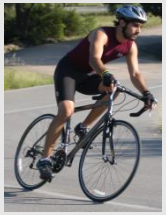
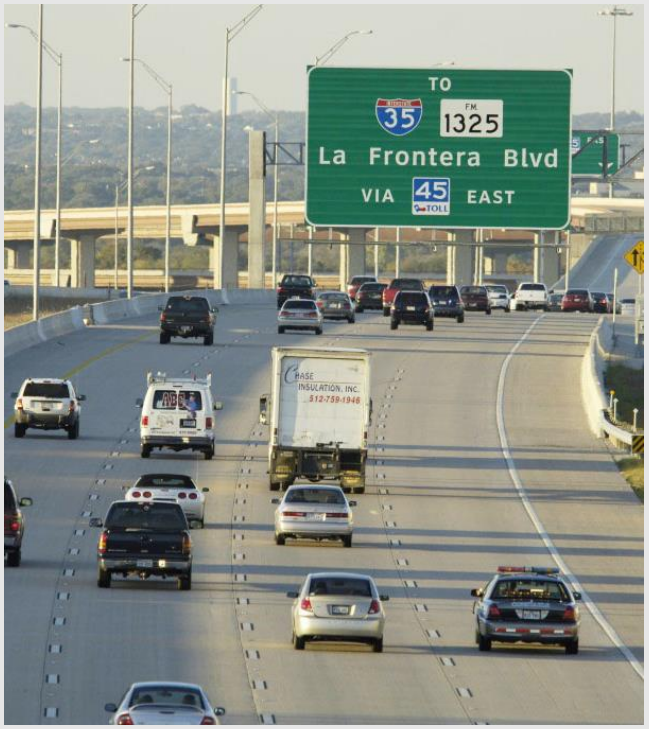
TEXAS DEPARTMENT OF TRANSPORTATION



0-6920: PROACTIVE TRAFFIC SIGNAL TIMING AND COORDINATION FOR CONGESTION MITIGATION ON ARTERIAL ROADS



TxDOT Houston District

October 10, 2017

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CO-PI: HAO YANG, PHD

DEPT. OF CIVIL & ENVIRONMENTAL ENGINEERING
LAMAR UNIVERSITY

Address Congestion

Contents

Backgrounds

- Traffic Congestion

– National congestion
  - 5 million-hour delay of daily commutes;
  - $100 billion financial lost:

– State-wide congestion - Texas
  - 60 –hour delay annually for each commuter in Houston Area;
  - Increase to 100 hours in 2025;
  - $12 billion financial lost in 2025:

Reference: Lomax, T., Lasley, P., Ellis, D., and Stockton, B., *Mobility Investment Priorities Project*, Tech. Rep, Texas A&M Transportation Institute, Texas, USA, 2013

Background

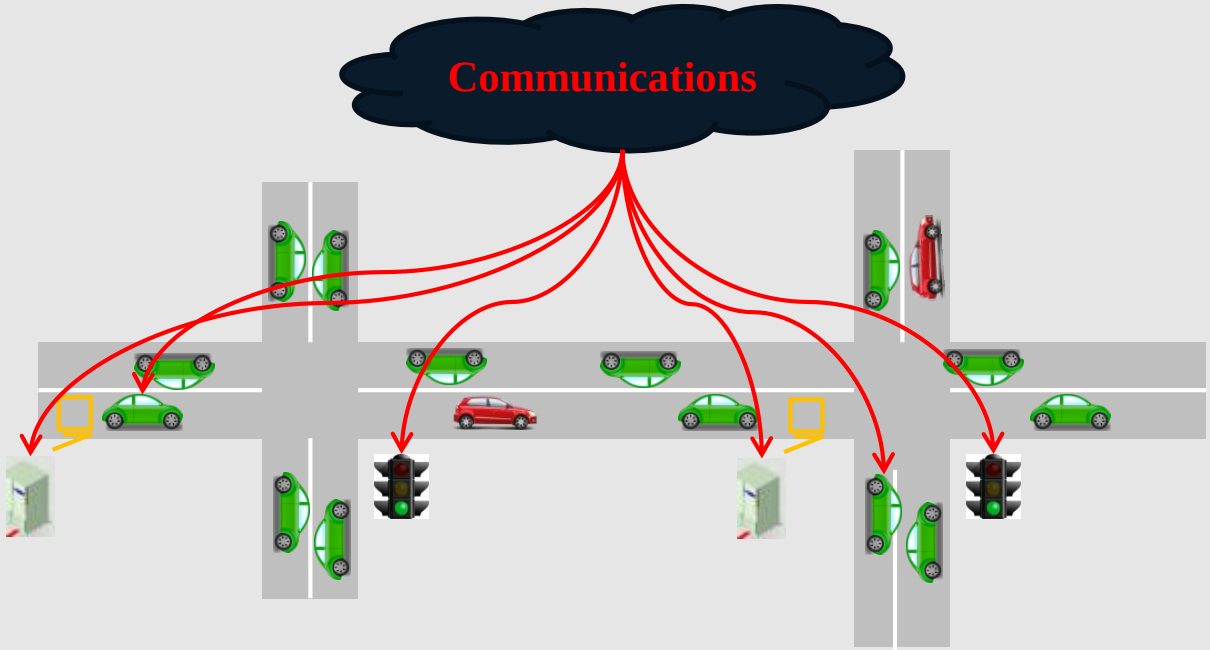
- Typical Signal Control Algorithms
  - Fixed-time Plan
    - The phase sequence and the duration of each phase are predefined.
  - Reactive/Actuated Control
    - The phase at each time interval is assigned to the one with the highest delay -- found by detectors.
  - Proactive Control
    - The phase at each time interval is assigned to the one with this highest predicted delay based on the *short-term predicted* timing –varying traffic volume.

Research Objectives

- Proactive Signal Control System
  - Develop a fully collaborative vehicle-signal control systems
    - Utilize communications among loop detectors, traffic signals and connected vehicles (if any);
    - Gather real-time traffic conditions and predict short-term conditions;
    - Update signal phasing and timing (SPaT) plan based on the short-time traffic prediction.
  - Optimize the performance of signalized intersections
    - Mitigate traffic congestions, vehicle emissions, and fuel consumption;
    - Reduce travel time and stop delay in the vicinities of intersections

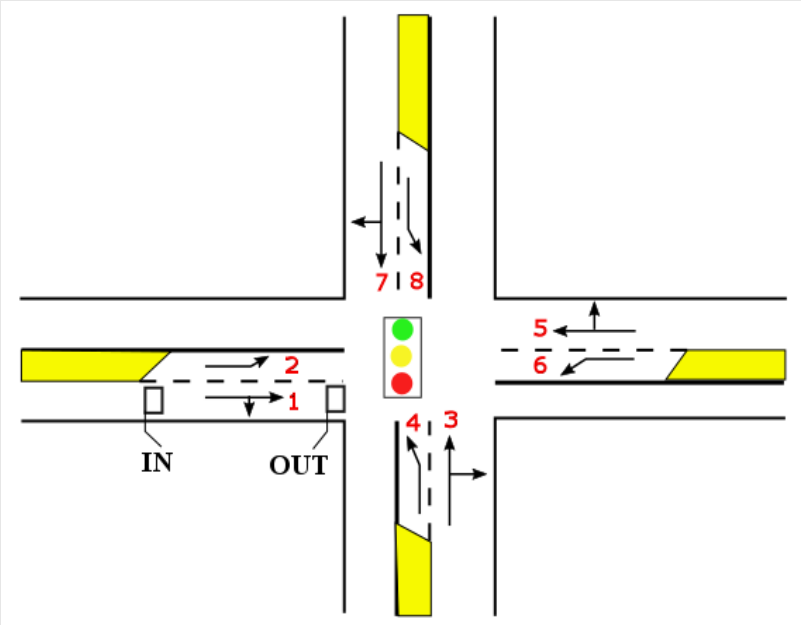
Proactive Signal Control Concept

- Collaborative Vehicle-signal Control Environment
  - Connections among vehicles, loop detectors and signals
  - Optimize phase assignments and duration without being restricted by cycle length
  - Optimize Signal Phasing and Timing (SPaT) plans of multiple signals with coordination



Proactive Signal Control Concept

- Signal Control at Intersections
  - Vehicle approaches (lane group)
  - Phases
  - Detectors
  - Delay on each approach



$$\boldsymbol{D_i(t)} = \sum_{\tau=0}^{t} \left(N_{I,i}(\tau) - N_{O,i}(\tau) - \frac{l_i}{v_i} \right)$$

$N_{I,i}(t)$: Cumulative inflow at the IN detector;

$N_{O,i}(t)$: Cumulative outflow at the OUT detector;

l_i : Distance between the IN and OUT detectors;

v_i : Road speed limit.

Proactive Signal Control Concept

- Signal Control at Intersections

Signal Optimization:

$$\min_{p_k(t),\forall k=1,2,\cdots,P} \sum_{i=1}^{N} D_i(T_0)$$

s.t.

$$N_{I,i}(t) = f_{\mathrm{I},i}(t);$$

$$N_{O,i}(t) = f_{\mathrm{O},i}(t);$$

$$f_{\mathrm{O},i}(t) = \begin{cases} 0 & m_i(t) = 0 \\ Q_i & m_i(t) = 1 \end{cases};$$

$$m_i(t) = \begin{cases} 1 & i \in \mathcal{M}_k, p_k(t) = 1, \forall i = 1,2,\cdots,N \\ 0 & \text{otherwise} \end{cases}.$$

$f_{I,i}(t)$: Flow rate detected by the IN detector at time t;

$f_{O,i}(t)$: Flow rate detected by the OUT detector at time t;

Q_i : Road capacity for the approach i;

P : total number of phases;

N : total number of approaches;

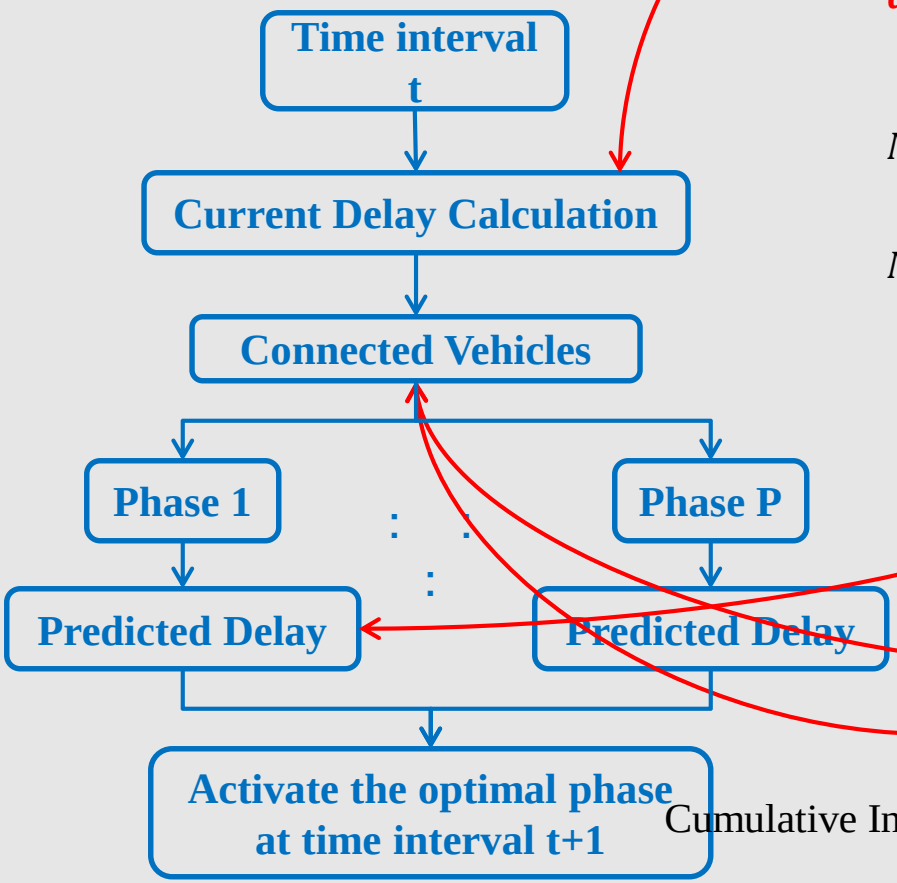
$p_k(t)$: signal indicator for the phase k;
0: red; 1: green.

$m_i(t)$: Permissive indicator for the approach i;
0: prohibited; 1: permitted.

$\mathcal{M}_k$: set of approaches associated with the phase k.

Proactive Signal Control Concept

- System Development

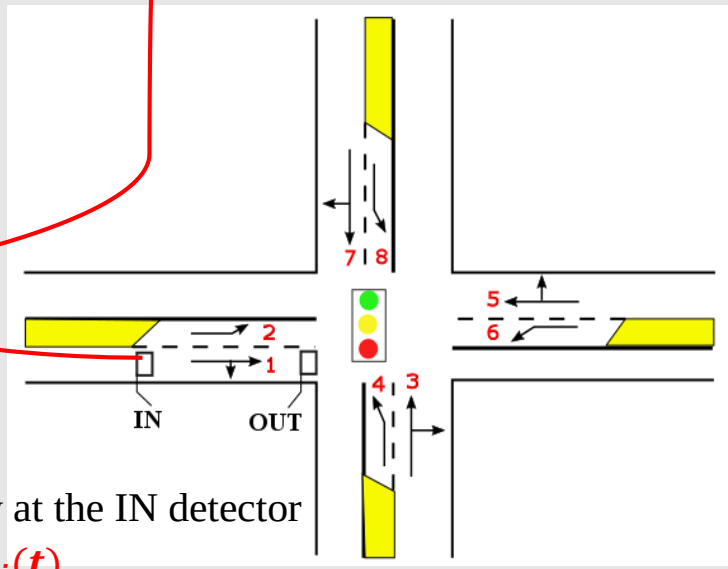


$$\boldsymbol{D_i(t)} = \sum_{\tau=0}^{t}\left(N_{I,i}(\tau) - N_{O,i}(\tau) - \frac{l_i}{v_i}\right)$$

$$\boldsymbol{d_k(t_{n+1})} = \sum_{i=1}^{N}\left(D_i(t_n) + \sum_{t=t_n}^{t_{n+1}}\left(N_{\mathrm{I},i}^{k}(t) - N_{\mathrm{O},i}^{k}(t) - \frac{L_i}{v_i}\right)\right)$$

$$N_{\mathrm{I},i}^{k}(t) - N_{\mathrm{I},i}^{k}(t-1) = f_{I,i}(t), i = 1,2,\cdots,N;$$

$$N_{\mathrm{O},i}^{p}(t) - N_{\mathrm{O},i}^{p}(t-1) = \begin{cases} Q_i & i \in \mathcal{M}_p \\ 0 & \text{otherwise} \end{cases}$$

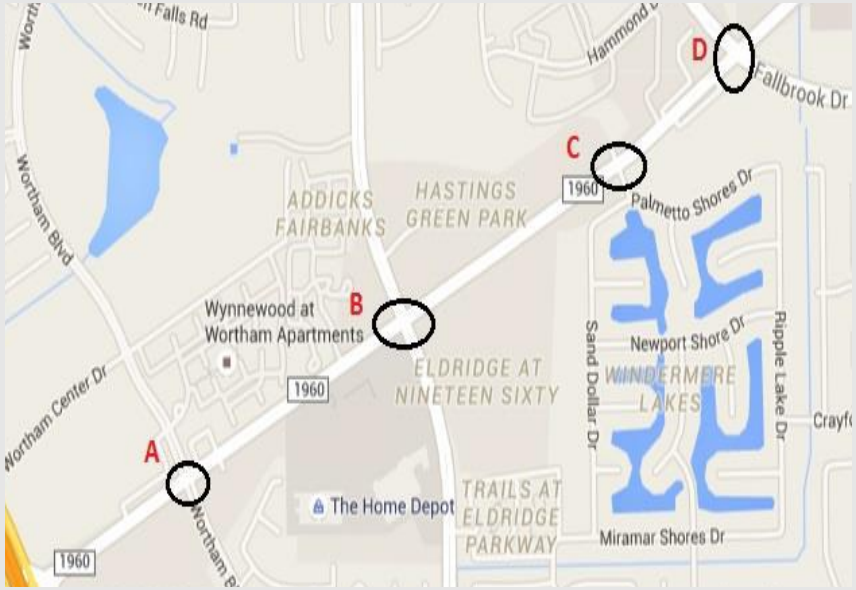


Cumulative Inflow at the IN detector

$\boldsymbol{f_{I,i}(t)}$

Test based on Simulation

- Testbed – FM1960
  - Four Intersections
    - Wortham Blvd.
    - N Eldridge Pkwy.
    - Windermere Lake Blvd.
    - Fallbrook Dr.



Test based on Simulation

- Testbed – Major road (FM1960)
  - Total Length
    - 7713 Feet
  - Speed Limits on the major road
    - 40 mph
  - Number of lanes of the major road
    - Three lanes, and additional one left-turn lane ahead of each intersection

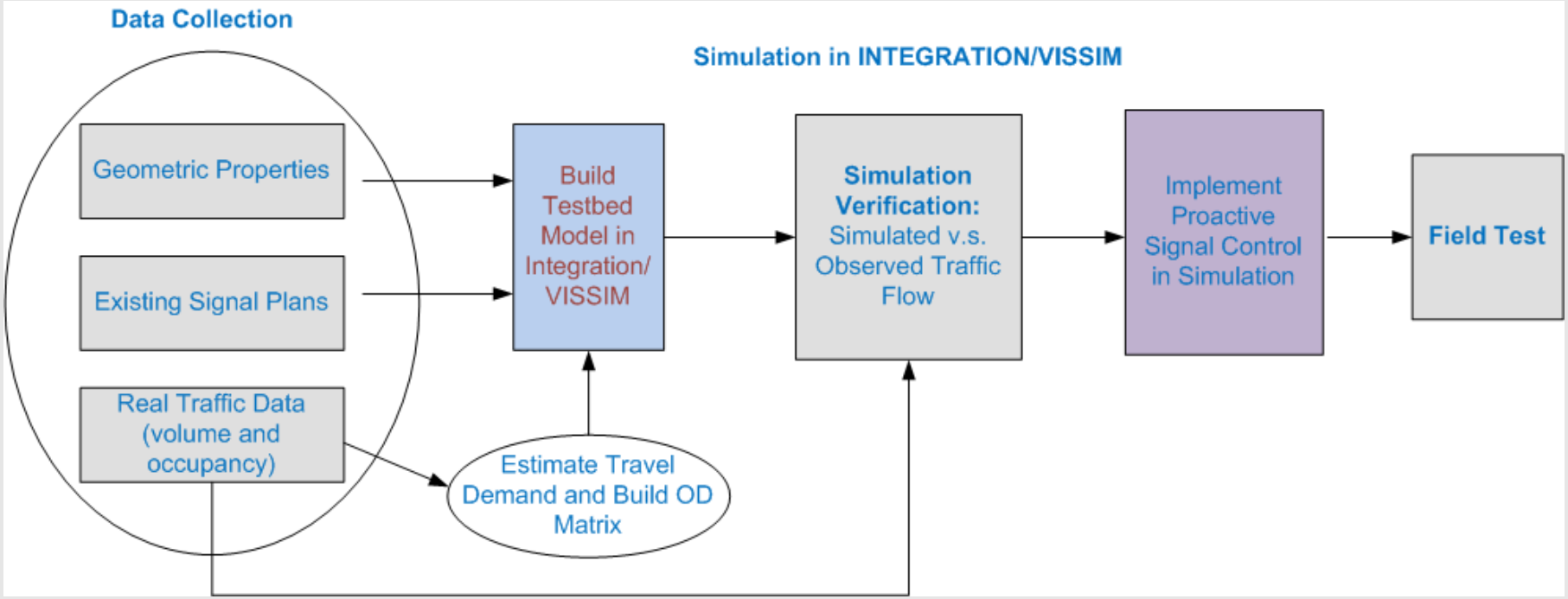
Test based on Simulation

- Testbed – Minor roads

Direction	Intersection	Intersection Name	Speed Limit (mile/hour)	Center to Center Distance (feet)	Cumulative Distance from Start point (feet)
West to East	Start				0
	A	Wortham Blvd.	35 (N), 35(S)	984*	984
	B	N Eldridge Pkwy.	40 (N),40(S)	2247	3232
	C	Windermere Lake Blvd.	30(S)	2215	5446
	D	Fallbrook Dr.	30 (N), 35 (S)	1328	6775
	End			820	7713

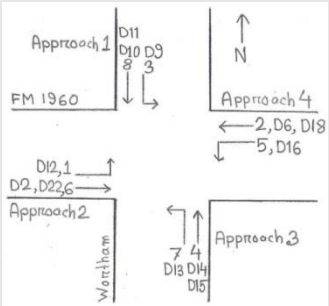
Test based on Simulation

- Methodological Framework

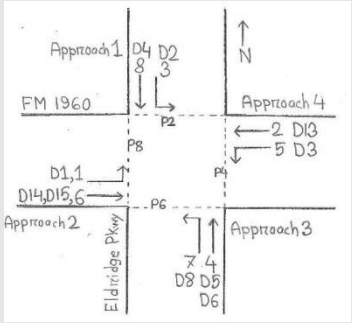


Test based on Simulation

- Signal Plans



A



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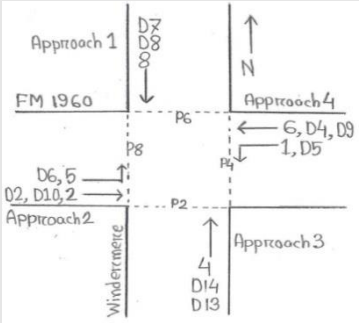

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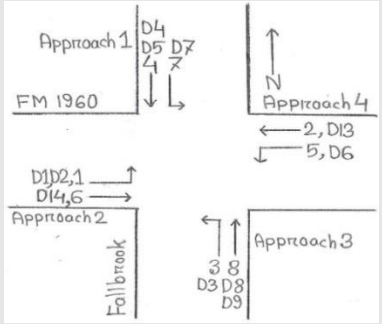
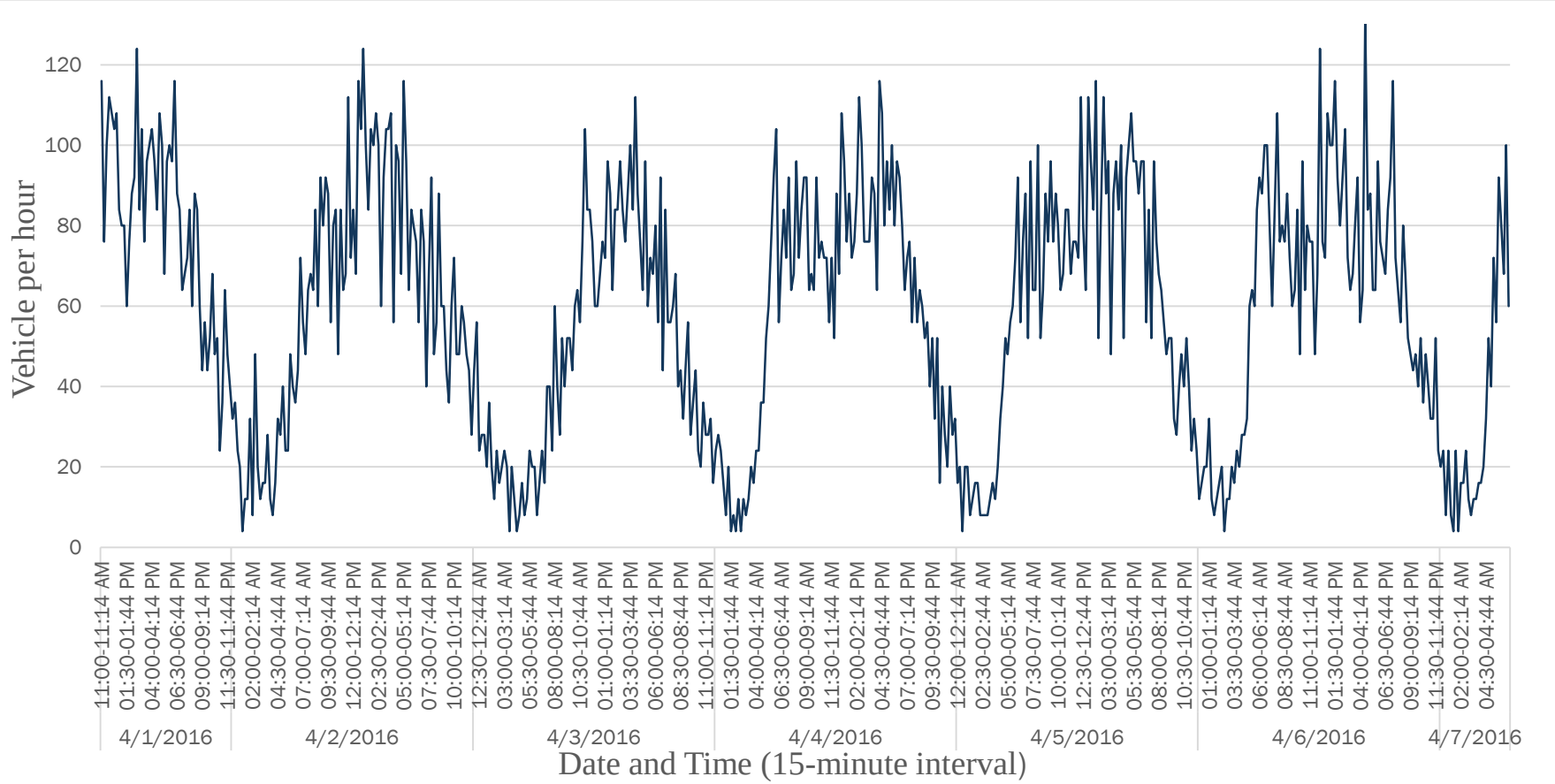


D

- Data Collection
  - The road traffic data was collected from 11 am, 04/01/16 to 7 pm, 04/07/16;
  - The data was read from the loop detectors for every 1 minute;
  - The data was summarized as every 15 minutes for each phase to measure the congestion level of the test bed.

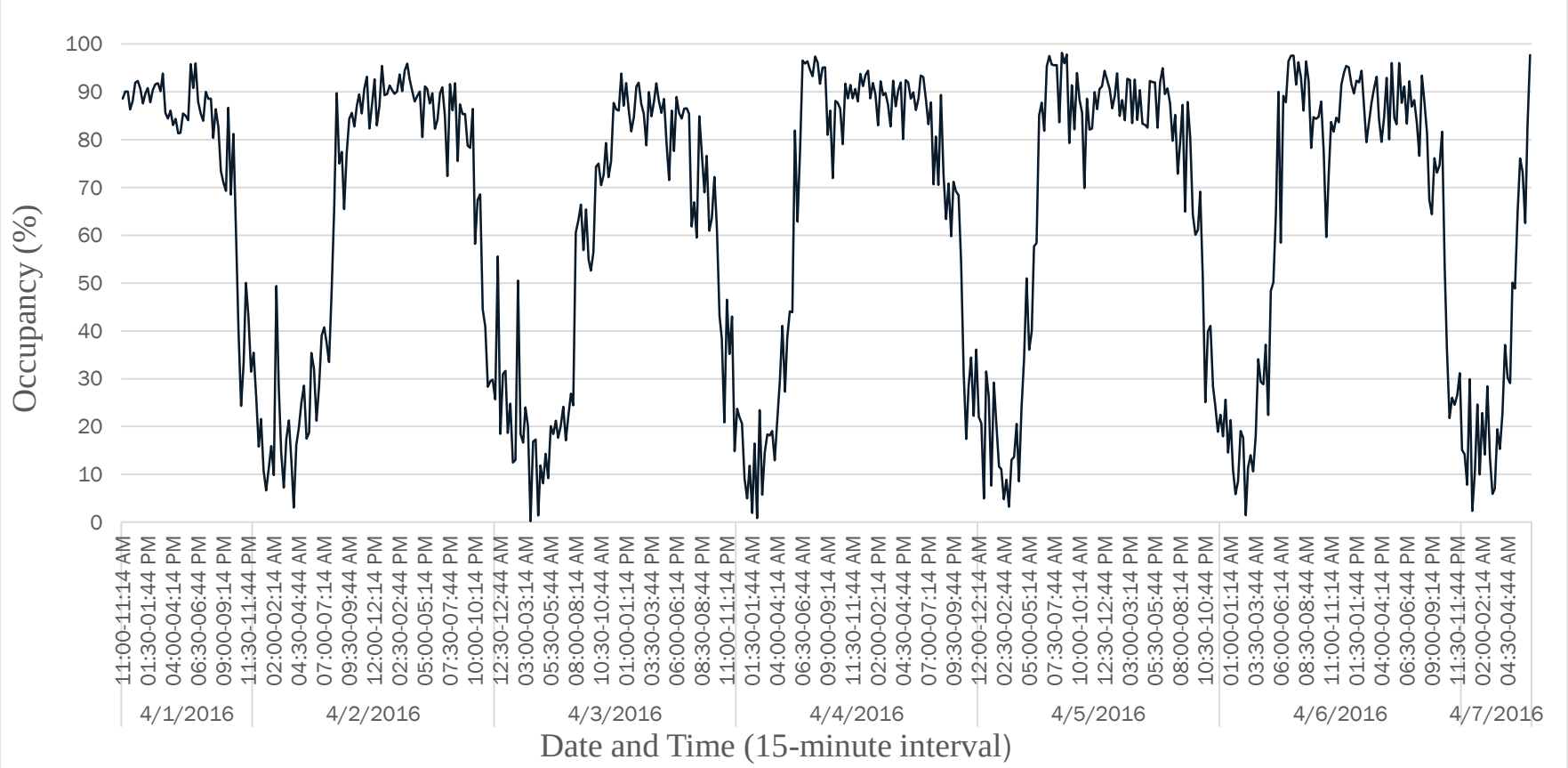
Test based on Simulation

- Hourly Volume for Phase 5 (Left-turn traffic movements at major road FM 1960, Intersection B at N Eldridge Pkwy)



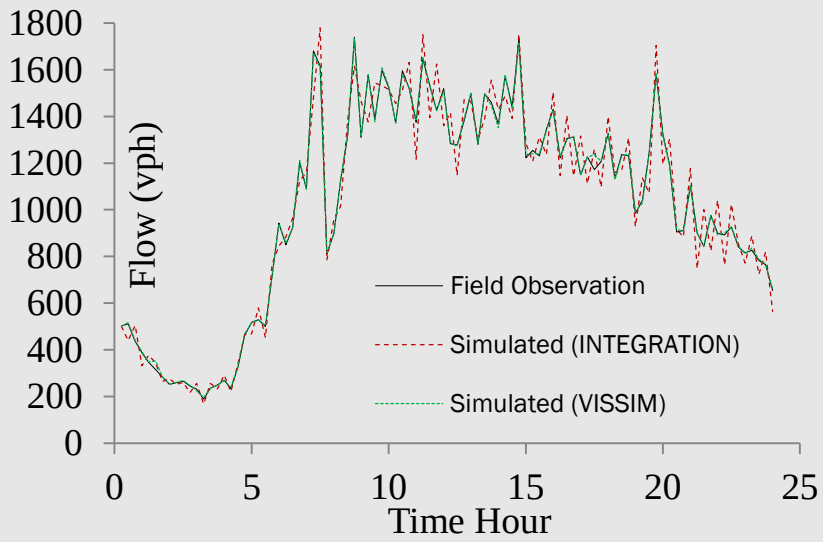
Test based on Simulation

- Occupancies for Phase 5 (Left-turn traffic movements at major road FM 1960, Intersection B at N Eldridge Pkwy)

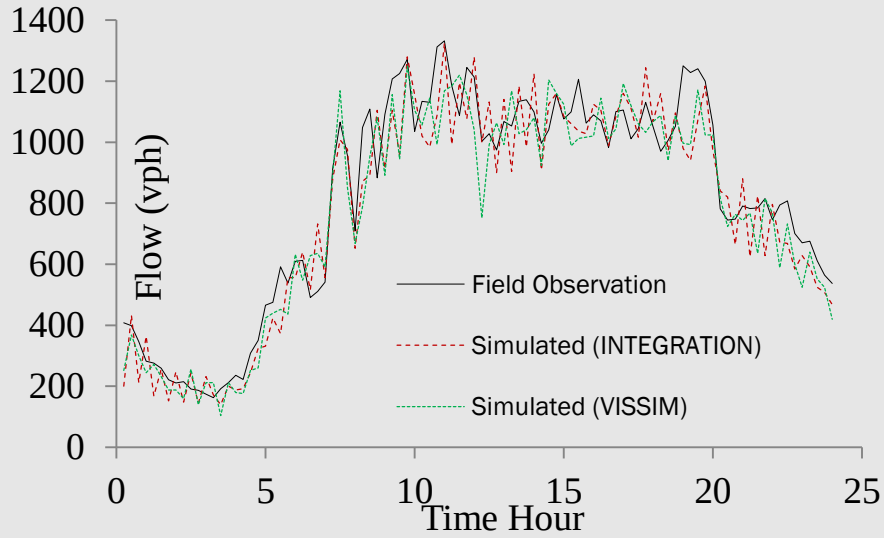


Test based on Simulation

- Simulation Verification
  - Based on the existing signal plan and the collected traffic data, two simulation packages, *INTEGRATION* and *VISSIM*, were used to simulate the traffic of the testbed.



Eastbound, in-flow at major road in a weekday



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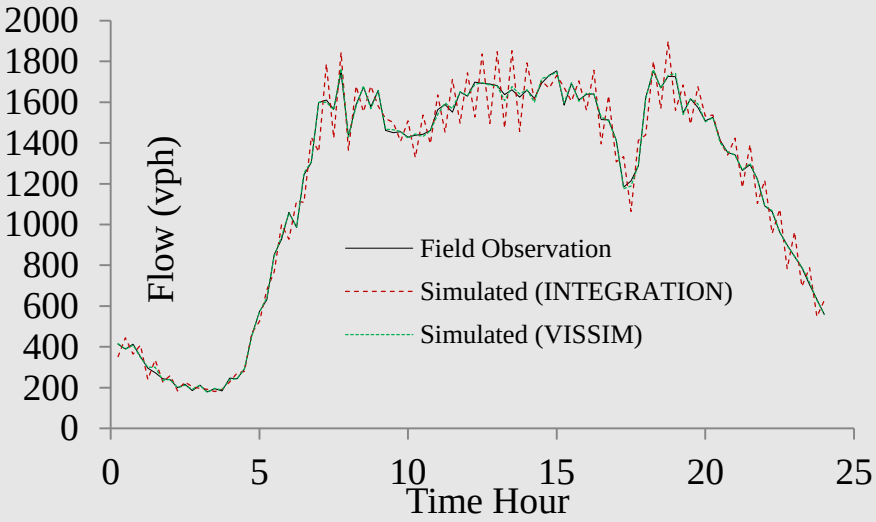
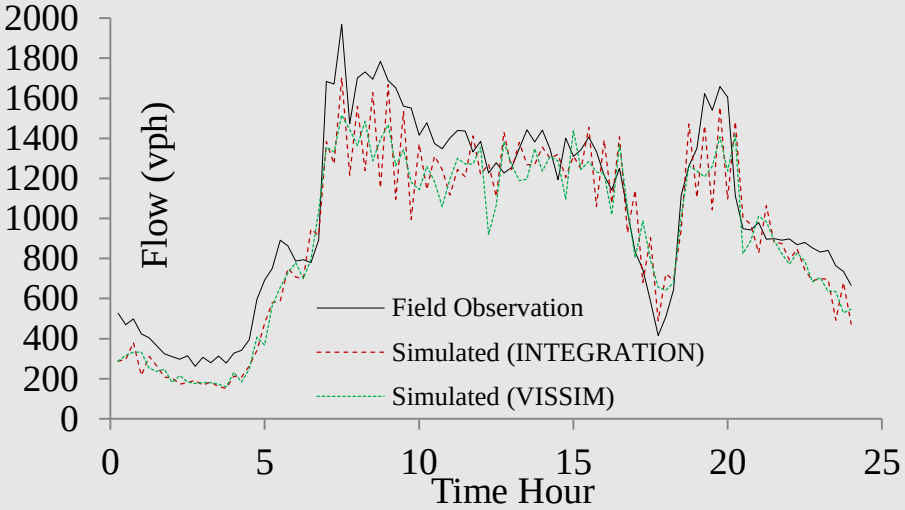


Westbound, in-flow at major road in a weekday



Westbound, out-flow at major road in a weekday

Test based on Simulation

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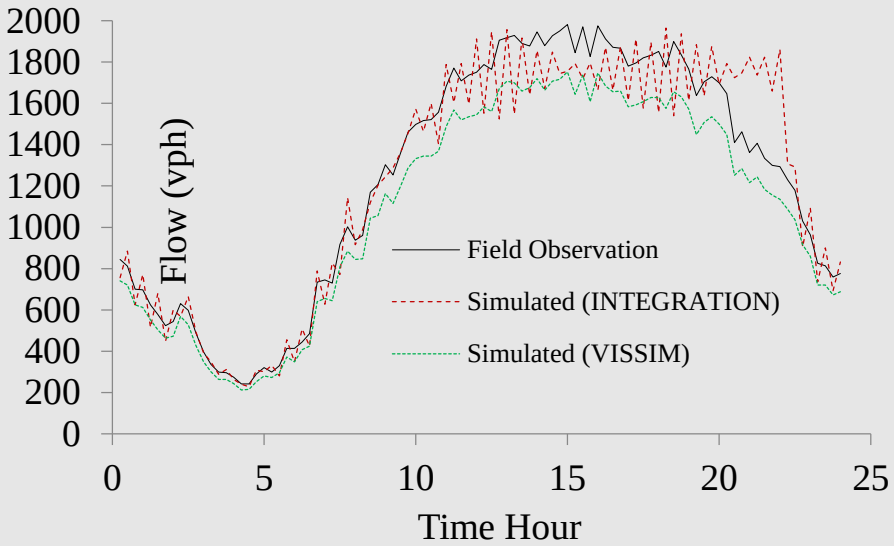
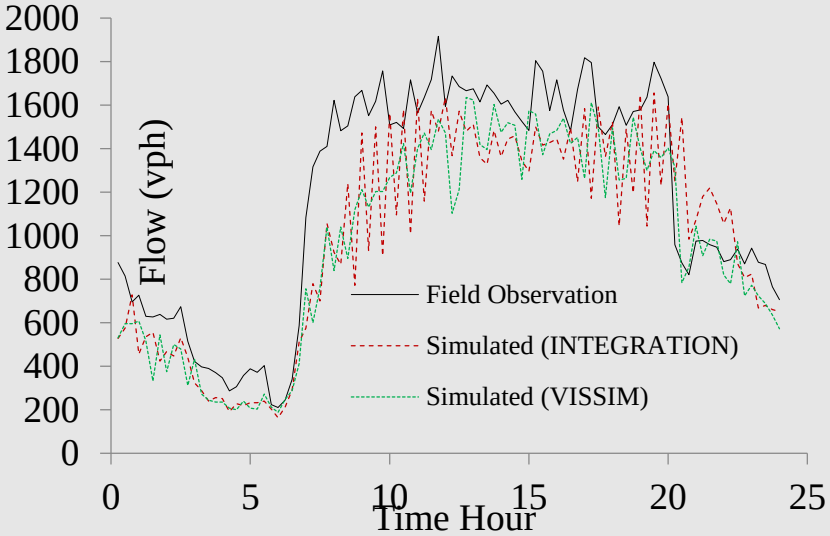


Westbound, in-flow at major road in a weekend



Westbound, out-flow at major road in a weekend

Test based on Simulation

- System Evaluation
  - Performance on the major road, FM 1960 (Assume the existing of connected vehicles)

Overall network performance

Measurements (per trip)	Weekday			Weekend		
	Before	After	Diff	Before	After	Diff
Travel Distance (km)	1.64	1.64	0%	1.74	1.74	0%
Travel Time (second)	240.29	144.54	-40%	543.88	119.7	-78%
Delay (second)	166.92	41.67	-75%	207.98	42.52	-80%
Stop Delay (second)	107.34	14.68	-86%	131.31	14.44	-89%
Vehicle Stops	2.65	1.96	-26%	2.88	2	-31%
Fuel Usage (liter)	0.34	0.27	-21%	0.37	0.28	-24%
HC (gram)	1.78	2.05	15%	1.8	2.07	15%
CO (gram)	44.93	52.87	18%	45.11	53.47	19%
NOx (gram)	0.99	0.92	-7%	1.05	0.95	-10%
CO2 (gram)	713.91	566.31	-21%	786.46	589.04	-25%

Test based on Simulation

- System Evaluation
  - Performance on one minor road, N. Eldridge Pkwy. (Assume the existing of connected vehicles)

Overall network performance in a weekday

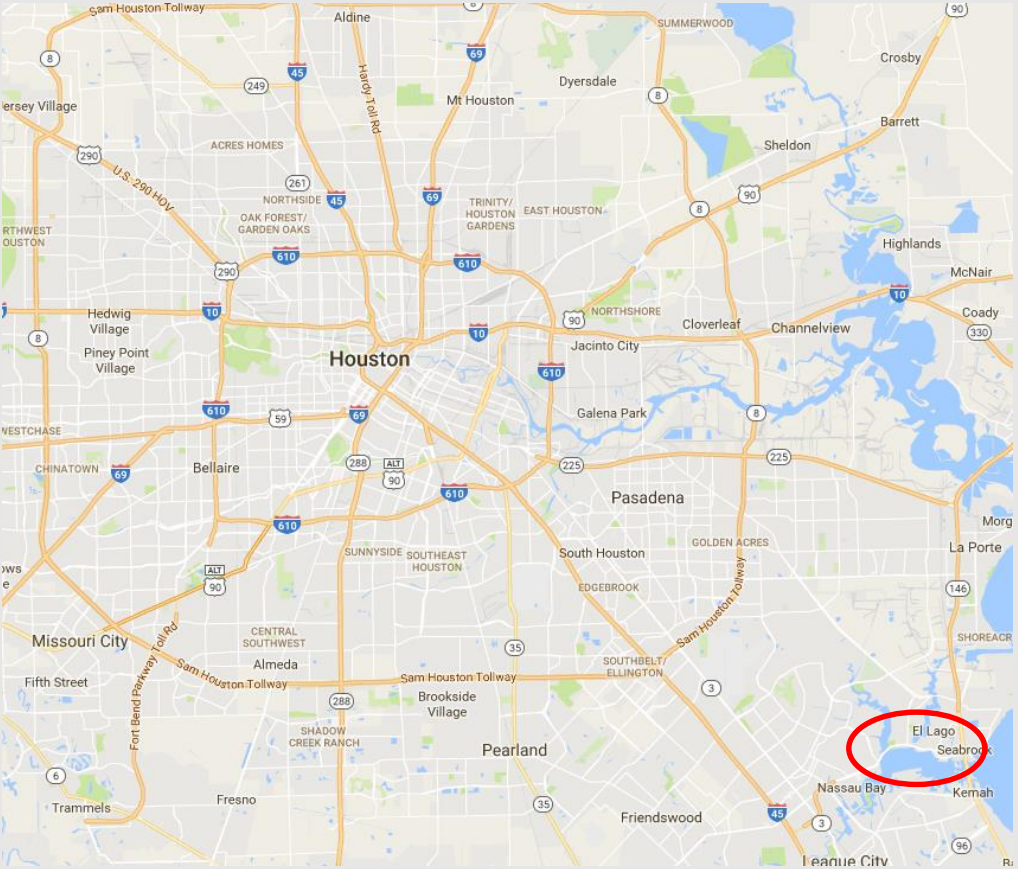
Approaches	Max Queue Length (veh)			Average Delay (second)		
	Before	After	Diff	Before	After	Diff
East Bound, FM1960	34.4	16.5	-52%	49.7	13.8	-72%
West Bound, FM1960	50.8	14.1	-72%	55.4	13.7	-75%
North Bound, Eldridge Pkwy	11.9	2.7	-77%	63.4	13.9	-78%
South Bound, Eldridge Pkwy	5.9	1.1	-81%	53.8	13.8	-74%

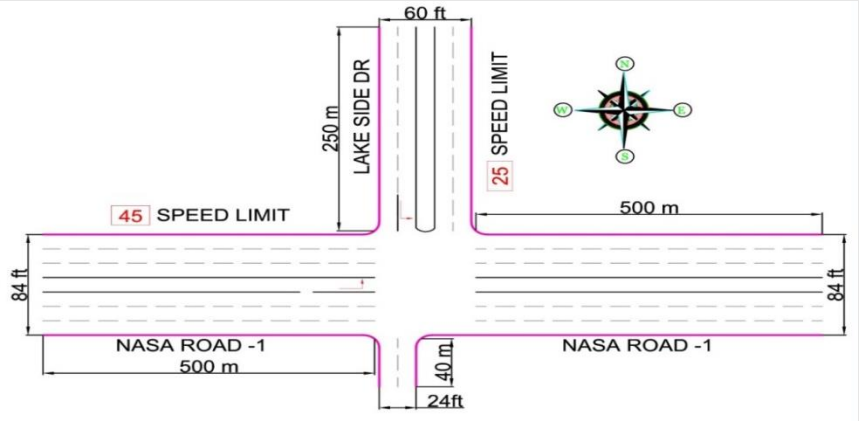
Overall network performance in a weekend

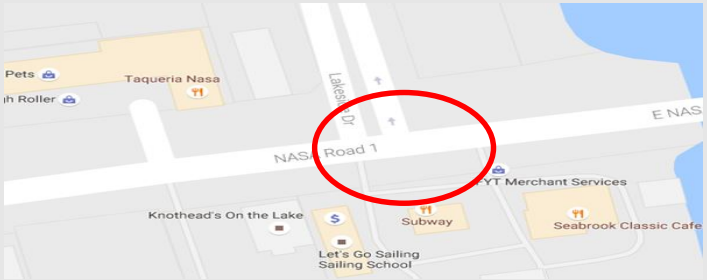
Max Queue Length (veh)			Average Delay (second)		
Before	After	Diff	Before	After	Diff
34.4	16.5	-52%	49.7	13.8	-72%
50.8	14.1	-72%	55.4	13.7	-75%
11.9	2.7	-77%	63.4	13.9	-78%
5.9	1.1	-81%	53.8	13.8	-74%

Field Test

- Test Bed 2: NASA ROAD 1

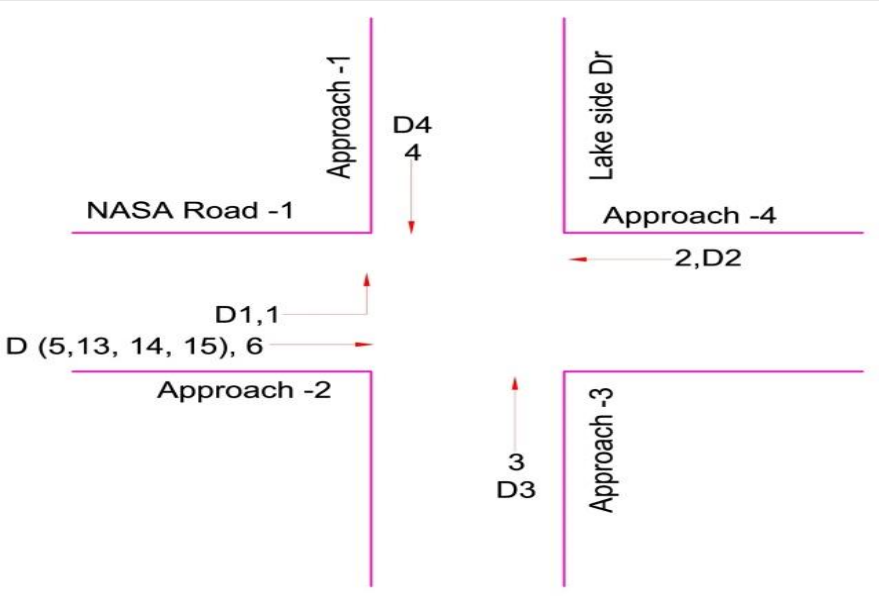






Field Test

- Test Bed 2: NASA ROAD 1



Phase and detector information

Approach Number	Phase Number	Detector Number
1	4	4(SBD)
2	1	1(SBD)
	6	5, 13, 14, 15 (UD)
3	3	3(SBD)
4	2	2(UD)

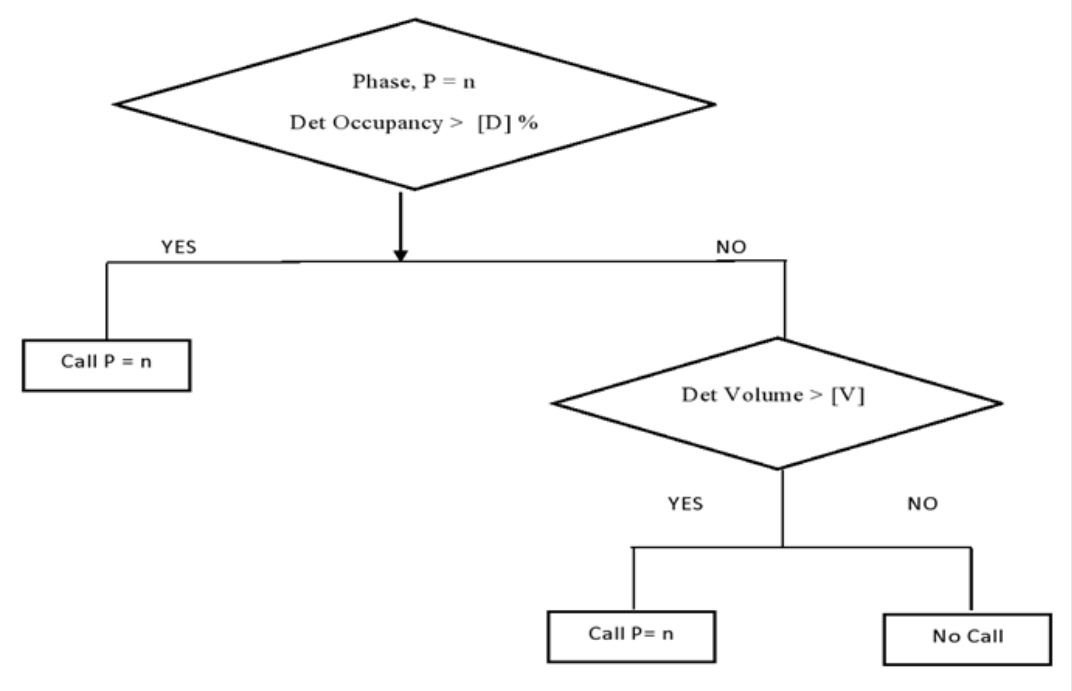
Existing signal control: actuated signal control

Field Test

- Test Bed 2: NASA ROAD 1

ASC/3-2100 Controller

Logic Statement that can be applied



Two key parameters:

1. Occupancy
2. Volume

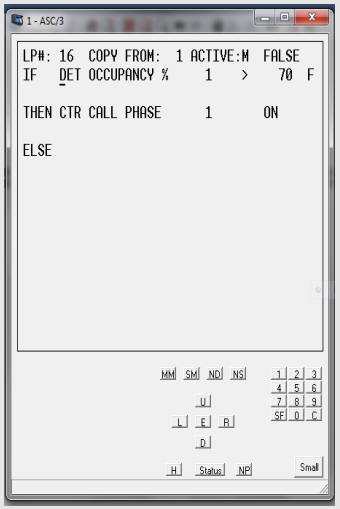
VISSIM has a package embedded to simulate this controller

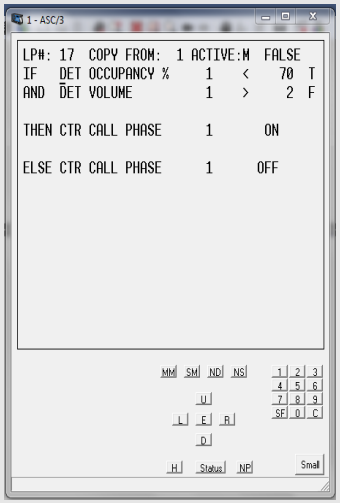
Field Test

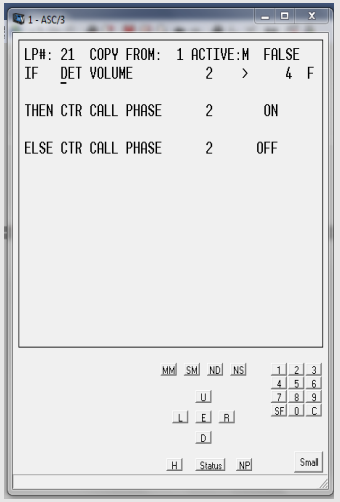
- Test Bed 2: NASA ROAD 1

Critical values for volume and occupancy

Phase Number	Detector	Volume	Occupancy (%)
1	1 (SBD)	2	70
2	2 (UD)	4	
3	3 (SBD)	2	70
4	4 (SBD)	2	70
6	5 (SBD)	6	
	13 (SBD)	2	
	14 (SBD)	2	
	15 (SBD)	2	



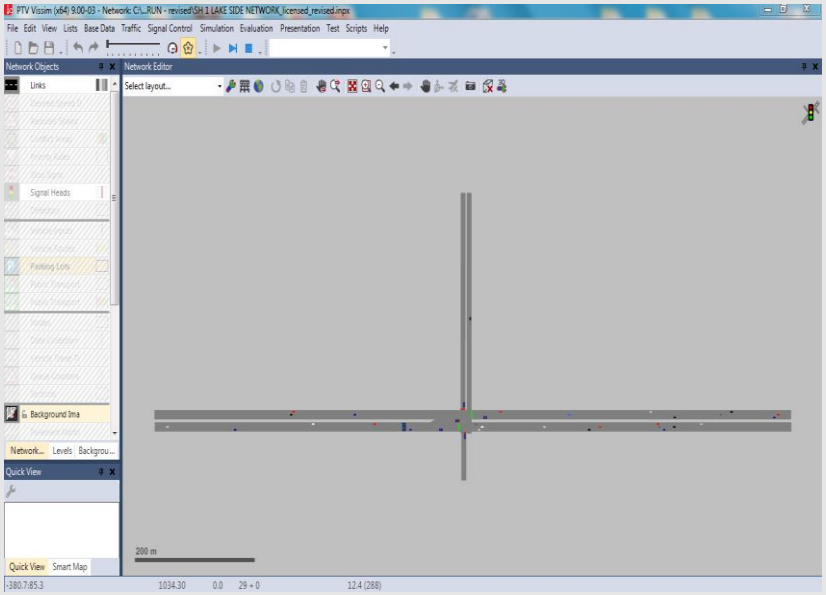




Logic Statement Setting in ASC/3-2100 Controller in VISSIM

Field Test

- Test Bed 2: NASA ROAD 1



Testbed simulated in VISSIM

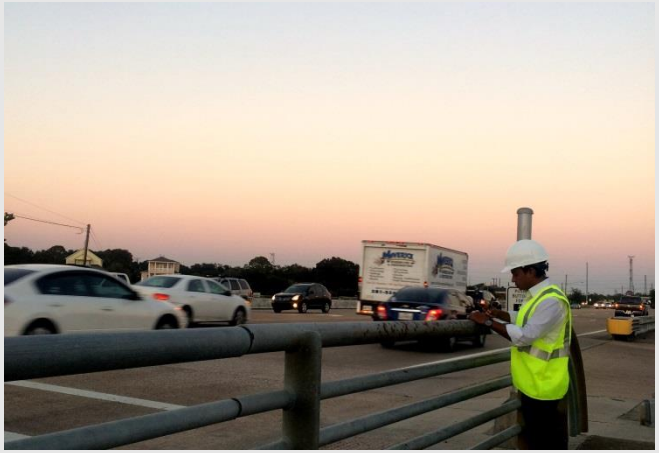
Change of parameter values

Phase	Minimum green time	Maximum green time	Vehicle Extension time
1 (actuated)	5	20	2.0
1* (proactive)	**0**	20	**3.0**
2 (actuated)	25	60	3.0
2* (proactive)	**5**	**70**	**5.0**
3 (actuated)	5	15	2.0
3* (proactive)	**0**	**20**	**3.0**
4 (actuated)	5	25	2.0
4* (proactive)	**0**	**30**	**3.0**
6 (actuated)	25	60	3.0
6* (proactive)	**10**	**90**	**5.0**

The highlighted values represent the corresponding changes

Field Test

- Test Bed 2: NASA ROAD 1

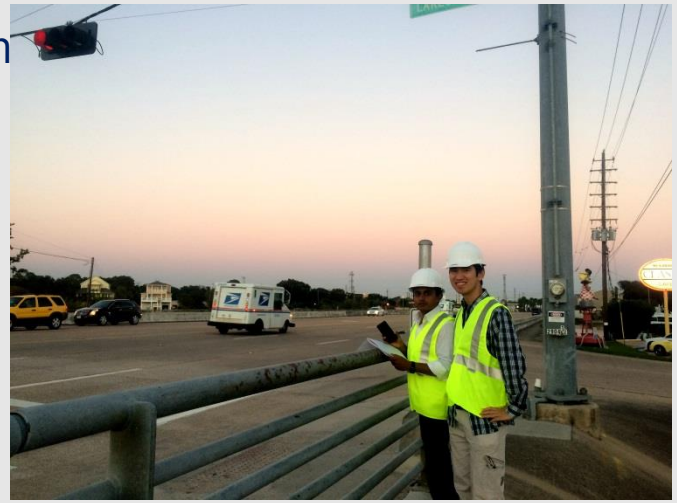


Date of Field Observation

- Proactive Signal Control (November 22, 2016)
- Actuated Signal Control (December 9, 2016)

Weekday Peak Hour

- Morning Peak (Observation from 6:30am to 9:00am
- Evening Peak (Observation from 3:00pm to 5:30pm)



Results

- Test Bed 2: NASA ROAD 1

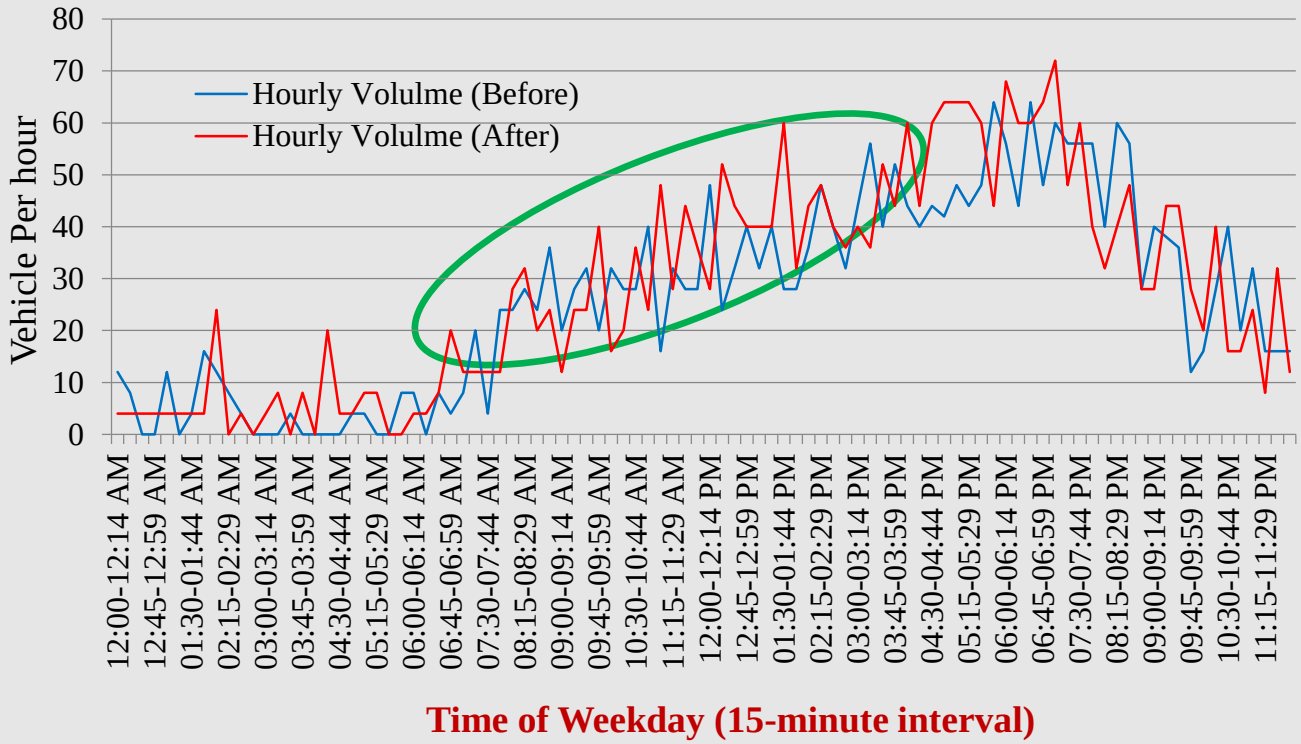
Evaluation of the proactive algorithm based VISSIM simulation

Parameters	Actuated Signal Control	Proactive Signal Control	Diff (%)
Average Delay (seconds)	6.71	6.00	**-11%**
Average Number of Stops	0.29	0.26	**-10%**
Average Stop delay (seconds)	3.28	2.54	**-29%**
Total Delay (seconds)	4878	4359	**-13%**
Speed Average (mile/hour)	60.84	61.59	**+1.2%**

Results

- Test Bed 2: NASA ROAD 1

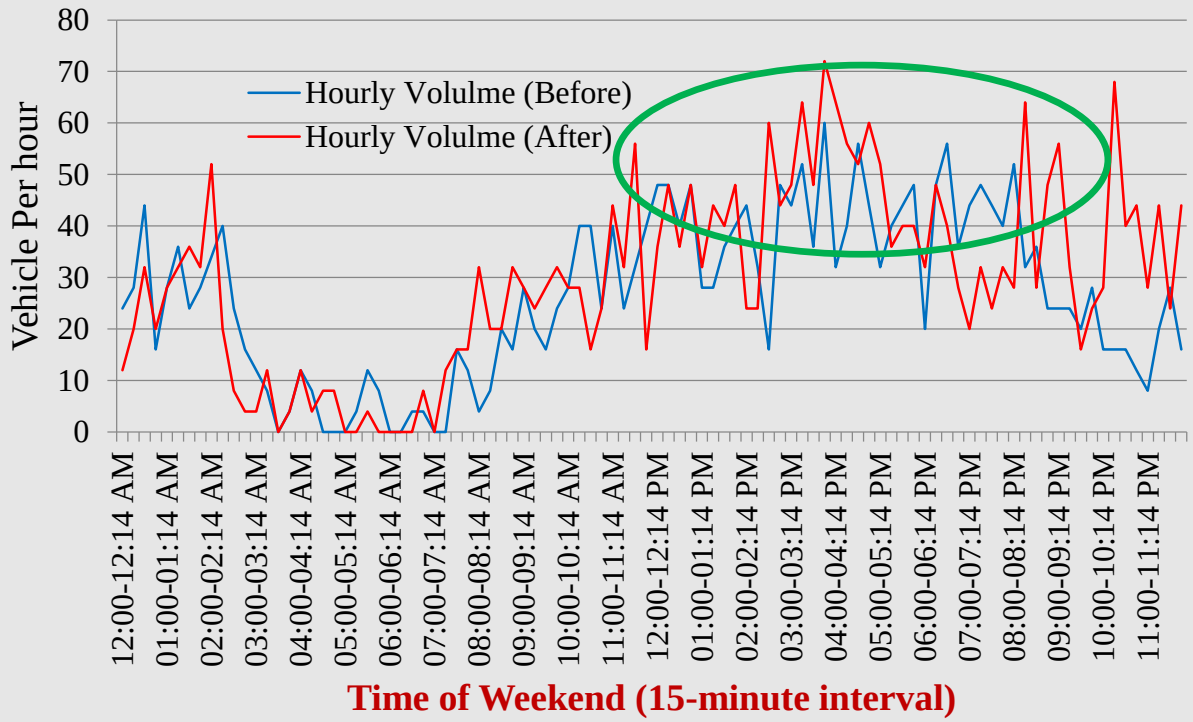
Field data observations: Phase 1 (left-turn from the major road to the minor road, east-north)



Results

- Test Bed 2: NASA ROAD 1

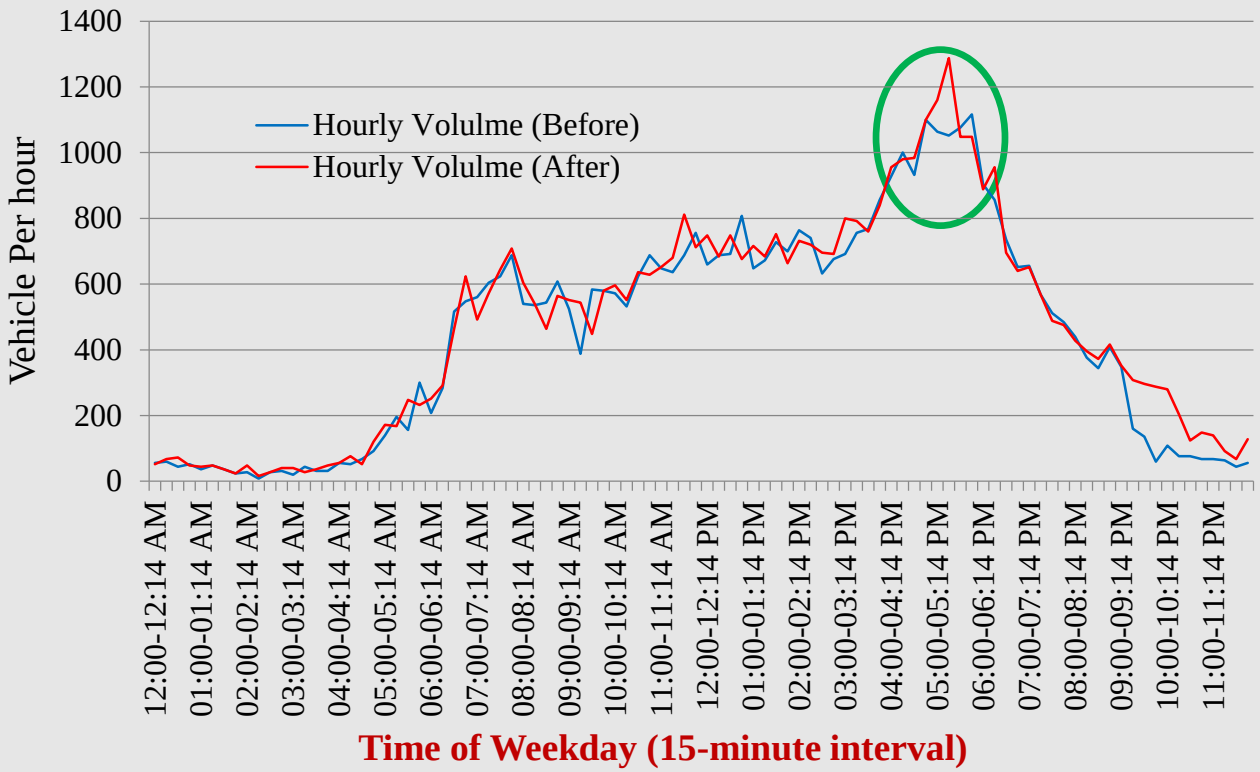
Field data observations: Phase 1 (left-turn from the major road to the minor road, east-north)



Results

- Test Bed 2: NASA ROAD 1

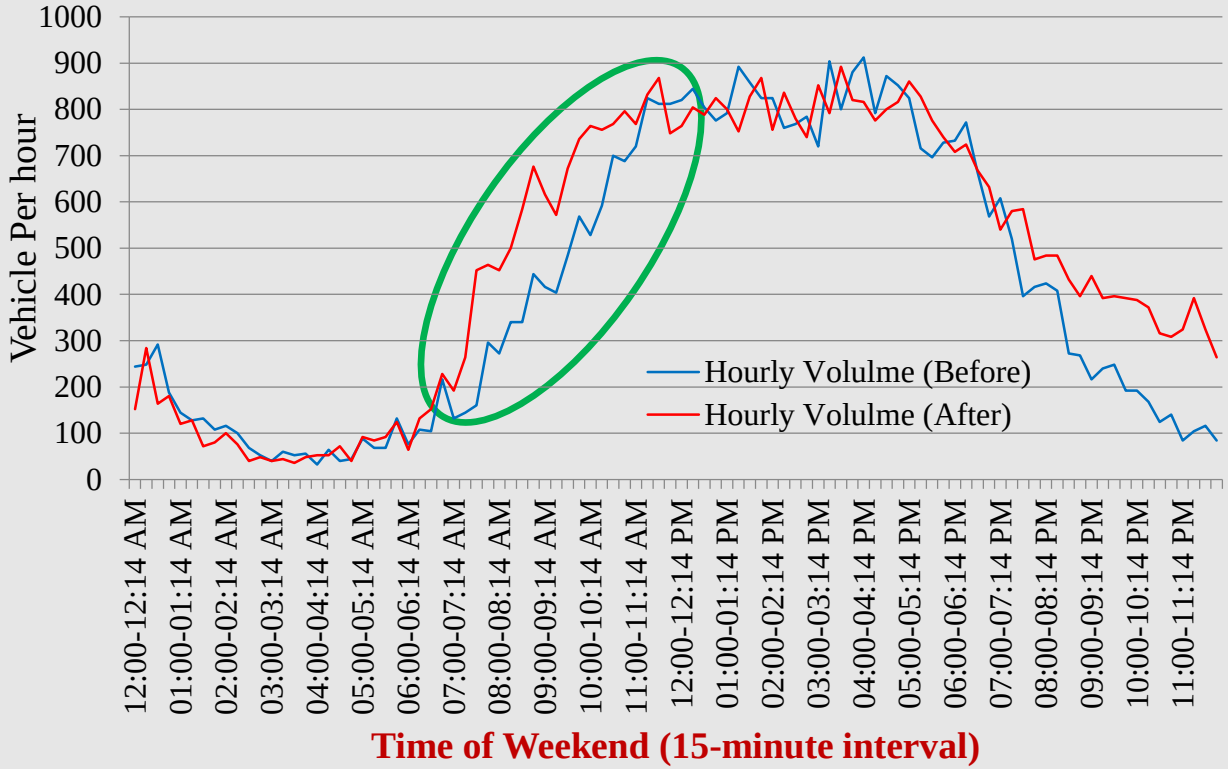
Field data observations: Phase 6 (eastbound through traffic on the major road)



Results

- Test Bed 2: NASA ROAD 1

Field data observations: Phase 6 (eastbound through traffic on the major road)



Results

- Test Bed 2: NASA ROAD 1

Evaluation of the proactive algorithm based field observation

Approach	Parameter	Actuated Control	Proactive Control	**Diff (%)**
Major Approach	Average Queue Length	24.80	10.00	**60**
	Maximum Queue Length	39.00	21.00	**46**
Minor Approach	Average Waiting Time	47.21	36.00	**24**
	Max Waiting Time	70.00	60.00	**14**

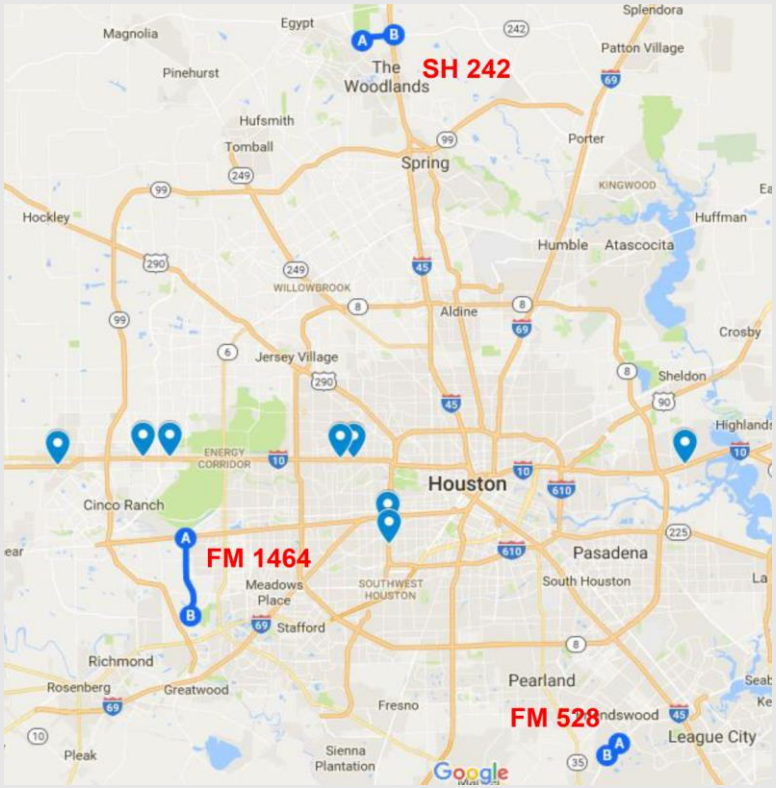
Summary

- ✓ The proactive control system can significantly mitigate road congestion on the test bed, and also reduce emission and fuel consumption.
  - From simulation (assuming connected vehicles existing in the network), it is seen that the vehicle delay reduced as high as 80%; the average number of stops of each vehicle reduced from 2.8 to 2; and the stop delay reduced up to 89%;
  - On weekdays, the fuel consumption and CO2 is reduced about 21%, and 25% on weekends: this is equivalent to $2,400/day savings of gas on weekdays, and $3,270 on weekends (based on simulation, assuming connected vehicles existing in the network).
- ✓ The field experiments also reports positive results:
  - The proactive signal control system increases the average traffic volumes during peak hours.
  - No complaint were received after the implementation
  - The average queue length on the major road can be reduced up to 60%, and the average waiting time of vehicles on the minor road decreases up to 24%.

Large-Scale Implementation

- 30 Intersections at the Greater Houston Area

– Three testbeds (FM 528, SH 242 and FM 1464), which have consecutive intersections, and are installed with an Ethernet Programmable Automation Controller (EPAC)
– Other separate 8 intersections are using the diamond controller mechanism.



What's Next

- Implementation of FM 528 corridor
- Intersection spacing and traffic volume at different time of day
- System perform better during Free mode operation
- Free mode operation Vs. Coordination mode
- Ability to automate the operation mode base on conditions
- Machine learning for the future

Questions

Contact

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