in the estimation of running speed, though the presence of driveways should be kept in mind. Unfortunately there is no data on driveways. In particular, short links will be more affected by slowing near intersections, resulting from intersection queuing, while longer links will have greater immunity to this phenomenon. Table 1 shows the summary statistics (mean and standard deviation) for the variables used in the analysis stratified by geographic area.

Lease squares regression analyses are conducted for links in three geographic areas: (1) suburbs located inside the beltway; (2) suburbs located outside the beltway; and (3) rural areas. The stratification is to test the hypothesis that the coefficient estimates in the areas are different. The differences are thought to be caused by the different nature of road and development standards in place when the roads in the three areas were constructed. Roads inside the beltway reflect pre-World War II standards predominantly. Many of the major arterials had streetcars until after the war, and lanes tend to be narrower than more recent construction. Roads in the suburban areas outside the beltway tend to have wider lanes, and as can be seen in Table 1, longer distances between intersections and higher freeflow speeds. Highways in rural areas are often not

TABLE 1. Mean and Standard Deviation of Key Variables

	Suburban Areas		
Variables (1)	Inside beltway (2)	Outside beltway (3)	Rural (4)
Speed [V (k/h)]	34.88	41.60	55.04
	12.51	15.42	12.39
Flow [Q (v/h/l)]	547.60	592.88	430.99
	292.06	334.27	361.38
Downstream intersection delay [T_S (min)]	0.27	0.24	0.09
	0.47	0.49	0.23
Highest all-day speed [V_H (k/h)]	48.24	57.97	69.86
	17.05	14.64	13.41
Length [L (km)]	0.46	0.72	1.64
	0.31	0.57	0.87
Number of lanes (N) [N]	2.38	1.85	1.00
	0.79	0.90	0.00
Major highways ($R2$) [0, 1]	0.85	0.74	0.30
	0.36	0.44	0.46
Major arterials ($R3$) [0, 1]	0.12	0.21	0.64
	0.32	0.41	0.48
Minor arterials ($R4$) [0, 1]	0.03	0.05	0.06
	0.18	0.22	0.24
Sample size (N)	179	712	50

Note: For each variable top values are means and bottom values are standard deviations.

built to standard, but are old farm-to-market roads, with fewer intersections, steeper grades, and sharper curves.

In any model there is some trade-off between accuracy and simplicity. Accuracy can be improved by adding variables, by adding interaction terms between variables, or by changing the mathematical relationship between independent and dependent variables. This accuracy improvement is at the cost of increasing complexity of the model, making it harder to interpret directly. Further research should test alternative functional forms, such as nonlinear transformations and interaction terms, in a systematic fashion. However, nonlinear transforms of many of the variables in isolation, as briefly discussed later, were attempted, but did not add to the explanatory power of the model. Similarly, the writer tested some interaction terms (multiplying independent variables), but these also did not improve the model's explanatory power. For this analysis, the simplest function form, linear, was chosen using all of the available variables. This enables direct interpretation of the regression results. The model can be expressed as:

$$V = \beta_0 + \beta_1 Q + \beta_2 L + \beta_3 N2 + \beta_4 N3 + \beta_5 N4 + \beta_6 R3 + \beta_7 R4 + \beta_8 V_H + \beta_9 T_S \quad (1)$$

HYPOTHESES

It is expected that flow per lane in the peak hour is positively associated with travel time per unit distance or pace, and, thus, negatively associated with running speed, the dependent variable. The higher the flow, the lower the speed, as more cars cause mutual interference and provide a constraint on how fast a driver can comfortably and safely drive. In theory, when flow exceeds capacity, queuing occurs, which suggests a two-part relationship, each part of which is linear in a sample, deterministic queuing model with steady approach flows. However, on signalized arterials, it is generally intersection, rather than link capacity, which is the binding constraint. Therefore, only flows less than link capacity are expected. This indicates only the first part of the relationship that will appear in the data.

Many variables describe the physical characteristics of the roadway. Link length (L) is thought to be positively related to running speed. A longer length allows a link to operate more efficiently, and stops will occur less frequently. A similar factor, for which there was unfortunately no available data, is signal progression, which should also reduce the number of stops per unit length.

While the number of lanes obviously affects link speed, it is not immediately obvious that each lane brings with it the same effect on link speed. For that reason, flow is converted to flow per lane, and the numbers of lanes are treated as a set of dummy variables ($N2$, $N3$, $N4$). Whether the number of lanes is positively or negatively associated with speed is an empirical question. While a second lane allows lane changing, enabling a driver to pass a slower car, the additional lane may also bring with it additional friction. This is further complicated by interactions between the number of lanes (discrete: 1–4) and the flow per lane (relatively continuous: observed to vary from 0–1,600), there is both a practical maximum and minimum to the number of lanes. There is also an interaction between the number of lanes and adjacent land uses which are found in practice, wider links are more likely to have adjacent commercial land uses, while one lane arterials are more likely to have adjacent residences, although current development standards discourage frequent driveways on through roads.

Each link is associated with a functional classification assigned by the county's Master Plan of Highways [freeway ($R1$), major highway ($R2$), primary arterial ($R3$), and secondary arterial, primary residential or business district ($R4$)]. Only the latter three classes are in this dataset, and dummies were assigned to the last two classes ($R3$, $R4$). The vast majority of the links in the sample are major highways ($R2$), and the lower class roads for which data was collected were those which provided important connections. It is expected that the higher the class of the road, the higher the speed, so the variables $R3$ and $R4$ should be negatively associated with speed.

Finally, the highest all-day speed measured on the link (V_H) is a surrogate for other design characteristics of the road, such as grade and curvature, not contained in the length, lanes, and route type variables.

A portion of the link running speed is not determined by physical characteristics, but by the more dynamic conditions relating to usage and signal timing. Intersection delay is a function of both flow on the link and on cross-links. In fact, depending on the signal policy, higher flows on the link, all other things being equal, may increase the green time given that link, and thus, reduce delay. Higher flows on cross-links clearly increase delay. This effect is measured through the T_S variable, downstream stopped delay. It is hypothesized that the higher downstream delay at the intersection will slow speeds on link because approach delay occurs as cars slow to a stop as they approach an intersection queue.

RESULTS

Table 2 shows the results of ordinary least-squares regressions testing the hypotheses about the influence of independent variables on peak hour link speed (V). Table 2 also allows a comparison of the results across geographical areas to see if they are statistically different. Difference of means tests were performed comparing the areas pairwise, which are shown in the last three columns of Table 2. In almost all cases (20 of 24 pairwise comparisons), the coefficient values were statistically different between areas. In addition, the average values were generally statistically different from zero, which is shown by the P(2 Tail) rows for each variable.

Taking the independent variables in order, the coefficient on flow (Q) varies from −0.0042 inside the beltway to −0.008 in suburban areas outside the beltway. This indicates that every 1,000 v/l will reduce speed by 4.2–8 k/h. The sign was negative as expected, and statistically significant (at the 5% level) in both suburban areas. It should be noted that flow was not

TABLE 2. Model of Morning Peak Hour Running Speed *V* (k/h)

Independent variables (1)	Suburban Areas			Difference of Mean *T*-Test		
	Inside beltway (2)	Outside beltway (3)	Rural (4)	Inside beltway —Outside beltway (5)	Outside beltway —Rural (6)	Rural—Inside beltway (7)
Constant	17.85	19.76	23.69	−5.73	−3.67	5.23
	4.30	2.33	7.55	—[a]	—[a]	—[a]
	0.00	0.00	0.00	—	—	—
Flow [Q (v/h/l)]	−0.0042	−0.0080	−0.0013	22.88	−15.81	6.40
	0.0021	0.0013	0.0030	—[a]	—[a]	—[a]
	0.0519	0.0000	0.6686	—	—	—
Downstream intersection delay [T_S (min)]	−7.06	−6.94	−20.82	−1.11	19.81	−19.46
	1.36	0.92	4.95	—	—[a]	—[a]
	0.00	0.00	0.00	—	—	—
Highest all-day speed [V_H (k/h)]	0.47	0.50	0.52	−10.94	−1.26	3.77
	0.04	0.03	0.10	—[a]	—	—[a]
	0.00	0.00	0.00	—	—	—
Length [L (km)]	5.03	3.05	−0.25	11.00	18.08	−20.93
	2.37	0.86	1.27	—[a]	—[a]	—[a]
	0.04	0.00	0.84	—	—	—
Two lanes ($N2$) [0, 1]	−2.20	−0.94	N/A	−5.07	N/A	N/A
	3.28	1.22	N/A	—[a]	N/A	N/A
	0.50	0.44	N/A	—	N/A	N/A
Three lanes ($N3$) [0, 1]	−4.88	−5.54	N/A	2.52	N/A	N/A
	3.48	1.21	N/A	—[b]	N/A	N/A
	0.16	0.00	N/A	—	N/A	N/A
Four lanes ($N4$) [0, 1]	−9.33	−1.00	N/A	−21.93	N/A	N/A
	4.66	4.04	N/A	—[a]	N/A	N/A
	0.05	0.80	N/A	—	N/A	N/A
Major arterials ($R3$) [0, 1]	−3.94	−3.62	−2.50	−1.32	−2.99	3.26
	3.20	1.20	2.62	—	—[a]	—[a]
	0.22	0.00	0.34	—	—	—
Minor arterials ($R4$) [0, 1]	−2.71	−7.18	−6.78	12.95	−0.58	−5.28
	4.51	2.05	4.90	—[a]	—	—[a]
	0.55	0.00	0.17	—	—	—
Sample size (N)	179	712	50			
Adjusted R-squared	0.59	0.43	0.68			
Standard error of estimate	5.02	7.28	4.41			
F-ratio	29.18	60.40	17.96			
Probability F	0.00	0.00	0.00			

Note: For each variable top values are all coefficients, middle values are all standard errors, and bottom values are all P(2 tail).

[a] Indicates statistically significant difference of means at 99% confidence level.

[b] Indicates statistically significant difference of means at 95% confidence level.

statistically significant on the farm roads in rural areas, despite their inferior design. There are several explanations for this. First, it may be an artifact of the fairly small sample size (50 observations). Second, there may be some interaction between flow and intersection delay (T_S) which is tested below. Since intersection delay is composed in part of both same-direction and cross-direction traffic, there could be some correlation of same-direction traffic component of these two variables (T_S and Q), and their effect on intersection queuing, which would manifest itself least on those links with the longest lengths, namely the rural links. However, as discussed elsewhere, attempts to control for this, including both interaction terms and nonlinearities in the link length variable, did not produce better results. Third, the average peak hour flow on rural links was relatively small. If the effect of flow on speed is nonlinear (with less impact at low flow levels), this third factor may be an indication of that. To test that hypothesis, various power terms were tested in regressions on Q divided by Q_0 (a measure assumed to equal 1,600 v/h/l, the highest recorded flow, which, while not strictly capacity, is the best available assumption), to model a volume/capacity ratio. These did not improve the results, and are not shown. The results relating flow to speed appear to make sense in the suburban areas, indicating a small but noticeable reduction in speed associated with flow. The lack of variability in the observed data for rural areas may limit the applicability of those results.

Length was significant and positive as expected in the suburban areas, the coefficient taking a value of 3.05 outside the beltway and 5.03 inside the beltway, indicating the increase in speed per kilometer of uninterrupted link length. The variable was not significant in the rural areas, where the average length is over 1 km. It is possible that length has an effect up to a point, beyond which it ceases to influence speed as the facility begins to operate as an uninterrupted flow roadway. However, the regression was not improved by replacing length with natural log of length or square root of length.

The lane dummy variables were tested in the suburban areas and all links in the rural area were one lane. A value near zero would suggest that each additional lane has about the same effect on link running speed after controlling for lane flow, that there are no economies or diseconomies of scale associated with adding lanes on the output measure of speed. The coefficients on the variables were not statistically different from zero in four cases, but were different in two: $N3$ in the suburban areas outside the beltway was associated with a 5.5 k/h reduction in speed (representing 215 of 712 links outside the beltway); and $N4$ inside the beltway was associated with a 9.3 k/h reduction in speed (representing only 7 of 179 links inside the beltway). Additional data should be used to corroborate this finding. In particular, it would be extremely useful to be able to correlate the number of lanes with adjacent land use, which tends to be more commercial and intense the more important the roadway, and which also would be expected to be associated with lower speeds.

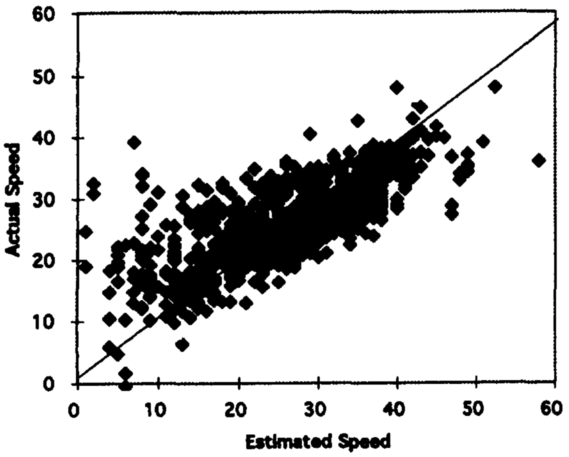

FIG. 2. Estimated versus Actual Speed

The highest all day speed variable (V_H) was as expected, positively and significantly associated with V, the coefficient varied from 0.47 to 0.52. Each additional unit of V_H added about 1/2 of a unit to the peak hour running speed.

As expected, the dummy variables reflecting roadway classification ($R3$, $R4$) were all negatively associated with running speed compared with the suppressed variable ($R2$), since arterial and primary residential roadways have lower speeds than major highways. However, the variables were statistically significant only in the suburbs outside the beltway. The lack of significance may be associated in part with the small sample of links with the lower classification. Because the study was designed to measure important roadways, less important roadways were only sampled when they were part of tours connecting more important roads.

Finally, capturing dynamic measures of the downstream intersection stopped delay, T_S, corroborates our hypothesis by being negatively and significantly associated with peak hour speed. Each additional minute of intersection delay reduces running speed by about 7 k/h in suburban areas (both inside and outside the beltway) and 21 k/h in rural areas. Alternate forms of the variable, computing intersection stopped delay per kilometer and intersection stopped delay squared, were tested in alternative regressions but not found to improve results.

For the three areas, the explanatory power, as measured by r-squared, varies from 0.43 to 0.68. Recognizing that there are other variables omitted from the analysis which could improve results, overall, the r-squared is 0.53, which falls in the range of the explanatory power for each of the three groups, as can be seen in the plot of estimated versus observed values for all 941 observations in Fig. 2. In the comparison of the estimated and actual speed, we find that in two of the 941 cases, the model predicted speeds below zero. Clearly this is not physically possible, but given both the positive and negative influence of the variables in this linear form, can occur in the statistical model. The use of truncated regression would eliminate this problem, but would make no difference in the ultimate conclusions. It should be noted that these links had very low actual speeds (below 10 m/h). The cluster around the 45° line of perfect fit is associated with standard error of estimate of between 7.0 and 11.7 (k/h) for the three areas, which compares favorably with a standard deviation from the mean for the observed speed ranging from 12.3 to 15.4.

TRAVEL TIME COMPARISONS

Using the model estimate of peak period running speed from Table 2, it is now possible to quantify the portion of peak period running time (T_R) which is due to traffic flow on the links (T_Q) and the amount of delay due to approaching the intersection (T_A) (all time measures are in minutes). This is done by solving the model with three sets of data: (1) the speed obtained from applying the model discussed in the previous section (estimated speed) ($\hat{V}$); (2) setting flow (Q) to 0 ($\hat{V}_{@Q=0}$); and (3) setting the intersection delay (T_S) to 0 ($\hat{V}_{@T_S=0}$), which is expected to be a more accurate representation of "freeflow" travel time than V_H, which was measured in the study, as even in the off-peak there is some delay.

$$T_Q = 60L/\hat{V} - 60L/\hat{V}_{@Q=0} \tag{2}$$

$$T_A = 60L/\hat{V} - 60L/\hat{V}_{@T_S=0} \tag{3}$$

$$T_R = 60L/\hat{V} \tag{4}$$

Total travel time (T_T) on a link is defined as the estimated running time plus the stopped delay. Total intersection delay (T_I) is defined as the sum of approach delay and stopped delay.

$$T_T = T_R + T_S \tag{5}$$

$$T_I = T_A + T_S \tag{6}$$

These variables are calculated for each link in the three geographic areas. Table 3 shows the results, weighed by linkflow, and totaled over all links in the area. Of total time on the signalized arterials in the sample, between 6 and 22% is stopped delay (line F of Table 3). Of the total running time

TABLE 3. Time Component by Geographical Area

Row ID (1)	Time category (2)	Calculation (3)	Inside beltway (4)	Outside beltway (5)	Rural (6)	Total (7)
		(*a*) Total Minutes				
A	Link stopped delay		51,978	187,175	3,306	242,458
B	Link running time		183,779	744,087	54,310	982,176
C	Approach delay		11,991	44,290	18,072	74,353
D	Flow delay		15,737	114,842	6,969	137,549
E	Total	A + B	235,757	931,262	57,615	1,224,634
		(*b*) Percentages				
F	Stopped	A/E	22	20	6	20
G	Running	B/E	78	80	94	80
H	Approach delay (running time)	C/B	7	6	33	8
I	Flow delay (running time)	D/B	9	15	13	14
J	Undelayed (running time)	1 − H − I	85	79	54	78
K	Due to intersection	F + H	29	26	39	27
L	Due to link	1 − K	77	74	61	73

Note: Total time computed as person minutes of travel on links in area.

(line G), between 6 and 33% is approach delay (line H), and between 9 and 15% is due to other traffic (line I). Between 26 and 39% of total time in the peak is in excess of freeflow time because of cross-traffic (line K), and between 7 and 12% is in excess of freeflow time due to vehicles sharing links (line I * line G).

CONCLUSIONS

This paper investigated the factors influencing speed on signalized arterials. It was found that both same-directional flow and cross-directional flow had significant impacts on peak hour speed. These findings suggest that the implicit hypothesis used in link volume-delay functions of route assignment models, that intersection delay can be ignored but link delay matters, is problematic for signalized arterials. It also casts doubt on some procedures used in the Highway Capacity Manual, which suggest that, aside from the use of stopped delay as a surrogate, arterial travel times are largely independent of the flow on them. Particularly, the "rule of thumb" used in the HCM, that approach delay equals 1.3 times stopped delay, is not supported by this data.

Policy issues, such as investment in link or intersection expansion can be informed by this research. On arterials, congestion due to same-directional flow is generally less than that caused by cross-traffic, suggesting investment decisions should consider expanding and improving intersections, and thus reducing stopped (and approach) delay, before expanding the link.

Questions of network design efficiency are also raised. There is an urban design and planning movement, sometimes called "neo-traditionalism" or the "new urbanism," favoring highly connected grid network. When optimizing network designs, connectivity, which creates more direct paths, must be traded-off against its decrease in link length and effects on downstream delay which increase travel time. Additional research could test models isolating the benefits of connectivity and costs of increased traffic interference on route choice and travel demand.

Future research in this area can be assisted through multiple observations on the same link, e.g., using loop detectors, which should reduce interlink variability not captured in the model. Intersection delay can be due to either uniform delay or overflow delay, but they have been combined in this research to a single delay measure. Future research associated with more detailed data, could better specify the nonlinear interactions of different magnitudes of intersection delay on approach delay. Various functional forms, including direct estimation of travel time, can be tried to make the model more useful for route assignment formulations. This work can be applied to integrated assignment/intersection control and delay models using accurate link delay functions considering downstream intersection delay.

APPENDIX. REFERENCES

Banks, J. H. (1992). "Freeway speed-flow-concentration relationships: More evidence and interpretations." *Transp. Res. Rec. 1225*, 53–60.

Boyce, D. E., LeBlanc, L. J., and Chon, K. S. (1988). "Network equilibrium models of urban location and travel choices: A retrospective survey." *J. of Reg. Sci.*, 28, 159–183.

Daganzo, C. (1995). "An informal introduction to traffic flow theory." Univ. of California at Berkeley, Institute of Transportation Studies, Berkeley, Calif.

Disbro, J. E., and Frame, M. (1992). "Traffic flow theory and chaotic behavior." *Transp. Res. Rec. 1225*, 109–115.

Douglas, B. (1992). *MNCPPC travel time and delay study*, prepared for Montgomery County Planning Department, Silver Spring, Md.

Gerlough, D. L., and Huber, M. J. (1975). *Traffic flow theory: A monograph TRB Special Report 165*. Transp. Res. Board, Washington, D.C.

Gilchrist, R. S., and Hall, F. L. (1992). "Three-dimensional relationships among traffic flow theory variables." *Transp. Res. Rec. 1225*, 99–108.

Greenhorne, and O'Mara. (1987). *1987 Traffic station volumes*. Montgomery County Department of Transportation, Rockville, Md.

Hagen, L. T., and Courage, K. (1992). "Comparison of macroscopic models for signalized intersection analysis." *Transp. Res. Rec. 1225*, 33–44.

Hall, F. L., Hurdle, V. F., and Banks, J. H. (1992). "A synthesis of recent work on the nature of speed-flow and flow-occupancy (or density) relationships on freeways." *TRB 71st Annual Meeting*, Washington, D.C.

Horowitz, A. J. (1992). "Implementing travel forecasting with traffic operational strategies." *TRB 71st Annual Meeting*, Washington, D.C.

Horowitz, A. J. (1989). "Tests of an ad hoc algorithm of elastic-demand equilibrium traffic assignment." *Transp. Res. Rec. 23B*, 4, 309–313.

Hurdle, V. F. (1982). "Signalized intersections: A primer for the uninitiated." *Transp. Res. Rec. 971*, 96–105.

Levinson, D., and Kumar, A. (1994). "Integrating feedback into the transportation planning model: structure and application." *Transp. Res. Rec. 1314*, 70–77.

McShane, W., and Roess, R. (1990). *Traffic engineering*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 558.

Pensaud, B. N., and Hurdle, V. F. (1991). "Some new data that challenge some old ideas about speed-flow relationships." *Transp. Res. Rec. 1194*, 191–198.

Ross, P. (1991). "Some properties of macroscopic traffic models." *Transp. Res. Rec. 1194*, 129–134.

Spiess, H. (1988). "Conical volume delay functions." Univ. of Montreal Centre for Transportation Research, Montreal, Canada.

Teply, S. (1992). "Accuracy of delay surveys at signalized intersections." *Transp. Res. Rec. 1225*, 24–32.

Transportation Research Board (TRB). (1985). *Highway capacity manual: special report 209*. Transp. Res. Board. Washington, D.C.

Webster, F. V., and Cobbe, B. M. (1966). Traffic signals. *Road Research Technical Paper No. 56*, HMSO, London, U.K.