FINAL REPORT

A SIMULATION-BASED APPROACH TO EVALUATE SAFETY IMPACTS OF INCREASED TRAFFIC SIGNAL DENSITY

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ABSTRACT

One of the most controversial access management techniques practitioners face is also one of the most common: restricting signal density. Increased signal density can improve access for minor approaches to a corridor; however, it can also increase delays and rear-end crashes for vehicles on the mainline (major) approach. An ability to evaluate the impacts of increased signal spacing is thus critical for decision makers. Because crash data are not always easy to obtain, a logical question arises: Can simulation models be used to evaluate the safety impacts of increased traffic signal density?

This report describes a method for using simulation models to evaluate the safety impacts of increased traffic signal density in suburban corridors. Using 10 years of data from two major arterials in Virginia, actual crash rates were compared to operational performance measures simulated by the Synchro/SimTraffic model. As expected, crash rates were positively correlated with stops per vehicle and delay per vehicle and negatively correlated with mainline speed.

Three findings were significant. First, the correlation between crash rates and select mainline performance measures (delay, speed, and stops) was relatively strong despite the inherent variability in crash rates: R^2, a measure of explained variance in crash rates, yielded values from 0.54 to 0.89. Second, three distinct regimes relate stops per vehicle to signal density: the installation of the first few signals causes a drastic increase in stops, the addition of the next set of signals causes a moderate increase in stops, and the addition of a third set of signals does not significantly affect the number of stops per vehicle. Third, multiple regime models also relate delay per vehicle to signal density.

This study recommends two practical applications. To the extent these mainline performance measures correlate with crashes, simulation modeling may be used to estimate safety impacts of increased signals, which is appealing because simulation packages are becoming easier to apply. Further, three regime models can suggest when, in the timeline of corridor development, the addition of a traffic signal is likely to degrade corridor performance significantly versus when it will have little effect, thereby allowing decision makers to expend political capital when it is most beneficial (e.g., the occasions when the degradation of corridor performance is significant). Most important, the approach herein suggests a long-range corridor-planning tool for evaluating the impacts of different access densities.

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INTRODUCTION

Access management has been defined as "the process that provides (or manages) access to land development while simultaneously preserving the flow of traffic on the surrounding road network in terms of safety, capacity, and speed."[1] Techniques include maintaining minimum corner clearances; eliminating U-turns; and the focus of this report, keeping signal density as low as possible. Unfortunately, access management requires a tradeoff between competing goals, and stakeholders may not agree where a particular road falls on the axes shown in Figure 1.

Although the tradeoff between access and throughput is not new,[2-4] the justification for access management techniques (such as maintaining a minimum spacing between traffic signals) can be controversial. Although they can improve the operation and safety of a roadway by smoothing traffic flow, access management techniques can also reduce the accessibility of the roadway for immediately adjacent homes or businesses. In attempts to determine the tangible benefits of access management techniques, analytical or mathematical models, usually based on regression, have been developed that try to quantify the operational and safety impacts of various access management strategies.[5] Miller et al. recently investigated the transferability of particular mathematical methods in terms of safety.[6]

Four possible motivations arose in the course of applying models that predict crashes as a function of signal density:

1. *A weakness in using mathematical models is the variability of crashes*. Multiple human factors (fatigue, distractions and inattention, etc.) and other causes of crashes (e.g., poor weather) can increase variance.

2. *Not all crashes are reported, a trend that is exacerbated by changes in reporting thresholds.* For example, the current Virginia threshold for which accidents are

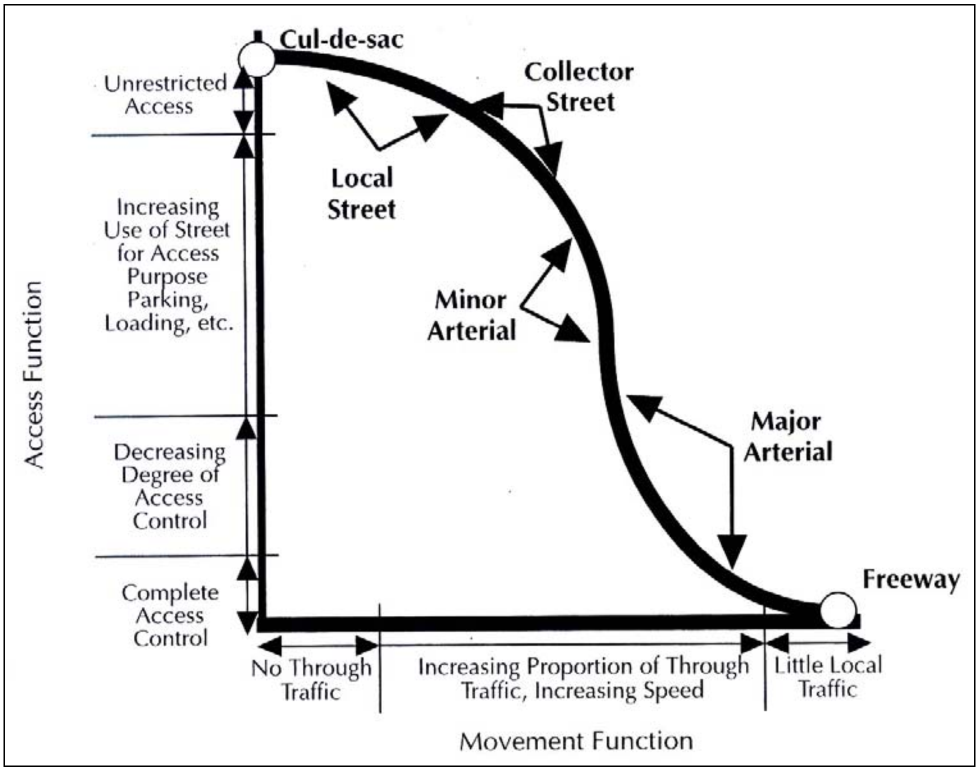


Figure 1. Relationship Between Access Management and Traffic Movement. From *A Policy on Design of Urban Highways and Arterial Streets,* Copyright 1973, by the American Association of State Highways and Transportation Officials, Washington, D.C. Used by permission.

reportable is $1,500 in property damage and/or an injury or fatality, although this threshold has increased over the years.

3. *The actual number of crashes is only one measure of the relative safety of a particular initiative.* Because crashes are relatively rare events, other surrogates for safety have been proposed such as the number of observed traffic conflicts (e.g., near misses, activation of brake lights), speed variance, delay per vehicle, and other operational performance measures.[7,8]

4. *The impact of increased signal density may be nonlinear.* Preston et al. suggested a sharp increase in crash risk when a particular threshold of access density is exceeded.[9] Should this threshold be corridor dependent (e.g., 5 signals per mile for corridor *x* but 2 signals per mile for corridor *y*), then simulation models, with their rich set of data outputs, may be one tool that can forecast when this threshold is reached.

Because of these four factors, simulation models seem to be a logical device for evaluating the impact of traffic signal density on safety. By looking at multiple performance measures (e.g., stops and delay) as a surrogate for crashes, simulation models may address the first three factors. Further, the fact that simulation packages are increasingly being used for operational analyses makes them an attractive option, and a method that connects their results to safety analyses may save time and resources.

PURPOSE AND SCOPE

The purpose of this study was to assess whether simulation modeling may be used to evaluate the safety impacts of signalized access density. (Signalized access density is the number of traffic signals for a corridor of fixed length, usually measured in units of signals per mile or signals per kilometer.) The scope of work was limited to two sites in Virginia that had been used in a related study by Miller et al: Route 17 in York County and Route 250 in Staunton.[6] This study focused on one access management technique: the density of signalized access points.

The focus on signalized access resulted from the view that the VDOT is increasingly being asked to increase the number of signals within a corridor. (For a corridor of fixed length, therefore, an increase in the number of signals is an increase in the number of signals per mile, also known as the signal density.) With the continuous growth of commercial developments along many of the roadways, there is added pressure on the transportation industry to continue to add signals to accommodate each new major development. In fact, the *Manual on Uniform Traffic Control Devices for Streets and Highways* states "laymen believe that traffic signals provide the solution to all traffic problems at intersections. This has led to their installation at a number of locations where no legitimate factual warrant exists."[10]

Thus, there were two primary objectives for this effort.

1. To investigate the feasibility of relating the output parameters from simulation software to actual crash profiles; i.e., is there a link between the number of crashes in a corridor and performance measure such as delay, stops per vehicle, and speed?

2. To investigate the breakpoint concept; i.e., is there a point at which once a certain number of traffic signals are added, there is a notable change in corridor performance?

METHODS

Two Virginia corridors (Route 17 and Route 250) were selected as the case study sites for use in simulation monitoring. These corridors were selected for two key reasons: first, signalized access had changed significantly without major geometric changes, and second, approximately 10 years of historical data pertaining to geometric conditions, traffic volumes, and crashes were available or could be reasonably estimated.

Route 17 is a 7-mi (11.2-km) four-lane divided suburban arterial in York County with annual daily traffic (ADT) between 30,000 and 50,000 depending on the year and the section. Route 250 is a 2.5-mi (4-km) four-lane suburban arterial in Staunton and Augusta County, with ADTs between approximately 20,000 and 27,000 depending on the year.

Four key steps—literature review, data collection, data entry, and data analysis—comprised the methods for this project.

Review of Literature Relating Crashes and Performance Measures

Two types of literature were reviewed: literature that related traffic flow parameters to safety, and literature that applied simulation to access management situations. In both cases, measures of safety were of interest.

Data Collection

To ensure that the simulated sites reflected real-world conditions and to apply the simulation software, data were collected. Data included geometric characteristics (number of lanes, access points, and traffic signals), operational characteristics (volume, signal timings, and delay), and crash data (number of crashes by location and date). The geometric and operational characteristics were obtained through visits to the selected corridor and through in person interviews with the VDOT or local jurisdiction personnel in the respective district, residency or locality with traffic engineering, data entry, or operations responsibilities. These personnel included a district traffic engineer, a city traffic engineer, residency personnel charged with traffic signal timing or data entry. The crash data were obtained from VDOT's Highway and Traffic Records Information System (HTRIS).

For the selected sites, the extent to which crashes have varied over time and the different crash types were documented to provide an understanding of the historic variability of crashes at each site. The crash profile consisted of the severity (fatal, injury, or property damage only), type of collision (rear end, sideswipe, run off the road), and number of crashes. Tables 1 and 2 summarize the crash profiles and Figures 2 and 3 show the corridor diagrams for these two corridors.

Table 1. Summary of Total Crashes per Year by Collision Type for Route 17

Year	Rear End	Angle	Sideswipe	Fixed Object	All Others	Total
1990	91	45	16	10	11	173
1991	90	60	10	6	3	169
1992	92	50	4	6	5	157
1993	100	43	8	4	3	158
1994	124	55	10	6	6	201
1995	112	56	9	8	5	190
1996	90	52	14	5	6	167
1997	120	65	14	8	5	212
1998	144	50	7	11	11	223
1999	126	49	11	9	8	203
Total	1089	525	103	73	63	1853

Table 2. Summary of Total Accidents per Year by Collision Type for Route 250

Year	Rear End	Angle	Sideswipe	Fixed Object	Others	Total
1990	0	6	3	0	0	9
1991	2	4	0	0	0	6
1992	5	3	2	6	2	18
1993	6	4	5	0	2	17
1994	20	8	0	4	0	32
1995	33	12	5	6	2	58
1996	19	9	1	4	2	35
1997	34	11	3	6	0	54
1998	37	13	5	2	1	58
1999	49	17	4	3	1	74
Total	205	87	28	31	10	361

Data Entry

After the data were assembled, the next step was to enter them into a simulation package. The operational and geometric data were entered into *Synchro Plus SimTraffic*, the simulation software chosen for this project because of its relative ease of use. The simulation model was verified by comparing field delay data with delay output from the simulation package. The field delay from a technical memorandum that examined Route 17 for VDOT's Hampton Roads District was used for this research.[18] The field delay for Route 250 was based on data collected using video cameras to analyze the field delay in a previous research effort.[15] Therefore, the delay was not collected explicitly since it was readily available and could be used to ensure that the simulation runs for the base year (1999) produced reasonable results. Once the corridor file was built and running properly to reflect the corridor, the analysis could begin.

A number of assumptions had to be made to translate the data into a form suitable for use by the simulation software. These assumptions are detailed in the Appendix and pertain to the software itself (e.g., setting of the individual link speeds, the length of the simulation, the installation of turning bays, and the reports generated), the conversion of crash and volume data to crash rates, and the estimates of the number of unsignalized commercial driveways (as these change over time) from VDOT's historical data.

Data Analysis

The simulation output reports showed simulated performance measures including vehicle delay, queuing penalty, stops, fuel consumption, fuel efficiency, emissions, travel time, and average speed. The first step entailed comparing the relationships between the simulated performance measures and the crash rates, based on signal installation dates, for the period 1990 through 2000. Although a dozen performance measures were tested, mainline delay per vehicle, mainline stops per vehicle, and stops per vehicle overall were selected for further consideration.

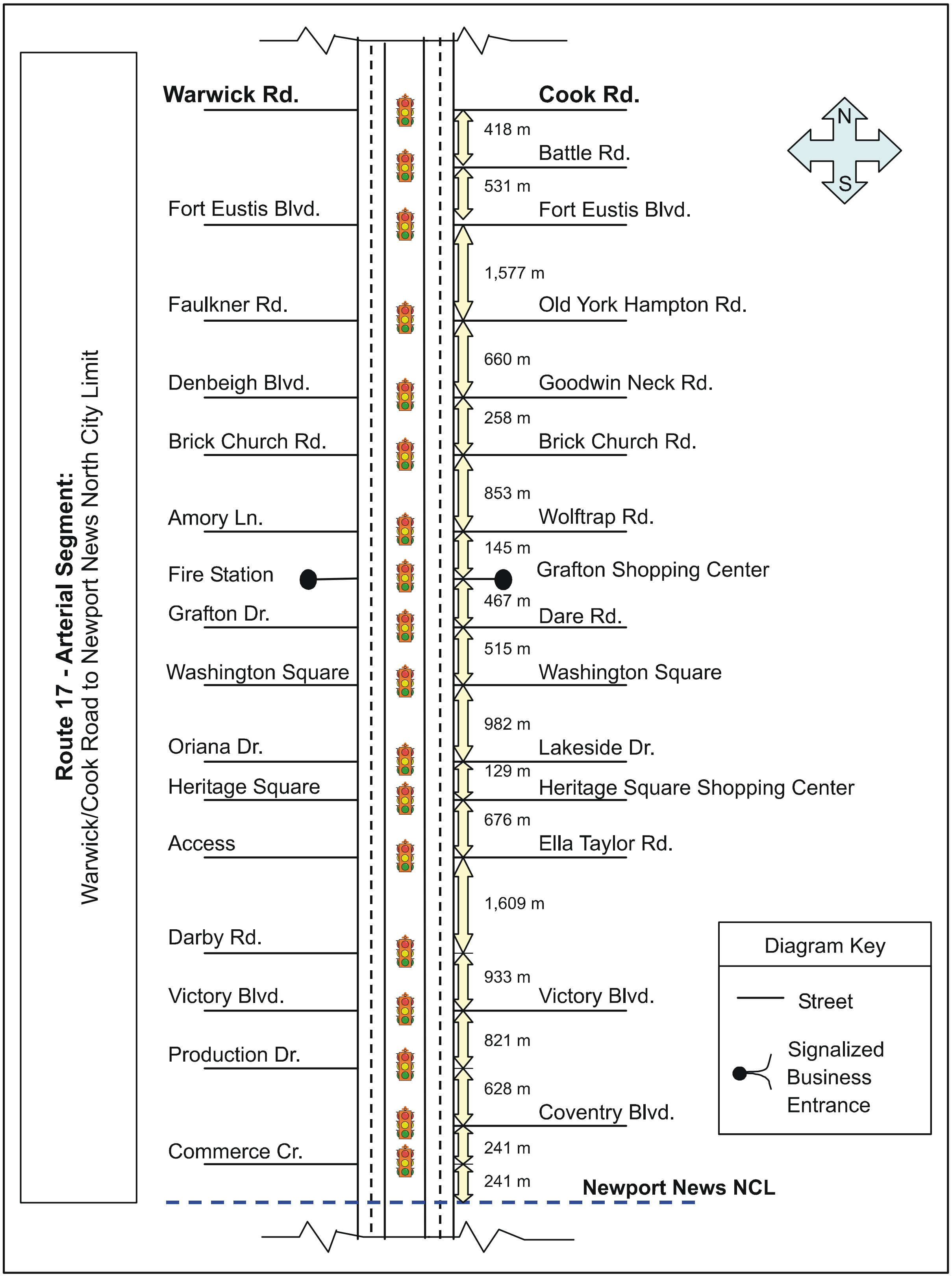


Figure 2. Corridor Diagram of Route 17

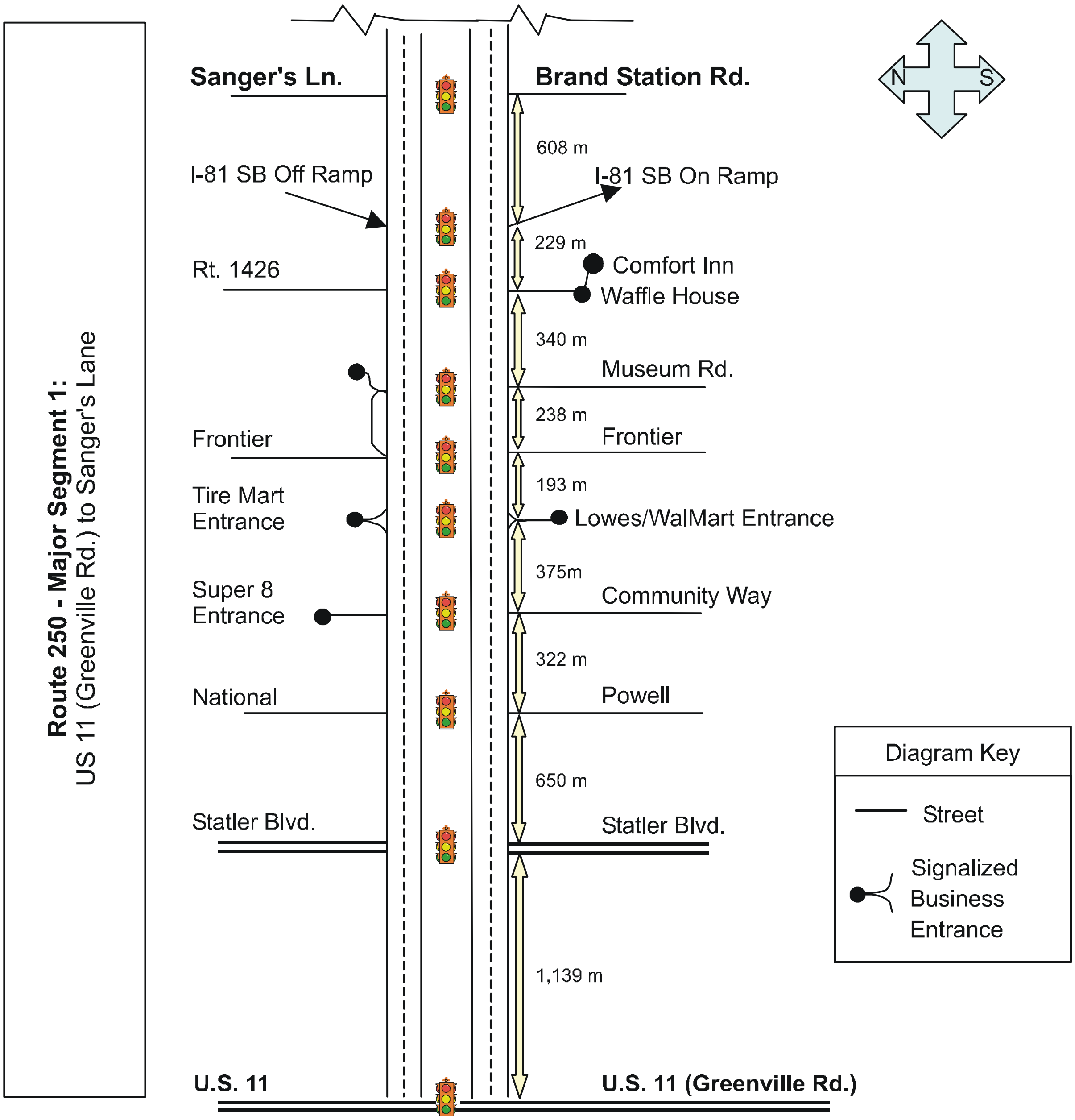


Figure 3. Corridor Diagram of Route 250

The first two reflected solid relationships with the crash history and could be readily understood (e.g., one can mainline measure delay per vehicle in the field and readily conceptualize its meaning). The "stops per vehicle overall" was chosen for further study because it could be readily compared to mainline stops.

Then, the simulation software was used to modify the corridor with incrementally additional traffic signals, keeping volumes and other parameters the same, to see when the addition of an extra signal caused a dramatic change in the corridor's performance trends. The second step entailed using the simulation model to investigate changes in performance measures as the number of signals for the corridor increased from 0 (the way the corridors appeared several decades ago) to the maximum that could be physically accommodated by the corridors (the way they might appear a few decades into the future). Regimes (e.g., linear relationships changes in the number of signals and changes in performance measures) were identified and breakpoints noted to relate these measures to the number of signals in the corridor.

RESULTS

Literature Review

Studies have related traffic flow parameters to safety, as it is generally well known that particular parameters, such as speed variation, influence roadway safety.

Haas et al. quantified the impact of driveway spacing and turning volume on safety, by using the number of "evasive maneuvers" observed during field studies instead of comparisons to actual crash data.[8] An *evasive maneuver* was defined as the brake lights of a through vehicle turning on as the result of the lead vehicle making a right turn. The data were fit to a probability analysis and a linear regression analysis such that one could estimate the percentage of right lane through vehicles that would be affected as a function of driveway spacing and right-turning volume.

In 1996, Vargas and Reddy sought to evaluate the impacts of access management on traffic flow.[11] As part of this study, they also evaluated the NETSIM microsimulation model as a tool to measure improvements in traffic flow caused by the application of access management techniques. Because of their belief in the positive relationship between access management and safety, their study areas were chosen based on their history of high crash rates. (The crash rate is the number of crashes per 100 million vehicle miles traveled; hence, the crash rate incorporates the raw number of accidents and the volume of traffic on a particular segment.) Then they modeled the existing and proposed networks in NETSIM and calibrated the models using field data. Measures of effectiveness for the entire network were then compared before and after the simulated access management deployments. The researchers concluded that access management could improve traffic flow if properly designed and that NETSIM can reasonably simulate and estimate these improvements. This becomes relevant because of the desire to relate simulation output variables to measurable safety impacts: that is, if one hypothesizes that traffic flow variables (e.g., delay) influence crash risk, then the ability to model these traffic flow variables appears quite promising.

While studying the effect of speed on urban traffic safety management, Stark discovered that speed variance has a greater relationship with predicted accident rates than speed itself on most sections.[12] Speed variance may also cause increases in lane changing and weaving, both movements that increase the likelihood of a collision.

Although not directly focusing on simulation tools, Zhou and Sisiopiku looked at relating one measure of traffic flow—the volume to capacity (v/c) ratio—to safety.[7] They found that the relationship between v/c and crash rates is usually parabolic, with the minimum number of crashes per 100 million VMT being at a v/c of 0.5 to 0.6. Interestingly, however, they determined that this relationship could vary when specific crash types were considered: single-vehicle crashes, for example, were at a minimum rate when *v/c* approached 1.0. This variation is significant in light of this study's focus on signal spacing because certain types of crashes may cause more problems than others (e.g., at a particular site, rear-end crashes may warrant greater concern than single-vehicle crashes).

Finally, one challenge to using historical crash data to ascertain the expected impact on safety of specific access management techniques is that crashes are rare events. There are plenty of conditions under which crashes do not occur. Taber stated: "while it is attractive to measure accident likelihood based on historical information, previous discussion has shown that predictions are not usually that statistically significant because of the random nature of reported accidents."[13] Research by Garber and Ehrhart indicated that crash rates are not dependent on any one factor, but on an interaction of many variables (e.g., mean speed, standard deviation of speed, flow per lane per hour, lane width, shoulder width, site length, number of lanes, and grade).[14]

It is not clear how to relate the measures of effectiveness available from simulation analysis to measurable impacts on safety. That is, the literature does not directly indicate a method for linking the operational results from simulation tools (e.g., average vehicle delay) to safety measures of effectiveness (e.g., total number of crashes or crash severity). This linkage is the main focus of this research.

Correlation Between Crash Rates and Performance Measures

Table 3 illustrates the positive relationship between the delay per vehicle on the mainline and the crash rates (defined in units of vehicle miles traveled) for both corridors. A similar relationship existed for total delay; however, delay per vehicle was chosen because of its usefulness in practice. There was also an increasing relationship between stops per vehicle and the crash rates for both corridors. R^2 values between crash rates and these performance measures were moderately strong, with values between 0.63 and 0.87. (The R^2 is the square of the correlation coefficient.[16]) Given that there was an increasing relationship between delay per vehicle and the crash rate, one would expect to find a similar increasing relationship between the stops per vehicle and the crash rate. Logically, the more stops there are, the greater the chances

Table 3. Correlation of Performance Measures and Crash Rates for 1990-2000: R^2 values

Simulated Performance Measure	Route 17	Route 250
Delay per mainline vehicle	0.73	0.87
Stops per mainline vehicle	0.63	0.72
Travel time per mainline vehicle	0.78	0.82
Average speed per mainline vehicle	0.87	0.89
Fuel consumption per mainline vehicle	0.54	0.57
Delay per vehicle overall	0.00	0.86
Stops per vehicle overall	0.38	0.83
Travel time per vehicle overall	0.49	0.78
Average speed per vehicle overall	0.00	0.81
Fuel consumption per vehicle overall	0.61	0.57
Queuing penalty overall	0.83	0.71
Range over which model is valid	11 to 18 signals in corridor	3 to 10 signals in corridor

for a rear-end collision; rear-end collisions accounted for roughly 60 percent of the total accidents for the 10-year period for both corridors.

Table 3 also shows that other performance measures, i.e., travel time, average speed, and fuel consumption, also had relatively strong correlations with crash rates, with the average speed approaching an R^2 of 0.9. Ultimately the first two measures, stops and delay per vehicle, were selected for further analysis because they can be readily understood conceptually and lend themselves to field validation; the other measures hold promise for future analysis.

The first five performance measures shown in Table 3 are specific to the mainline only, e.g., the through vehicles on Route 17 or Route 250. The six "overall" performance measures shown in the lower portion of Table 3 reflect all vehicles on the network—both the mainline vehicles and the minor stream vehicles. This latter category includes the queuing penalty performance measure, which gives a feel for the blocking and queue lengths created by traffic and is the product of "the volume of the blocked movement" and "the amount of time it is blocked." according to the reference documentation found with the particular simulation package.[17] Although the six overall performance measures in the lower portion of Table 3 tended not to be as correlated with crash rates as the five mainline performance measures shown in the upper portion of Table 3 for Route 17, the *queuing penalty overall* is a notable exception.

Within the limits of the available data, the relationships between crash rates and performance measures can be used to evaluate the impacts of additional signals. For example, for the first performance measure *delay per mainline vehicle*, Eqs. 1 and 2 derive from the data for Route 17 and Route 250 with R^2 values of 0.73 and 0.87, respectively:

$$\text{Route 17 crash rate} = 2.90(\text{Mainline delay per vehicle}) - 9.44 \quad \text{[Eq. 1]}$$

$$\text{Route 250 crash rate} = 30.67(\text{Mainline delay per vehicle}) - 197.9 \quad \text{[Eq. 2]}$$

The limitation of this method is that it is valid only for the range over which the crash data were collected. In both corridors, the *range* was the crash rates obtained during the years

1990 through 2000, when Route 17 increased from 11 to 18 signals or when Route 250 increased from 3 to 10 signals. The question as to whether these relationships hold for these corridors outside these boundary conditions is unresolved with this analysis alone.

Corridor Regime and Breakpoint Analysis

The next step was to rerun simulation analyses for each corridor, letting the signals grow from 0 to the maximum number that space limitations would allow. Starting with 0 traffic signals to get a baseline result, the intersections were incrementally changed from unsignalized to actuated-coordinated, and the simulation was rerun. This process continued by adding the traffic signals in the correct historical order until all of the real-world signals were in place. Next, future signals were added with their order based on the personal judgment as to which intersection was most likely to be signalized next. For example, in 2000, Route 17 included 18 signalized intersections and 17 unsignalized intersections. Thus, 36 simulation runs were performed for Route 17: a run with 0 signals, a run with 1 signal, a run with two signals … a run with 35 total signals, respectively, as shown in Table 4.

Similarly, runs were performed for Route 250 from 0 to 14 signals as shown in Table 5. Reports for a variety of performance measures (delay, speed, emissions, number of stops, stop delay, emissions, fuel efficiency, and so forth) were generated, and two performance measures—the number of stops per vehicle on the mainline and the total delay per vehicle—are further discussed because of their ease of understanding in practice.

Correlation of Stops per Vehicle and Signal Density

Three regimes emerged when the number of stops per vehicle on the mainline and the increase in signals were compared, as suggested in Figures 4 and 5. The first regime was from 0 to 4 signals for Route 17 and 0 to 3 signals for Route 250. The second regime ranged from 5 to 19 signals for Route 17 and 4 to 9 signals for Route 250. The third regime included installation of 20 or more signals for Route 17 or 10 or more signals for Route 250. Each regime reflects several years of data since signals are usually added over time rather than all at once.

Alternatively, these results suggest that the corridors have two points where the performance changes dramatically. For Route 17, the first breakpoint (at the installation of the 5th signal) simply changes the degree to which corridor performance declines. The second breakpoint indicates that after the installation of roughly the 20th signal, the installation of additional signals has little effect as performance oscillates around the horizontal fitted line for the third regime. For Route 250, there is a breakpoint at the 4th signal and then again at the 10th signal installation. As noted previously, each data point is an entire simulation run; thus, the production of Figure 4 required 36 simulations: one with 0 signals, one with 1 signal . . . one with 35 signals.

Table 4. Order of Signal Installation for Breakpoint Analysis for Route 17

Cross Street Name	Number of Signals	Signal Density (signals per mi)	Signal Density (signals per km)
All unsignalized	0	0	0
Grafton Shopping Center	1	0.14	0.09
Denbeigh	2	0.29	0.18
Oriana/Lakeside	3	0.43	0.27
Fort Eustis	4	0.57	0.36
Heritage Square	5	0.71	0.45
Warwick/Cook	6	0.86	0.54
Victory	7	1.00	0.63
Wolftrap	8	1.14	0.71
Battle	9	1.29	0.80
Kiln	10	1.43	0.89
Ella Taylor	11	1.57	0.98
Washington Square	12	1.71	1.07
Grafton/Dare	13	1.86	1.16
BrickChurch	14	2.00	1.25
Production	15	2.14	1.34
Coventry	16	2.29	1.43
Faulkner	17	2.43	1.52
Darby	18	2.57	1.61
Theatre	19	2.71	1.70
Hundley	20	2.86	1.79
York Crossing	21	3.00	1.88
Green	22	3.14	1.96
Terrebonne	23	3.29	2.05
Mill	24	3.43	2.14
General Emerson	25	3.57	2.23
Showalter	26	3.71	2.32
Burts	27	3.86	2.41
Cockletown	28	4.00	2.50
Shamrock	29	4.14	2.59
Whites	30	4.29	2.68
Byrd	31	4.43	2.77
North Dare	32	4.57	2.86
Pine	33	4.71	2.95
Rich	34	4.86	3.04
Oak	35	5.00	3.13

Table 5. Order Of Signal Installation For Breakpoint Analysis For Route 250

Cross Street Name	Number of Signals	Signal Density (signals per mi)	Signal Density (signals per km)
All unsignalized	0	0	0
Frontier	1	0.40	0.25
Statler	2	0.80	0.50
Western State	3	1.20	0.75
Sanger's	4	1.60	1.00
Greenville	5	2.00	1.25
Walmart	6	2.40	1.50
I-81 Southbound Ramp	7	2.80	1.75
Community Way	8	3.20	2.00
National/Powell	9	3.60	2.25
Museum Way	10	4.00	2.50
Bell	11	4.40	2.75
I-81 Northbound On Ramp	12	4.80	3.00
Young	13	5.20	3.25
I-81 Northbound Off Ramp	14	5.60	3.50

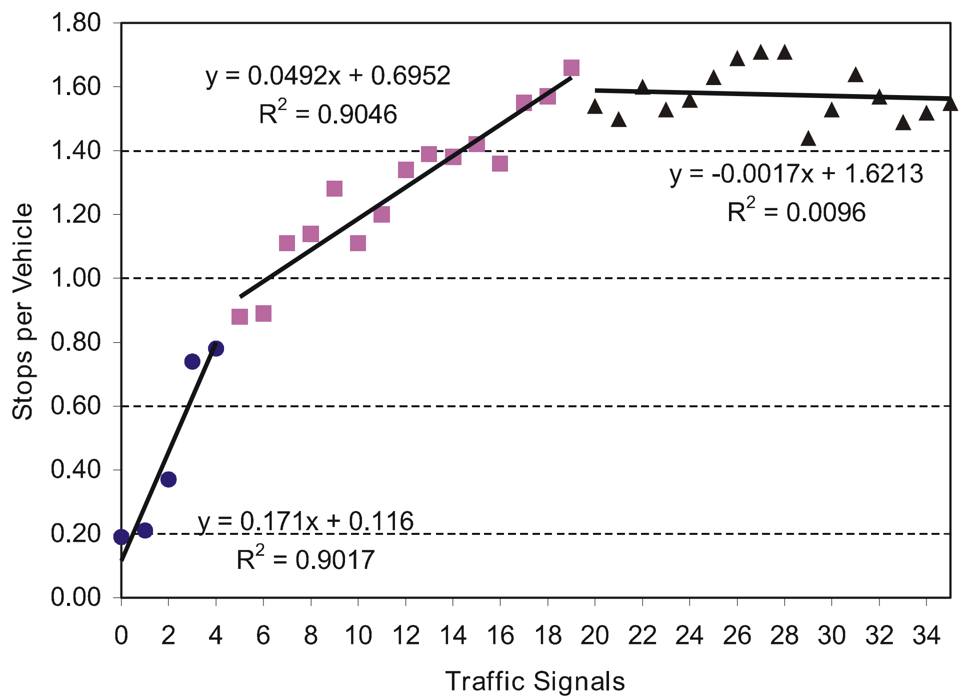


Figure 4. Mainline Stops per Vehicle vs. Number of Traffic Signals (Route 17)

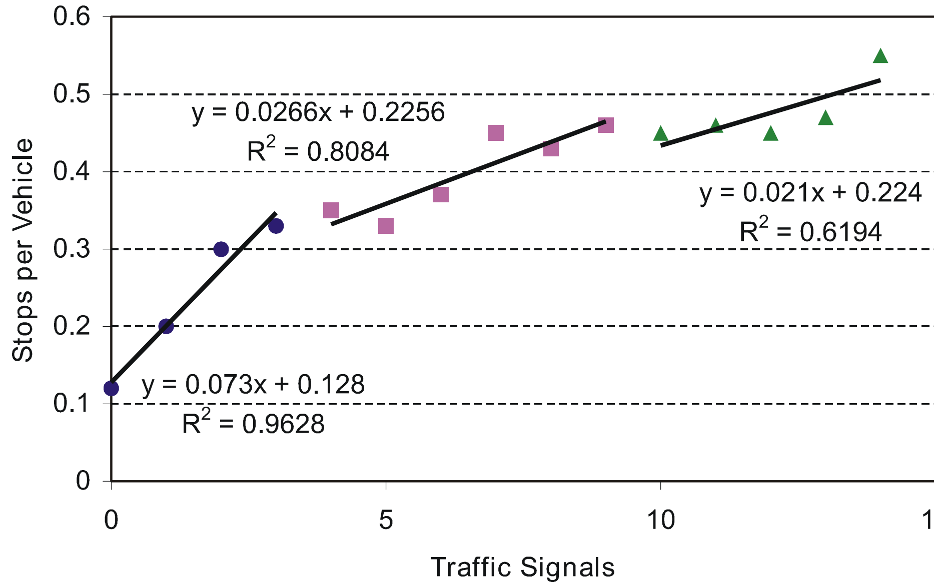


Figure 5. Mainline Stops per Vehicle vs. Number of Traffic Signals (Route 250)

A similar three-regime model became evident with regard to the total stops per vehicle (i.e., stops for both major and minor stream vehicles), as shown in Figures 6 and 7. Although a two-regime model could describe each of these scenarios, the regimes are not quite as well defined as those for the mainline stops per vehicle. The reason for this disparity could be that mainline stops reflect rather directly the propensity for rear-end crashes to occur, and rear-end crashes tend to be the most common type of crash, whereas total stops include stops on the minor stream that do not affect the rear-end crashes on the mainline.

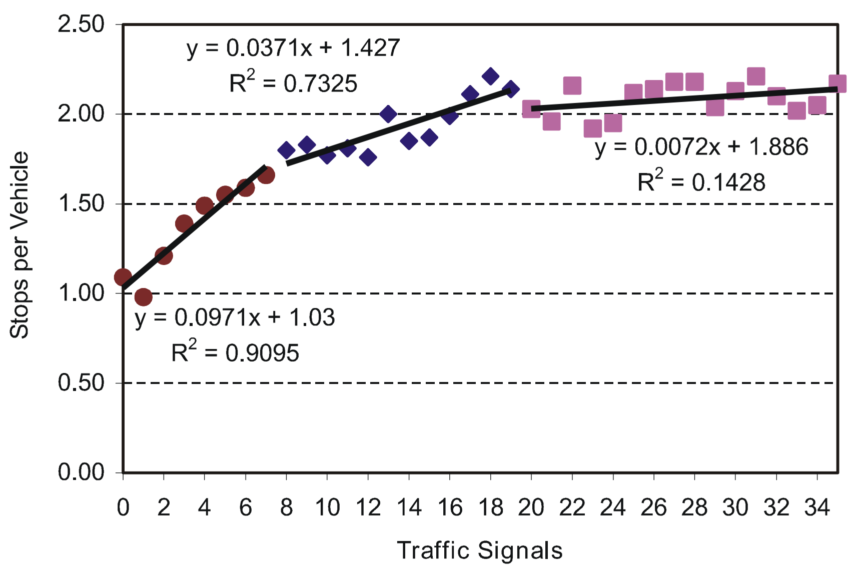


Figure 6. Total Stops Per Vehicle vs. Number of Traffic Signals (Route 17)

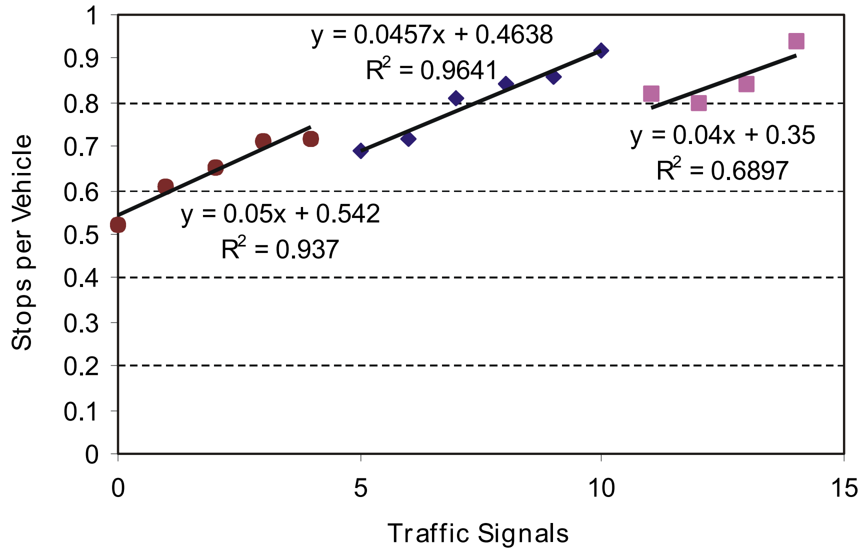


Figure 7. Total Stops Per Vehicle vs. Number of Traffic Signals (Route 250)

Correlation of Total Delay per Vehicle and Signal Density

The total delay per vehicle, i.e., average delay based on both the mainline arterial and the minor approaches, dramatically decreased with the installation of the first few signals and then leveled off. This is logical: when intersections were unsignalized and the minor streets had stop signs, the mainline traffic simply kept moving. The addition of signals essentially shifted the delay from the minor stream vehicles to the major stream vehicles. Figures 8 and 9 suggest two

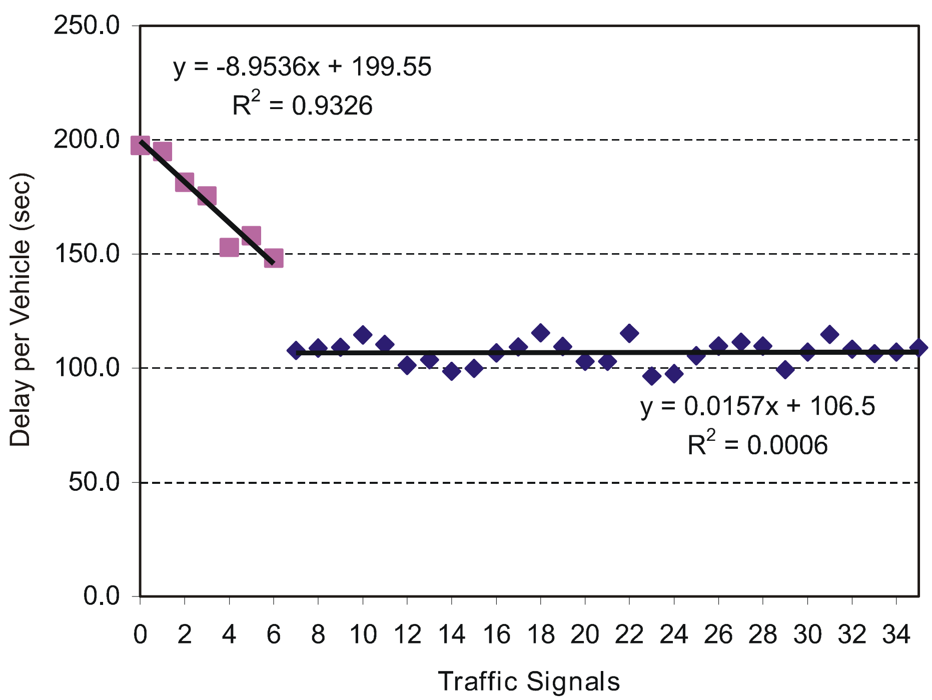


Figure 8. Total Delay per Vehicle vs. Number of Traffic Signals (Route 17)

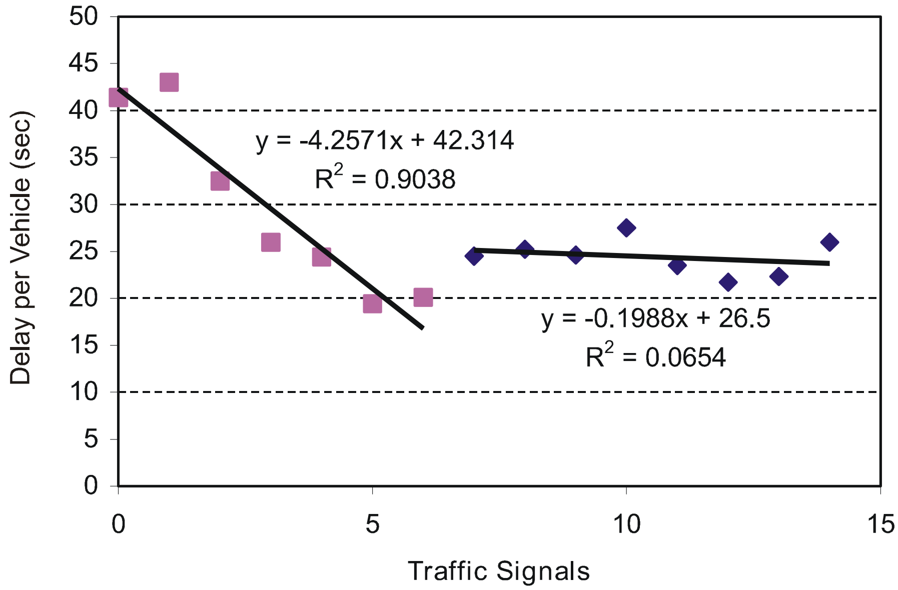
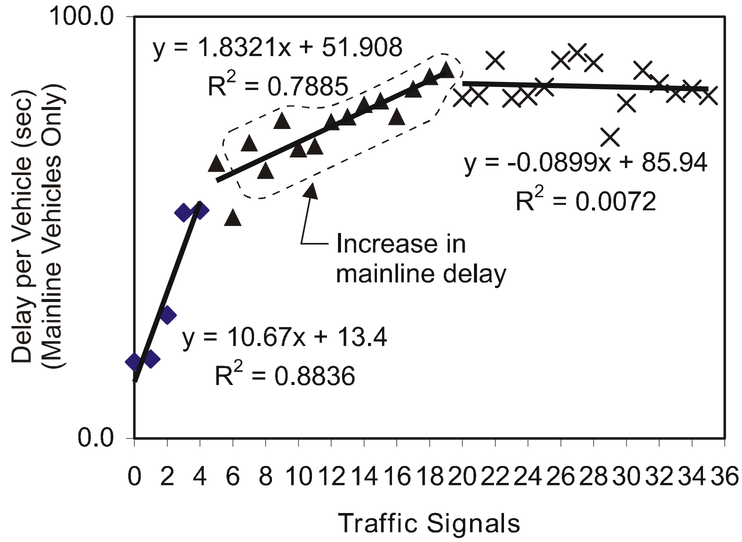


Figure 9. Total Delay per Vehicle vs. Number of Traffic Signals (Route 250)

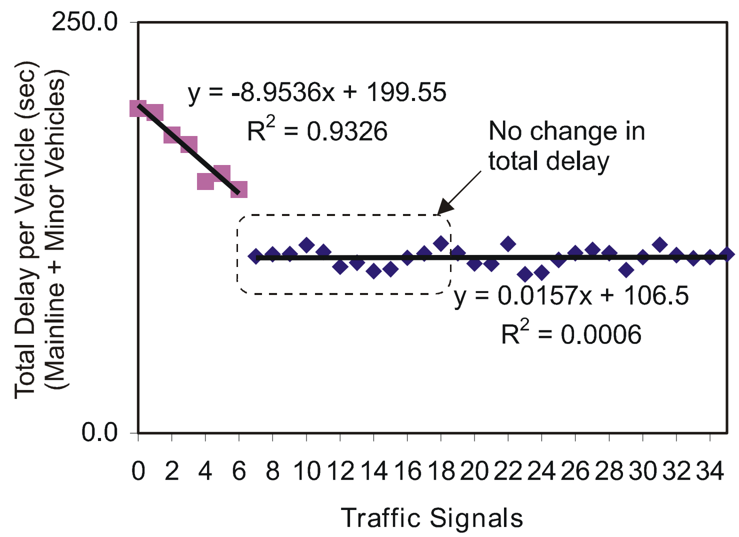
regimes for relating total delay per vehicle to number of signals. For Route 17, there is a dramatic drop in the delay per vehicle from 0 to 6 signal installations. However, after the 7th signal is installed, the network delay oscillates about the fitted line that defines the regime. Similarly, the delay per vehicle on Route 250 shows the two-regime relationship.

These results indicate there is only one breakpoint in a corridor where the addition of extra signals does not further reduce total delay per vehicle. This observation is relevant because when total delay per vehicle (Figure 10b) is viewed in conjunction with the mainline delay per vehicle (Figure 10a), it is apparent that a point is reached where additional signals only shift delay from minor stream vehicles to major stream vehicles rather than reducing overall delay.

Similarities in the patterns of delay and stops are not surprising because these parameters are related; of course, it is not surprising that the number of traffic signals influences them. Even when safety considerations are set aside, Figures 8 through 10 are of value in that they present a framework within which analysts may consider whether adding signals will incrementally change the performance of the network. The multiple regimes suggest that this is not the case, with sharp breakpoints rather than a uniform, steady rate of change being the rule. The poor performance of total delay per vehicle in Table 3 for Corridor I is suggested in Figure 10b. Realizing that Table 3 is based on the period from 11 to 18 signals for Corridor I, one can see that the corresponding period in Figure 10b shows “no change in total delay.” Thus, as the number of signals grew from 11 to 18 and the crash rate increased, total delay did not change. Thus, total delay was a poor predictor of crash rates for Corridor I. On the other hand, mainline delay did change as the number of signals increased from 11 to 18 (Figure 10a), and Table 3 shows that mainline delay was a good predictor of crash rates for Corridor I.



(a)



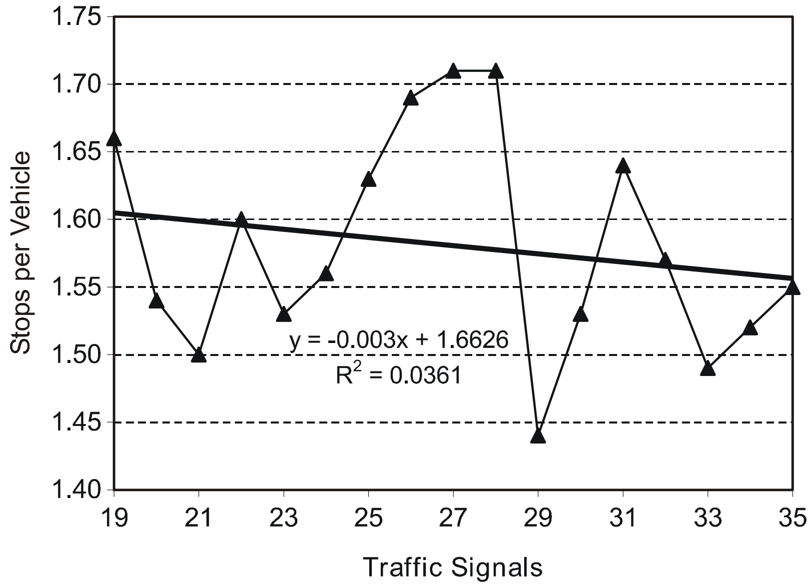
(b)

Figure 10. Route 17: (a) Mainline Delay per Vehicle, (b) Total Delay per Vehicle

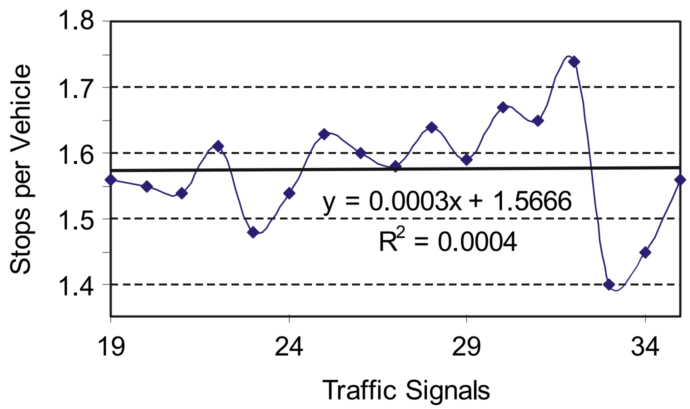
Effect of Changing Order of Future Signals

To determine whether the low R^2 relationships shown for the third regime in Figures 4 through 7 were a result of the particular hypothetical order in which future signals were installed, random numbers were used to determine an alternative order of the "future" signals 19 to 35 for the Route 17 corridor. For example, instead of the 19th signal being Theatre Road, the random number routine assigned the 19th signal to Burts Road. With this new order, the simulations were run again and the plots of mainline delay per vehicle, mainline stops per vehicle, total delay per vehicle, and total stops per vehicle were obtained. The plots continued to show low R^2 values, ranging from 0.00 to 0.17. Thus, although changing the order of the signals did affect the rightmost regime, the impact was relatively small.

Figures 11a and 11b compare one of these plots for the original and the new signal installation order. Figure 11a plots the arterial stops per vehicle as a function of signals using the order shown in Table 4; Figure 11b shows the plot obtained using the alternative signal order just described. Figure 11a is very similar to Figure 4 except that the 19th signal is included with signals 20 through 35 to facilitate a comparison of the two figures.



(a)



(b)

Figure 11. Route 17: (a) Original Signal Order, (b) New Signal Order

DISCUSSION AND LIMITATIONS

Although no simulation model can replace real data, the regime and breakpoint analyses enable estimation of potential trends. Table 3 for Route 17, for example, shows that a plausible relationship between performance measures and crash rates was obtained based on a 10-year history of the corridor, with high R^2 values. Figure 4, however, places that relationship in its proper context: the correlation between crash rates and performance measures in Table 3 is based only on the corridor growing from 11 to 18 signals, a region, shown in Figure 4, to be dominated by the second regime. Figure 4 thus suggests that the linear relationship indicated by Table 3 is valid but only for the range covered by the second regime, which is from about 5 to 19 signals. Because the authors picked the Table 3 data period (1990 through 2000) before knowing the simulation results, it is only by coincidence that the nice linear relationship shown by some of the high R^2 values in Table 3 is neatly encompassed in the second regime shown in Figure 4.

Thus, the multiple-regime analysis provides a possible long-term view of the effects of signal density changes in the absence of multiple decades of longitudinal data. In practice, therefore, analysts who are evaluating corridor management strategies may assess how simulated performance measures such as stops or delay per vehicle change as the number of signals increases and then graph the results. If the number of signals being considered is within the bounds of a single regime, the analyst has reason to suspect that a crash rate model, such as that shown in Eqs. 1 and 2 and derived from Table 3, is valid. If, however, the number of signals being considered is in a different regime, then the linear crash prediction model from Table 3 should probably not be used without expert modification, although increases in traffic volumes are incorporated in the computation of the crash rates.

Four limitations to this study should be noted:

1. *The actual crash rates for this effort were within only a single regime for Route 17 even though they reflected 10 years of data.* In other words, to have crash rates for a single corridor such as Route 17 as it grew from 0 to 35 signals, several decades of data would be needed! Yet, there may be corridors where these historical data are available. In such a case, it would be beneficial to expand the crash rate analysis shown in Table 3 to compare performance measures to crash rates beyond a single regime.

2. *The breakpoint analysis did not always reveal clearly identifiable breakpoints.* Figure 12 shows that although the existence of three regimes may be postulated, it is not immediately clear that a two-regime model does not hold.

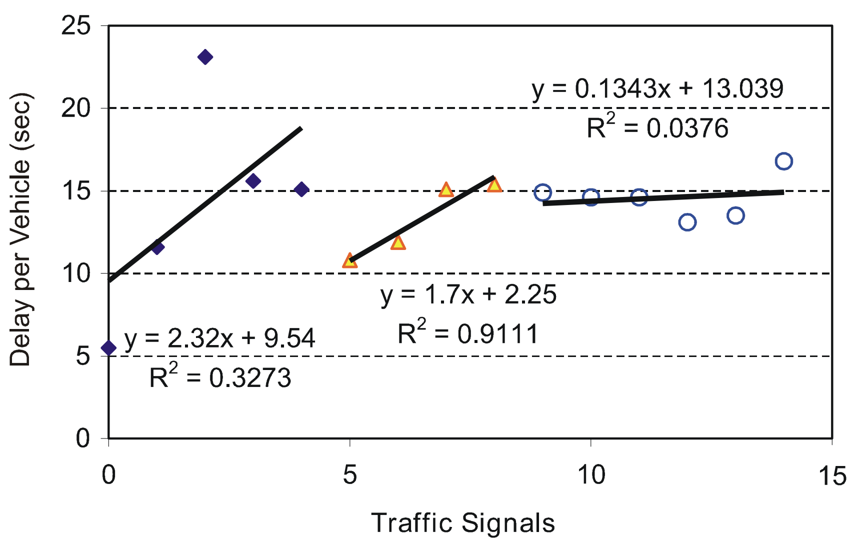


Figure 12. Arterial Delay per Vehicle (Route 250)

3. *The data were imperfect*, e.g., one data point for Route 17 crash comparisons was excluded from the analysis since the signal was installed for only 2 months before another signal was added to the corridor.

4. *Not all crash types have an equal impact,* e.g., installation of a signal where warranted because of insufficient sight distance for the minor stream approach may eliminate a few high injury angle crashes and produce instead many non-injury rear-end crashes.

CONCLUSIONS

1. *Crash rates and select performance measures obtained from simulation were correlated,* notably, stops per mainline vehicle and delay per mainline vehicle, with R^2 values ranging from 0.63 to 0.87 for the two corridors. Other parameters were also correlated with crash rates but varied substantially between the two corridors. In this sense, correlation is the square root of the R^2 value shown in Table 3.

2. *Equations for predicting crashes as a function of these performance measures may be derived, but they are corridor specific*. The two equations that predict crash rate as a function of delay per vehicle have substantially different coefficients, meaning that they must be developed—at least for these two cases—for each specific corridor.

3. *Simulated performance measures may pinpoint instances when an additional signal could cause a dramatic change in corridor performance.* Figures 4 through 10 illustrate how each additional signal is associated with a change in delay per vehicle or stops per vehicle. The limitation of this interpretation is that even though 10 years of crash data were used for the corridors in question, only a single regime was covered by the model.

4. *The results of this study do not lead to a prescriptive mandate for corridor analysis. They do, however, suggest that simulation is one viable tool for evaluating the impacts of additional signals when either of two conditions occur: crash data are lacking (or mathematical models for predicting crashes are infeasible) or a corridor is on the verge of changing regimes as implied in Figures 4 through 10.*

RECOMMENDATIONS

1. *When crash data are lacking (or mathematical models for predicting crashes are infeasible) or a corridor is on the verge of changing regimes, VDOT should consider using corridor simulation as an early planning tool, before a corridor is fully developed.* Although VDOT district planning or engineering staff would most likely be the entities to apply this method, it is suggested that the VDOT Access Management Committee consider this method as one of several potential tools for evaluating the pros and cons of minimum signal spacing in specific corridors.

2. *This analysis should be repeated with a corridor for which the full historical data are available, from zero signals to packed with signals.* In such a case, it would be beneficial to expand the crash rate analysis shown in Table 3 to compare performance measures to crash rates beyond a single regime.

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APPENDIX: ASSUMPTIONS IN THE SIMULATION

Entering and Interpreting Data

- All signals were initially coded as fully actuated and coordinated.

- The default values were used for many of the input variables, including the ideal saturated flow (1900 vphpl), the total lost time (3.0 s), leading detector length (50 ft), no extension detectors were used (0 ft in length), the peak hour factor (1.00), the percentile delay method, growth factor (1.00), percentage of heavy vehicles (2%), minimum left turn splits (12.0 s), turning speeds were set to 15 mph for left turns and 9 mph for right turns, and there were no conflicting pedestrians (0).

- The link speeds were as follows: along Route 17 from Kiln Creek to Goodwin Neck was 45 mph and from Old York Hampton Road to the end of the study corridor (Warwick/Cook Roads) was 50 mph. The link speeds for the cross streets were set to 30 mph, with the exception of Victory Boulevard (Route 171) and Goodwin Neck Road (Route 173), which were set to 40 mph, and Ft. Eustis Blvd (Route 105), which was set to 45 mph. Any right-turn storage pockets that were not measured were set to 50 ft in length. For Route 250, the link speed for the arterial was set to 45 mph, and the cross streets were set to 35 mph.

- Each simulation run simulated a 13-minute period consisting of a 3-minute seeding period, followed by a 10-minute recording period.

- The SimTraffic arterial summary report and the total network performance report, rather than the individual intersection reports, provided the performance measures. The reason for this is that the study focused on the corridor as a whole rather than the contributions of each individual intersection.

- For the breakpoint analysis, 15-m storage bays were added whenever necessary to preserve the correct lane channelization along the corridor.

Converting Crash and Volume Data

Crash rates rather than absolute numbers of crashes were used, as shown with the following equation, which has units of crashes per 100 million vehicle miles per selected time period.[6]

$$\text{Crash rate} = \frac{(\text{Number of crashes})(100{,}000{,}000)}{(\text{Number of days})(\text{Length in miles})(\text{ADT})}$$

The crashes include both the accidents at the intersection and the accidents between intersections.

The available volume data were based on 1998 ADT volumes and intersection configurations for Route 17. The volume data for Route 250 were primarily based on sources from 1998 and 1999, and the intersection configurations were based on 1999 conditions. There was a lack of intersection volume data for the intersections for the entire 10-year study period. However, AADT mainline volumes are historically recorded by VDOT. Thus, the mainline AADT volumes for the arterials were known along the corridor for the past and present conditions, enabling an estimation of the volume in the past from these data and the AADT proportion factor. The following formula was used to estimate the volumes needed.

$$\text{Past volume estimate} = \frac{(\text{Present volume})(\text{Past AADT})}{(\text{Present AADT})}$$

For example, the AADT in the early 1990s was approximately 32,500 for the segment between Warwick and Dare Roads along Route 17. The 1998 AADT for that segment was 36,000. Thus, the estimated volumes for the northbound through traffic for the 1990 simulation scenario would be (1,415 vph)(32,500/36,000) = 1,277 vph. This estimation method does consider assumptions. For instance, this method assumes that the volume growth is proportionate to the AADT growth. It also assumes no change in hourly distribution; however, the error from this assumption is reduced because the current volume data were available in vehicles per hour. Tables A-1 and A-2 show the mainline ADTs for Route 17 and Route 250.

Table A-1. Mainline ADTs for Route 17

Segment\Period	1990-1991	1992-1994	1995-1996	1997-1999
Kiln to Darby	40,500	32,333	30,000	31,000
Darby to Grafton	42,500	46,333	49,000	50,000
Grafton to Warwick	32,500	34,000	35,000	36,000

Table A-2. Mainline ADTs for Route 250

Period	1990	1991-1993	1994	1995	1996	1997	1998	1999
(Entire Section)	19,988	21,000	23,000	24,000	25,000	26,000	27,000	27,000

Accounting for Locally Generated Traffic

Many businesses and residential driveways were added as the corridors developed over the 10-year period. However, there was a problem collecting these data from VDOT's records. The volumes given at the intersections reflect these numbers, but the simulation software allows the user to set traffic from a mid-block option. The mid-block option allows a percentage of the volumes to be assigned from the midpoint in the link between two signals. When the mid-block option is used, the program generates the specified volumes from a location between the signals and, therefore, provides a better representation of traffic entering the corridor from driveways or businesses along the corridor. Thus, to help account for this increase in driveways, the mid-block option was used in this analysis. The percentages assumed for the mid-block factors are presented in Table A-3.

Table A-3. Percentages for Mid-Block Volumes Between the Intersections

Year	Mid-Block Traffic (%)
1990	10
1992	11
1995	12
1997	13
1998	14

For the breakpoint analysis, the volumes for the newly signalized intersections had to be interpolated since they were not included in the original data collected. These volume data were kept constant throughout the breakpoint analysis so the number of signalized intersections could be studied without any other factors changing.