Coordination of Traffic Signals across Jurisdictional Boundaries: Field and Modeling Results

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Abstract

The Phoenix Metropolitan Model Deployment Initiative (MMDI) is a seven-year project that attempts to develop and integrate intelligent transportation systems for the Phoenix Metropolitan area. As part of this project, this paper provides some insight as to the potential benefits of coordinating traffic signals across jurisdictional boundaries along the Scottsdale/Rural Corridor in the cities of Tempe and Scottsdale, Arizona. In addition, the paper demonstrates the feasibility of using GPS second-by-second speed measurements and simulation tools for the evaluation of environmental and safety impacts of operational-level traffic improvement projects. The simulation results demonstrate the unique opportunities that simulation tools provide for conducting different sensitivity analyses and for the evaluation of conditions that are not necessarily observed in the field. Finally, the paper demonstrates that optimizing the location of the break in traffic signal coordination can impact the efficiency of travel, the environment and the number and severity of vehicle crashes.

While this study does provide some insight as to the potential benefits of coordinating traffic signals across jurisdictional boundaries, more importantly it demonstrates the feasibility of using GPS second-by-second speed measurements and simulation tools for the evaluation of operational-level traffic improvement projects. Specifically, the use of statistical models allows for the evaluation of efficiency, energy, emissions and safety benefits of operational-level traffic improvement projects without having to invest in expensive equipment, like for example emission analyzers. Furthermore, it allows for the evaluation of MOEs that would not otherwise be evaluated, like for example the accident risk.

Based on a field evaluation of the main corridor, the study concluded that over three analysis periods (AM peak, midday and PM peak) the mainline average speed increased by 6 percent. In addition, the number of vehicle stops was found to be reduced by 3.6 percent, while the fuel consumption was reduced by 1.6 percent on average. The HC and NO_x emissions were found to remain constant while the CO emissions increased by 1.2 percent. The crash risk was found to be reduced by 6.7 percent.

The results for the AM peak indicated statistically significant benefits to the approaches of the re-timed traffic signals, however, these benefits were found to be statistically insignificant when the entire mainline was considered (21 traffic signals). The study demonstrated consistency between field and simulation results in terms of mainline findings. Furthermore, the simulation results demonstrated that the traffic signal re-timing resulted in statistically significant localized benefits to the cross-streets and that the benefits at the network level were statistically insignificant. The simulation results, however, did indicate a reduction is speed and delay variability as a result of the traffic signal re-timing at the network level.

1. Introduction

1.1 Phoenix Metropolitan Model Deployment Initiative

The Phoenix Metropolitan Model Deployment Initiative (MMDI), also known as AZTech, is a seven-year project that attempts to develop and integrate intelligent transportation systems for the Phoenix Metropolitan area. The goal of AZTech is to produce freeway and arterial street networks that are safer and more efficient for the traveling public, decrease travel time and enhance mobility.

AZTech implements and integrates several ITS projects to achieve a regional ITS system. The major efforts include the instrumentation of eight arterial Smart Corridors for cross-jurisdictional signal coordination and traffic detection. A multi-modal Advanced Traveler Information System (ATIS) is being developed to provide real-time traveler information via an array of media and devices. A GPS-based Automatic Vehicle Location (AVL) system with a Mobile Data Terminal (MDT) is being implemented to assist transit operations and provide real-time bus status information to transit users. A Total Station computer-aided incident investigation system is being deployed to reduce incident clearance time. Finally, a regional communication network and a central server are being developed to integrate traffic, transit, and incident management functions across different jurisdictions.

As part of the Smart Corridors, the Scottsdale/Rural Road is one of the busiest north-south arterial corridors in the east valley of the Phoenix Metropolitan area. This corridor serves two major activity centers, Arizona State University (Tempe) to the south and downtown Scottsdale to the north. This paper describes a study that attempts to quantify the efficiency, energy, environmental, and safety benefits of coordinating traffic signals across jurisdictional boundaries along the Scottsdale/Rural Road corridor.

1.2 Evaluation Approach

This section describes how the efficiency, energy, emission and safety Measures of Effectiveness (MOEs) were computed using GPS and micro-simulation second-by-second speed estimates.

1.2.1 Efficiency Estimation

The estimation of efficiency using the GPS field data and within the simulation environment involved computing the average speed for the entire trip, the delay, and the number of vehicle stops. The computation of the average trip speed from second-by-second speed measurements involved summing up all speed measurements and dividing by the number of observations. Conversely, the instantaneous delay (d_i) was computed using Equation 1 as the difference in time it would take the vehicle to travel at free-speed (u_f) versus traveling at the instantaneous speed measurement (u_i). The total delay for the entire trip was computed as the sum of all instantaneous delay estimates.

$$d_i = 1 - \frac{u_f}{u_i} \quad \forall\, i \qquad [1]$$

The estimation of stops was computed as the ratio of the instantaneous speed reduction to the free-speed, as indicated in Equation 2. Consequently, a reduction in speed from the free-speed to a speed of zero would constitute a complete stop while a reduction in speed from a speed equal to half the free-speed to a speed equal to one quarter the free-speed would constitute 0.25 of a stop. The total number of stops was computed as the sum of the stops for all observations (each second).

$$S_i = \frac{u_i - u_{i-1}}{u_f} \quad \forall\, i \quad \ni u_i < u_{i-1} \qquad [2]$$

The efficiency estimation within the simulation environment was identical to that utilized with the GPS data.

1.2.2 Energy and Emission Estimation

The evaluation of energy and emissions involved the processing of the second-by-second GPS speed measurements, in the case of the field evaluation, and second-by-second speed estimates within the simulation environment, in the case of the microscopic simulation tool, to compute second-by-second acceleration estimates. Utilizing the second-by-second speed and acceleration estimates it was possible to estimate the fuel consumption and vehicle emissions by applying a set of 4th order regression equations that were fitted to experimental data collected at the Oak Ridge National Lab (ORNL) (West *et. al*., 1997). The specifics of how the statistical models were derived using the ORNL data are described in Ahn *et all. al*. (1999) and the application of these models within a microscopic simulation environment are described in Rakha *et. al*. (1999). The use of instantaneous speed and acceleration estimates for the estimation of energy and emissions provides a major advantage over state-of-practice methods, which compute fuel consumption and emissions based exclusively on the average speed and the number of vehicle miles traveled. Specifically, the method explicitly considers that different speed profiles, while exhibiting the same average speed, may result in very different fuel consumption and emission rates, depending upon the amount of speed variability about this average.

It should be noted that the only direct measurement of fuel usage and vehicle emissions took place during the data collection effort at the Oak Ridge National Lab, where a set of vehicles were systematically paced through a sequence of different speed and acceleration sequences in an instrumented laboratory setting. All other estimates of fuel consumption were based on either direct field measurements of instantaneous speed and acceleration estimates or based on simulated speed and acceleration estimates.

A final note is that the GPS data exhibited problems with outliers, which involved accelerations that exceeded the capabilities of typical vehicles. Consequently, prior to applying the energy and emission models robust data smoothing techniques were applied to the GPS data. The specifics of the data smoothing are beyond the scope of this paper, however, they will be presented in a separate paper.

Again, the methods for estimating energy and emissions was consistent in both the field and the simulation evaluation. The only difference was that in the field evaluation the speeds were measured every second using GPS-equipped vehicles, while in the simulation the speed and acceleration estimates were tracked for each vehicle every second.

1.2.3 Safety Estimation

The evaluation of the safety impacts of alternative ITS scenarios was based on regression models that predict the expected frequency of 14 different crash types every second based on the facility type that the vehicle is traveling on. In addition, the expected damage and injury levels, per crash event, are estimated based on the instantaneous speed each vehicle is traveling at each second (Avgoustis *et. al*., 2000).

The crash rates, in each of the above applications of the safety computational method, were derived from the General Estimates System (GES) national crash database of more than 6,000,000 annual crashes. This crash database was subsequently supplemented with vehicle exposure data, which were stratified by facility type. The merging of crash frequencies with exposure data resulted in crash rates per unit distance and per unit time for different facility types. The conversion, from crash frequencies into crash frequencies by damage and injury level, was performed by considering speed dependent damage and injury levels for each of the 14 different crash types.

Again, as was the case for efficiency, energy and emissions, the safety model was applied to the second-by-second GPS data and was also integrated within the simulation environment.

1.3 Objectives and Layout of Paper

The objectives of the paper are threefold. First, the paper demonstrates the feasibility of using second-by-second GPS data for evaluating the efficiency, energy, environmental, and safety impacts of operational-level traffic improvement projects, in this case traffic signal coordination. Second, the paper demonstrates the consistency between field and validated simulation tools, in this case the INTEGRATION model (Van Aerde, 1998). The use of simulation provides unique opportunities to conduct different sensitivity analyses and evaluate conditions that were not necessarily observed in the field. Furthermore, simulation provides an opportunity to analyze other factors like for example induced/forgone traffic and induced/forgone demand. The third and final objective of the paper is to demonstrate that changing the location of the break in traffic signal coordination can impact the efficiency of travel, the environment and the number and severity of vehicle crashes.

In terms of the layout of the paper, the first section provides a brief background of the spatial and temporal scope of the study. The next section describes how the field data were gathered and utilized to evaluate the efficiency, energy, environmental, and safety impacts of traffic signal coordination. This section also summarizes the findings of the field evaluation. The third section describes the details of constructing a micro-simulation model of the corridor and the findings of the microscopic simulation analysis in terms of network-level impacts of the traffic signal coordination. Finally, the conclusions of the study are presented together with recommendations for further analyses.

2. Background

This section describes the spatial extent of the study area along with a description of the changes that were made to the traffic signal timings.

2.1 Spatial Scope of Study Area

The objective of the Scottsdale/Rural Road project was to evaluate the benefits of coordinating traffic signal timings across jurisdictional boundaries. The study area consisted of a 9.6-kilometer section of Scottsdale/Rural Road that traversed the City of Tempe to the South and the City of Scottsdale to the North, as illustrated in Figure 1. The section of the roadway in the city of Tempe is named Rural Road while the section in the city of Scottsdale is named Scottsdale Road, and thus the corridor is named Scottsdale/Rural Road. The 9.6-kilometer section included a railway crossing (near University Drive) and a total of 21 traffic signals, 16 located in the City of Tempe and 5 in the City of Scottsdale. The traffic signals within each city operated at different cycle lengths resulting in a break in traffic signal coordination at the city boundary. Specifically, the traffic signals in the City of Tempe operated at a cycle length of 110 seconds while the signals in the City of Scottsdale operated at a cycle length of 102 seconds. Ideally, both cities would operate at a common cycle length in order to improve traffic progression, however that was not possible due to other confounding factors. Consequently, an attempt was made to improve traffic progression by shifting the break in traffic signal coordination from the less efficient city boundary to a functional boundary where traffic signal coordination was less of an issue. The shift in the boundary was achieved by changing the cycle length of three traffic signals, namely; at the intersection of Scottsdale/Rural Road with McKellips Road, Weber Road, and Curry Road.

2.2 Before/After Signal Timings

The signal timings for the AM peak before and after making the signal changes are illustrated in Figure 2. The figure illustrates the phase sequencing and numbering for each of the traffic signals together with the duration of each phase. For example, the traffic signal at the intersection of Rural Road and Curry Road included four phases and operated at a cycle length of 110 seconds for the before scenario versus 102 seconds for the after scenario. The four phases included an advanced left turn phase for the eastbound and westbound direction (Curry Road) followed by a through phase for the eastbound/westbound direction, followed by the two phases for the northbound/southbound direction (Scottsdale/Rural Road). Figure 2 indicates minor changes to the signal timings between the before and after signal timings during the AM peak. This was the case for the other periods of analysis (PM peak and off-peak). Alternatively, major changes were made to the traffic signal offsets as indicated in Table 1. Consequently, the signal changes focused on changing the traffic signal coordination as opposed to changing the phase split.

3. Field Data Collection and Analysis

In order to evaluate the efficiency, energy, environmental and safety benefits of traffic signal coordination across a jurisdictional boundary, two data collection efforts were conducted within a month of one another (January 1999 and February 1999). It was felt that a month was a sufficient duration to confine the potential benefits to the changes in the signal coordination but still allow enough time for the signal timings to be tested and fine tuned. The data collection efforts were conducted during the mid-week period (Tuesday through Thursday) in order to reflect typical weekday traffic conditions. Mondays and Fridays were not considered because studies have shown that they are not necessarily reflective of typical weekday conditions (Rakha and Van Aerde, 1995). The only abnormal conditions that occurred during the data collection effort was the fact that the railway crossing was closed to the traffic traveling along Scottsdale/Rural Road. The closing of the roadway occurred during the before and after data collection efforts at approximately the same time during the PM peak (around 4:30 PM on Thursday). Given that the roadway was closed for both data collection efforts (before and after) during the same analysis period (PM peak) it was felt that it would not bias the results.

The first of these data collection efforts involved collecting mainline and turning movement counts at a number of traffic signals before and after the signal timings were changed. The second data collection effort included collecting speed measurements from floating cars that traveled along Scottsdale/Rural Road before and after the signal timings were changed. The floating cars attempted to travel at the average speed of the general traffic by overtaking as many vehicles as overtook them. These floating cars were equipped with a Global Positioning System (GPS) unit that measured the vehicle's speed every second.

The objective of the first data collection effort was twofold. First, the data were utilized to quantify any short-term induced traffic and induced demand (e.g. changes in routes or time of departure) impacts on the corridor as a result of the traffic signal re-timing. Second, the data were utilized to calibrate the demand for purposes of modeling the network benefits of the signal coordination. The objective of the second data collection effort was to utilize the before and after instantaneous speed measurements in order to quantify the fuel consumption, emission and safety impacts of the traffic signal re-timing. Furthermore, the GPS data were also utilized to calibrate the microscopic simulation model.

3.1 Turning Movement and Tube Counts

Turning movement counts were collected at seven intersections along the 9.6-kilometer section of Scottsdale/Rural Road. The turning movement counts were collected for the AM peak, midday and PM peak at 15-minute intervals for a single day (Wednesday) for the before and after conditions. The intersections for which turning movement counts were collected included the intersections of Scottsdale/Rural Road with the following: Southern, Broadway, University, Curry, McKellips, McDowell, and Thomas. Figure 3 illustrates how the before and after total intersection (computed from the turning movement counts), northbound and southbound counts compared. The figure indicates that the total intersection counts were generally higher, the northbound volumes were generally lower, and the southbound volumes were generally higher for the after versus before conditions. The statistical analysis of these differences is described later in the paper.

In addition to the 15-minute turning movement counts that were collected, pneumatic-tube traffic counters were also installed at six locations, namely: Lakeshore, Hermosa, Alameda, Rio Salado, Weber, and Oak. The traffic counters collected 15-minute counts for three continuous days. Figure 4 illustrates the temporal variation in traffic volume at all six locations for the northbound and southbound directions for one of the analysis days (Wednesday). The figure demonstrates a peak in the northbound direction for the AM peak for all locations south of Arizona State University (ASU). Similarly, the southbound direction indicates a peak in traffic volume for the locations north of ASU during the AM peak. Consequently, it is evident from the temporal variation in the volume that ASU is a major trip attractor during the AM peak. The same peak that exhibits in the northbound direction exhibits itself during the PM peak in the southbound direction. Figure 4 also illustrates that the average volume across all locations in either direction appeared to be similar for both the before and after conditions. Again, the differences in total volumes were tested using Analysis of Variance (ANOVA) techniques in order to establish any statistically significant differences, which are presented later in the paper.

3.2 GPS Data Collection

Three GPS-equipped vehicles were driven along the study corridor (along Scottsdale/Rural Rd.) for three days (Tuesday through Thursday) before and after changing the signal timings. The GPS runs were conducted during the AM peak (7:00 to 9:00 AM), the off-peak (11:00 to 1:00 PM), and the PM peak (4:00 to 6:00 PM). The GPS unit measured the vehicle's location (i.e., latitude and longitude), its heading, and its speed every second. It should be noted that the GPS unit that was utilized did not include any differential correction, which reduced the location accuracy from 2 meters to within 100 meters. However, the relatively low accuracy in locating the vehicle had no bearing on the accuracy of the speed estimates given that they were not computed from the vehicle location.

A total of 141 runs were conducted for the before conditions and a total of 160 runs were conducted for the after conditions, as demonstrated in Table 2. Each run involved driving the 9.6-kilometer section from one end of the network to the other end of the network.

Using the GPS speed measurements it was possible to compute the vehicle's acceleration every second. Because the acceleration levels included some unrealistic observations (acceleration levels beyond the capabilities of the vehicle), a form of robust Kernel smoothing was applied to the acceleration levels. The details of the data smoothing are beyond the scope of this paper, however, it is sufficient to mention that the estimates of fuel consumption based on the smoothed speed and acceleration levels were found to range from a minimum of 0.96 to a maximum 1.59 liters/trip. It should also be noted that the fuel consumption estimates were found to be consistent with the Environment Protection Agency (EPA) standard Federal Test Procedure (FTP) drive cycles (Dion *et. al*., 2000).

4. Mainline Impacts of Traffic Signal Coordination: Field Results

This section summarizes the field results of the study. The first step in the evaluation was to quantify any induced demand/traffic into the Scottsdale/Rural Road corridor as a result of the improved traffic signal timings. The next step in the evaluation was to compute and statistically compare the various Measures of Effectiveness (MOEs) for the before and after scenarios.

4.1 Traffic Counts

The first step in the evaluation of the induced traffic and demand impacts of traffic signal coordination was to statistically quantify the difference in total intersection volume and tube counts for the AM peak between the before and after scenario. An ANOVA type of analysis that considered three factors was performed on the turning movement counts, as summarized in Table 3. The three factors included the intersection location (variable INT), a before/after flag (B_A) and the approach direction (DIR). As the table indicates there were 7 intersections that were considered, 2 before/after conditions, and four directions of traffic movement.

The ANOVA analysis indicated that both the intersection location and the approach direction were statistically different, however, there did not appear to be a statically significant difference (5 percent level of significance) in the approach flows between the before and after conditions. Consequently, there is no statistical evidence to indicate that the changes in traffic signal timings resulted in induced traffic or induced demand.

4.2 Floating Car Runs

The next step in the analysis was to quantify the efficiency, energy, environmental and safety impacts of the traffic signal re-timing.

The differences in the various MOEs, as computed from the GPS runs, were evaluated considering all three periods of analysis collectively (AM peak, Midday, and PM peak), and considering each period separately. Furthermore, the analysis considered the localized impacts at the signalized approaches in addition to the impacts on the 9.6-kilometer section of Scottsdale/Rural Road.

4.2.1 Results for all Periods

The various MOEs were computed for each of the 301 trips and summarized by direction and period, as demonstrated in Table 4. The results of Table 4 indicate a 6 percent increase in the average speed between the after and before conditions when averaged over all three periods. This increase in average speed was in the range of 5 percent for the AM peak and 31 percent for the PM peak in the southbound direction. ANOVA tests were performed on the data considering three factors, namely: before/after, period (AM, midday, PM), and direction (northbound and southbound). The ANOVA results indicated that the difference in speed between before and after was statistically significant (F=24.34, DF=(1,289), p=0.0001).

The number of vehicle stops was found to be reduced by 3.6 percent overall from an average of 7.2 stops/trip to 6.9 stops/trip. These results were found to be marginally statistically insignificant (F=3.52, DF=(1,289), p=0.0615).

Fuel consumption was found to be reduced by 1.6 percent on average from 1.20 liters/trip to 1.18 liters/trip. These findings were found to be statistically significant (F=6.03, DF=(1,289), p=0.0146). The reduction in fuel consumption as a result of the signal re-timing represents an annual saving of 5.32 liters/year/trip (assuming 261 workdays in a year) or an average yearly weekday savings of 261,900 liters/year (using an average daily tube count of approximately 50,000 vehicles).

In terms of emissions, overall there was no change in the HC emissions, there was a statistically significant increase in CO emissions (1.2 percent (F=6.68, DF=(1,289), p=0.010)), and there was a statistically insignificant reduction in NO_x emissions.

The total crash risk was found to be reduced by 6.7 percent (F=25.22, DF=(1,289), p=0.001) from 27.76×10^{-6} crashes to 25.56×10^{-6} crashes. These crash risks correspond to a crash rate of approximately 2.7 crashes per million vehicle kilometers for the before scenario and a crash rate of approximately 2.5 crashes per million vehicle kilometers for the after scenario. These crash rates are consistent with average national rates for typical arterial roadways as identified in the General Estimates System (GES) database.

4.2.2 AM Peak Results

Averaging over the 26 AM peak northbound before runs and the 29 after runs, there appears to be a consistent increase in the average speed between the after and before scenarios, as illustrated in Figure 5.

The x-axis shows the distance along the trip with a gridline at each of the 21 traffic signals. The thick (red) gridlines identify the signals for which the signal timings were altered (McKellips, Weber and Curry) which are located at 3200, 4000, and 4500 meters from the north end of the section (Thomas Road). The thick green hatched line is the location of the grade railway crossing (7600 meters from Thomas Road).

Comparing the northbound and southbound speed profiles there appears to be a more significant increase in the average speed between the before and after scenarios, in the southbound direction. Furthermore, the difference in speed is more pronounced in the section between McKellips and Curry Road for the southbound direction than it is for the northbound direction.

The ANOVA results for the AM peak concluded that there was no statically significant difference between the before and after MOEs (5 percent level of significance), with the exception to the average speed that was found to be marginally statistically significant (p=0.046). Specifically, the average speed increased as a result of the traffic signal re-timing from 45.4 km/h to 47.9 km/h in the northbound direction and increased from 47.5 km/h to 48.2 km/h in the southbound direction.

Additional ANOVA tests were performed on the computed MOEs at the signalized approaches for the AM before and after runs. Four factors were considered in the analysis: before/after flag, direction of trip (northbound and southbound), intersection (21signals in total, 18 not re-timed, 3 re-timed) and period (AM, midday, PM). The ANOVA tests concluded that there was a statistical difference between the before and after MOEs with the exception to CO emissions and the expected number of fatal crashes for the approaches to the three signals that were re-timed (Curry, Weber and McKellips). Alternatively, for the traffic signals that were not re-timed there was not enough statistical evidence to conclude that the differences in the computed MOEs were significant (5 percent level of significance).

Table 5 summarizes the changes in MOE, between the before and after scenarios, for each intersection for the AM peak. The shaded cells represent changes that are statistically significant at the 5 percent level of significance. The table does indicate improvements at approaches to the signals that were re-timed (e.g. a 19 increase in average speed at the approaches to McKellips Road) and mixed results at the approaches to the signals that were not re-timed. Apart from the approaches to McKellips Road, there does not appear to be any statistically significant changes in the various MOEs between the before and after scenarios.

In conclusion, it appears that the benefits of the signal coordination were confined to the approaches to the traffic signals that were re-timed. These benefits were not apparent when the entire 9.6-kilometer section of Scottsdale/Rural Road was considered.

5. Network Impacts of Signal Coordination: Simulation Construction & Results

Given that field GPS data were only collected for the mainline (Scottsdale/Rural Road), it was not possible to quantify the impacts of the signal coordination on the cross-traffic nor was it possible to quantify the overall network impacts of the signal re-timing. The modeling effort that is described in this section attempts to evaluate the overall benefits of the signal re-timing ignoring traffic diversion (i.e. the vehicle routes were held constant). Further analyses, that are beyond the scope of this paper, will consider the potential for temporal and spatial diversion of traffic in evaluating the traffic signal changes.

Prior to discussing the results of the network analysis, this section first describes how the simulation network was constructed and how the network was calibrated.

5.1 Network Construction and Cropping

The modeling of the Scottsdale/Rural Rd. network was conducted using the INTEGRATION microscopic traffic simulation and assignment model. The network was constructed using the Maricopa Association of Governments (MAG) planning model (in this case EMME/2) of the Greater Phoenix area, as illustrated in Figure 6. The planning model covered an area of over 7,200 square kilometers with a total of 9,529 nodes, 27,840 links and a total demand in excess of 2 million vehicle trips for the AM peak.

The O-D demand for the AM peak included Single Occupancy Vehicle (SOV), High Occupancy Vehicle (HOV), and bus trips. The demand was created using the standard four-step transportation planning process — trip generation, trip distribution, mode split, and traffic assignment. The network was converted from EMME/2 format to INTEGRATION format and then cropped to include the Scottsdale/Rural section and any alternative parallel routes. The network was sufficiently large enough to allow the modeling of traffic diversion (approximately 60 square kilometers). This network included Scottsdale/Rural Rd. from Southern Road to the south to a couple of kilometers north of Thomas Road to the north and included Hayden Rd. (an alternate parallel route to Scottsdale/Rural Road). The resulting Scottsdale/Rural Rd. network included a total of 499 nodes and 1021 links.

The cropping of the Scottsdale/Rural Road network also involved extracting the O-D pairs that traversed the sub-network from the full O-D matrix. In order to identify whether an O-D demand traversed the network an All-or-Nothing (AOL) traffic assignment was made between each origin/destination combination, if the tree passed through the network it was included in the sub-network O-D demand.

After constructing the network further details were added to the network which included turning bays, lane striping at signalized approaches, signal timings, and the type of control of traffic signals. A total of 72 traffic signals were added to the base network. Information on signal timings, type of signal phasing, and type of signal control (actuated, coordinated, or actuated/coordinated) were provided by Maricopa County Department of Transportation (MCDOT) and the cities of Tempe and Scottsdale.

5.2 Calibration of Demand

Although the EMME/2 O-D demand was available, it was not consistent with the tube and turning movement counts that were collected in the field (coefficient of determination of 0.42 between the observed and estimated flows). Consequently, the O-D demands were fine-tuned to match the tube and turning movement counts more accurately. The calibration of O-D demands to field observed link flows is a problem that has been the focus of extensive research. The most renowned of the approaches is the maximum likelihood approach that was first formulated by Willumsen (1978) and Van Zuylen and Willumsen (1980). The O-D demand was calibrated using the QUEENSOD model that numerically solves the maximum likelihood problem.

The calibration of the O-D demand to the tube and turning movement flows resulted in a consistency between the final O-D demand and the field conditions (coefficient of determination of 0.94 between the estimated and observed flows), as illustrated in Figure 7. The refined O-D demand was then simulated within the microscopic simulation environment demonstrating a high correlation between the synthetic flows (Flow "B" in Figure 6) and the simulated flows (Flow "C" in Figure 6), as illustrated in Figure 7. The final test that was conducted was to compare the micro simulated flow estimates to the tube and turning movement flows that were observed in the field. This comparison indicated a relatively good correlation (coefficient of determination of 0.72) between the simulated (Flow "C" in Figure 6) and field observed flows (Flow "A" in Figure 6), as illustrated in Figure 7.

In order to put the level of calibration in context, an attempt was made to quantify the typical level of variability in 15-minute tube flows from one day to another during the AM peak (i.e. variability in flow from 8:00 to 8:15 on day 1 versus 8:00 to 8:15 on day 2). An analysis of the seven tube locations indicated that the daily 15-minute flow variability during the AM peak ranged from a coefficient of determination of 0.70 to 0.98. Consequently, it was concluded that the error between simulated and observed flows was within the typical daily variability that was observed in the field.

5.3 Field and Simulation Consistency

A comparison was made between the speed profile of simulated vehicles that traveled along the 9.6-kilometer section of Scottsdale/Rural Rd. and the GPS vehicles in order to ensure consistency between the simulated and field conditions. Given that the speed profile of a vehicle changes depending on when within the cycle length it encounters the first traffic signal, a comparison of a single profile could be misleading. Consequently, the average speed profile over all trips during the AM peak for the before signal timings was computed together with the 95 percent confidence limits, as illustrated in Figure 8. Figure 8 demonstrates a significant level of variability in the speed profile especially upstream the traffic signals depending on when the vehicle arrives at the signal.

The confidence limits for the mean were computed by dividing the confidence limits by the square root of the number of observations in the sample, as illustrated in Figure 9. In addition, 200 probe vehicles (vehicles that collect second-by-second information) were simulated within the simulation environment that provided information on the vehicle speed, acceleration, fuel consumption, emissions, crash risk, etc. These probe vehicles traveled along Scottsdale/Rural Road in both directions (northbound and southbound). The average simulated speed profile was then super-imposed on the field confidence limits in order to ensure consistency between the simulated and field conditions, as illustrated in Figure 9. The figure does demonstrate consistency between simulated and field observed speed profiles along the entire 9.6-kilometer section in both directions. In addition, Figure 10 illustrates that there was no systematic error between the simulated and field observed speed estimates along the entire 9.6-kilometer section (points symmetric around the line of perfect correlation). Similar consistency between the simulation and field speed profiles was found for the northbound and southbound direction using the after signal timings.

5.4 Simulation Results

This section summarizes the simulation results of the study. The results for the mainline are presented first in order to deomonstrate consistency between the field and simulation approaches. Subsequently, the results for the cross street are presented followed by the network impacts of the signal re-timing. Each of these scenarios was analyzed for the AM peak for the before and after conditions.

5.4.1 Mainline Results

As described earlier, probe vehicles traveling along Scottsdale/Rural Road were simulated within the simulation environment. A total of 200 probe vehicles completed the 9.6-kilometer section between Southern Avenue to the south and Thomas Road to the north. These probe vehicles included 103 trips for the after case and 97 trips for the before case.

In order to ensure consistency between the simulated and field results, ANOVA tests were performed on the simulated MOE estimates. As was the case with the field data, the ANOVA results indicated statistically significant localized benefits as a result of the traffic signal re-timing, however, the results were statistically insignificant when the entire 9.6-kilometer mainline section was considered. Specifically, in the case of the re-timed signals the differences in MOEs were statistically significant, with the exception for number of vehicle stops per signalized approach that was found to be marginally statistically insignificant (p=0.0534) and the HC and CO emissions that were not statistically significant. For the signals that were not re-timed, as was the case with the field data, the differences in MOEs were found to be statistically insignificant.

5.4.2. Cross-Street Results

In order to evaluate the impact of signal coordination on the cross streets, additional probe vehicles that traveled along selected cross-streets were simulated within the simulation environment. Two cross-streets were selected, one with a traffic signal that was re-timed (Weber Street) and another with a traffic signal that was not re-timed (Terrace Road). Weber Street was selected, because is was the only re-timed traffic signal that maintained the same cross street green interval duration between the before and after scenarios, as illustrated in Figure 2.

Figure 11 illustrates the total delay for each probe vehicle before and after the signal timings were altered. The figure clearly indicates that the delay associated with the traffic signal that was not re-timed (Terrace Road) is consistent between the before and after conditions. Alternatively, for the case of the re-timed signal, the delays for the after condition for the AM peak are significantly lower than for the before condition. These results were supported by statistical *t* tests. Specifically, the differences in delay were found to be statistically insignificant for the traffic signal that was not re-timed (Terrace Road (P (T<t)=0.996)), while the difference in delay for the re-timed traffic signal (Weber Street) was found to be statistically significant (P (T<t)=0.029). Consequently, while the results are not conclusive because not all signals were considered, it appears that the signal re-timing did result in localized benefits to both the mainline and cross-streets.

As was mentioned earlier, field GPS data for the cross-streets were not available to compare simulation and field results. However, these findings demonstrate the importance of simulation for replicating field conditions and for evaluating conditions that were not measured or observed in the field.

5.4.3 Network Results

As described earlier the field and simulation results indicated that the changes in signal timings did result in localized benefits to the mainline (Scottsdale/Rural Road), however, it was not possible to evaluate the network impacts of the signal coordination using the field data.

The calibration of the demand to the field observed tube and turning movement counts resulted in a total demand of 123,518 over the two hour AM peak period. The demand was then simulated several times (5 random number seeds representing 5 different days) using the before signal timings and after signal timings. The results of the simulation indicate that on average the changes in the signal timings resulted in an increase in the system efficiency and positive environmental and safety impacts, as demonstrated in Table 6. A statistical analysis of the results indicates that the differences are not statistically significant compared to the noise within typical days, as shown in Table 6 and in Figure 12. For example, while Figure 12 illustrates that the changes in signal coordination reduced the average delay and the variability in delay, the reduction is within the noise across different runs.

The statistically insignificant difference between the before and after conditions can be attributed to the fairly large extent of the network under consideration (approximately 60 km^2) and to the fairly minor changes that were made to the signal timings (offsets changed for only 3 signals of the 72 signals).

It should be noted, however, that the changes in the signal timings reduced the variability in the different MOEs in most cases. The variability for the different MOEs between the before and after conditions were compared using statistical *F* tests. The results concluded that, for a level of significance of 10 percent, there was statistically significant evidence that the variance of the speed, total delay, stopped delay, acceleration and deceleration delay and average crash risk were reduced as a result of the traffic signal re-timing. For the other MOEs there is not statistical evidence to conclude that the variances between the before and after situation were different.

6. Conclusions and Recommendations for Further Research

While this study does provide some insight as to the potential benefits of coordinating traffic signals across jurisdictional boundaries, more importantly it demonstrates the feasibility of using GPS second-by-second speed measurements and simulation tools for the evaluation of operational-level traffic improvement projects. Specifically, the use of statistical models allows for the evaluation of the efficiency, energy, emissions and safety benefits of operational-level traffic improvement projects without having to invest in expensive equipment.

In terms of the specific conclusions of the study, based on a field evaluation of the mainline, the results, when averaged over all three periods (AM peak, Midday, and PM peak), showed that the mainline average speed increased by 6 percent. In addition, the number of vehicle stops was found to be reduced by 3.6 percent, while the fuel consumption was reduced by 1.6 percent on average. The HC and NO_x emissions were found to remain constant while the CO emissions increased by 1.2 percent. Finally, the crash risk was found to be reduced by 6.7 percent. The AM peak field data demonstrated statistically significant localized benefits as a result of the signal re-timing, however, these benefits were statistically insignificant when the entire 9.6-kilometer mainline section was considered.

The INTEGRATION simulation model demonstrated mainline findings that were consistent with the field data, namely, statistically significant localized impacts with statistically insignificant overall mainline impacts. Furthermore, the simulation results indicated that the signal re-timing resulted in localized cross-street benefits, however, the benefits of the signal re-timing were found to be insignificant at the network level. The simulation results did indicate that at the network level there was a reduction in the speed and delay variance as a result of the traffic signal re-timing. It should be pointed out that the network-level analysis did not consider changes in vehicle routing, changes in time of departure, nor did it consider changes in mode of travel.

Further work is required to investigate long-term impacts of operational-level traffic improvement projects and to quantify the potential benefits of coordinating the entire corridor off-line as one sub-area, applying isolated adaptive signal control, and applying coordinated adaptive signal control.

Acknowledgements

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List of Tables

List of Figures

Table 1. Before and After Traffic Signal Offsets

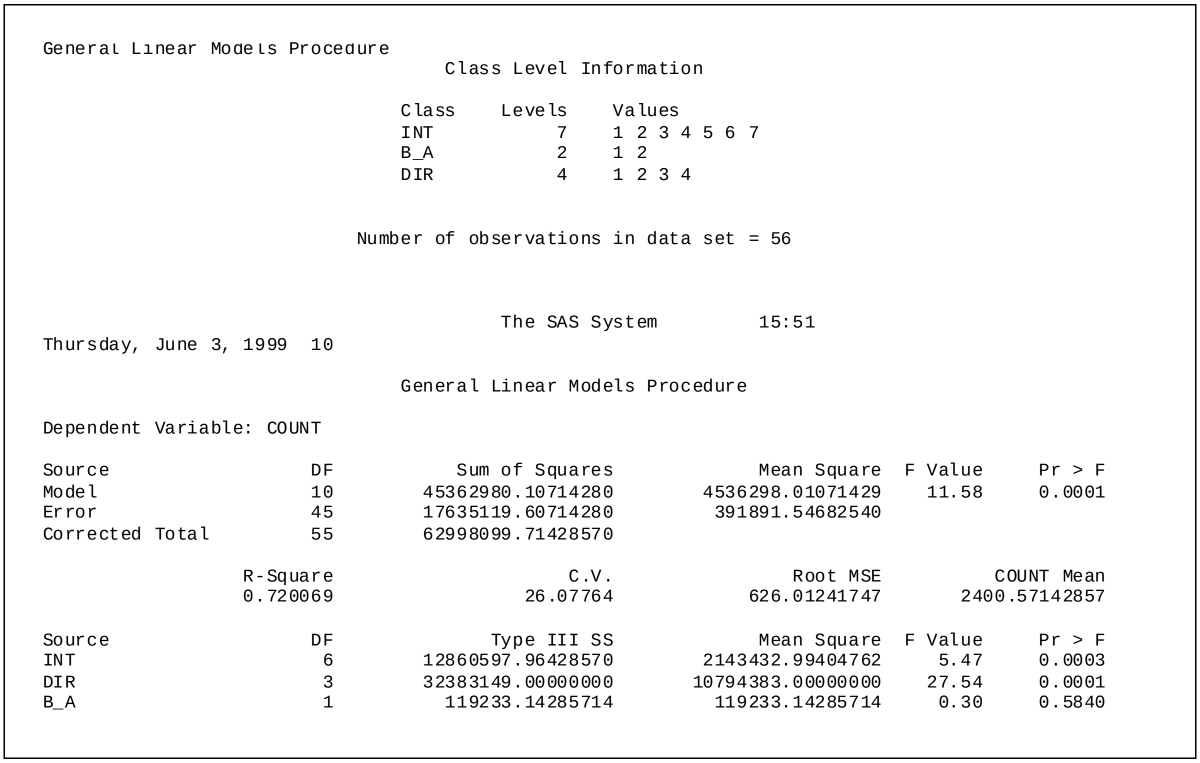
	AM Peak Plan		PM Peak Plan		Off-Peak Plan	
	Before	**After**	**Before**	**After**	**Before**	**After**
Rural/S202	10	10	0	0	20	20
Rural/Curry	95*	41*	100*	58*	55*	37*
Rural/Weber	75	22	2	51	45	32
Rural/McKellips	36*	98*	46*	4*	0*	4*
Scottsdale/Continental	38	38	38	38	32	32

* Offsets refer to phase 4 in Figure 2

Table 2. Classification of GPS Before and After Runs

	Northbound			Southbound			
	AM Peak	**Midday**	**PM Peak**	**AM Peak**	**Midday**	**PM Peak**	**Total**
Before	26	26	17	27	27	18	141
After	29	27	26	27	26	25	160
Total	55	53	43	54	53	43	301

Table 3. ANOVA Results on Turning Movement Counts



```
General Linear Models Procedure
                                    Class Level Information

                                Class    Levels    Values
                                INT           7    1 2 3 4 5 6 7
                                B_A           2    1 2
                                DIR           4    1 2 3 4


                            Number of observations in data set = 56



                                         The SAS System         15:51
Thursday, June 3, 1999  10

                                General Linear Models Procedure

Dependent Variable: COUNT

Source                  DF           Sum of Squares             Mean Square  F Value     Pr > F
Model                   10        45362980.10714280        4536298.01071429    11.58     0.0001
Error                   45        17635119.60714280         391891.54682540
Corrected Total         55        62998099.71428570

                  R-Square                     C.V.                Root MSE          COUNT Mean
                  0.720069                 26.07764            626.01241747       2400.57142857

Source                  DF              Type III SS             Mean Square  F Value     Pr > F
INT                      6        12860597.96428570        2143432.99404762     5.47     0.0003
DIR                      3        32383149.00000000       10794383.00000000    27.54     0.0001
B_A                      1          119233.14285714         119233.14285714     0.30     0.5840
```

Table 4. Mainline MOE Comparison (Average MOEs for entire 9.6-kilometer trip)

		Northbound			**Southbound**			**Average**
		AM Peak	**Midday**	**PM Peak**	**AM Peak**	**Midday**	**PM Peak**	
Before	**Speed (km/h)**	45.4	43.5	38.5	47.5	46.9	29.5	41.9
	Stops/trip	6.6	6.6	7.3	6.4	6.2	10.0	7.2
	Fuel (l/trip)	1.15	1.16	1.23	1.14	1.14	1.39	1.20
	HC (g/trip)	1.17	1.17	1.23	1.19	1.17	1.38	1.22
	CO (g/trip)	15.4	15.2	15.5	15.6	15.3	15.7	15.4
	NO$_x$ (g/trip)	3.13	3.06	3.17	3.18	3.13	3.39	3.18
	Crashes×10^{-6}/trip	24.8	25.7	29.0	23.7	24.0	37.4	27.4
After	**Speed (km/h)**	47.9	46.0	41.0	48.2	45.4	38.7	44.5
	Stops/trip	6.4	6.4	7.5	6.4	6.6	8.1	6.9
	Fuel (l/trip)	1.13	1.15	1.22	1.14	1.17	1.27	1.18
	HC (g/trip)	1.17	1.19	1.25	1.19	1.22	1.29	1.22
	CO (g/trip)	15.4	15.5	15.7	15.6	15.6	15.7	15.6
	NO$_x$ (g/trip)	3.00	3.16	3.27	3.06	3.22	3.28	3.17
	Crashes×10^{-6}/trip	23.5	24.5	27.4	23.3	24.8	29.9	25.6

Table 5. Percent Change in Mainline MOEs for AM Peak

Intersection	Speed	Stops	Delay	Fuel	HC	CO	NO_X	Crashes
Thomas Rd	-1	26	20	5	6	5	1	12
Oak Street	1	2	-7	2	5	2	9	-2
Mc Dowell	3	13	-24	-6	-4	-4	-14	-13
Los Arcos Mall	5	-27	-25	-2	-4	3	-4	-6
Continental	1	12	-6	-1	-1	-2	-10	0
Mc Kellips Rd	19	-40	-52	-10	-9	0	-11	-21
Weber	4	-34	-24	-6	-7	-2	-17	-6
Curry Rd	13	-24	-21	-9	-9	-1	-14	-10
S 202	-6	30	16	0	0	-4	-11	7
Rio Salado Parkway	-1	23	6	4	7	3	9	0
6th Street	8	-23	-27	-5	-3	1	-1	-12
University Drive	-1	5	7	5	7	5	-3	5
Terrace Road	-2	-6	2	3	6	4	-1	1
Lemon Street	6	-3	-45	-9	-7	-3	2	-19
Apache Boulevard	1	20	15	2	2	0	-2	10
Spence Avenue	-2	-7	43	10	13	4	19	14
Vista del Cerro Drive	-3	20	29	8	8	5	13	8
Broadway Rd	-5	17	-13	-1	1	-3	5	-8
Broadmar	6	-40	-29	-6	-5	-1	-22	-7
Alameda Drive	4	-24	-27	2	4	7	8	-3
Southern Avenue	-4	10	10	-4	-1	-9	-1	-2

Table 6. Summary of Network Simulation Results

	Before		After		P(T<t)
	Mean	Std. Dev.	Mean	Std. Dev.	
Avg. trip duration (minutes)	8.7	0.77	8.3	0.24	0.31
Avg. delay (minutes)	4.5	0.33	4.5	0.15	0.89
Avg. stopped delay (minutes)	2.5	0.22	2.6	0.11	0.22
Avg. acceleration/deceleration delay (min.)	2.0	0.16	1.9	0.06	0.27
Avg. number of stops	4.1	0.06	4.1	0.03	0.65
Avg. fuel consumption (l)	0.6	0.01	0.6	0.01	0.76
Avg. HC emissions (g)	9.9	0.12	9.9	0.11	0.46
Avg. CO emissions (g)	67.8	0.34	67.9	0.74	0.73
Avg. NO_x emissions (g)	1.6	0.01	1.6	0.01	0.18
Avg. crash risk$\times10^{-6}$	15.2	0.69	15.3	0.31	0.78

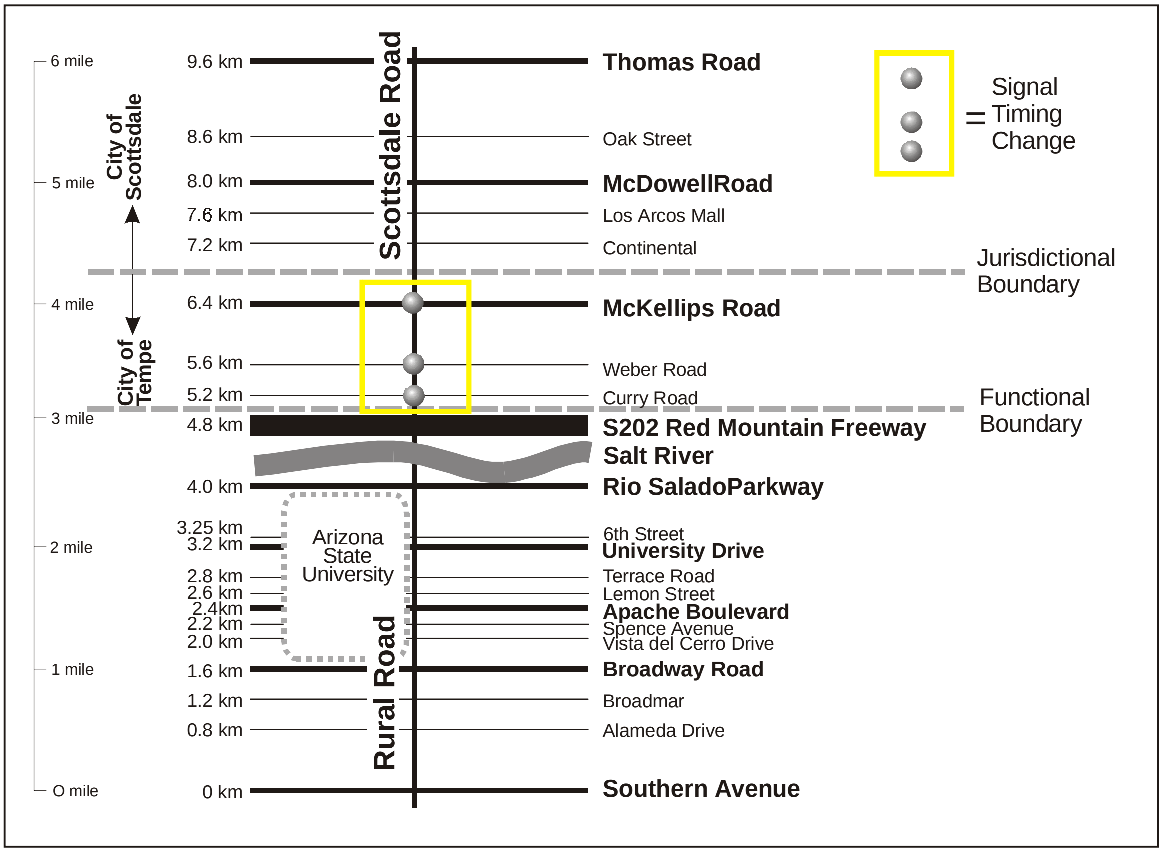


Figure 1. Scottsdale/Rural Road Study Corridor

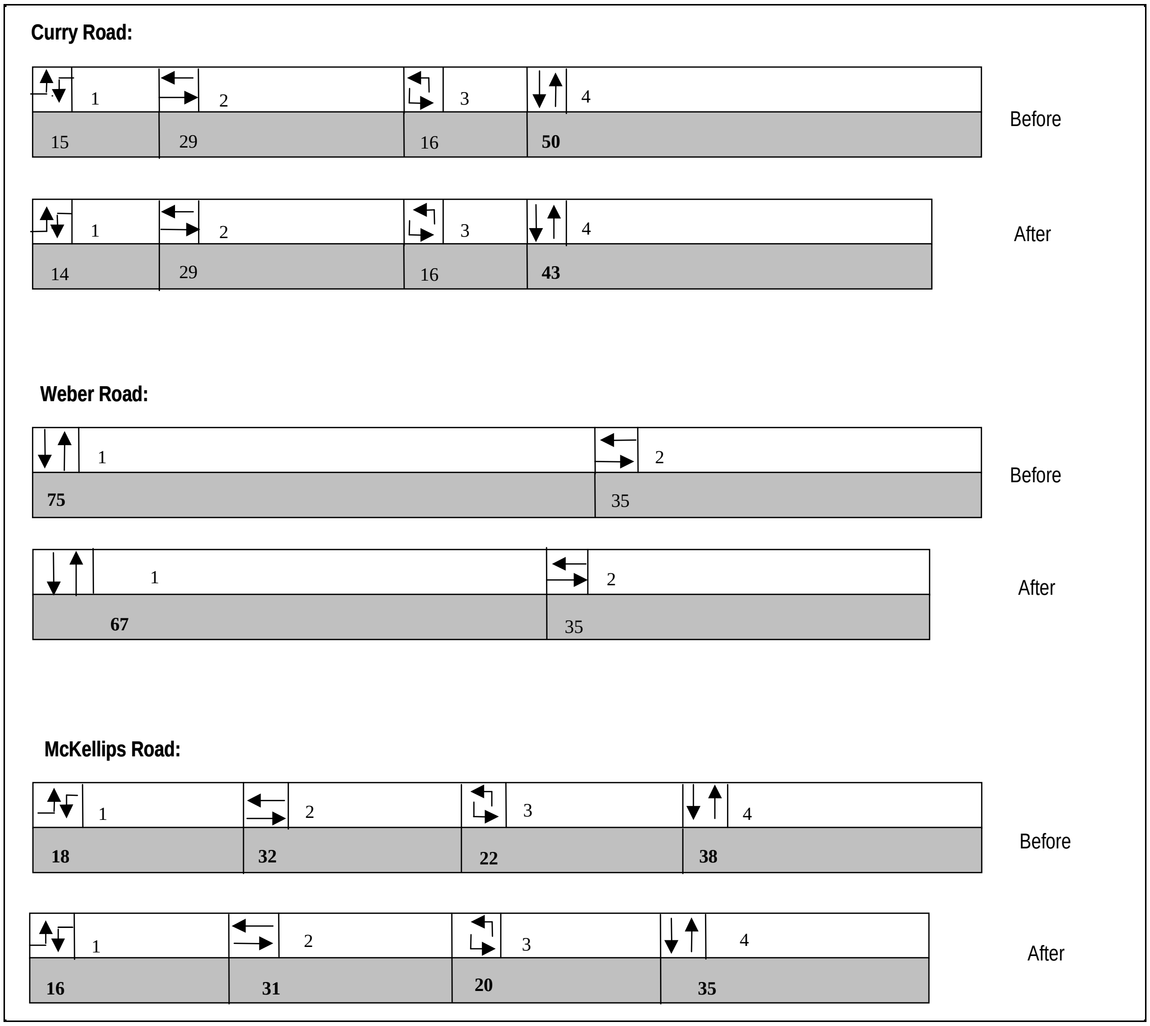


Figure 2. Before/After Signal Timings (AM Peak Plan)

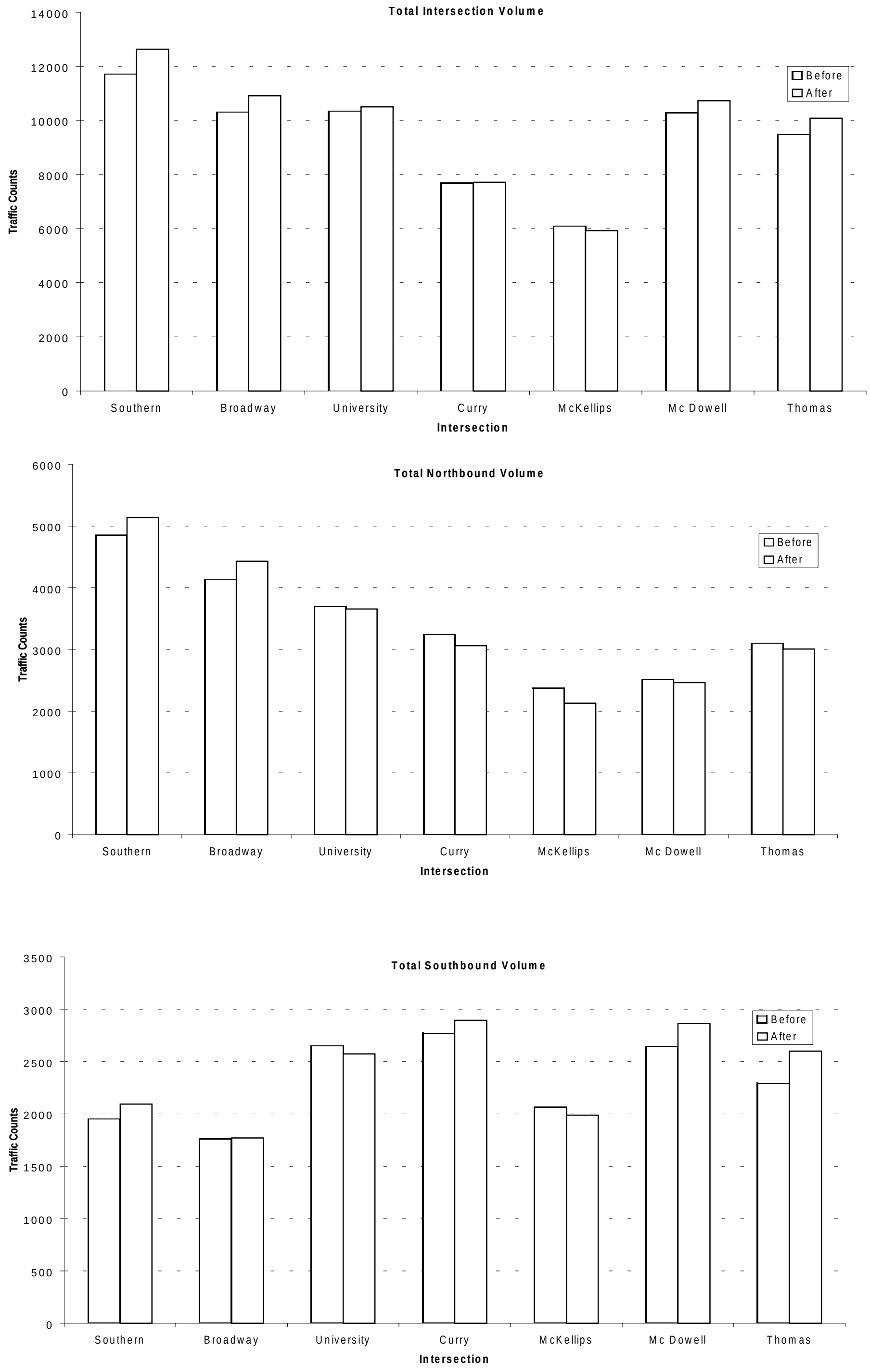
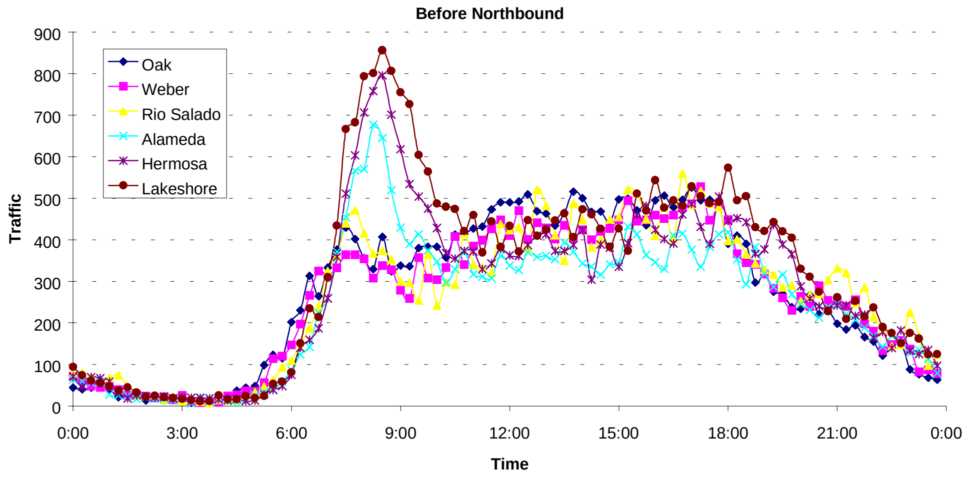
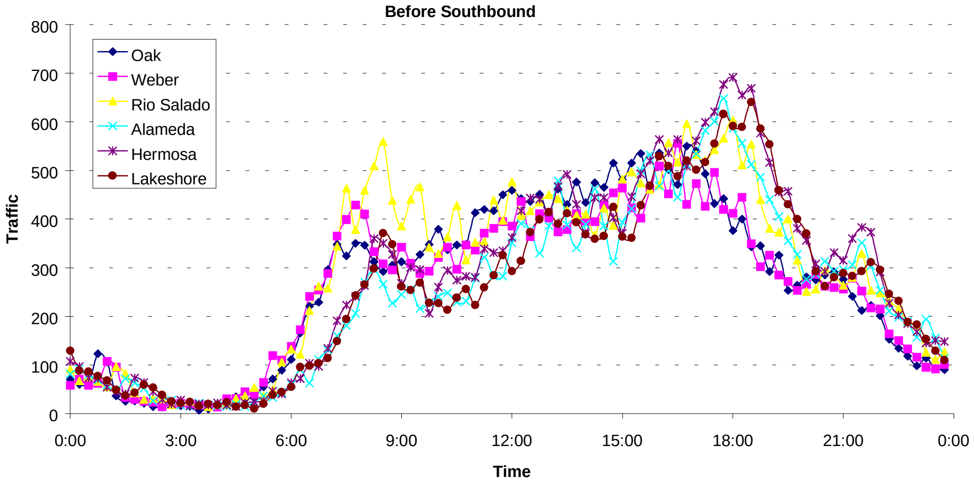


Figure 3. Before/After Intersection Volumes Computed from Turning Movement Counts

a. Before Southbound Flow



b. Before Northbound Flow



c. Average Flow

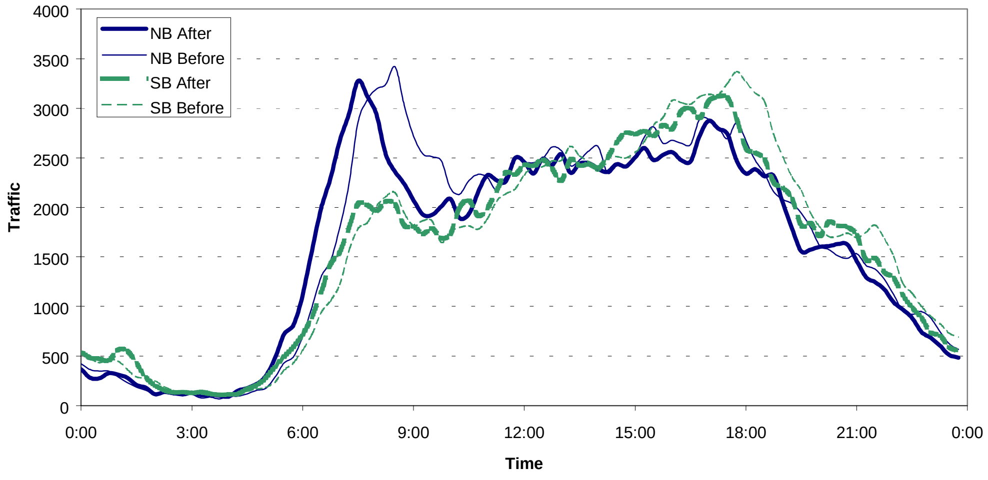
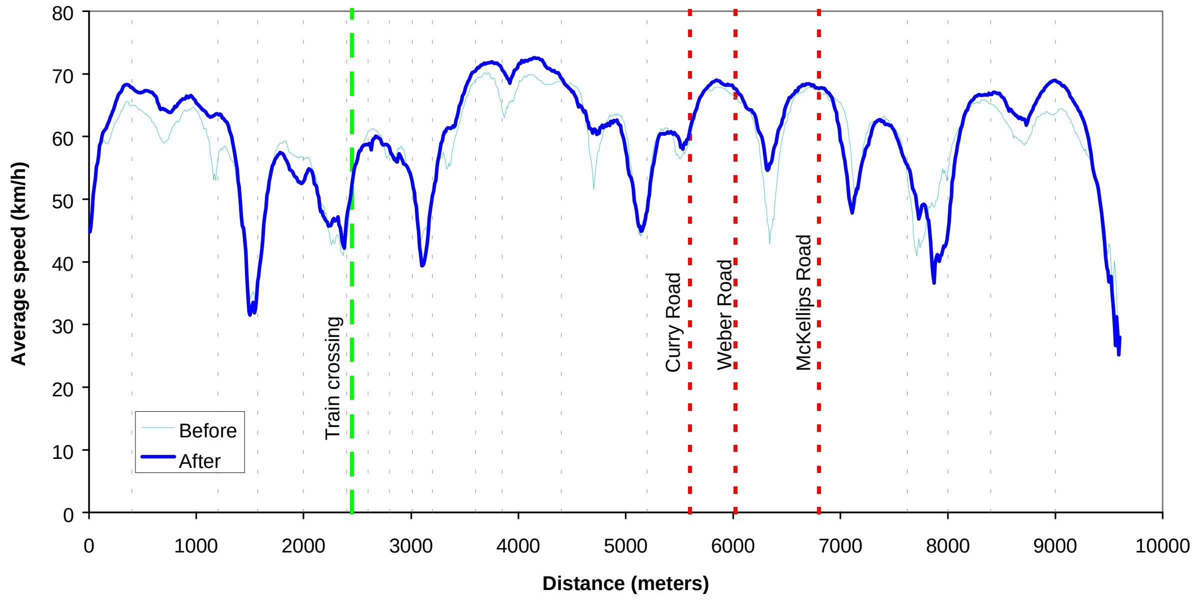


Figure 4. Before/After Temporal Variation in Demand

a. Northbound Speed Profile Comparison



b. Southbound Speed Profile Comparison

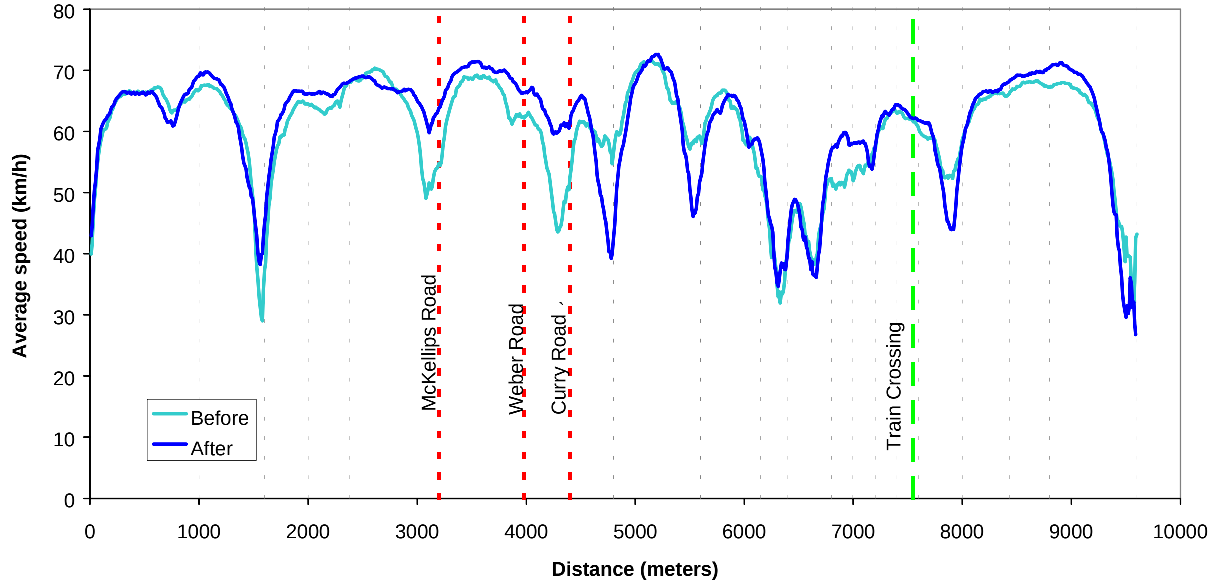


Figure 5. AM Peak Northbound and Southbound Speed Profile

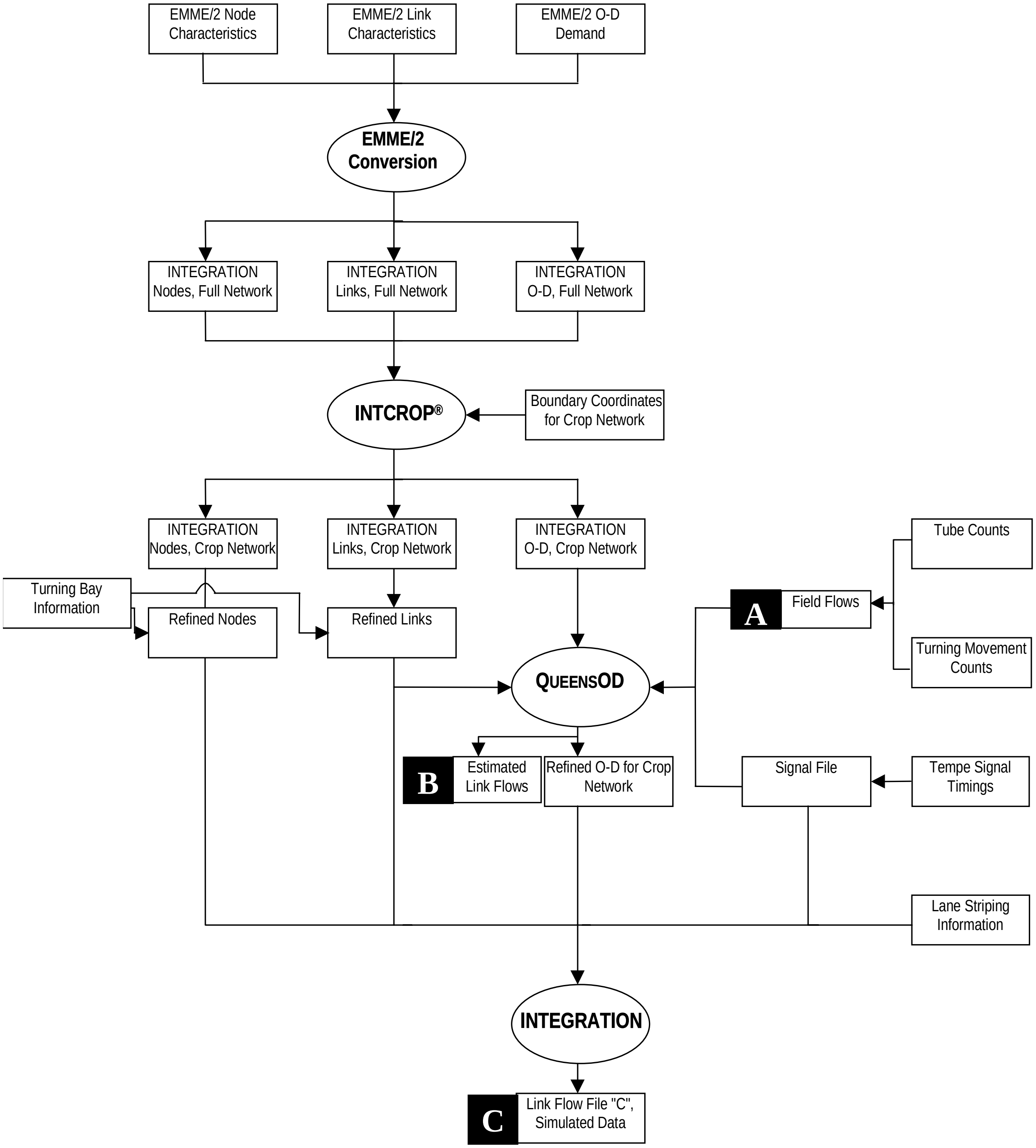
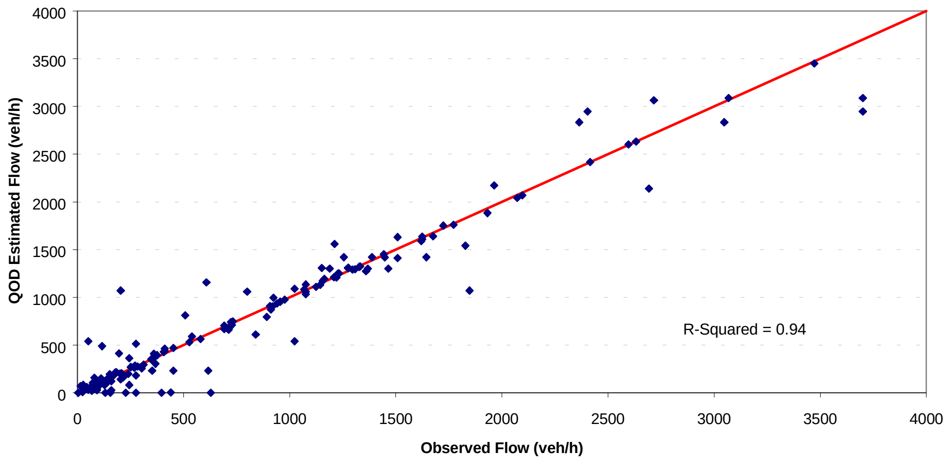
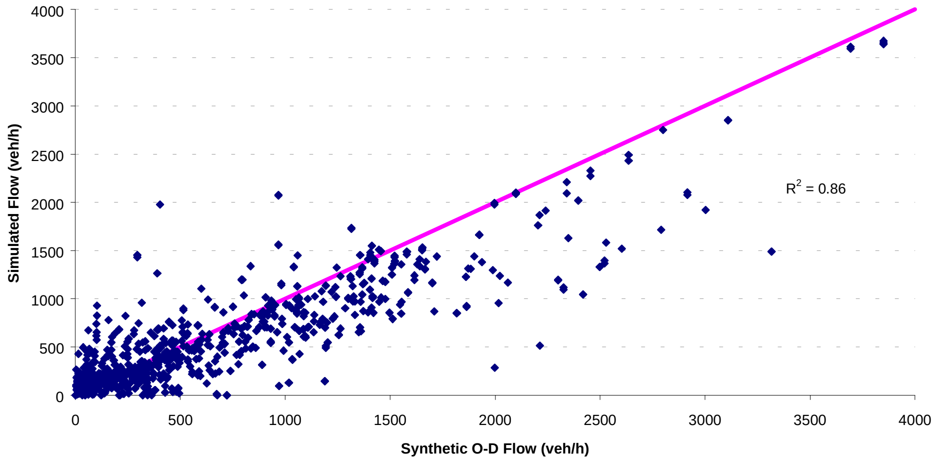


Figure 6. Overview of Simulation Methodology

a. Comparison of Flow "A" and Flow "B"



b. Comparison of Flow "B" and Flow "C"



c. Comparison of Flow "A" and Flow "C"

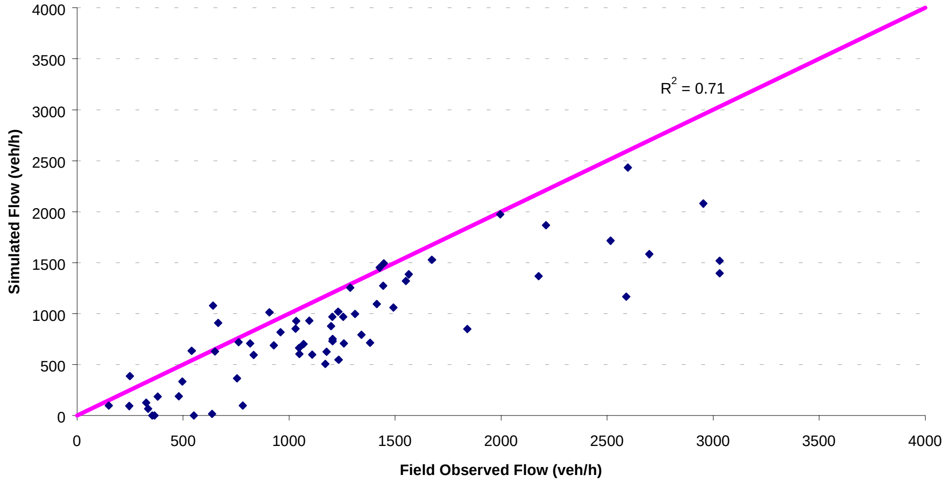


Figure 7. Comparison of Estimated Flows to Tube and Turning Movement Flows

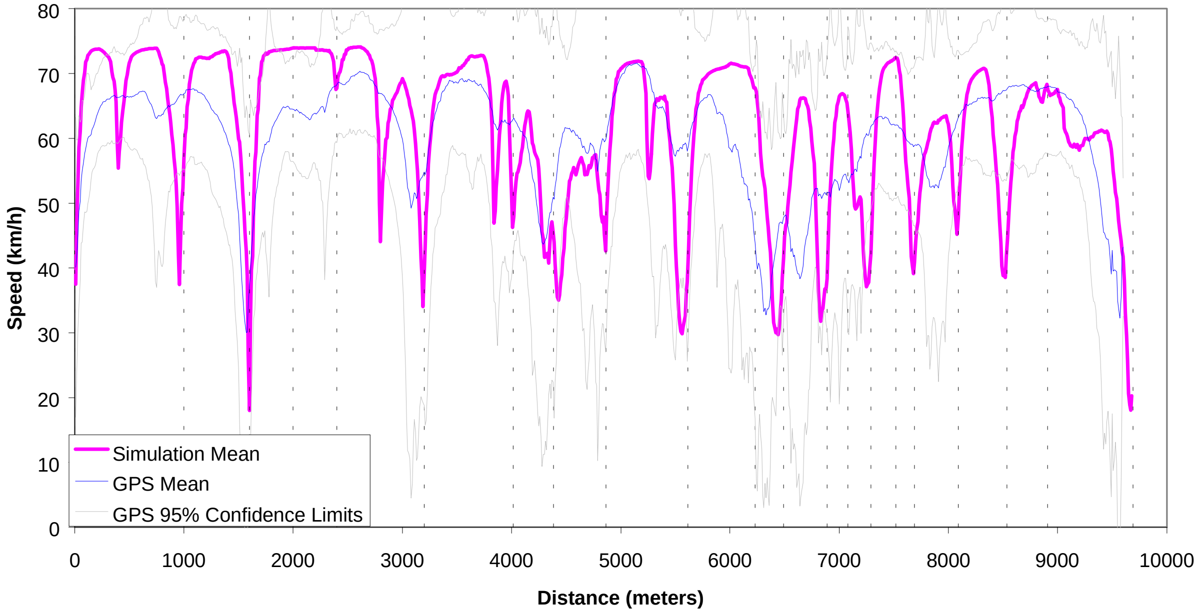
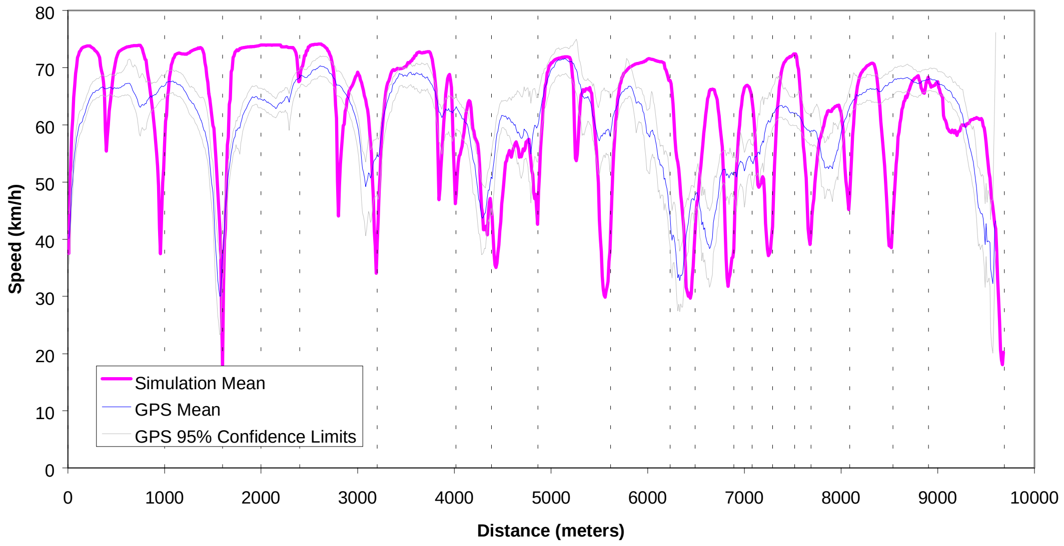


Figure 8. Speed Variability in Field Data (Southbound Direction during AM Peak)

a. Southbound Speed Profile Comparison



b. Northbound Speed Profile Comparison

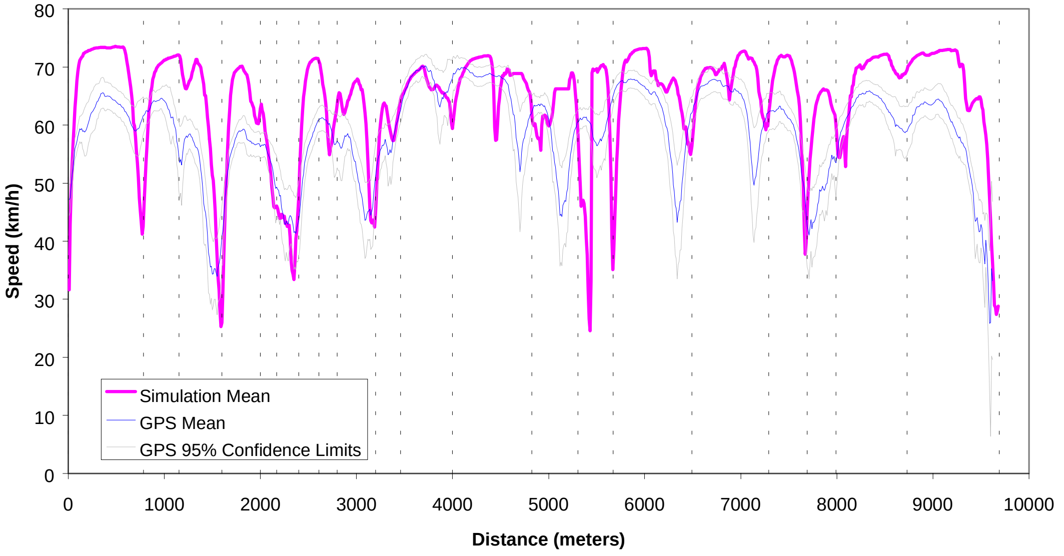


Figure 9. Simulated versus Field Speed Profile Comparison (Southbound and Northbound Before)

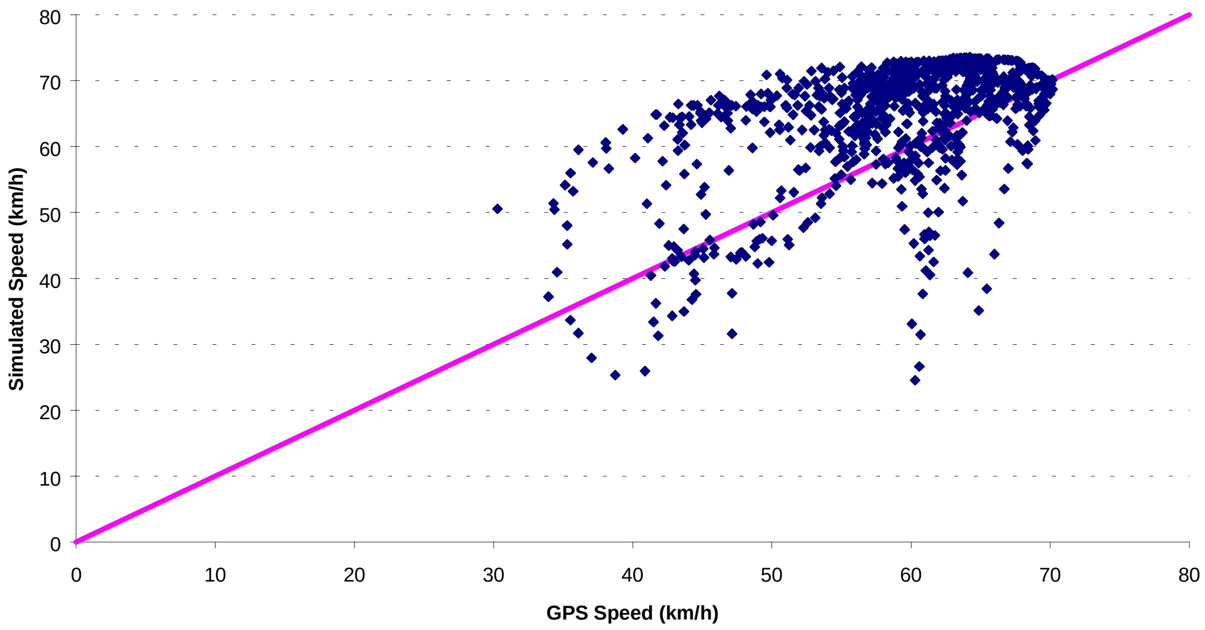
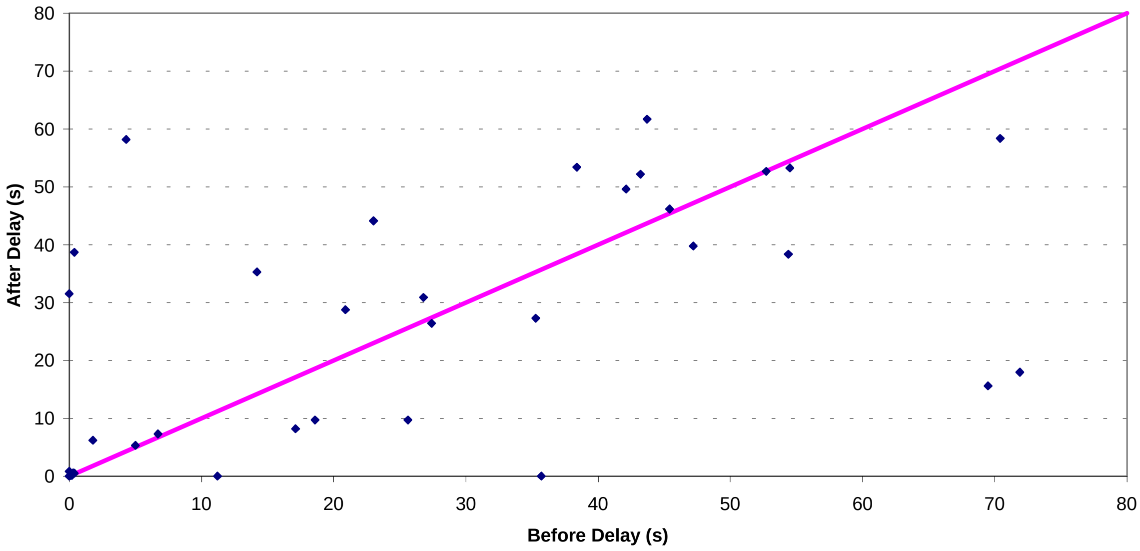


Figure 10. Scatter Plot of Simulated versus Field Speed Estimates (Northbound Before)

a. Non Optimized Signal



b. Optimized Signal

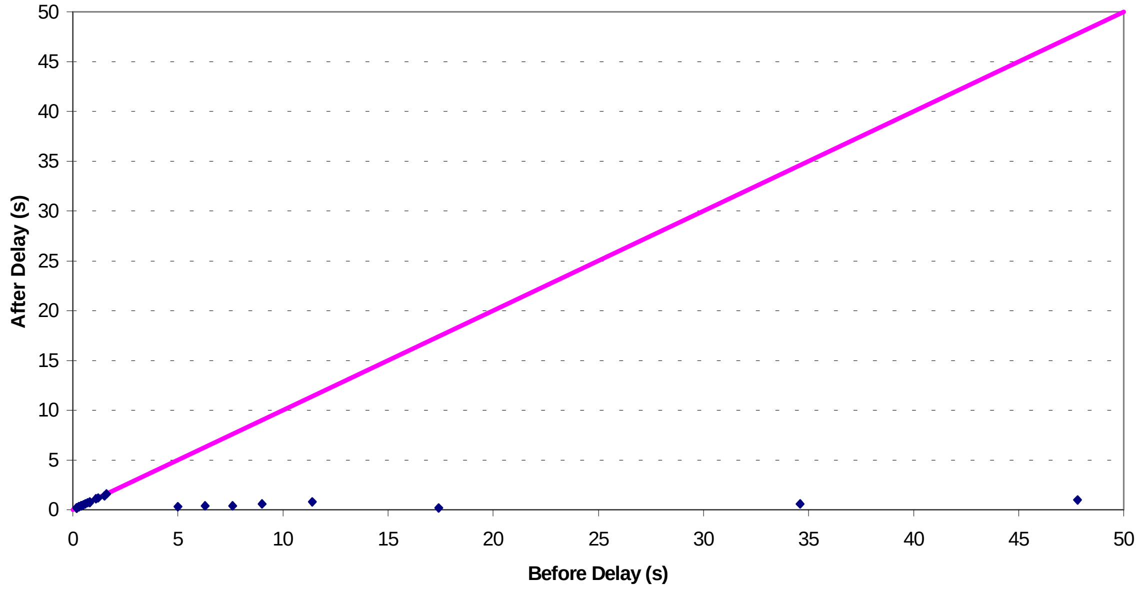


Figure 11. Scatter Plot of Before versus After Simulated Delays for a Non-Optimized Signal (Terrace Road) and an Optimized Signal (Weber Street)

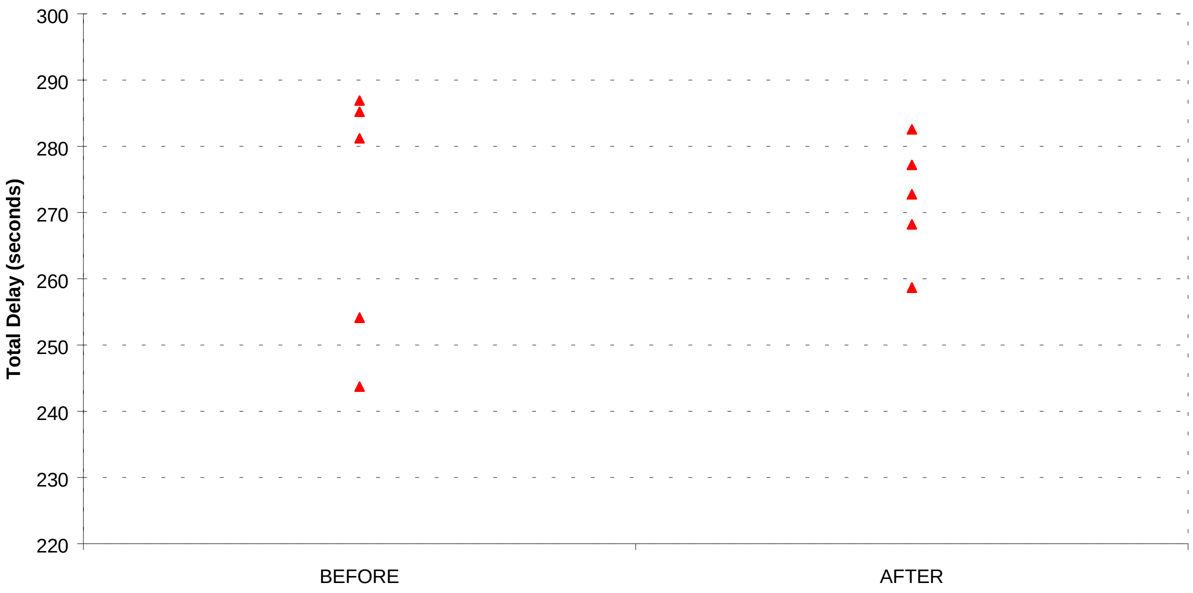


Figure 12. Average Total Delay for Different Simulation Runs