Real-Time Adaptive Traffic Signal Control for Urban Road Networks: The East Liberty Pilot Test

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1. Overview

This report summarizes the results of a pilot test of a real-time adaptive traffic signal control system on a nine-intersection road network in the East Liberty region of the city of Pittsburgh, PA. The adaptive traffic signal control system tested, called SURTRAC (Scalable Urban TRAffic Control), is designed specifically for urban road networks, where there are multiple, competing dominant flows that shift dynamically through the day. In contrast to commercial adaptive traffic control systems, SURTRAC takes a totally decentralized approach to control of traffic in a road network [Xie, et. al 2012a,b]: each intersection allocates its green time independently based on current incoming vehicle flows, and then projected outflows are communicated to neighboring intersections to increase their visibility of future incoming traffic. Reliance on decentralized intersection control ensures maximum real-time responsiveness to actual traffic conditions, while communication of projected outflows to neighbors enables coordinated activity and creation of green corridors. The system is inherently scalable to road networks of arbitrary size, since there is no centralized computational bottleneck.

To demonstrate the potential of SURTRAC, a performance comparison was carried out with the existing traffic signal control scheme for the nine-intersection test site, which consists of a combination of coordinated, fixed timing plans for AM and PM rush periods and simple actuated control (free mode) in non-rush periods. A series of "before" and "after" drive through runs were performed at 4 different periods of the day, and various performance metrics (travel time, speed, number of stops, wait time, emissions, fuel efficiency) were computed for each test condition. Across all metrics studied, SURTRAC is seen to produce significant performance improvement, ranging from 21%-40% overall.

2. Pilot Test Environment

The pilot test site (see Figure 1) consists of nine intersections in the East Liberty region of Pittsburgh surrounding the Target Department Store. The portion of Penn Circle identified for the pilot was reconfigured about a year ago to support two-way traffic and new traffic lights were installed at 8 of these intersections at this time.

Each of these new intersections is equipped with cameras pointing in all flow directions, and all 8 are inter-connected with fiber-optic cable, providing the sensing equipment and networking infrastructure needed to deploy the SURTRAC system. More specifically, this network of 8 traffic lights consists of:

- The sequence of 6 lights starting at the intersection of Penn Circle and South Highland and following former path of Penn Circle past the Target department store to Collins Street,
- 1 light on Penn Avenue moving east from the intersection of Penn Circle and Penn Avenue (associated with the newly reconfigured bus way property),
- 1 light at intersection of Broad Street and Larimer Avenue (at the entrance to the Target parking lot)

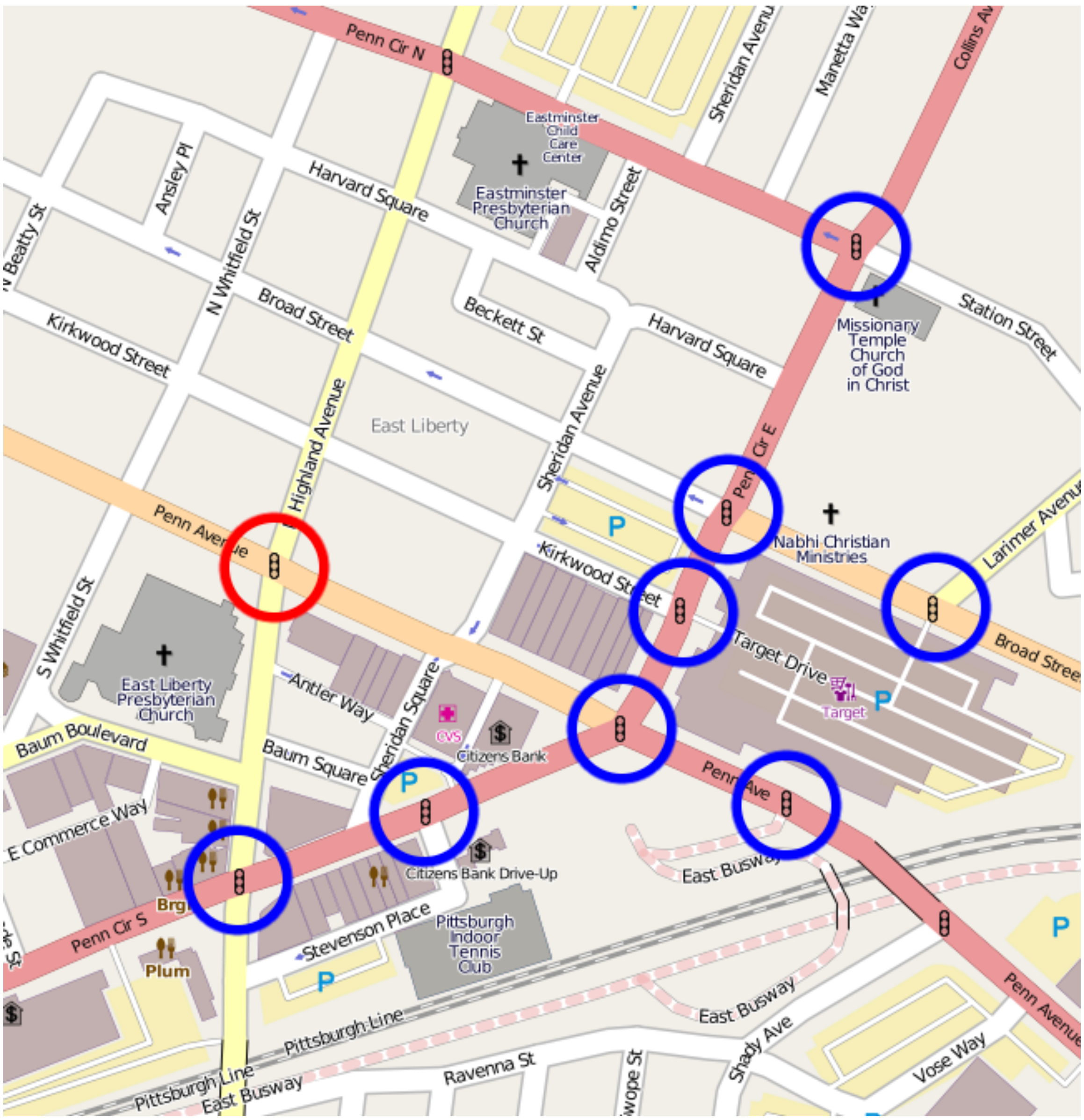

Figure 1: Pilot Test Site

Currently these 8 intersections are controlled during AM and PM rush periods by coordinated fixed timing plans, that were optimized using SYNCHO, based on expected traffic volumes and flows. During non-rush periods, the network is run in actuated "free mode" with the default green favoring movement on Penn Circle for those 6 intersections along Penn Circle, favoring Penn at the Penn/Easeside3 intersection and favoring Broad at the Broad/Larimer intersection.

In addition to these 8 lights, a 9th traffic light – at the intersection of Penn and Highland Avenues (depicted in red in Figure 1) – was also incorporated to create more of a grid structured traffic light network that is more broadly representative of traffic flow problems throughout the city. Until recently, this intersection had been running independently with a "vintage 1985" timing plan. Using funds provided by the Heinz Endowments to carry out the pilot test, the Penn/Highland intersection was upgraded in April 2012 with a new controller, video detection capabilities, and radio communication to the rest of the network.

To install SURTRAC at the pilot test site, a dedicated processor running the SURTRAC system was added to each intersection controller cabinet, along with network switches to enable communication with neighbors over fiber-optic cable and/or radio, and connections to both the video boards (for receiving detected traffic flow information) and the intersection controller. In operation, the controller is simply run in passive mode with SURTRAC issuing calls to the controller that indicate when to switch to the next phase. Through the use of a cell modem connection to one of the intersections, it is possible to remotely switch between SURTRAC and pre-existing control modes, and to remotely monitor traffic flows at all intersections. The basic hardware configuration at an intersection is shown in Figure 2.

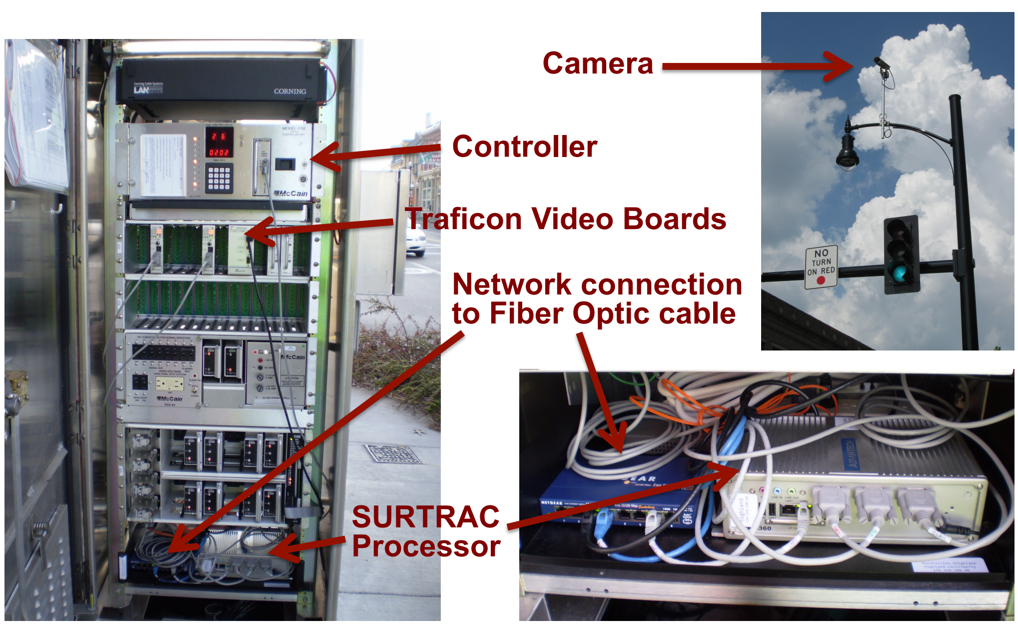

Figure 2: SURTRAC Hardware Configuration at an intersection

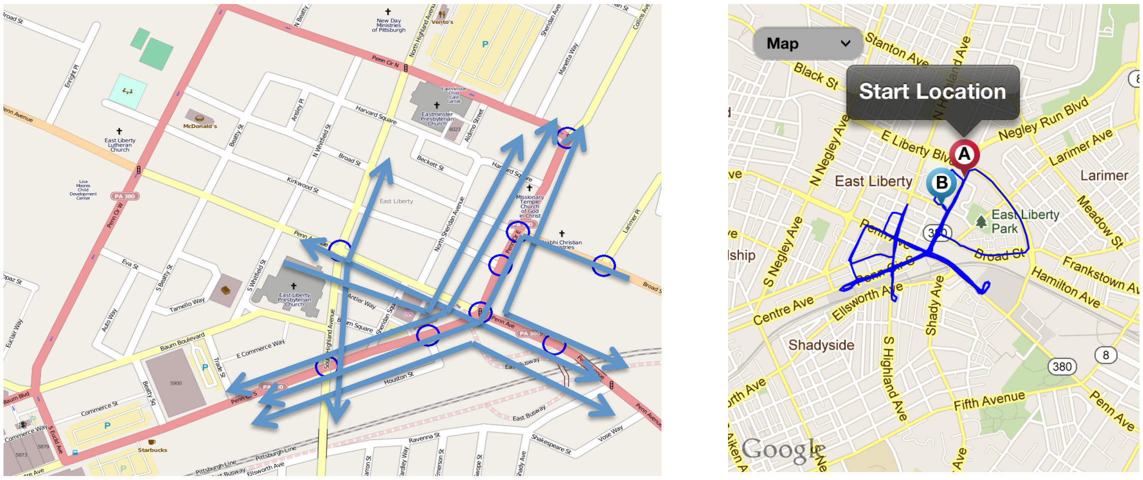

Figure 3: (left) 12 dominant routes through test site; (right) graphical view of GPS trail generated by one drive through run

3.0 Pilot Test Experiment Design

To evaluate the performance potential of the SURTRAC system, a series of timed, drive-through runs of the pilot test site were conducted for each of two conditions. First a series of drive through runs were performed while the intersections were being controlled by the current combination of fixed timing plans and actuated free mode (termed the "before" condition). Then a second series of drive through runs were performed while the intersections were being controlled by the SURTRAC adaptive strategy (termed the "after" condition).

More specifically, the 12 highest volume routes through the pilot test site were identified and a drive through run involved a traversal of all 12 of these routes. The 12 routes considered are graphically depicted in Figure 3 (left) and included:

- Beatty→ Collins
- Rodman → Highland-W (inverse)
- Beatty → Eastside3
- Shady → Highland-W (inverse)
- Shady → Highland-N
- Whitfield → Eastside3 (inverse)
- Shady → Collins
- Rodman → Eastside3 (inverse)
- Harvard-Square → Highland-W
- Railroad-Bridge → Highland-N (inverse)
- Whitfield → Collins
- Broad → Highland-W

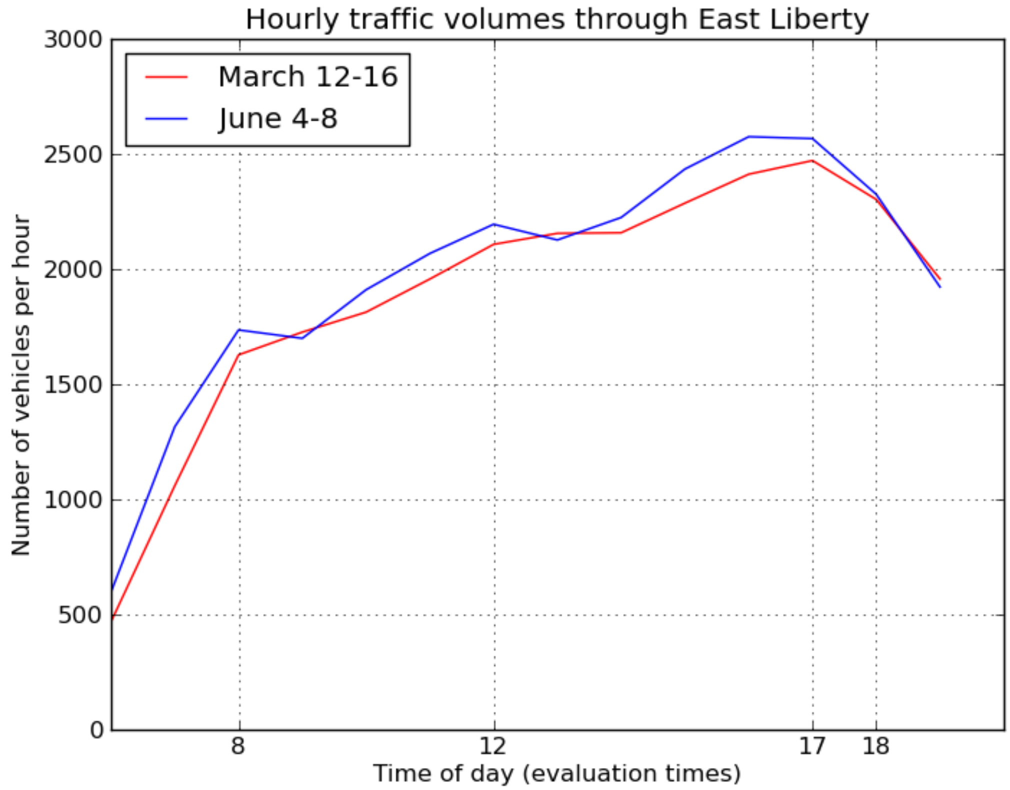

Figure 4: Hourly Traffic Volumes through East Liberty

Travel data for a given run was collected through use of an iPhone App called GPS Kit Pro, which generates a timed sequence of GPS locations from start of the run until completion (see Figure 3 (right) for a graphical display of one run). This data was then post processed to extract only those subsequences corresponding to travel time along the above 12 routes, and travel time metrics were computed from these subsequences.

Three drive-through runs are conducted under each condition for each of 4 periods of the day:

- AM-Rush [8:00AM-9:00AM]
- Mid Day [12:00PM -1:00PM]
- PM-Rush [4:00PM – 6:00PM]
- Evening [6:00PM – 7:00PM]

All of these 24 runs (12 for each condition) were performed on weekdays other than Friday (i.e., on Monday, Tuesday, Wednesday or Thursday). Additionally, a 4th PM-Rush run was conducted for each condition on a Friday (with these runs both starting at 3:30PM) to test this exceptionally high volume condition. All "before" condition runs were conducted in March 2012; all "after" runs were conducted in June 2012. An analysis of traffic volume data for representative weeks of these respective months (see Figure 4) indicates roughly a 5% difference in volume (i.e., the volumes are essentially the same, but slightly higher in June).

For each of the 12 designated routes, for each of the 4 periods of the day, for each condition, we compute the following set of performance metrics:

- *Average Speed* – total time required to traverse the route in question divided by the measured distance traveled
- *Average Travel Time* – the total time (on average) that it takes to traverse the route in question. To compensate for differences in the measured distances traveled from run to run due to the GPS sampling rate, we apply the *Average Speed* to the actual (canonical) distance of each route to normalize the average travel time computation.
- *Number of Stops* – The number of stops are defined as the number of time intervals during traversal of a route in which the measured GPS signals indicate that the vehicle's speed is 0
- *Wait Time* – the total amount of time during the traversal of a route in which the vehicle's speed is measured to be 0.
- *Measured Fuel Consumption* – For fuel consumption, the following calculation is performed for a given route [Wallace et. al 1984]:
    - *Measured-Route-Distance-in-Miles* * k1 + *Wait-Time-in-hours* * k2 + *Number-of-Stops* * k3*, where*
        - *k1 =* (0.075283 - 0.0015892 * *cruise-speed* + 0.000015066 * $\textit{cruise-speed}^2$)
        - *k2 =* 0.7329
        - *k3 =* 0.0000061411 * $\textit{cruise-speed}^2$
- *Fuel Consumption* - To compensate for differences in measured distances on different runs due to the GPS sampling rate*,* the *Measured Fuel Consumption* value for a given route is normalized to produce the final fuel consumption measure. This is accomplished by dividing the canonical distance of a given route by *Fuel Efficiency* (defined below),
- *Fuel Efficiency – Total-Distance-in-miles* / *Measured Fuel Consumption*
- *CO_2 Emissions* – CO_2 Emissions are calculated as function of fuel consumption using the following rates (taken from [EIA 2012]:
    - Gasoline: 8.91 kg/gal
    - Diesel: 10.15 kg/gal

  It is assumed that 3% of vehicle traffic is diesel following a recent JD Powers estimate.
- *CO, NOx, VOC Emissions* – Toxic emissions are calculated as a function of fuel consumption, according to the following emissions impact model (taken from [Wallace et. al 1984]):

- CO = *Fuel Consumption* * 69.9 grams/gal
- NOx = *Fuel Consumption* * 13.6 grams/gal
- VOC = *Fuel Consumption* * 16.2 grams/gal

- *Hydrocarbons* – Finally the amount of hydrocarbons is calculated at a rate of 60.2 grams/gallon of fuel consumed (taken from [EPA 2012]).

The metric scores obtained on individual runs over a given route were averaged to produce performance results for that route. When combining data from individual routes to produce aggregate performance results, the relative volumes along different routes were used to determine weights. These derived weights are listed in Appendix A.

4.0 Results

Table 1 summarizes the overall performance improvement achieved by the SURTRAC adaptive control approach over the pre-existing traffic control scheme at the pilot test site. The levels of improvement are exceptional across all performance metrics computed. With respect to efficiency of traffic flows, average travel times through the pilot site are reduced by over 25%, average vehicle speed is increased by 34%, the number of stops is reduced by over 31%, and the average wait time is reduced by over 40%. From the perspective of improving the quality of the air, which was the motivating reason for the funding provided by the Heinz Endowments, overall emissions are reduced by over 21%[1].

% Improvement	Travel Time	Speed	Nbr. of Stops	Wait Time	Emissions / Fuel Consumption
AM rush	30.11%	33.78%	29.14%	47.78%	23.83%
Mid Day	32.83%	48.55%	52.58%	49.82%	29.00%
PM rush	22.65%	27.45%	8.89%	35.60%	18.41%
Evening	17.52%	27.81%	34.97%	27.56%	14.01%
Overall	25.79%	34.02%	31.34%	40.64%	21.48%

Table 1: Summary Pilot Test Results

Tables 2, 3, 4, and 5 drill down and indicate the average performance improvement achieved by SURTRAC on each of the 12 routes measured. Looking at these results by period of day, all metrics show improvement on 8 of the 12 routes evaluated during the AM rush period and all but two metrics (Wait Time and Emissions) improved on 9 of the 12 routes. Of the 4 routes that incurred reduced performance, the 3 most significant were routes involving movement along Penn Circle. To some extent this is understandable, as this is the movement that is emphasized by the AM rush fixed timing plan. The 4th route along the Highland avenue corridor exhibited minor performance reductions of 1-5% across the set of computed metrics.

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[1] Emissions reduction is projected as a function of fuel consumption.

The largest percentage improvement was observed during the Mid Day period. During this period, only 1 of the 12 routes tested, Whitfield → Collins, exhibited performance degradation with respect to any of the metrics computed. This route was also one of only 4 to experience any degraded performance during the PM rush period, and in all other cases, degradation was observed for just 1 or 2 metrics. In both the Mid Day and PM Rush periods, where vehicle volumes were the greatest, the performance improvement was observed to be the most robust over all routes.

% Improvement	Travel Time	Speed	# of Stops	Wait Time	Emissions
Beatty->Collins	31.52%	35.13%	33.33%	46.38%	19.63%
Beatty->Eastside3	-10.64%	4.56%	0.00%	-75.00%	-6.84%
Broad->Highland-w	44.66%	69.32%	28.57%	80.21%	37.90%
Harvard->Highland-w	4.59%	-1.83%	0.00%	-4.88%	-4.86%
Railroad->Highland-n	26.64%	47.20%	0.00%	45.09%	22.65%
Rodman->Eastside3	-5.67%	-14.37%	0.00%	-7.50%	-1.44%
Rodman->Highland-w	-18.90%	-16.96%	0.00%	-79.78%	-15.79%
Shady->Collins	37.39%	44.99%	0.00%	75.93%	25.02%
Shady->Highland-w	33.11%	57.49%	28.57%	40.77%	24.21%
Shady->Highland-n	61.49%	170.32%	75.00%	86.76%	59.54%
Whitfield->Collins	14.31%	13.99%	11.11%	22.44%	11.97%
Whitfield->Eastside3	34.60%	55.57%	42.86%	53.67%	31.39%
Weighted Average	30.11%	33.78%	29.14%	47.78%	23.83%

Table 2: Performance along each route for AM Rush period

% Improvement	Travel Time	Speed	# of Stops	Wait Time	Emissions
Beatty->Collins	32.18%	46.99%	60.00%	45.91%	27.57%
Beatty->Eastside3	47.37%	84.26%	71.43%	59.03%	37.25%
Broad->Highland-w	26.81%	29.72%	33.33%	58.97%	21.89%
Harvard->Highland-w	28.80%	57.64%	50.00%	58.86%	30.14%
Railroad->Highland-n	20.96%	44.70%	66.67%	53.45%	26.44%
Rodman->Eastside3	47.63%	87.24%	66.67%	74.87%	41.30%
Rodman->Highland-w	37.26%	68.09%	44.44%	75.70%	35.58%
Shady->Collins	24.30%	43.04%	50.00%	35.16%	18.80%
Shady->Highland-w	29.94%	46.29%	55.56%	41.96%	32.25%
Shady->Highland-n	30.70%	41.32%	28.57%	49.33%	26.24%
Whitfield->Collins	-16.38%	-11.07%	-10.00%	-12.18%	-1.94%
Whitfield->Eastside3	33.70%	32.42%	50.00%	41.78%	29.99%
Weighted Average	32.83%	48.55%	52.58%	49.82%	29.00%

Table 3: Performance along each route for Mid Day period

In the final evening period, performance improvement was again observed for all metrics on 8 of 12 routes. In this case, 3 of 4 routes experiencing degraded performance involve flows between Penn Circle and Penn Avenue east. The 4th was Broad → Highland-W.

% Improvement	Travel Time	Speed	# of Stops	Wait Time	Emissions
Beatty->Collins	29.77%	46.23%	-18.18%	42.00%	13.32%
Beatty->Eastside3	15.16%	16.75%	0.00%	17.23%	6.21%
Broad->Highland-w	10.04%	2.60%	12.50%	17.51%	6.39%
Harvard->Highland-w	8.74%	21.42%	0.00%	29.03%	11.36%
Railroad->Highland-n	35.31%	62.26%	44.44%	55.80%	35.76%
Rodman->Eastside3	37.95%	61.98%	52.94%	45.14%	31.63%
Rodman->Highland-w	21.06%	18.84%	28.57%	33.13%	16.42%
Shady->Collins	9.37%	-13.16%	-22.22%	28.09%	13.76%
Shady->Highland-w	11.58%	7.90%	30.00%	18.09%	13.37%
Shady->Highland-n	58.12%	137.50%	63.64%	85.27%	53.61%
Whitfield->Collins	-4.56%	-12.61%	11.76%	-5.61%	-1.07%
Whitfield->Eastside3	17.30%	21.02%	-20.00%	32.26%	17.75%
Weighted Average	22.65%	27.45%	8.89%	35.60%	18.41%

Table 4: Performance along each route for PM Rush period

% Improvement	Travel Time	Speed	# of Stops	Wait Time	Emissions
Beatty->Collins	28.57%	51.44%	50.00%	46.38%	22.63%
Beatty->Eastside3	28.94%	34.93%	60.00%	60.45%	32.39%
Broad->Highland-w	0.54%	-4.29%	-40.00%	-31.00%	-13.00%
Harvard->Highland-w	17.02%	37.48%	40.00%	11.90%	11.92%
Railroad->Highland-n	9.28%	38.93%	0.00%	7.79%	7.29%
Rodman->Eastside3	-17.20%	0.85%	42.86%	-74.80%	-14.82%
Rodman->Highland-w	32.00%	44.62%	57.14%	60.00%	24.18%
Shady->Collins	-24.74%	-20.19%	-20.00%	-161.90%	-28.86%
Shady->Highland-w	-8.28%	-8.20%	0.00%	-11.84%	-8.14%
Shady->Highland-n	43.79%	86.19%	71.43%	77.17%	39.73%
Whitfield->Collins	30.32%	52.81%	40.00%	56.33%	22.54%
Whitfield->Eastside3	22.10%	47.58%	28.57%	42.76%	21.74%
Weighted Average	17.52%	27.81%	34.97%	27.56%	14.01%

Table 5: Performance along each route for Evening period

To quantify the absolute impact of SURTRAC on emissions, it is necessary to consider traffic volumes through the pilot test site, which are given in Table 6. Given an average daily number of vehicles of 29,940, Table 7 indicates projected savings in fuel and pollutant emissions. A daily savings in fuel of 247 gallons is estimated, which implies in a total reduction in emissions of 2.253 metric tons. Given this, an annual reduction in emissions of 588 metric tons (tonnes) is expected if SURTRAC continues to run the 9 intersections at the pilot test site. The last column in Table 7 speculates about the potential impact with respect to emissions if SURTRAC adaptive signal control were installed at all 600 intersections in the city of Pittsburgh (assuming the same level of improvement per intersection).

AM Rush	Mid Day	PM Rush	Evening	Daily
5,228	8,007	9,548	7,157	29,940

Table 6: Average number of vehicles per weekday

	Daily	Annual	City-Wide
Fuel Consumption	247 gal.	64,580 gal.	4,305,353 gal.
Carbon Dioxide (CO2) Emissions	2253 kg	557.8 tonnes	38,521 tonnes
Carbon Monoxide (CO) Emissions	17.3 kg	4.5 tonnes	301 tonnes
Nitrogen Oxides (NOx) Emissions	3.4 kg	0.9 tonnes	58 tonnes
Volatile Organic Compounds (VOC)	4 kg	1.0 tonnes	70 tonnes
Hydrocarbons	14.9 kg	3.9 tonnes	259 tonnes
Total Emissions	2253 kg	588 tonnes	39,209 tonnes

Table 7: Projected Emissions Savings

Finally, we can estimate the monetary savings provided by SURTRAC by applying the benefit-cost model specified in [Chien et. al 2005]. This model quantifies costs in terms of the value of travelers' time, a per-gallon fuel price and a pollutant unit price for each of CO, NOx and VOC emissions. The parameters and values assumed by this model are summarized in Table 8.

Parameters	**Value**		
Value of Traveler time	Cars	Trucks	
	12.75 ($/hour)	21.25 ($/hour)	
Vehicle Occupancy	1.59	1.0	
Vehicle Split	98%	2%	
Gas Unit Price	3.48 ($/gallon)		
Pollutant Unit Price	CO	NOx	VOC
	0.0063 ($/kg)	1.28 ($/kg)	1.28 ($/kg)

Table 8: Benefit Model Parameters

With these cost assumptions, the projected benefit in cost savings provided by SURTRAC at the pilot site is $7,184 daily and $1,875,127 annually (based on 261 weekdays per year). If we extrapolate to a city-wide implementation that achieves the same level of improvement, the projected annual savings is over $125 million.

The SURTRAC pilot implementation capitalized on the fact that 8 of the 9 pilot test site intersections were already equipped with video detection capabilities, recently upgraded controllers and fiber-optic network communication infrastructure; resulting in total intersection upgrade costs of just over $40,000. However, note that even if we were to assume a system hardware/software installation cost of $50,000 per intersection (which is representative of current commercial adaptive traffic signal control systems), return on investment at the pilot test would have been achieved after roughly 3 months of operation. Moreover, by its nature, the SURTRAC system will require only negligible ongoing support as traffic conditions evolve over time. After just 5 years of operations, a benefit-cost ratio of almost 20:1 would be expected.

5.0 Summary

The East Liberty pilot test results convincingly demonstrate the effectiveness and potential of decentralized, adaptive traffic signal control in urban road networks. In comparison to the current conventional approach to traffic control in use at the pilot test site, which involves a combination of fixed, coordinated timing plans during rush periods and actuated free mode during non-rush periods, the SURTRAC adaptive signal control system improved traffic flow efficiency through the pilot site by 25% - 40% (depending on the metric considered) and reduced emissions by over 21%.

Current commercial approaches to adaptive traffic signal control tend to aggregate sensed traffic flow data and coordinate network control centrally (which limits real-time responsiveness) or drive local intersection control with static, pre-computed global coordination plans. These approaches have proven most effective in arterial settings, where there is a single dominant traffic flow and traffic from side streets must be efficiently integrated. The SURTRAC system design, in contrast, aims specifically at urban road networks, where there are multiple, competing traffic flows that dynamically shift through the day. By controlling each intersection locally, responsiveness to real-time traffic conditions is maximized, and by communicating planned outflows to neighboring intersections larger corridor flows can be established on demand to match actual traffic flow volumes. Since the system operates in a totally decentralized manner, it is easily extended to incorporate additional intersections and inherently scalable to road networks of arbitrary size.

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Appendix A:

	AM Rush	Mid Day	PM Rush	Evening
Beatty->Collins	0.0877	0.1097	0.1239	0.1024
Beatty->Eastside3	0.0976	0.1341	0.1346	0.1249
Broad->Highland-w	0.0814	0.0725	0.0636	0.0700
Harvard->Highland-w	0.1145	0.0869	0.0752	0.0743
Railroad->Highland-n	0.0793	0.0881	0.0993	0.0956
Rodman->Eastside3	0.0185	0.0295	0.0290	0.0279
Rodman->Highland-w	0.0814	0.0725	0.0636	0.0700
Shady->Collins	0.0908	0.0958	0.1268	0.1327
Shady->Highland-w	0.0466	0.0403	0.0318	0.0402
Shady->Highland-n	0.1310	0.0881	0.0871	0.1056
Whitfield->Collins	0.0244	0.0287	0.0211	0.0210
Whitfield->Eastside3	0.1469	0.1538	0.1441	0.1354

Table 8: Route volume weights by period