

SPEED AND DELAY ON SIGNALIZED ARTERIALS

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ABSTRACT

This research presents a model to predict the influence of demand and capacity on the running speed of signalized arterials in Montgomery County, Maryland. 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 1000 vehicles per lane per hour reduces speed by 4 - 8 kph. Longer links have higher speeds, indicating that they more closely approximate free-flow conditions. A surprising result comes from measuring the effect of an additional lane on link speed, after controlling for flow per lane. It is found that there are slight diseconomies of additional lanes in terms of speed, each additional lane is associated with somewhat slower speeds. Measures of intersection and link travel times are also compared. Although link running times exceed intersection stopped delay, total intersection delay (stopped and approach) exceeds the delay caused by same-direction traffic. This information can inform investment decisions about roadway and intersection improvements.

Key Words: volume-delay function, signal delay, approach delay, traffic flow theory, running speed, highway capacity, Montgomery County Maryland

INTRODUCTION

While a significant amount of traffic uses signalized arterials, estimates of average travel and running speed 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, while for intersections, queuing models have been developed. Approaches used in practice include methods from the Highway Capacity Manual (HCM) (TRB 1985) and volume-delay functions used in route assignment models (Spiess 1988). However, as might be expected, the approaches emphasize different things. Typically route assignment models ignore intersection delay or treat it crudely (and exogenously), while the HCM method for signalized arterials does not consider same directional flow as an important factor influencing running speed on signalized arterials. Neither approach is complete. An important research question is the degree to which each misses important influences on travel time.

The research objectives of this paper are twofold:

- I 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 and capacity measures)
- I 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 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 delay due to same-direction traffic and cross-traffic can be applied to other networks.

Approaches for understanding the interaction of flow and running and travel speed are described in the next section. A brief description of the region of study, Montgomery County, is presented. This paper then discusses the data sets used in the analysis. The specific hypotheses for the speed model are presented. Subsequent are the results from an ordinary least squares model and their interpretation. 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.

BACKGROUND

The context underlying the approach taken here for estimating running speed and delay on signalized arterials is derived first from economic equilibrium theory. Because we are concerned with signalized arterials, which combine aspects of traffic streams with queues, both will be briefly touched on. These are compared to the practical approaches taken to this problem, specifically the Highway Capacity Manual and volume-delay functions used in assignment models.

Economic equilibrium theory suggests that the market price is found where the supply and demand curves intersect. The supply curve gives the quantity supplied at a given price, the inverse supply curve returns the price at a given quantity supplied (Varian 1993). The inverse supply curve is analogous to the link volume-delay function used in route assignment models, where price (time or pace) is a function of flow. In the case of a roadway (ignoring dynamic aspects of intersection cross-traffic), the capacity is invariant over the short term, lanes cannot easily be added. If we are at “equilibrium” and demand does not exceed capacity, then the

amount of traffic flow “supplied” on a fixed roadway is equal to the amount demanded. Figure 1 illustrates the intersection of hypothesized supply and demand curves. Demand is expected to be downward sloping. Some theoretical work has shown that the supply curve is approximately flat until flow comes very near capacity, when queuing may begin (Daganzo 1995). So the approximation of these several components (below, near, and above capacity) with a single convex relationship is principally an analytic convenience rather than a pure theoretical relationship .

Macroscopic traffic flow theory relates traffic flow, running speed, and density. Analogizing traffic to a stream, it has principally been developed for limited access roadways (Leutzbach 1988). The fundamental relationship “ $Q=KV$ ” (flow (Q) equals density (K) times speed (V)) is illustrated in Figure 2 (Gerlough and Huber 1975). Many empirical studies have quantified the component bivariate relationships (Q vs. V , Q vs. K , K vs. V), refining parameter estimates and functional forms (Pensaud and Hurdle 1991; Ross 1991; Hall, Hurdle and Banks 1992; Banks 1992; Gilchrist and Hall 1992; Disbro and Frame 1992).

Various models of intersection delay at isolated intersections have been put forward, combining queuing theory with empirical observations of various arrival rates and discharge times (Webster and Cobbe 1966; Hurdle 1985; Hagen and Courage 1992, Teply 1992). Clearly intersections on arterials are more complex phenomena, including factors such as signal progression and spillover of queues between adjacent intersections. Delay is broken into two parts: *uniform delay*, which is the delay that would occur if the arrival pattern were uniform, and *overflow delay*, caused by stochastic variations in the arrival patterns, which manifests itself when the arrival rate exceeds the service flow of the intersection for a time period.

Signalized arterials comprise a complex in-between state. While they are stream-like in some respects, there are many slow-downs and 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. Though theory is well developed for idealized cases, signalized arterials are hybrids, and theory needs to be combined with an empirical approach.

To explain the speed on signalized arterials, two major practical approaches have been developed. The first emerges from traffic engineering, the second from transportation planning. Engineering references such as the Highway Capacity Manual (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 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 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.

While the problems of estimating intersection delay given flow, and of estimating route choice given signal timings are usually treated in isolation, there have been some efforts to combine them (Horowitz 1988, 1992; Levinson and Kumar 1994). However, the use of conventional signal policies may not guarantee convergence to a network equilibrium. This casts doubts on the usefulness of the equilibrium approach, as opposed to an evolutionary or simulation approach recognizing the inherent complexity involved as well as bounded rationality

(Simon 1955). Nevertheless, despite difficulties in modeling, it is crucial to consider appropriately the influence of intersection delay on link travel times.

Though there are difficulties, there are also opportunities for improvement. While the traditional link volume-delay function in an assignment model depends only on freeflow trip time, traffic flow, and a fixed capacity per lane, there is additional data available with which to apply a more expansive and general equation.

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 figure 3. 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 even major arterials. The outer suburbs have been built mostly since that time, with accompanying higher highway engineering standards. The rural areas have old farm to market roads, which have been paved and widened since their original construction, but which mostly would be considered sub-standard.

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 turning movement counts at intersections. The traffic counts used in this study were taken during the morning peak hour over the course of 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 (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 performed in each time period

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 to measure approach (non-stopped) delay directly were made, they were not-consistent between drivers and not carried forward to the final data set for analysis. Therefore, only the two direct time measures: time in motion, which includes deceleration and acceleration and time stopped are used in this study.

The third data source is the road network used in the transportation planning model used by Montgomery County. The 1987 network with its length, lanes, and geographical coding was combined with the traffic count and speed data. Each directional link which had both morning peak hour (running and travel) speed and flow data in 1987 was selected for this study, giving 941 total.

METHODOLOGY

Because we know neither the supply nor the demand curves, but we have point data of link (running and travel) speed, traffic flow, and capacity characteristics, we will estimate a variant on the inverse supply curve, which will tell us the price (time or pace) in terms of flow and capacity. Here we take morning peak hour running speed, the reciprocal of pace, as the dependent variable.

Flow per lane (Q) is the analog to quantity, and there are a number of other measures explaining capacity, or the remaining supply characteristics. The physical characteristic measures 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 (N_2), three lanes (N_3), or four or more lanes (N_4), the classification of the highway (major highway (R_2), primary arterial (R_3), secondary arterial (R_4)), 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 free-flow facility, should also be a factor in the estimation of running speed, though the presence of

driveways should be kept in mind. 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, standard deviation) for the variables used in the analysis stratified by geographic area.

Ordinary least squares regressions are conducted for links in three geographic areas: suburbs located inside the Beltway, suburbs located outside the Beltway, and rural areas. The reason for stratifying the sample this way is to test the hypothesis that the coefficient estimates in the areas are different. The differences are thought to be due to the different nature of road and development standards in place when the roads in the three areas were constructed. Inside the Beltway reflects pre-World War II standards predominantly. Many of the major arterials had streetcars until after the war, and lanes tend to be narrower. 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 built to standard, but are old farm to market roads, with fewer intersections, but steeper grades and sharper curves.

The functional form of the model is an issue worth discussion. 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, but these increase the complexity of the model, making it harder to interpret directly. Further research should test alternative functional forms, such as non-linearities and interaction terms, in a systematic fashion. However non-linear transforms of each variable in isolation, as discussed briefly below, were attempted but did not add to the explanatory power of the model. Similarly, the author 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 along with 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

Since we are estimating an analog to the inverse supply curve, we expect quantity (Q), defined as flow per lane in the peak hour, to be positively associated with the price (time or pace), and thus negatively associated with running speed, our 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. When flow exceeds capacity, queuing occurs, which suggests a two part relationship, each part of which is linear in a simple, deterministic queuing model with smooth approach flows. However, as noted before, 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 will appear in the data.

Many variables serve as indicators of the fixed part of capacity, that which is associated with 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, 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 capacity, it is not immediately obvious that each lane brings with it the same capacity. For that reason, flow is converted to flow per lane, and the numbers of lanes are treated as a set of dummy variables (N_2, N_3, N_4). 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 get by 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 0-1600), 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 variable V_H , representing the highest all-day speed measured on the link, 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 capacity 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, *ceteris paribus*, may increase the green time given that link and thus reduce delay. But clearly, higher flows on cross-links increase delay. This cross-elasticity is measured through the T_S variable measuring downstream stopped delay. It is hypothesized that the higher downstream delay at the intersection will slow speeds on link, 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 1000 vehicles per lane will reduce speed by 4.2 kph to 8 kph. 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 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 and (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 non-linearities 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 non-linear (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 capacity measure assumed to equal 1600, the highest recorded flow), to model a volume/capacity ratio, but these did not improve the results, and so 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 kilometer. 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 a uninterrupted flow roadway. However, replacing length with neither its natural log nor its square root in the regression improved results.

The lane dummy variables were tested in the suburban areas, all links in the rural area were one lane. The variables were not statistically significant in four cases, but were in two: N3 in the suburban areas outside the Beltway was associated with a 5.5 kph reduction in speed; and N4 inside the Beltway was associated with a 9.3 kph reduction in speed. A value near zero would suggest that each additional lane adds about the same amount of capacity, that there are no economies or diseconomies of scale associated with adding lanes on the output measure of speed after controlling for flow. However, it should be noted that in all six cases, the signs were negative, indicating that additional lanes bring with them a reduction in speed (slight and statistically not significant in most cases, but with a reasonable impact on average speed) relative to the one lane link. A slight diseconomy due to additional lanes, after controlling for flow per lane, may be inferred from the data. However additional data should be used to corroborate this finding. In particular, it would be extremely useful to be able to isolate changes in capacity with change in adjacent land use, which tends to be more commercial and intense the more important the roadway, and which would be expected to be associated with lower speeds.

The highest all day speed (V_H) variable 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 one half of a unit to the peak hour running speed.

The dummy variables reflecting roadway classification (R3, R4) were all negatively associated with running speed as expected, since arterial and primary residential roadways have lower speeds than major highways. The variables were statistically significant only in the suburbs outside the Beltway though. 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. The lack of significance may also be due to the somewhat

arbitrary way in which roads are classified, particularly in the older inner-suburb and rural areas, while the outer suburbs have more roads built to modern standards with consistent classifications.

Finally, capturing dynamic aspects of capacity, the measured 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 kph in both suburban areas and 21 kph 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. Though there are other variables omitted from the analysis which could improve results, in particular adjacent land uses, the general pattern looks good, as can be seen in a plot of estimated vs. observed values for all 941 observations in Figure 4. 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 mph). The cluster around the 45 degree line of perfect fit is associated with standard error of estimate of between 7.0 and 11.7 (kph) 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 observed peak period running speed from the previous section, 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). This is done by solving the model with three sets of data: the speed obtained from applying the model estimated in the previous section (estimated speed) ($\hat{V}$); substituting a value

of 0 for the measured Q ($\hat{V}_{@Q=0}$); and substituting a value of 0 for the actual intersection delay (T_S) measured in the study ($\hat{V}_{@T_S=0}$), 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.

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

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

$$T_R = 60L / \hat{V} \quad (4)$$

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.

$$T_T = T_R + T_S \quad (5)$$

$$T_I = T_A + T_S \quad (6)$$

These variables are calculated for the three geographic areas in table 3. Of total time on the signalized arterials in the sample, between 4% and 23% is stopped delay. Of the running time, between 6% and 18% of the time is approach delay, and between 6% and 12% is due to other traffic. All told, between 23% and 29% of total time in the peak is in excess of freeflow time because of cross-traffic, and between 5% and 10% is in excess of freeflow time due to vehicles sharing links.

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 arterial times are largely independent of the flow on them (except through the use of stopped delay as a surrogate). Particularly, the “rule of thumb” used in the HCM, that approach delay equals 1.3 times stopped delay, is not supported by this data.

CONCLUSIONS

This paper investigated the factors influencing speed on signalized arterials. It was found that both same-directional flow, measured directly, and cross-directional flow, measured via intersection delay, had significant impacts on peak hour speed. This suggests that methods which ignore either of these factors are incomplete.

Policy issues, such as investment in link or intersection expansion or the optimal design of a network can be informed by this research. On arterials, congestion due to same directional flow is generally less than that caused by cross-traffic, suggesting investments should focus on improving intersection capacity, and thus reducing stopped (and approach) delay. There is a movement, sometimes called “neo-traditionalism” or the “new urbanism,” favoring highly connected grid network in the urban design and planning fields. 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, for instance using loop detectors, which should reduce inter-link 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 non-linear 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 & delay models using accurate link delay functions considering downstream intersection delay.

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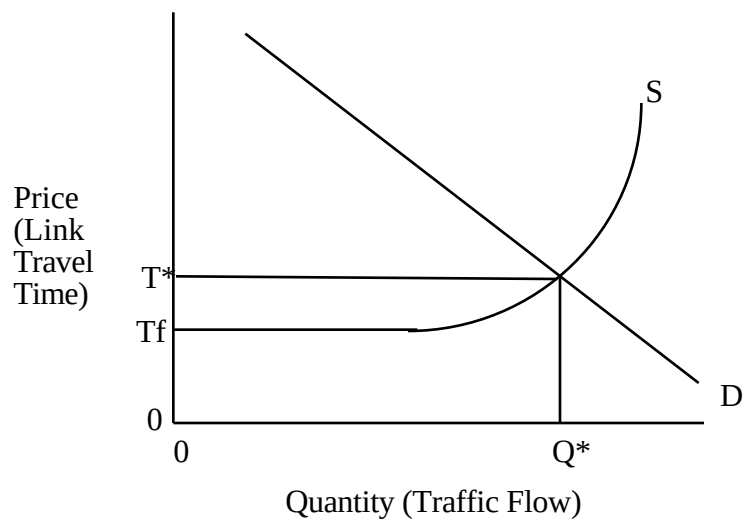
FIGURES:

FIGURE 1: Link volume-delay function as economic supply and demand curves

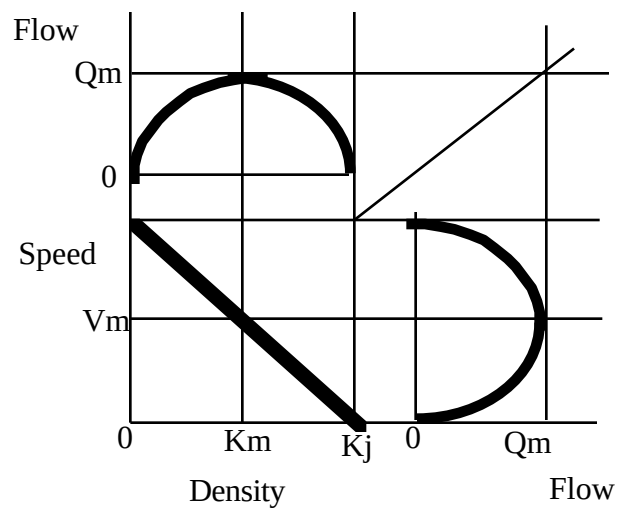


FIGURE 2: Flow-density, and speed-concentration curves (assuming single-regime, linear speed-concentration model)

FIGURE LEGENDS

Figure 1: Link Volume-Delay Function as Economic Supply and Demand Curves

Figure 2: Flow-Density and Speed-Concentration Curves (assuming single-regime, linear speed-concentration model)

Figure 3: Map of Montgomery County, Maryland

Figure 4: Estimated vs. Actual Speed

Policy Areas in Montgomery County, Maryland



Figure 4 Chart 1

ESTIMATED vs ACTUAL SPEED

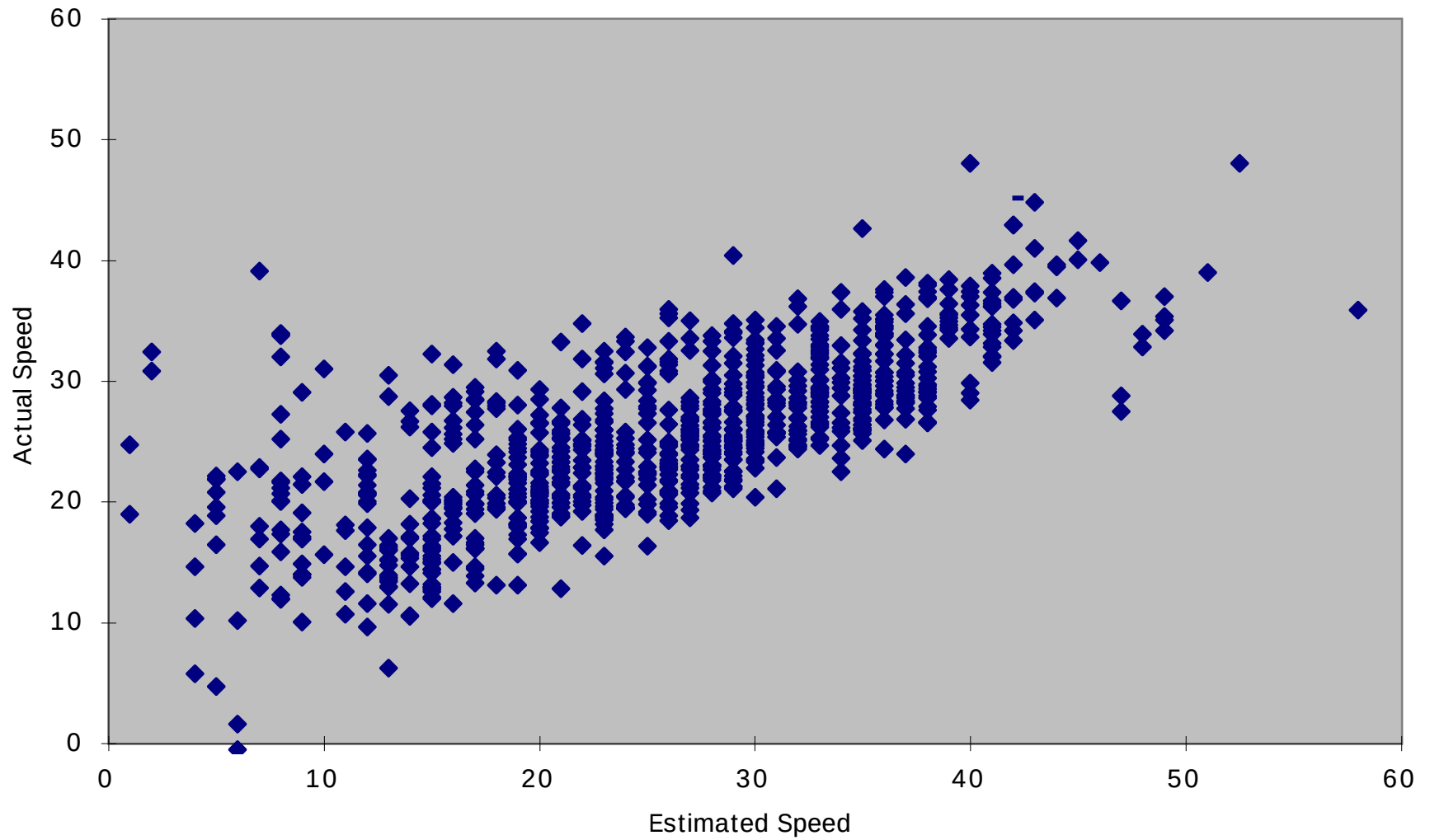


Table1

Table 1: Mean and Standard Deviation of Key Variables

Variables	Suburban Areas		Rural
	Inside the Beltway	Outside the Beltway	
Speed (V) (kph)	Mean	41.60	55.04
	Standard Deviation	15.42	12.39
Flow (Q) (vphpl)	547.60	592.88	430.99
	292.06	334.27	361.38
Downstream Intersection Delay (Ts) (min)	0.27	0.24	0.09
	0.47	0.49	0.23
Highest All-Day Speed (VH) (kph)	48.24	57.97	69.86
	17.05	14.64	13.41
Length (L) (Kilometers)	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

Table2

Table 2: Model of Morning Peak Hour Running Speed V (kph)

Independent Variables	Suburban Areas		Rural	Difference of Means T-Test		
	Inside the Beltway	Outside the Beltway		Inside Belt. - Outside Belt.	Outside Belt. - Rural	Rural - Inside Belt.
CONSTANT	17.85	19.76	23.69	-5.73	-3.67	5.23
coefficient						
standard error	4.30	2.33	7.55	***	***	***
P(2 Tail)	0.00	0.00	0.00			
Flow (Q) (vphpl)	-0.0042	-0.0080	-0.0013	22.88	-15.81	6.40
	0.0021	0.0013	0.0030	***	***	***
	0.0519	0.0000	0.6686			
Downstream Intersection Delay (Ts) (min)	-7.06	-6.94	-20.82	-1.11	19.81	-19.46
	1.36	0.92	4.95		***	***
	0.00	0.00	0.00			
Highest All-Day Speed (VH) (kph)	0.47	0.50	0.52	-10.94	-1.26	3.77
	0.04	0.03	0.10	***		***
	0.00	0.00	0.00			
Length (L) (kilometers)	5.03	3.05	-0.25	11.00	18.08	-20.93
	2.37	0.86	1.27	***	***	***
	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		***		
	0.50	0.44				
Three Lanes (N3) [0,1]	-4.88	-5.54	N/A	2.52	N/A	N/A
	3.48	1.21		**		
	0.16	0.00				
Four Lanes (N4) [0,1]	-9.33	-1.00	N/A	-21.93	N/A	N/A
	4.66	4.04		***		
	0.05	0.80				
Major Arterials (R3) [0,1]	-3.94	-3.62	-2.50	-1.32	-2.99	3.26
	3.20	1.20	2.62		***	***
	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	***		***
	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: ** Indicates statistically significant difference of means at 95% confidence level

Note: *** Indicates statistically significant difference of means at 99% confidence level

Table 3:

Time by Component by Geographical Area

		Suburban Areas		
		Inside the Beltway	Outside the Beltway	Rural
	Total Time in Area in Minutes:			
A	Stopped Delay	43.2	162.9	4.6
B	Estimated Running Time	140.9	742.8	106.6
C	- Approach Delay	10.0	46.0	19.4
D	- Flow Delay	9.7	86.8	7.1
E	Total (A + B)	184.1	905.7	111.2
	Percent of Time in Area:			
F	Stopped	23%	18%	4%
G	Running	77%	82%	96%
H	- Approach Delay (of Running)	7%	6%	18%
I	- Flow Delay (of Running)	7%	12%	7%
J	due to Intersection	29%	23%	22%
K	due to Link	71%	77%	78%