USF Seminar

Developing Advanced Traffic Signal Control Algorithms: The Role of Connected Vehicles

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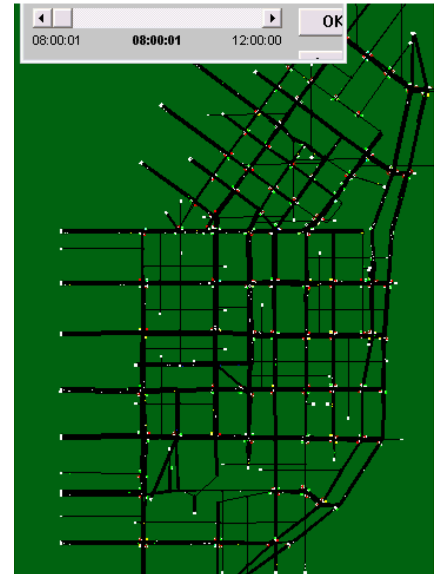
Background (1)

FHWA EAR Project -- Advanced Signal Control Strategies based on Connected Vehicle Data

PATH/UC Berkeley, UC Riverside, BMW

Objectives/Scope:

- **Estimating of performance measures from CV data**
  - Determine penetration rates and sampling protocols
  - Data fusion with loop detector data
- **Traffic signal control for mobility**
  - Queue spill-back avoidance
  - Perimeter control in grid networks to prevent gridlock
  - Dynamic lane grouping
- **Traffic signal control for safety**
  - Dynamic all-red extension
  - minimizing arrival rate on yellow change interval
- **ECO signal operations**
  - In-vehicle driver speed advisory for minimum fuel consumption
  - Integration of adaptive signal priority with driver advisory



Background: Traffic Flow Variability vs. Control

A

- Fixed-Time Plans
- Time of Day (TOD)
- No Detection
- May be actuated

B

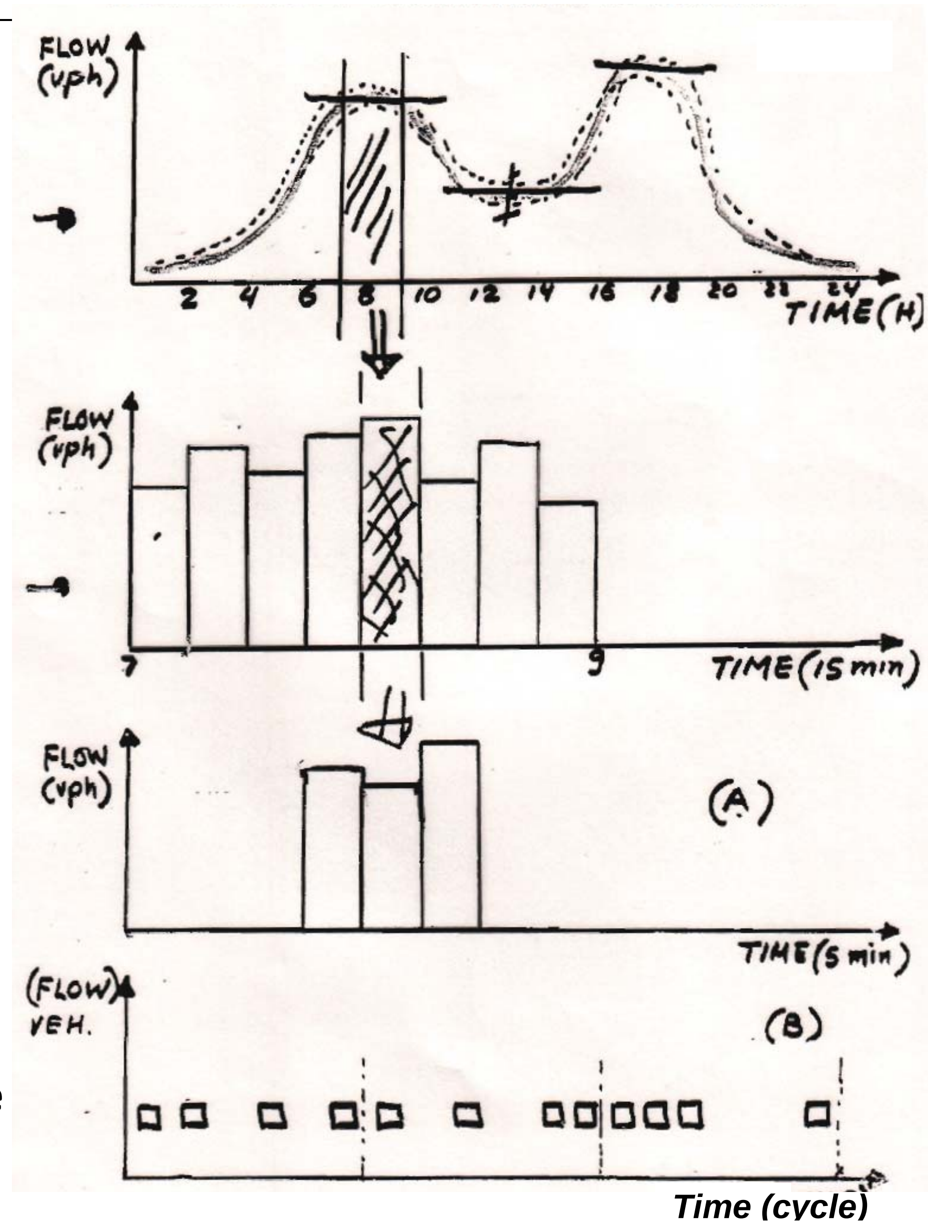
- Fixed time plans
- Traffic responsive plan selection
- System detection

C

- Traffic responsive control
- On-line timing development
- Approach & system detection

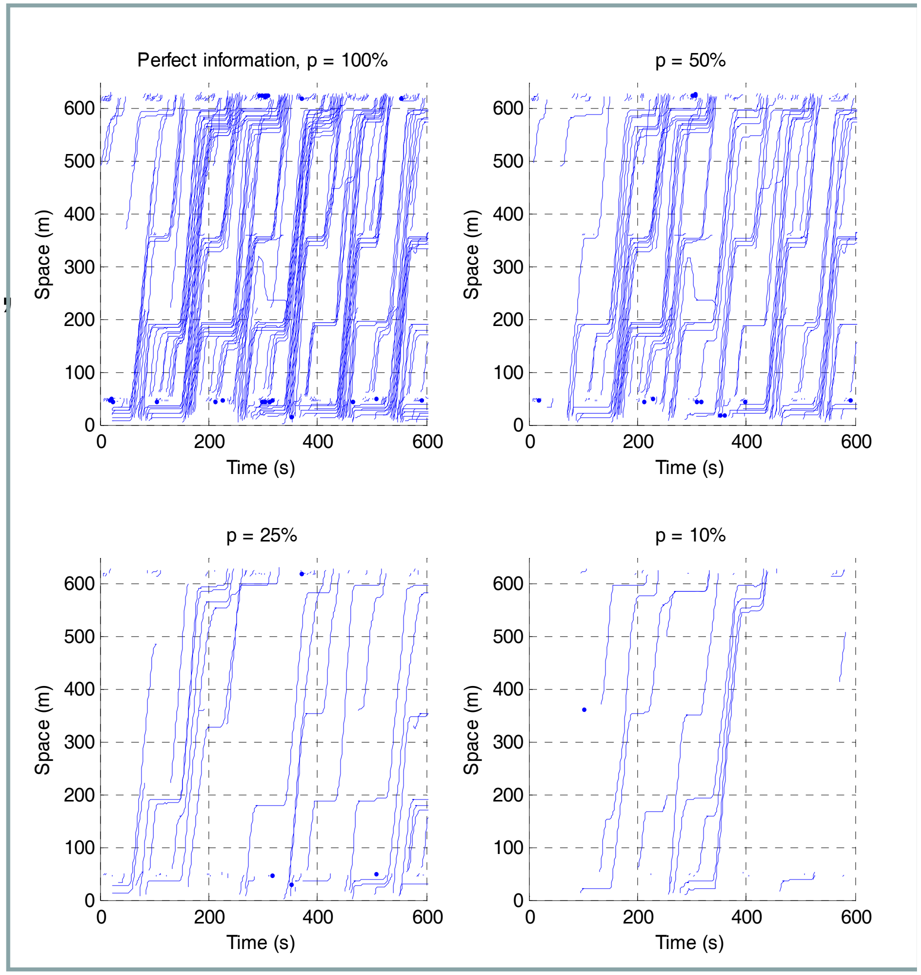
D

- Adaptive control
- Measure & predict arrivals per cycle
- Extensive detection



Estimation of MOEs: Overview

- Algorithms for estimating traffic conditions in arterials based on CV data
  - Intersection level
    - Queue length
  - Arterial level
    - Average speed, delay, # of stops, acceleration noise



- Analyze the algorithms' accuracy
- Determine minimum penetration rate requirements

Test Sites

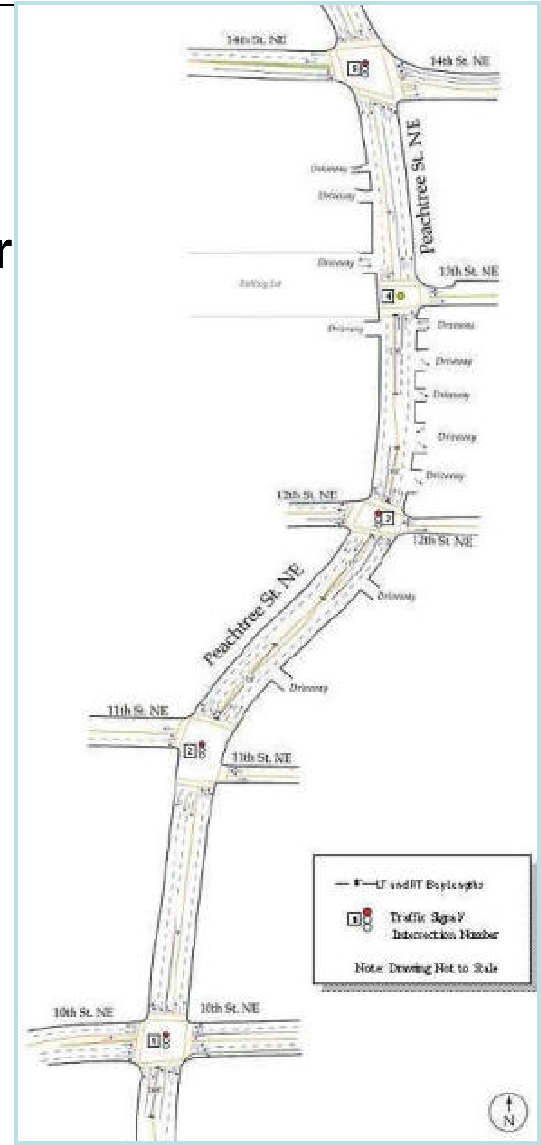
NGSIM Data: Peachtree St., Atlanta, GA

- **4 signalized intersections**
- **Vehicle ID, time, position, lane, speed, acceler**
- **Resolution=0.1 sec**
- **Undersaturated traffic conditions**

Simulated Data: El Camino Real, SF Bay Area

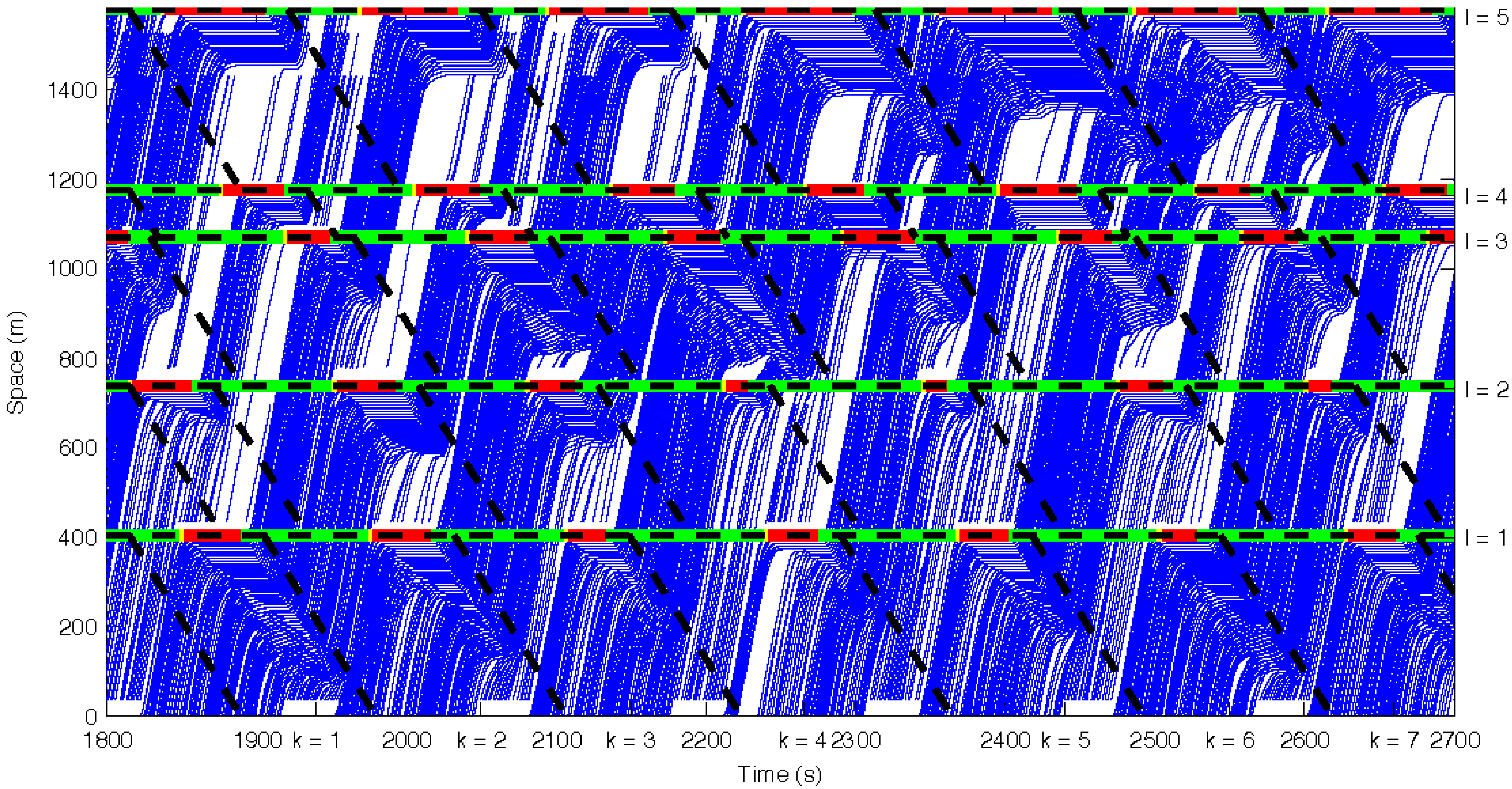
- **5 intersections**
- **Same trajectory information, resolution**
- **Oversaturated traffic conditions**

Argote J., E. Christofa, Y. Xuan, and A. Skabardonis "Estimation of Arterial Measures of Effectiveness with Connected Vehicle Data," paper 12-1493, 91st TRB Annual Meeting, Washington DC, 2012.



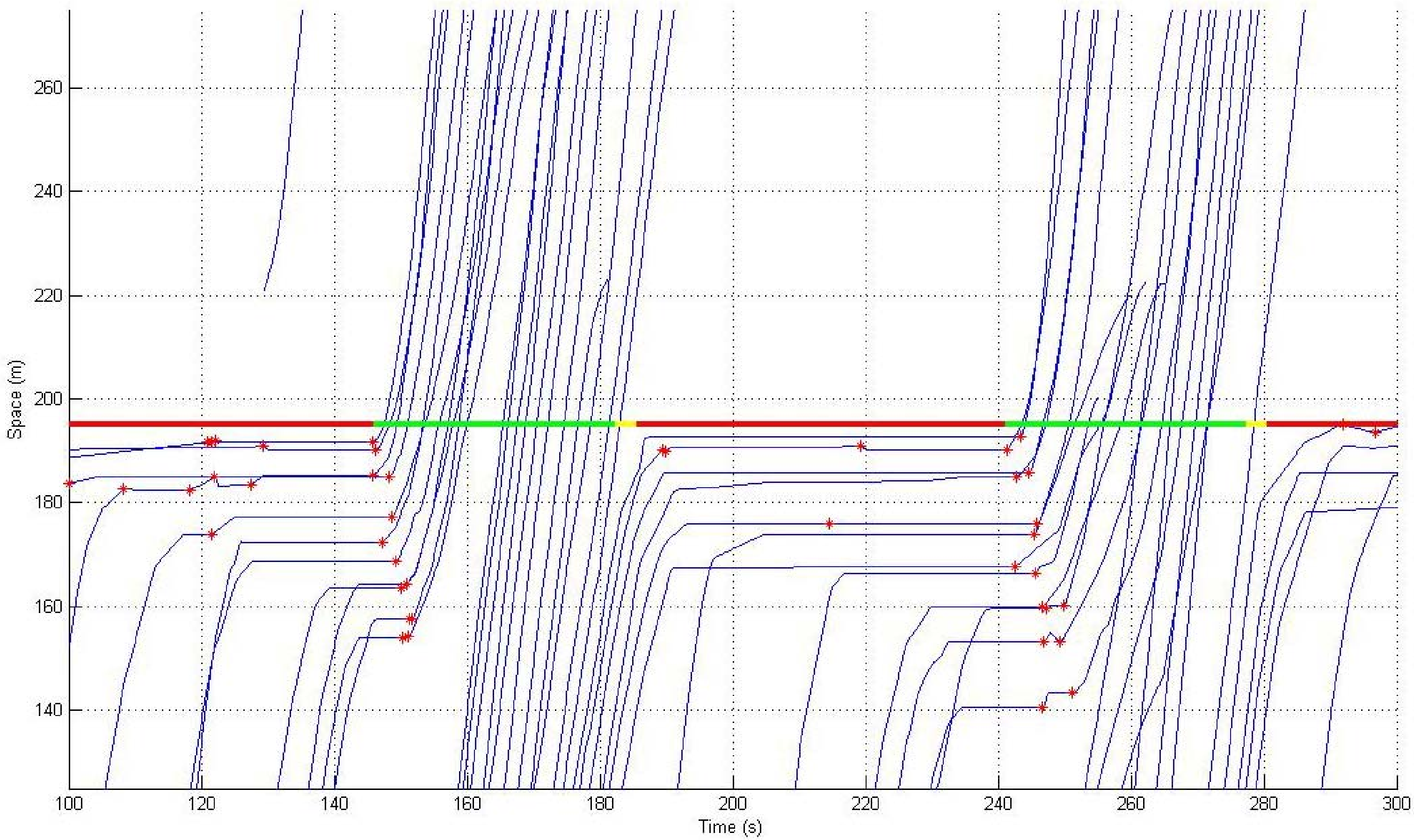
Intersection MOE – Queue Length (1/6)

Step 1. Discretization of time-space



Intersection MOE – Queue Length (2/6)

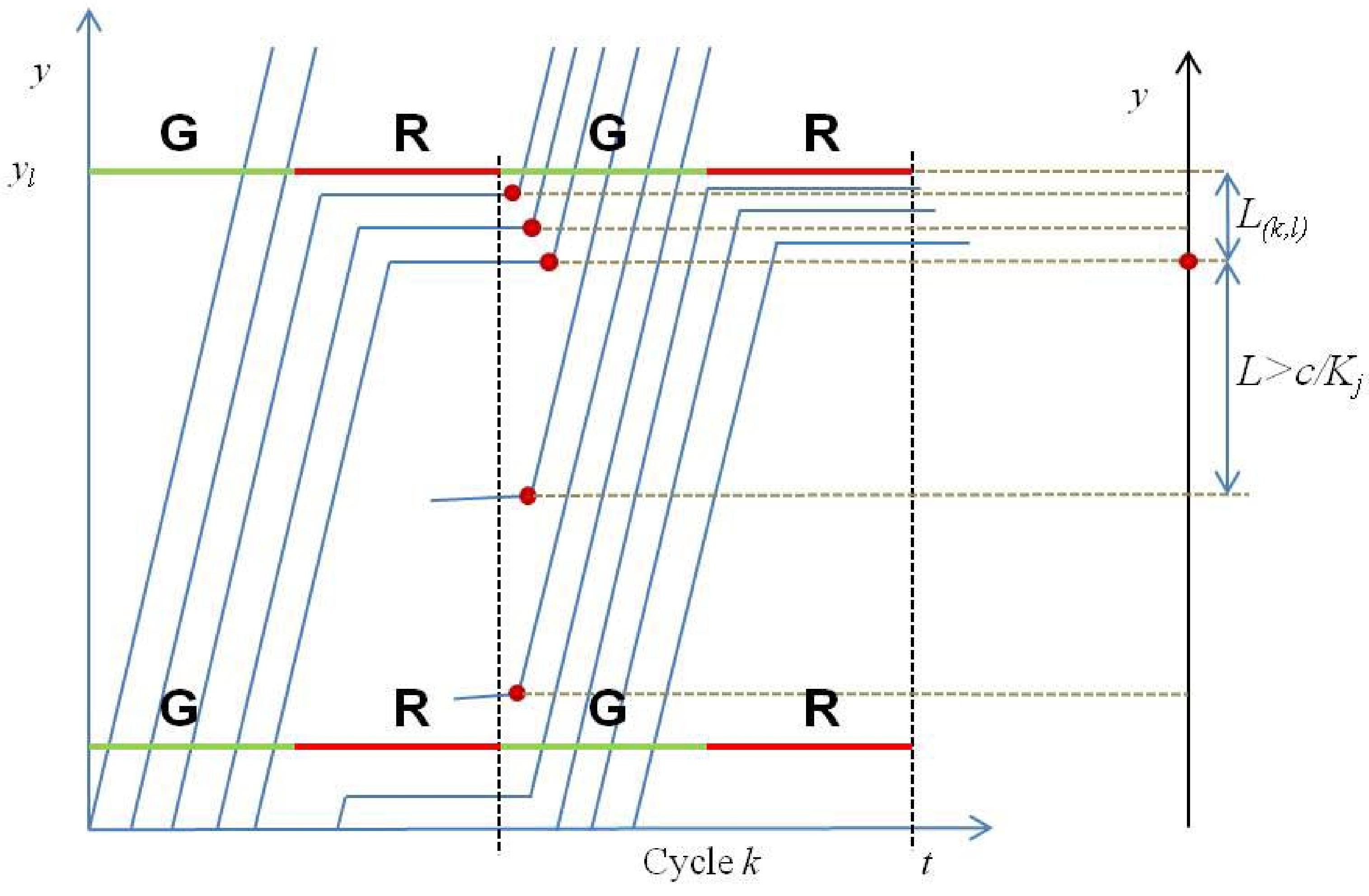
Step 2. Identification of deceleration/acceleration points



Intersection MOE—Queue Length (3/6)

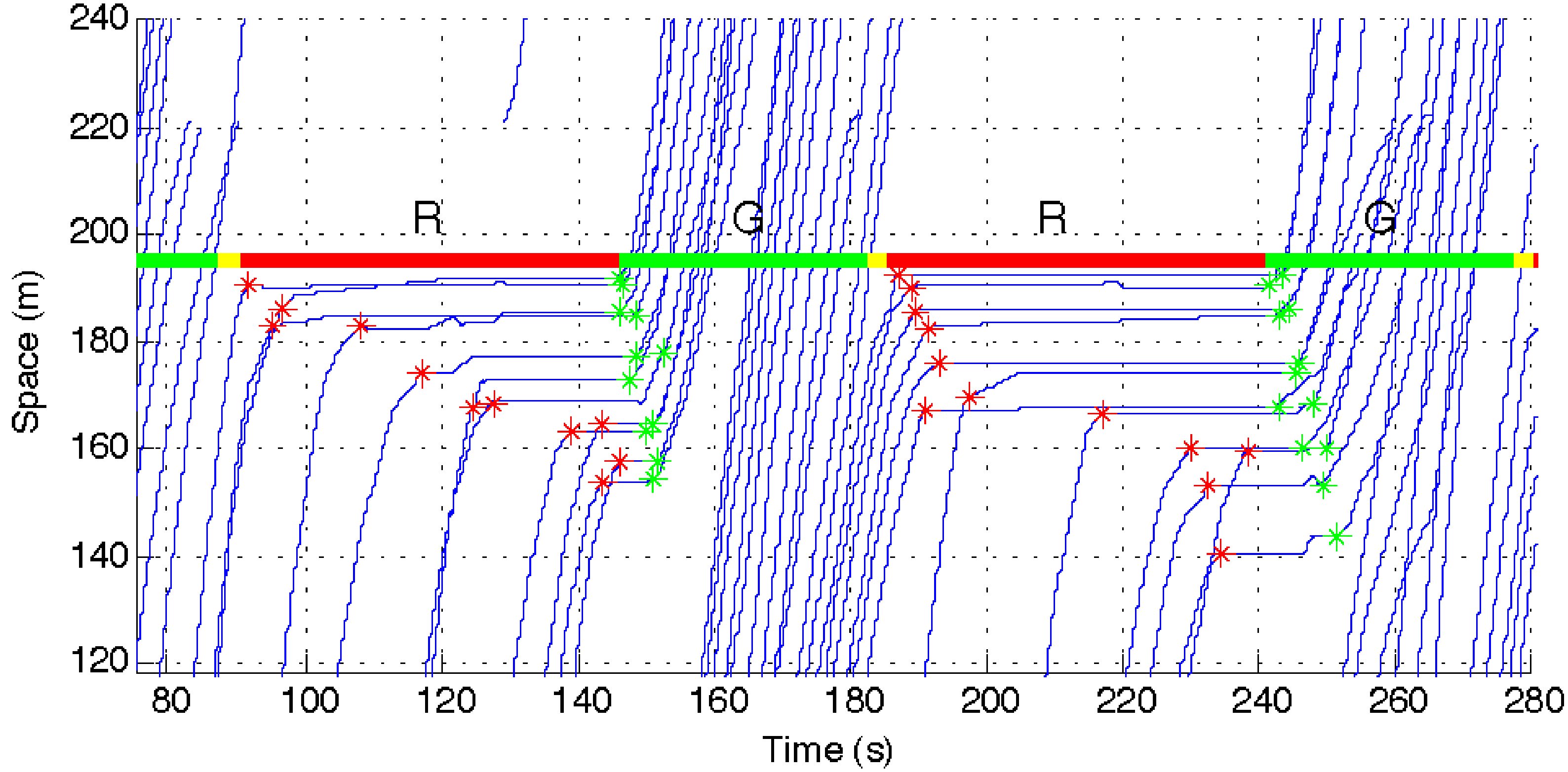
Step 3. Filter outliers:

consider average distance between sampled vehicles



Intersection MOE – Queue Length (4/6)

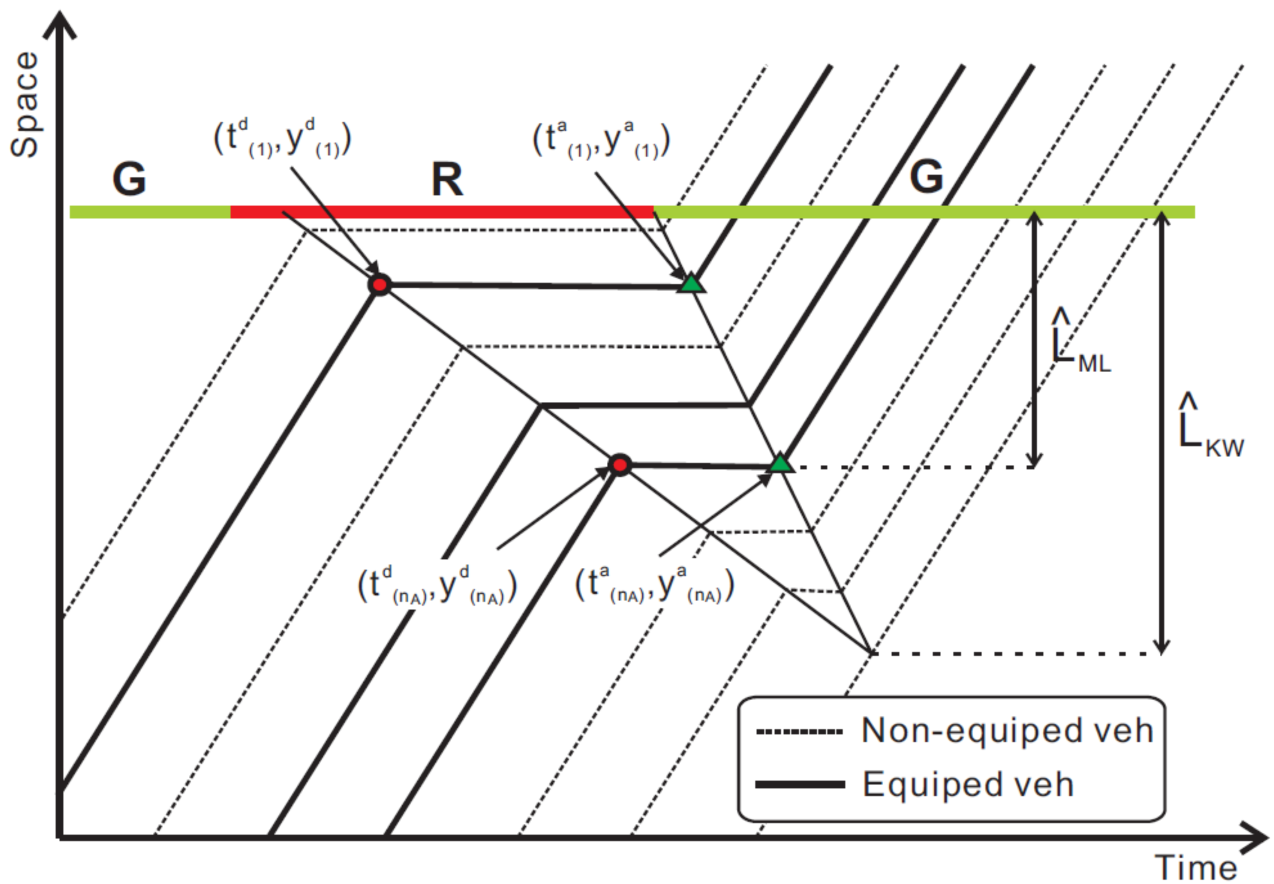
Step 4. Filtered deceleration/acceleration points



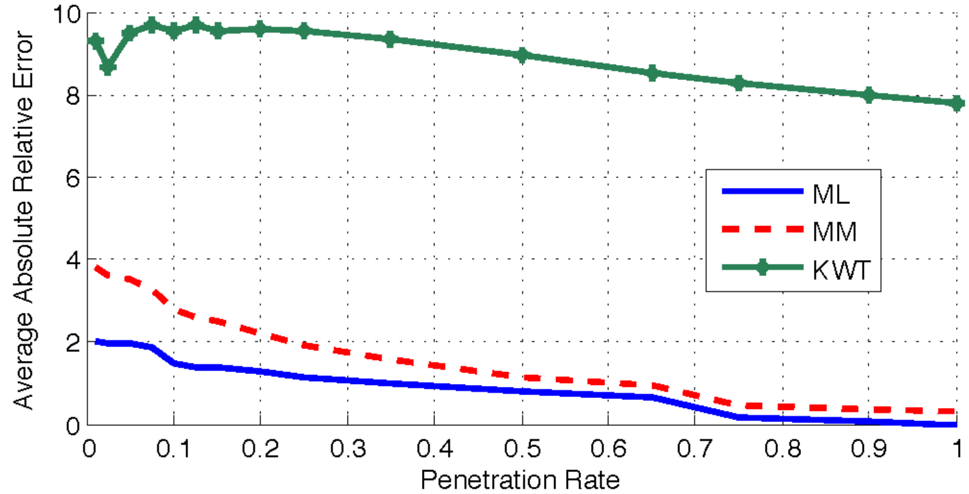
Intersection MOE—Queue Length (5/6)

Methods:

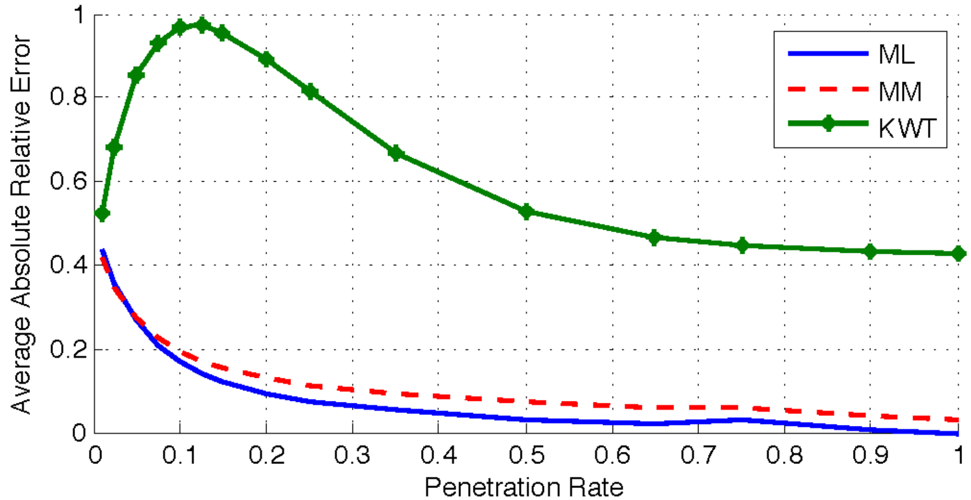
- **Maximum Likelihood (ML)**
- **Method of Moments (MM)**
- **Kinematic Wave Theory (KWT)**



Intersection MOE – Queue Length (6/6)



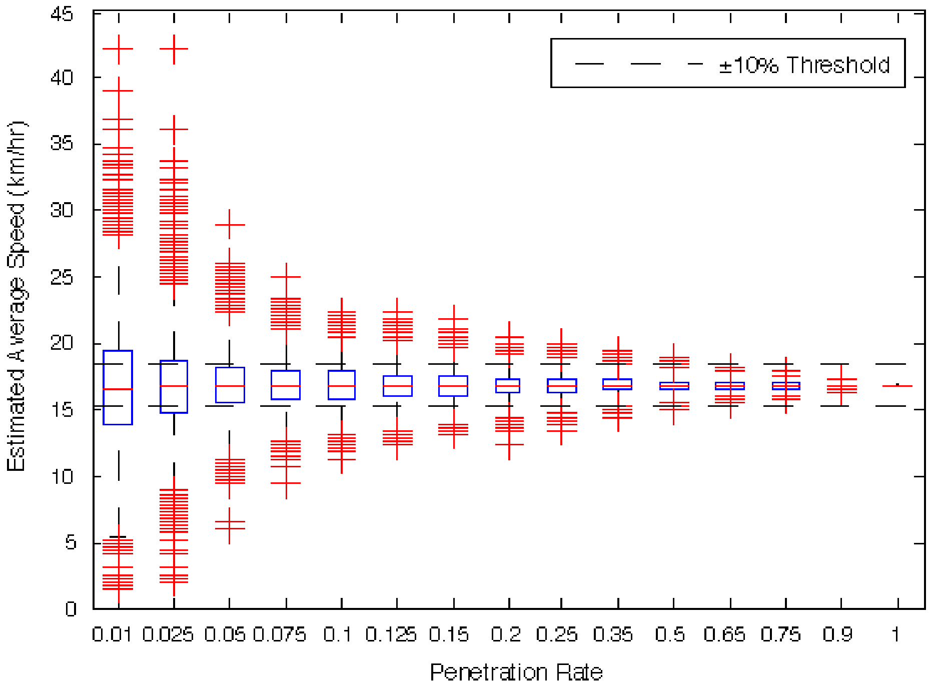
Undersaturated Traffic Conditions



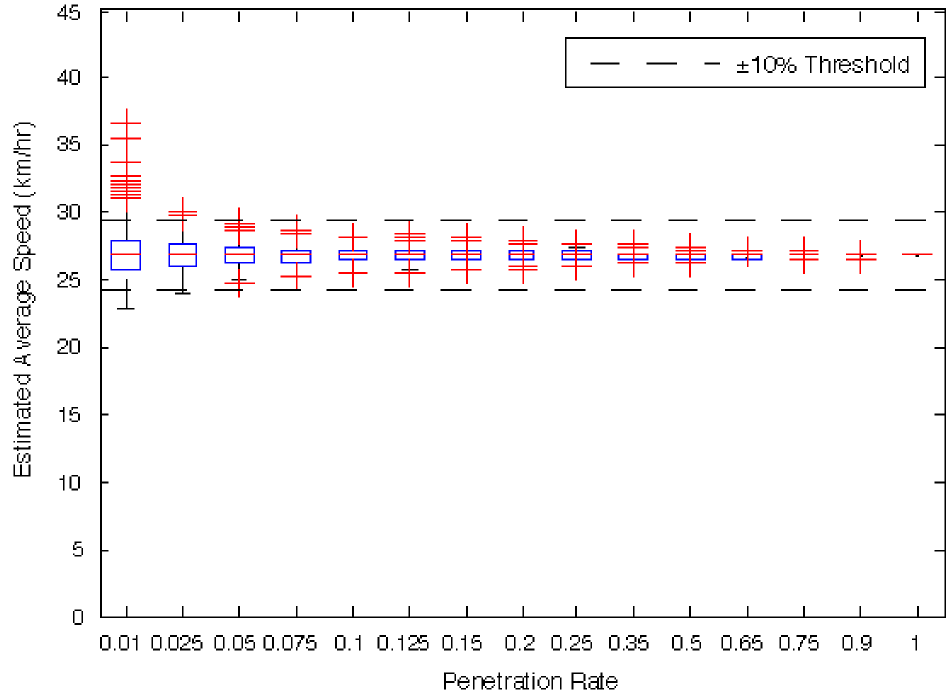
Oversaturated Traffic Conditions

Estimation of Arterial MOEs (1)

Average Speed



Undersaturated conditions



Oversaturated conditions

Estimation of Arterial MOEs (2)

Summary

MOE	Penetration Rate (undersaturated)	Penetration Rate (oversaturated)
Average Speed (km/hr)	35%	5%
Average Total Delay (sec/m)	50%	10%
Average Number of Stops	50%	20%
Acceleration Noise (m/s^2)	10%	1%

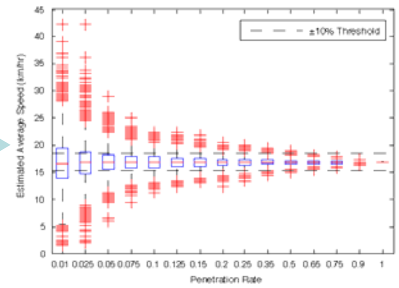
Argote J., E. Christofa and A. Skabardonis, "Connected vehicle penetration rate for estimation of arterial measures of Effectiveness, Transportation Research part C (2015), 298-312

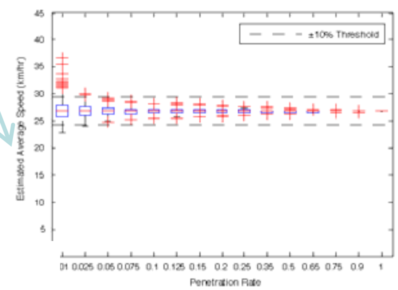
Minimum CV Penetration rate

- **Motivation:**

The minimum penetration rate requirements vary depending on the traffic conditions.

MOE	Min p (under-saturated)	Min p (over-saturated)
Average Speed (km/hr)	35%	5%
Average Total Delay (sec/m)	50%	10%
Average Number of Stops	50%	20%
Acceleration Noise (m/s^2)	10%	1%





- **Theoretical derivation:**

$$\left.\begin{array}{l} S \geq \left(\dfrac{\Phi^{-1}(1-\alpha)\sigma_{\bar{v}}}{0.1\bar{v}}\right)^2 \\ S = \min\left\{qpT, \left(\dfrac{G}{C}s\right)pT\right\} \end{array}\right\} \Rightarrow \begin{cases} p \geq \dfrac{S_{min}}{qT} & \textbf{undersaturated arterial} \\ p \geq \dfrac{S_{min}}{\left(\dfrac{G}{C}s\right)T} & \textbf{oversaturated arterial} \end{cases}$$

- **Simulation test:**

Model of San Pablo Avenue (4-link segment)

Testing multiple scenarios: G/C = {0.20, 0.30, 0.35, 0.40, 0.50, 0.60}

q/s = {0.35, 0.40, 0.50, 0.60}

Signal Control Strategies for Mobility

- **Infrastructure Control Based on Probe Data**

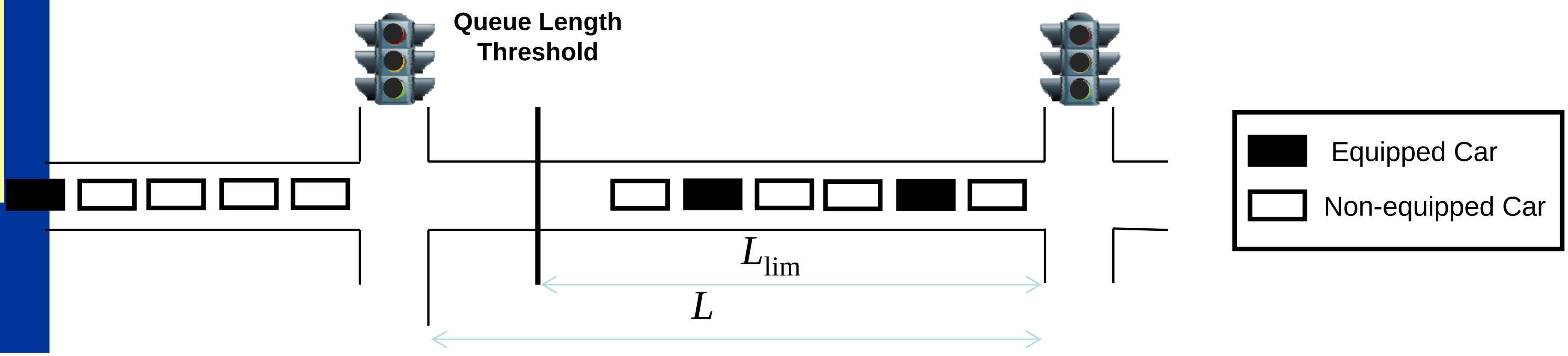
  - **Queue spill-back detection and control at an individual intersection approach**
  - **Control of congested urban grid networks**
  - **Adaptive priority for individual vehicles (*discussed in eco signal operations*)**
  - **Dynamic lane grouping**

- ***Christofa, E., J. Argote and A. Skabardonis, "*Arterial Queue Spillback Detection and Signal Control based on Connected Vehicle Technology, Transportation Research Record No. 2356, 2013, pp.61-70.**

Queue Spillback Detection & Control

Queue Length Threshold, L_{lim} (for the critical link)

- Early in the research: $L_{\lim} = (1 - k)L$ (e.g. k = 0.9)
  - Issues: Independent of traffic conditions, creates oscillations in the activation/deactivation of the alternative spillback control strategy.
- Currently: $$L_{\lim} = L - \max\left\{ F, \left(q_{CV}^{u} C / p - \sum_{i=1}^{I_{ca}^{d}} s_i^d G_i^d \right) / NK_j \right\}$$
  - Based on input-output analysis, to guarantee that a spillback cannot occur within the next cycle (dependent on traffic conditions).
  - Avoids oscillation issues in the activation of the alternative strategy.



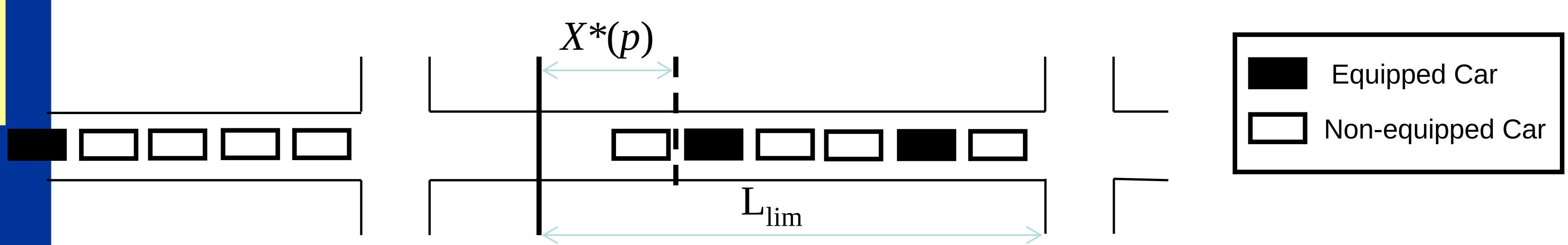
Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

- Gap length method, X*(p)
  - Only requires Connected Vehicle information and the signal cycle time.
  - Based on the assumption that the number of cars until behind the last CV vehicle in the queue follow a geometric distribution with probability 1-p, where p is the market penetration rate.

$$\Pr\left(X \le x \middle| L_{\lim}, p\right) = 1 - (1-p)^{(NK_j x)} \ge 1 - \alpha$$

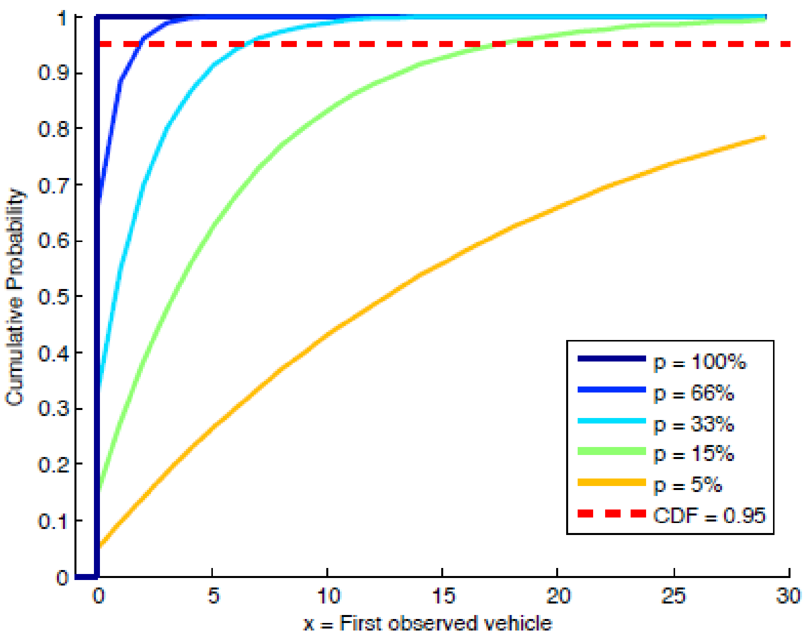
$$X^*(p) = \min\left\{L_{\lim}, \frac{1}{NK_j}\left\lceil \frac{\ln(\alpha)}{\ln(1-p)} \right\rceil\right\} = \min\left\{L_{\lim}, X(p)\right\}$$



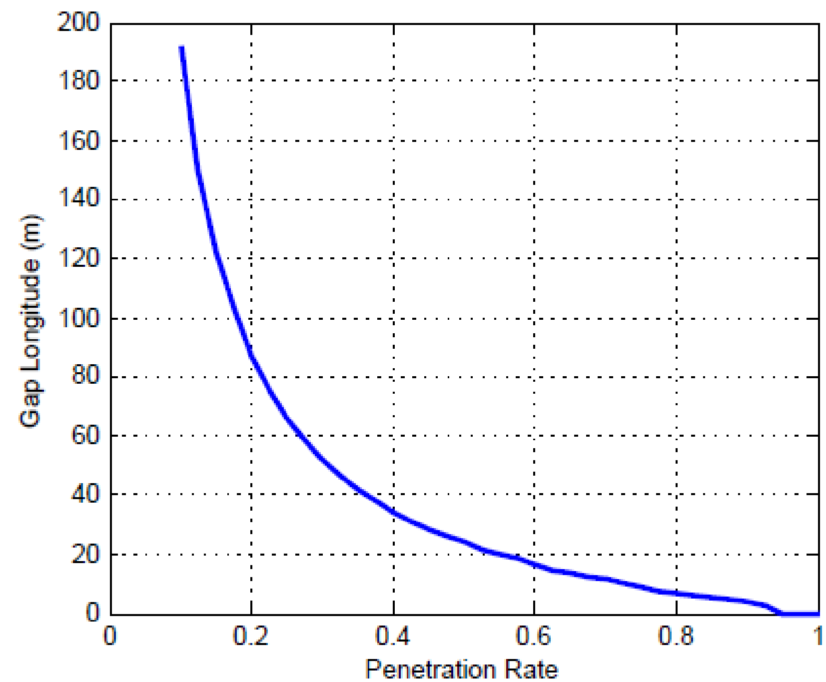
Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

- Gap length method, $X^{*}(p)$ (α = 0.05)



(a) The CDF of x for different penetration rates.



(b) Minimal gap length X^* vs penetration rate.

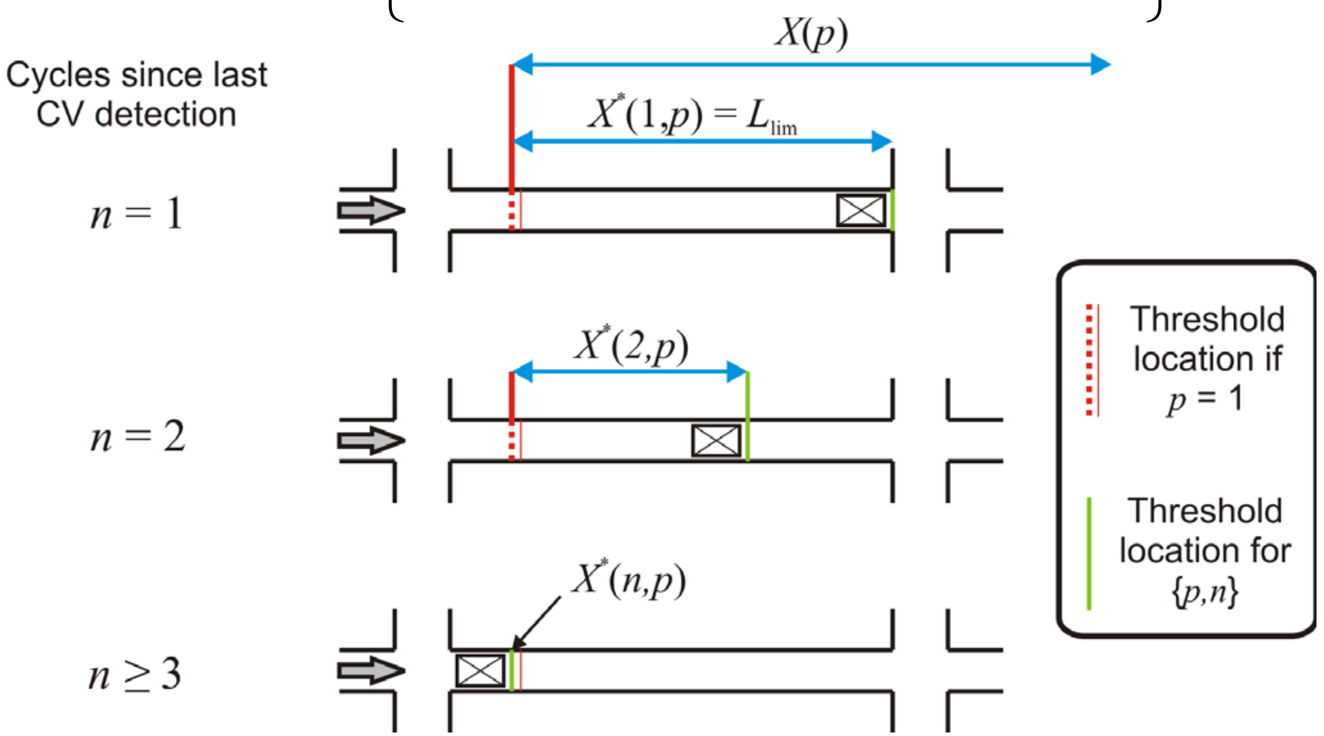
The method needs to be adapted when p is low (or $X^* > L_{th}$), it is necessary to account for the cycles since the last CV was observed

Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

- Gap length method, X*(p), adapted for low penetration rates

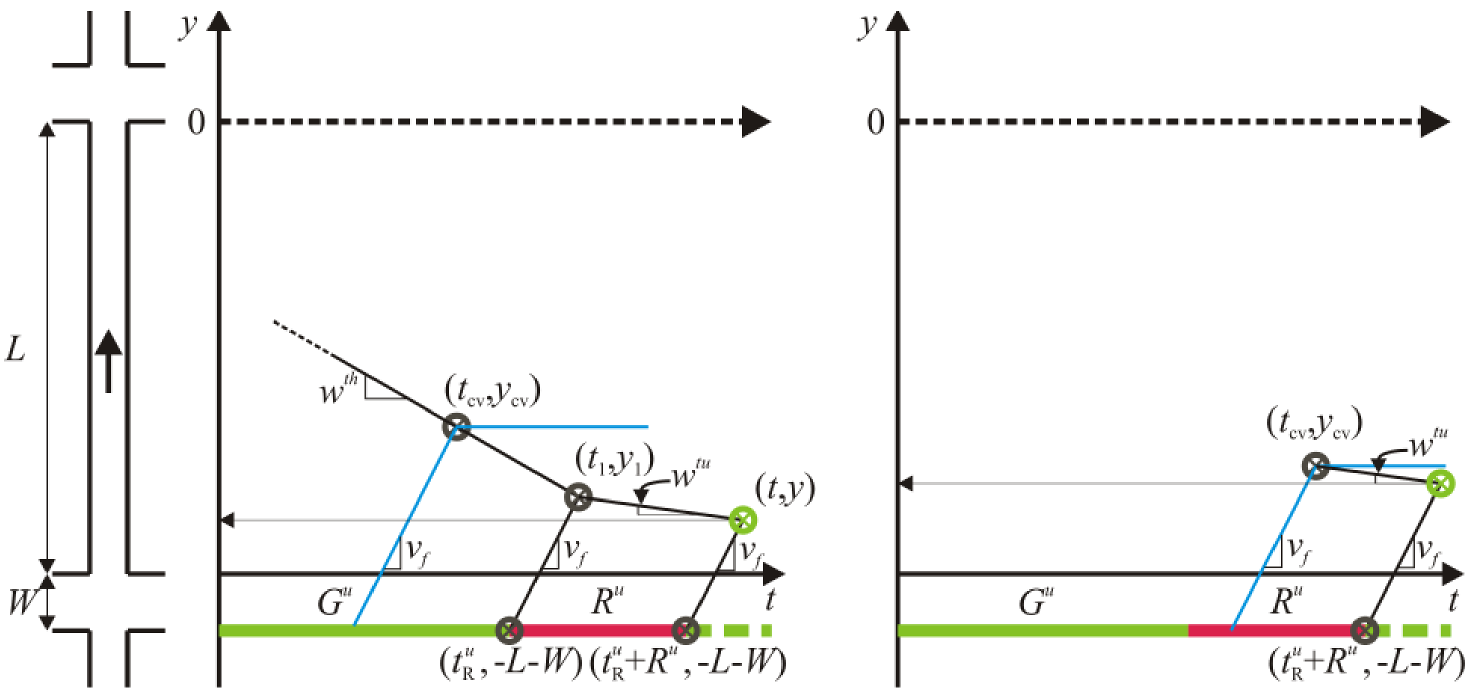
$$X^*(n,p) = \text{mid}\left\{0, X(p) - (n-1)\frac{\sum_{i=1}^{I_{ca}^d} s_i^d G_i^d}{NK_j}, L_{\lim}\right\}$$



Queue Spillback Detection & Control

Potential Spillback Detection (Methods):

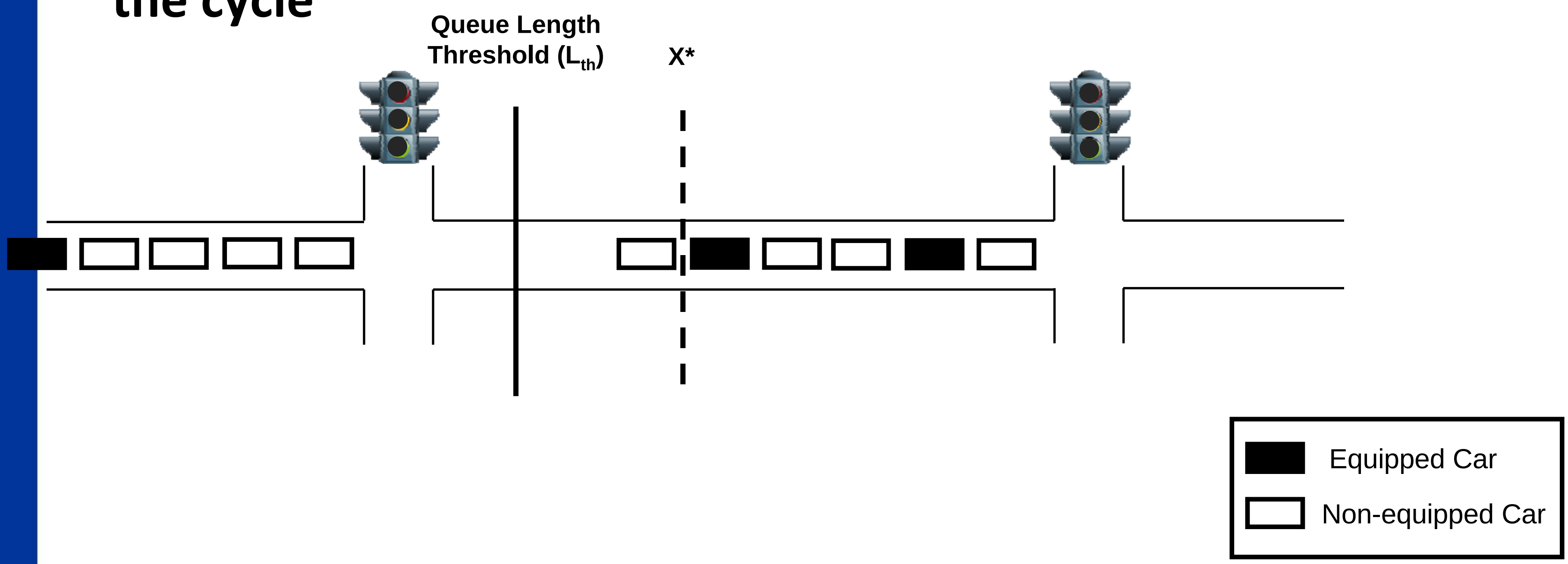
- Method based on kinematic wave theory
  - Requires CV info and signal settings (G/R, Cycle, Offset).
  - Method: use the last CV stopping point observed to project the queue length based on flow measurements, and compare that with L_{lim}.



Queue Spillback Detection & Control

Control concept

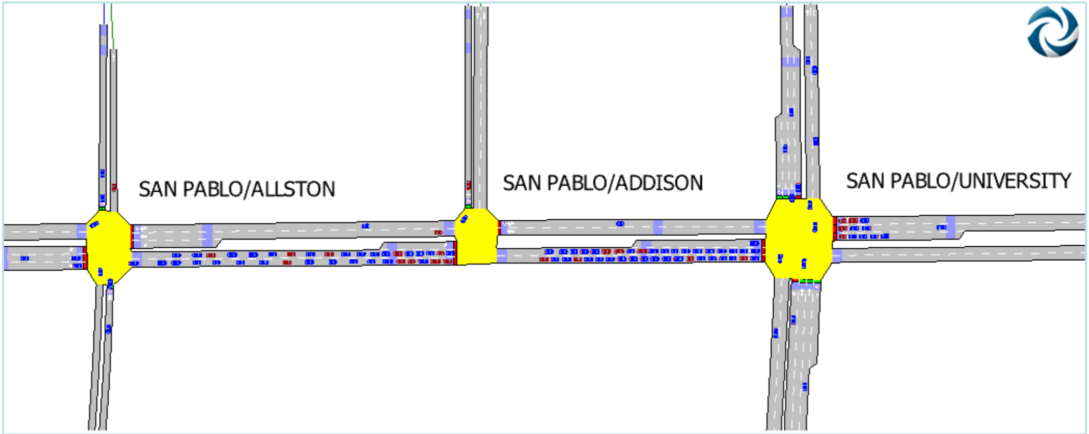
- **Reduce green time for main arterial at upstream intersection**
- **Reduction should be such to allow only as many vehicles as the ones that get served by the downstream intersection within the cycle**



Queue Spillback Detection & Control

Test Site and Simulation Approach

- Three intersection segment of San Pablo Ave, Berkeley, was used to test the detection and alternative control strategy (the critical intersection being San Pablo and University with G/C = 0.35).
- Emulation-in-the-loop-simulation tests performed in AIMSUN.
- 20 tests were ran for each penetration rate level (0.05, 0.1, 0.15, 0.2, 0.25, 0.5, and 0.75).
- Each run includes a 10 min warm up period and 1 hour simulation with a variable demand profile (charging until oversaturation and discharging of the arterial).



Queue Spillback Detection & Control

Spillback Control Results:

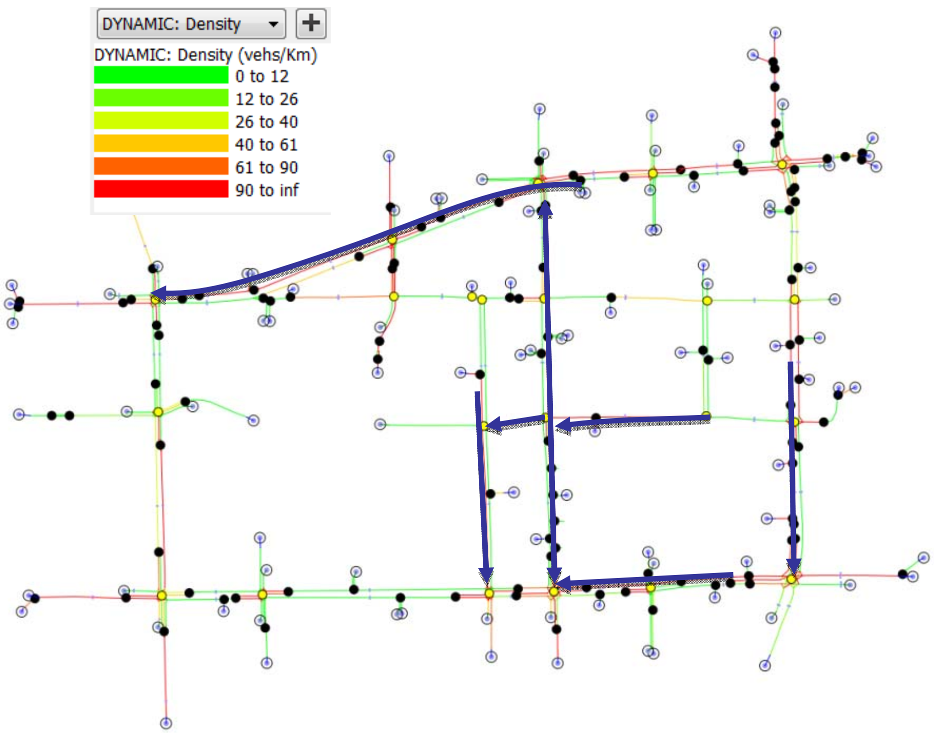
Results at the critical link

p	Average Delay (s/veh)	Maximum Queue Length (veh)	Average number of stops
Baseline	40.12	14.42	1.00
10%	37.83	13.80	0.92
20%	38.16	14.23	0.92
50%	36.90	14.07	0.88
75%	34.99	13.09	0.83

Results at the arterial

p	Travel time (s/veh)	Average number of stops
Baseline	112.95	1.64
10%	114.08	1.61
20%	115.70	1.64
50%	115.76	1.63
75%	112.43	1.54

Congested Grid Networks
Post Oak Network, Houston TX



MOEs	Units	Original
Total Delay Time	hr	2079.6
Average Density	veh/km	58.8
Average Speed	km/hr	7.6
Stop Time	hr	1944.7
Total Distance Travelled	km	20184.9
Total Travel Time	hr	2493.2
Vehicles Out	vehs	19120.8
Vehicles Waiting Out	vehs	4758.6
Time of spillback detection	%	81%

Queue spillbacks detected

Intense commercial and entertainment activities, major attraction in Houston Metropolitan Area.

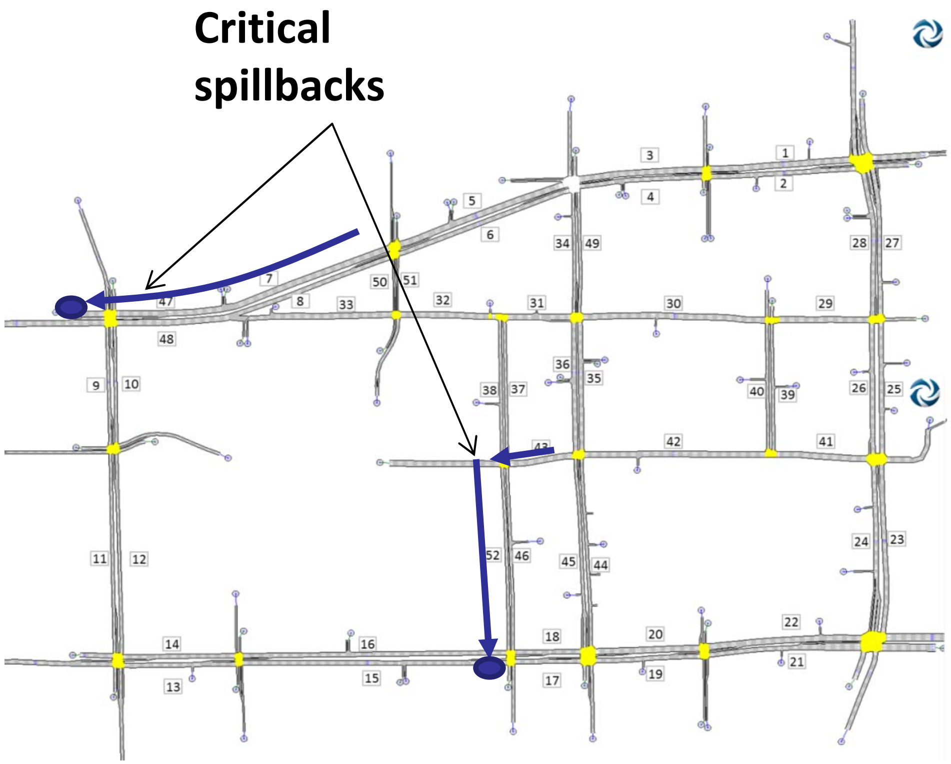
One of the most congested areas in Houston (average speeds of 7.6 mph– free flow speed 50 mph)

The period analyzed is the PM peak period

Arrows shown represent the extension of queue spillback detected in the model.

Post-Oak Existing Conditions

- **Fixed time signal control**
- **150 second cycle**
- **Arrows show the formation of the first spillbacks are showed in the network. These are defined as critical spillbacks**



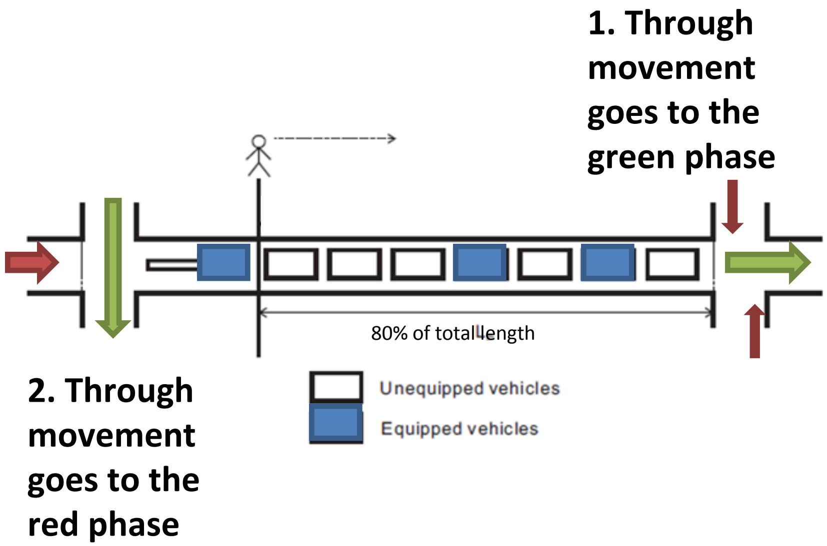
***Tudela, A., J. Argote and A. Skabardonis, “*Queue Spillback Detection and Signal Control Strategies based on Connected Vehicle Technology in a Congested Network,” paper 14-5565, 93rd TRB Annual Meeting, 2014.**

Spillback Detection & Control

A threshold of 80% was determined. If a CV was detected in this area with a velocity lower than 5 km/hr, spillback was considered detected.

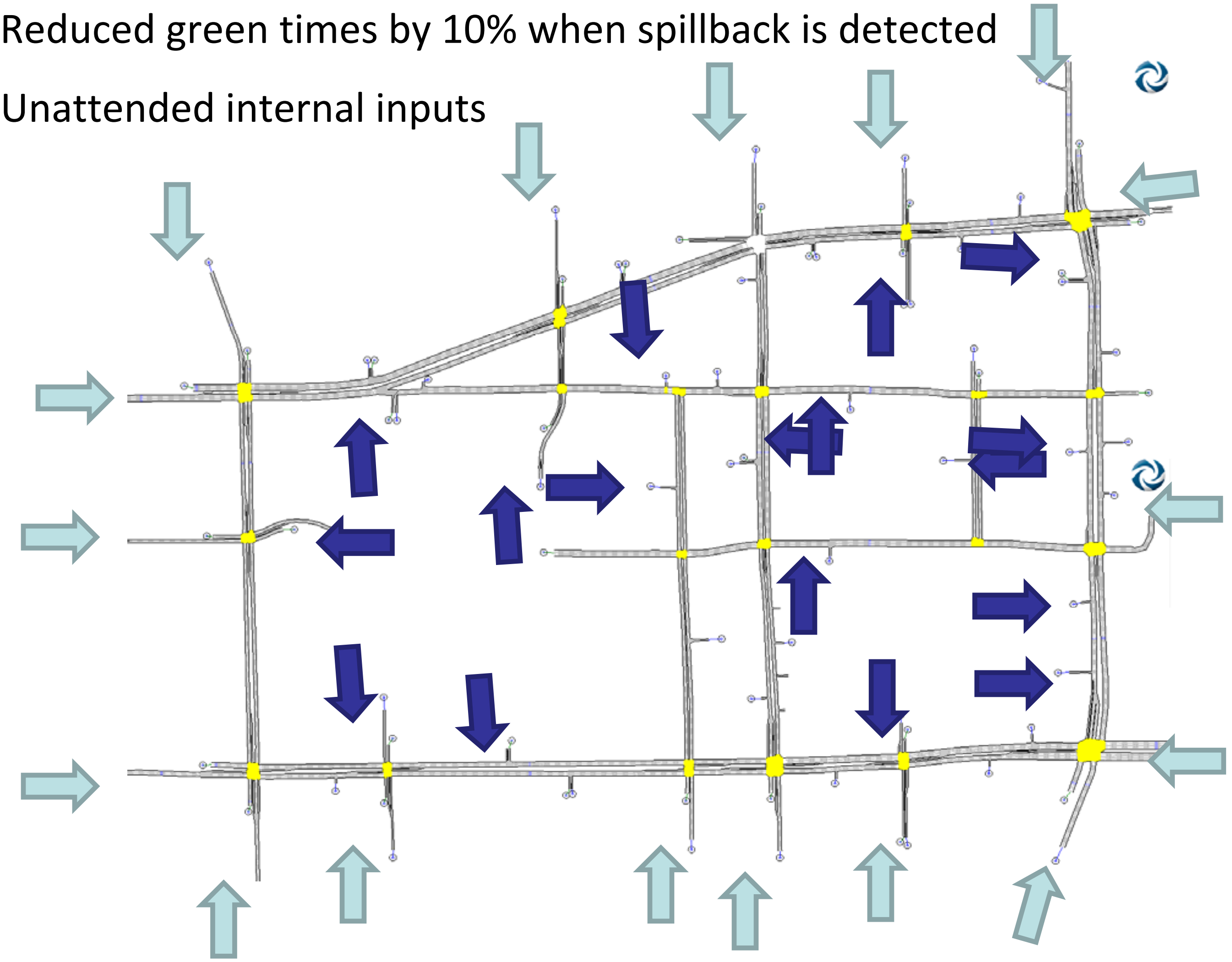
Once spillback is detected, the following mitigation control strategies are activated:

- **Perimeter control:** reduce the green times in the entrances of the network
- **Phase service change**: downstream intersection turns directly to green (to allow the through movement). The upstream intersection, the phase changes directly to red



Perimeter Control Strategy

- Reduced green times by 10% when spillback is detected
- Unattended internal inputs

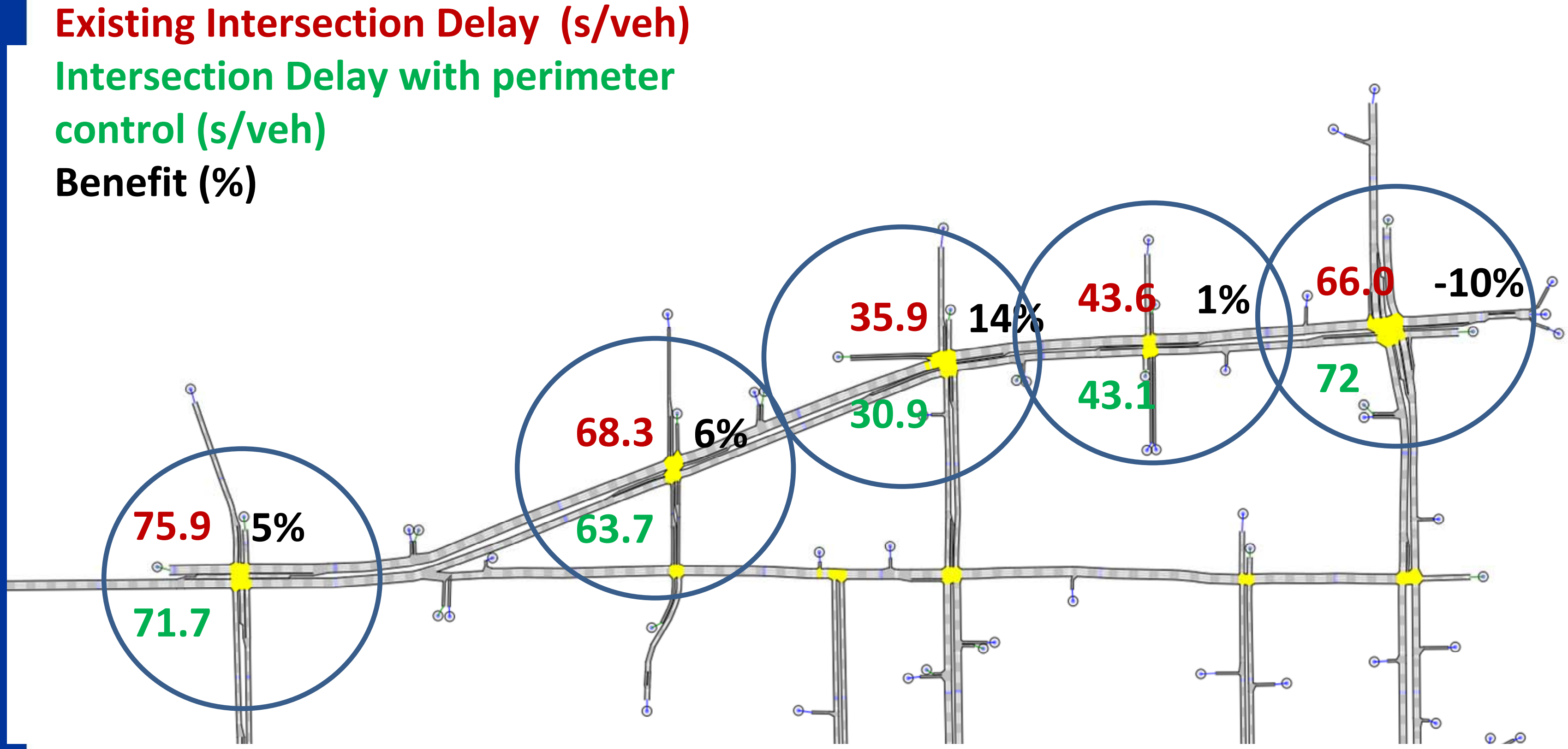


Results of Perimeter Control

MOEs	Units	Current strategy	Current strategy + spillback detection	% benefit
Total Delay Time	hr	2079.6	2089.0	-0.5%
Average Density	veh/km	58.8	55.2	6.2%
Average Speed	km/hr	7.6	7.8	2.9%
Stop Time	hr	1944.7	1951.9	-0.4%
Total Distance Travelled	km	20184.9	21050.5	4.1%
Total Travel Time	hr	2493.2	2513.5	0.8%
Vehicles Out	vehs	19120.8	19526.4	2.1%
Vehicles Waiting Out	vehs	4758.6	5077.2	-6.7%
Time of spillback detection	%	81%	85%	-4.7%

- **Once a spillback is detected, green time on main entrances to the network are reduced by 10%**
- **Effectiveness of strategy is affected by the internal flows in the network (peak PM period).**

Arterial Analysis –Perimeter Control

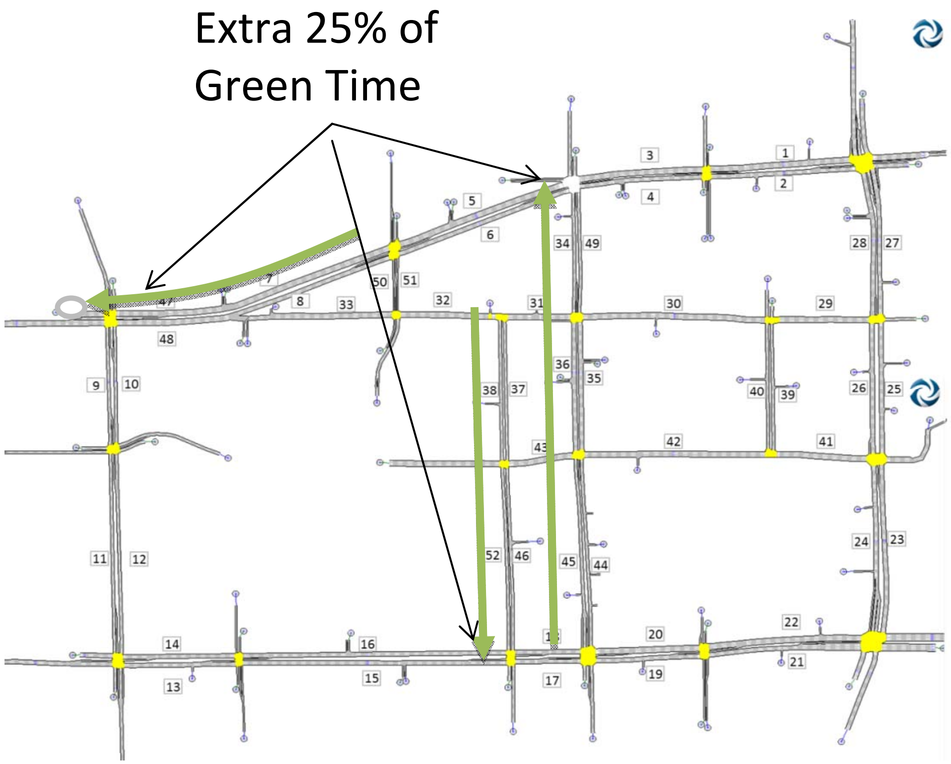


Improvements on intersection delay on arterial without internal flows

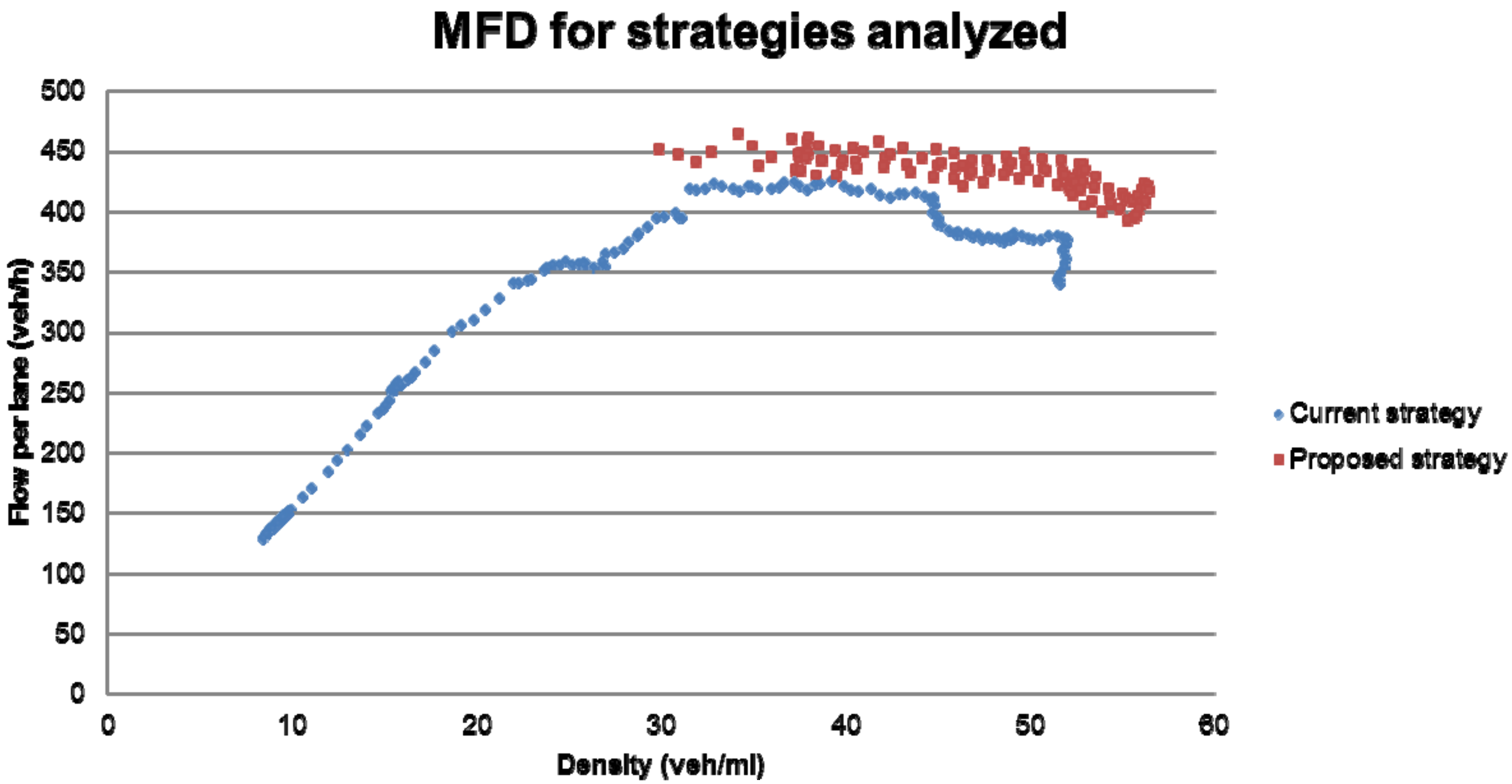
Alternative Strategy

- **Provide extra green time (to improve capacity) at the approaches with critical spillbacks.**

- **Reduce the system cycle time to 120 seconds.**



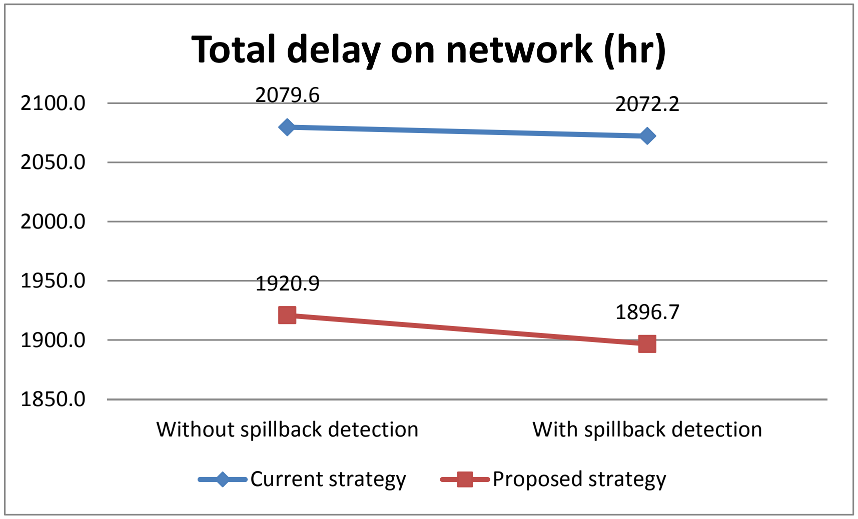
Discharge Flows: MFD Comparison

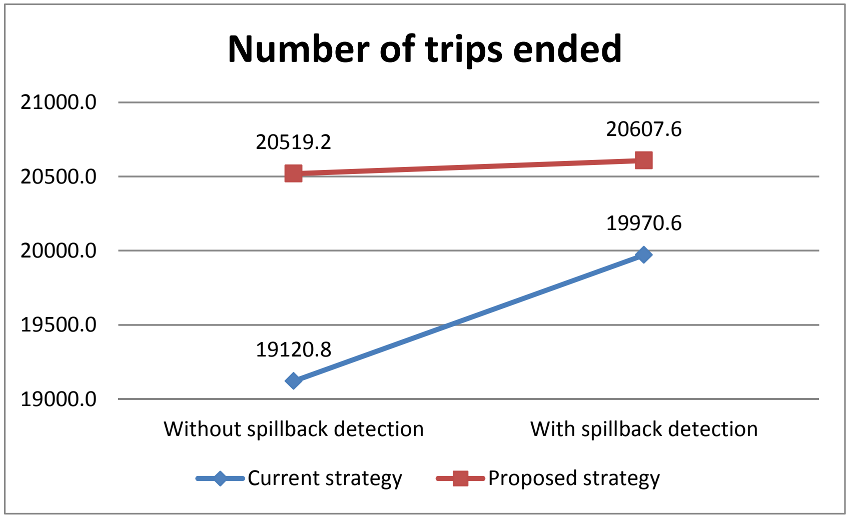


- **The proposed strategy allows a higher flow than the current strategy**

Results (20% penetration rate)

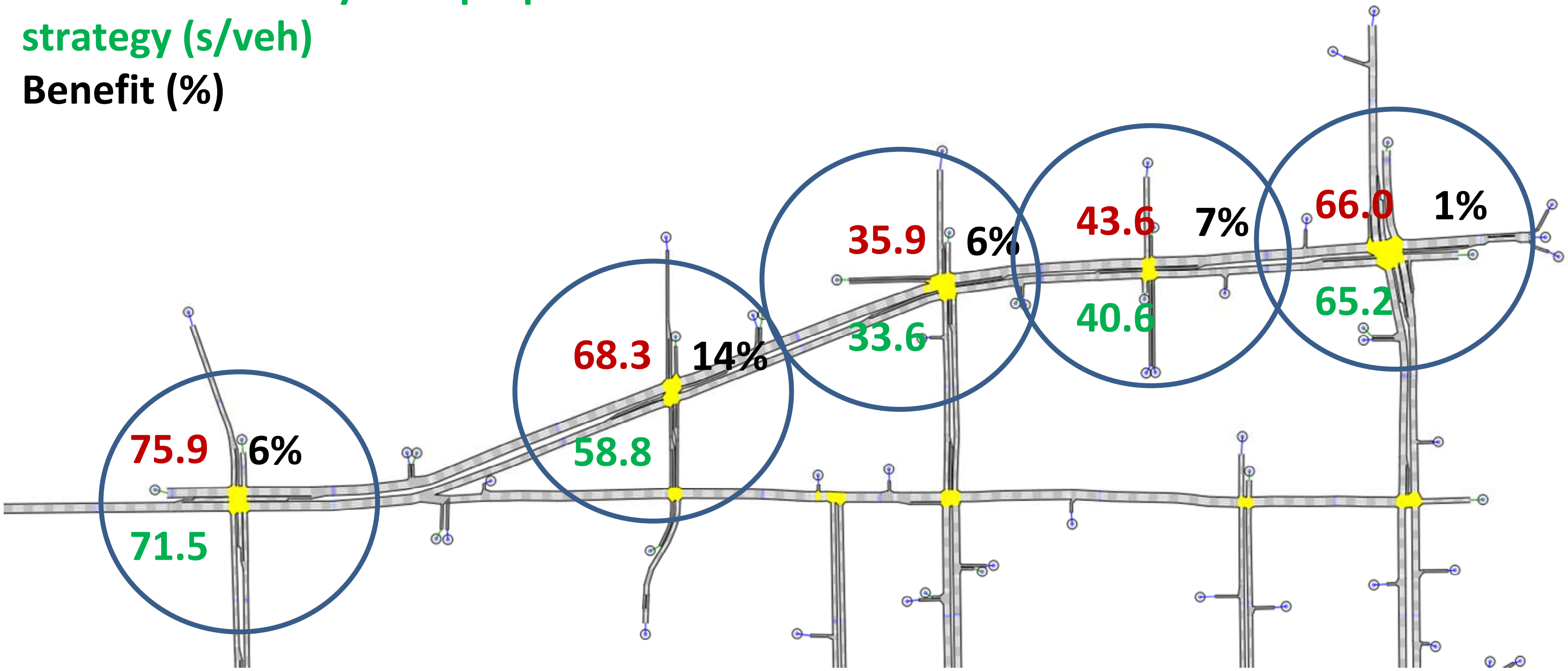
MOEs	Units	Current strategy	Current strategy + spillback detection	% benefit	Proposed strategy	Proposed strategy + spillback detection	% benefit
Total Delay Time	hr	2079.6	2072.2	0.4%	1920.9	1896.7	1.3%
Average Density	veh/km	58.8	54.5	7.4%	56.0	53.4	4.6%
Average Speed	km/hr	7.6	8.1	5.4%	8.8	8.8	0.3%
Stop Time	hr	1944.7	1926.6	0.9%	1774.9	1752.9	1.2%
Total Distance Travelled	km	20184.9	21624.3	6.7%	22468.1	22275.0	-0.9%
Total Travel Time	hr	2493.2	2533.6	1.6%	2441.2	2407.8	-1.4%
Vehicles Out	vehs	19120.8	19970.6	4.3%	20519.2	20607.6	0.4%
Vehicles Waiting Out	vehs	4758.6	4669.0	1.9%	3808.2	3563.0	6.4%
Time of spillback detection	%	81%	79%	1.6%	85%	75%	9.7%





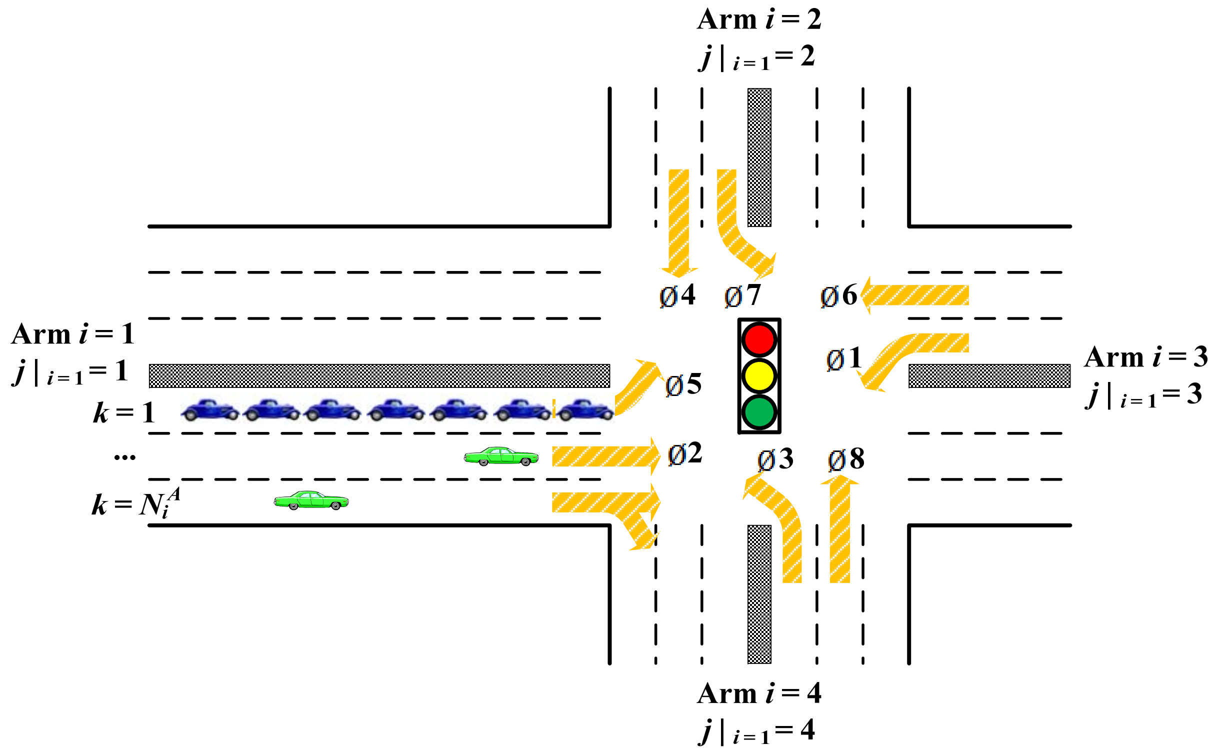
Impacts on an Arterial – Alternative Strategy

Existing Intersection Delay (s/veh)
Intersection Delay with proposed strategy (s/veh)
Benefit (%)



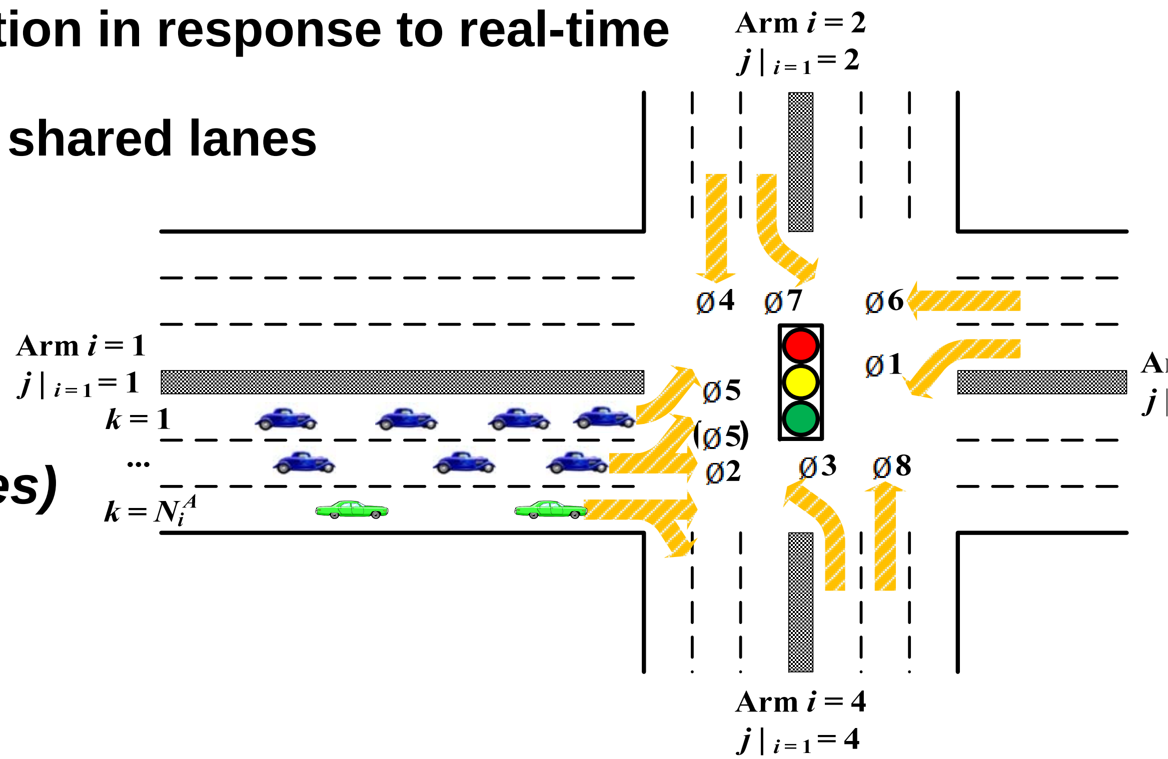
Dynamic Lane Allocation/Grouping (DLG) at Signalized Intersections

- **Most signal control strategies assume fixed lane utilization on intersection approaches**
- **Spatial variations in traffic demand degrade intersection performance**
- **Solutions for predictive situations (TOD lane assignments)**



Dynamic Lane Allocation/Grouping (DLG) (1)

- Changing lane allocation in response to real-time movement demands
- Allows exclusive and shared lanes

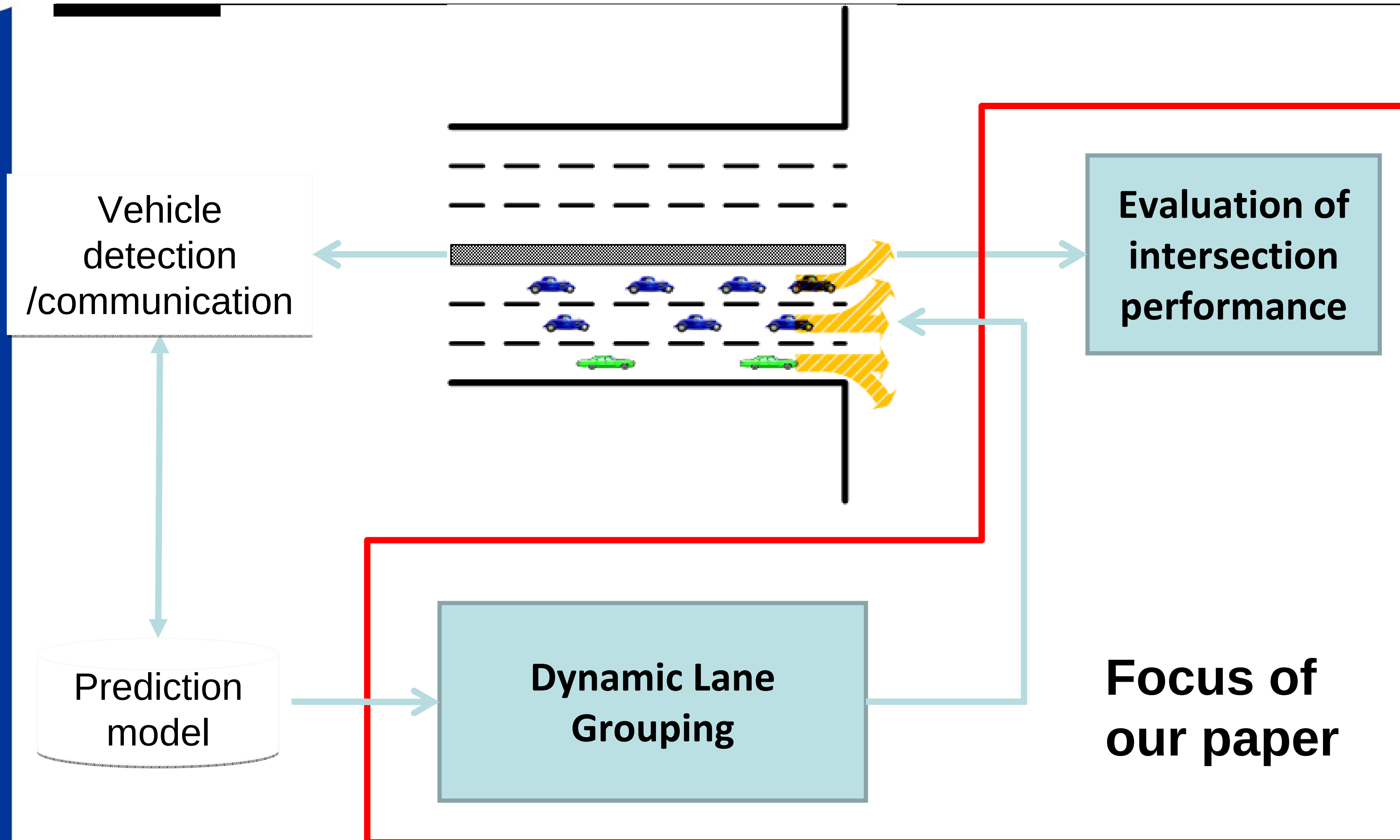


- Requirements
  - O-D information

  (*Connected vehicles*)

Zhang L., and G. Wu "Dynamic Lane Grouping at Isolated Intersections: Problem Formulation and Performance Analysis," Transportation Research Record No 2311, 2012, pp.

Dynamic Lane Allocation/Grouping (DLG) (2)



Assumed demand is known and can be predicted

DLG Problem Formulation

Given real-time O-D demands at a signalized intersection, how to dynamically determine the lane assignment to improve performance?

- **Approach:**
  - **For each intersection leg find the optimum lane grouping**

    Minimize the max lane flow ratio y

    (*y = flow/saturation flow*)

    St:

    Allowable movements (safety constraints)

  - ***Sub-problem:***

    Determine the steady state traffic flow among lanes within each lane group also

Evaluation of DLG

Numerical Analysis

- **Scenarios:**
- **Keep total demand fixed**
- **Increase total demand (oversaturated conditions)**
  - **Demand ratio among movements**
  - **# Lanes per approach**
  - **Fixed timing vs. "adaptive" timing (EQUISAT or HCM2000 QEM)**
- **MOEs** ***max lane flow ratio,, average delay sec/veh (per HCM)***

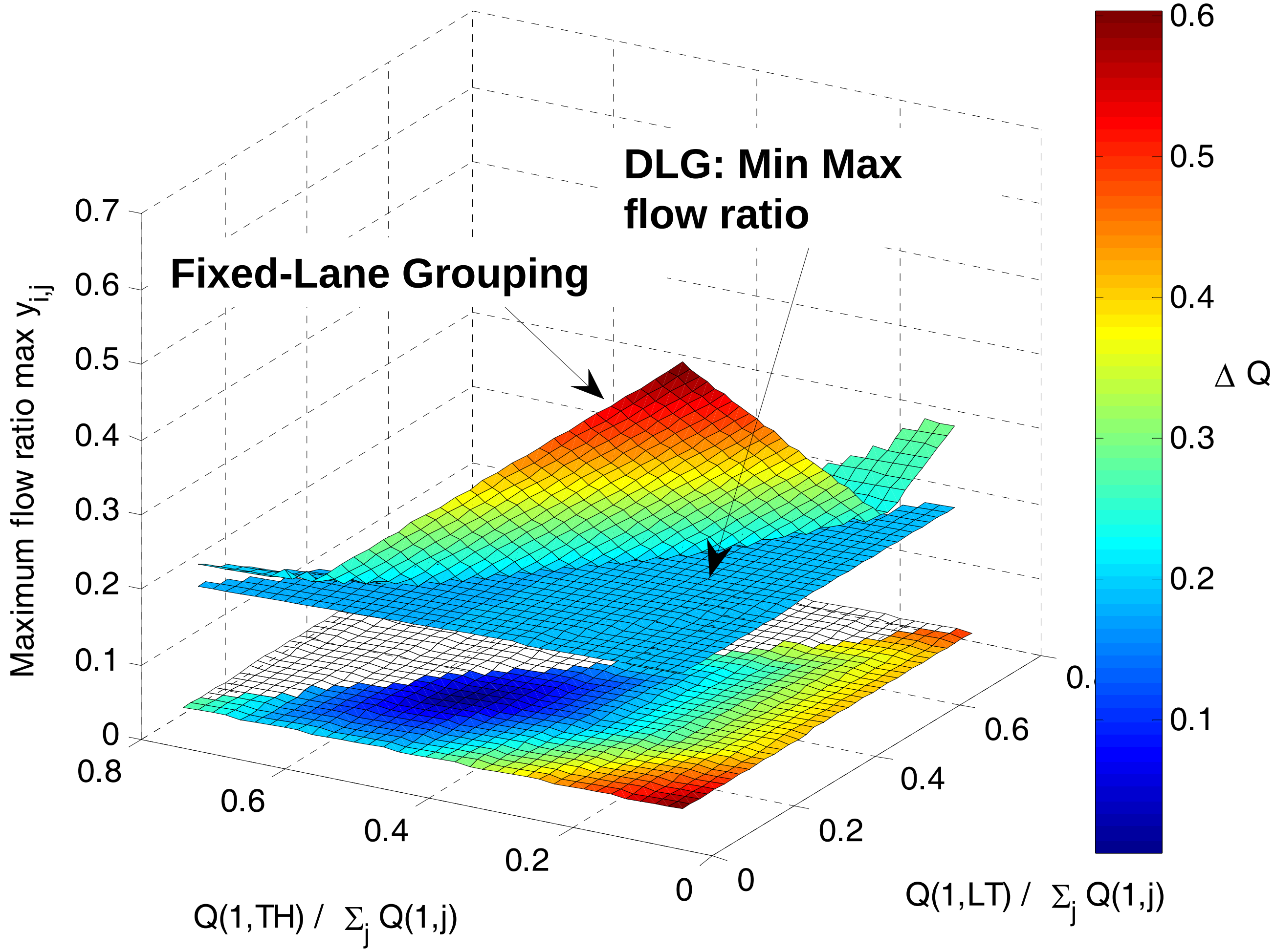
Simulation

- **PARAMICS microsimulation model**
- **MOEs: Delay, Stops, Fuel, Emissions**

- **Wu G., K. Boriboonsomsin, L. Zhang, M. Barth, "Simulation-Based Benefit Evaluation of Dynamic Lane Grouping Strategies at Isolated Intersections," Proceedings 15th IEEE ITSC Conference, Anchorage, AK, September 2012.**

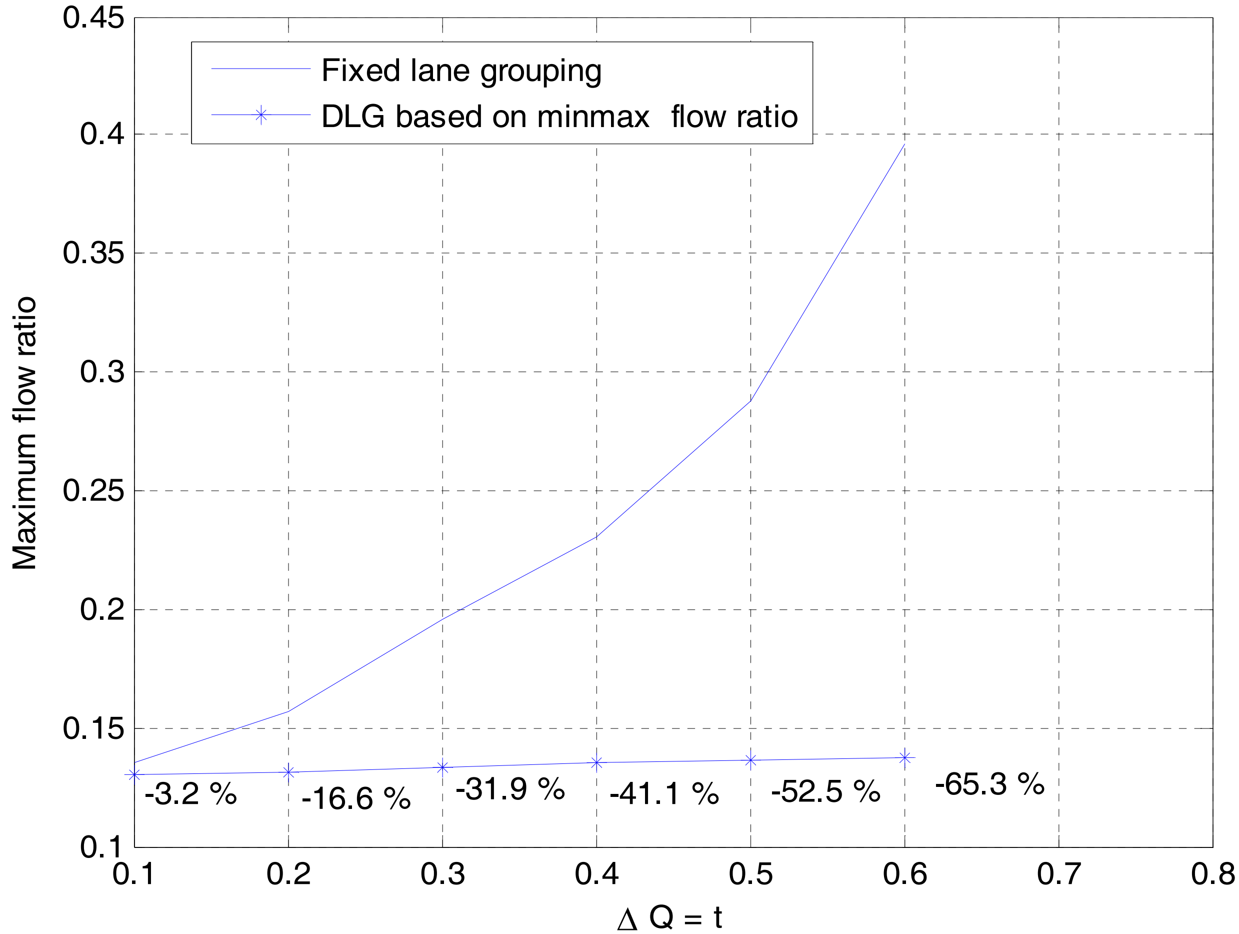
Results: Max Lane Flow Ratio/Lane (1)

Under DLG, max lane flow ratio always keeps as low as 0.2



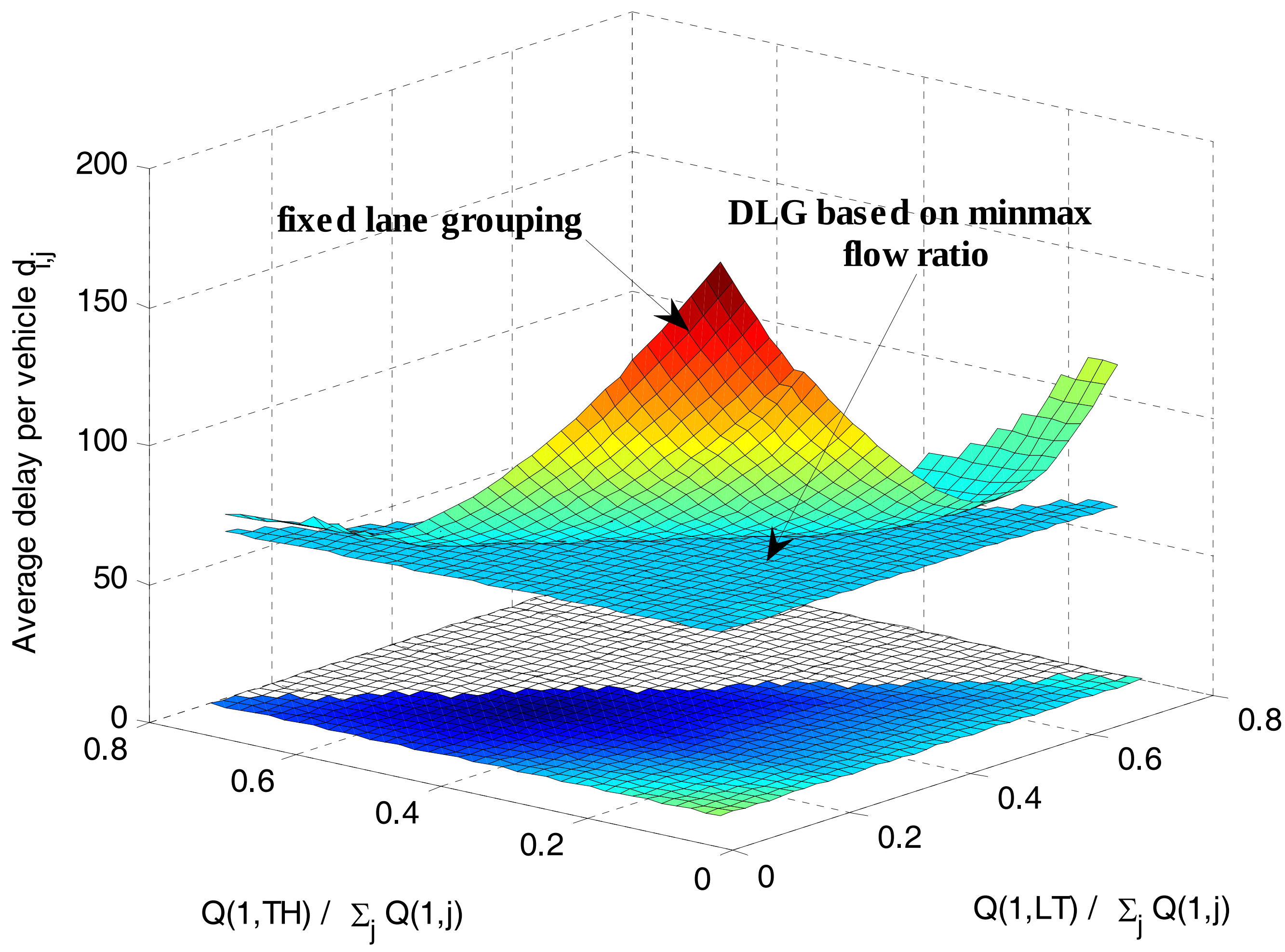
Results: Max Lane Flow Ratio/Lane (2)

Higher DLG benefit in terms of max lane flow ratio when demand deviation increases

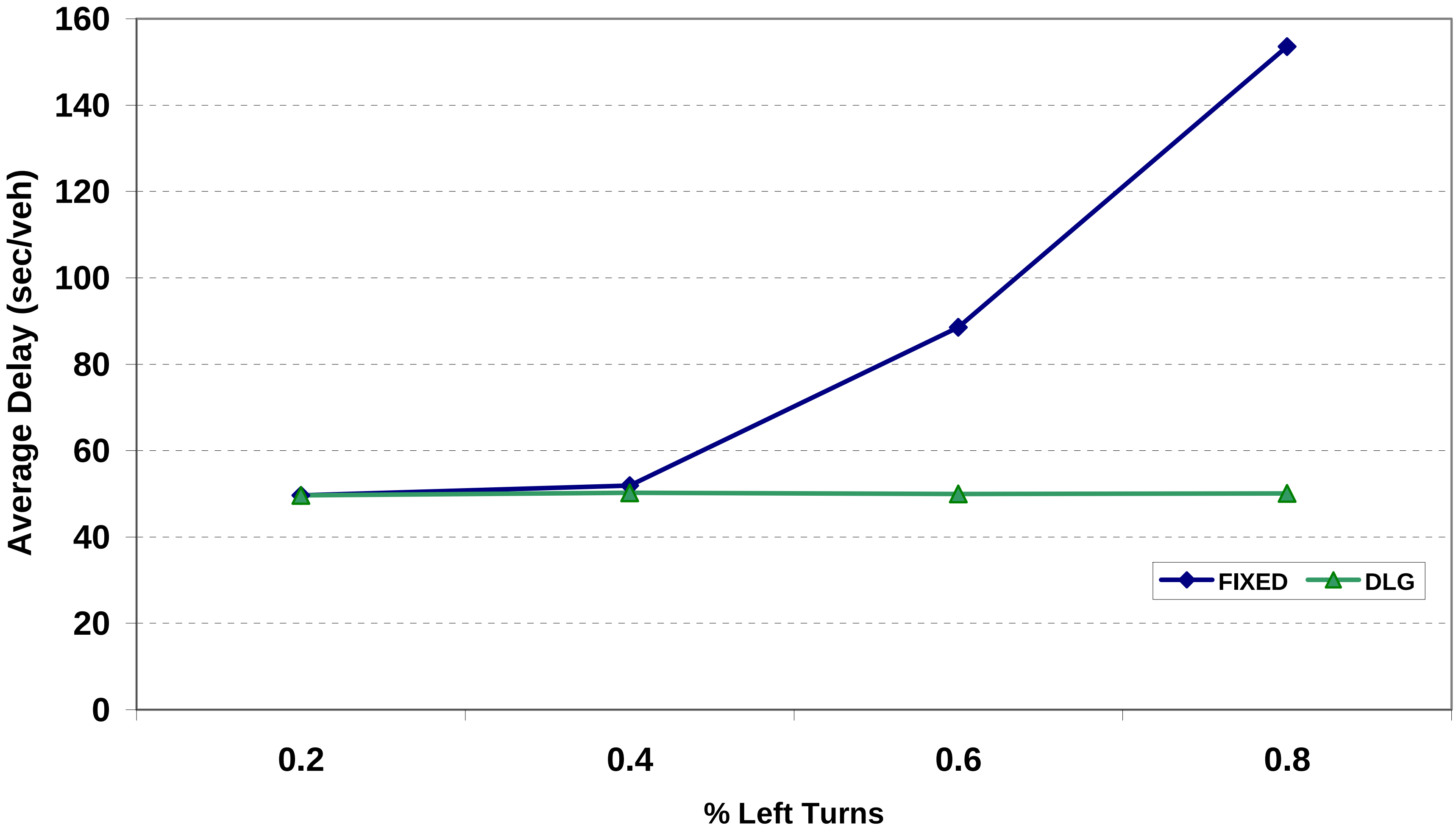


Performance Analysis: Average Delay

Under DLG scenario, average delay remains almost constant



Simulation Experiments



Discussion

- **Findings:**
  - **Dynamic lane allocation appears promising to address spatial demand variation**
  - **Improves efficiency and robustness**
  - **Higher benefits for multilane approaches**

- **Challenges:**
  - **Need O-D demands**

    Existing and emerging technologies
  - **Safety issues and potential capacity reduction:**

    Induced lane changes

    Lane transition in and out

    Driver expectancy warning

- **Opportunities:**
  - **Integration with adaptive signal control strategies**

Appendix I: Minimize max flow ratio

- Minimizing maximum flow ratio for each arm

Problem:

Given demand matrix $\boldsymbol{Q}(n)$, to find the optimum lane grouping $\boldsymbol{\delta} = \left(\delta_{i,j,k}\right)$ by the objective function

$$\min \max y_i\,(n), \tag{1}$$

subject to movement constraints.

Sub-problem: estimate steady state traffic flow by

Given $\boldsymbol{\delta} = \left(\delta_{i,j,k}\right)$, $\min(\max_k y_{i.k})$

such that $y_{i,k_1} = y_{i,k_2}$, for any $1 \le k_1, k_2 \le N_i^A$ that satisfies following conditions (2)

$$\delta(i,j,k_1) = \delta(i,j,k_2) \quad \forall j \text{ and } \textstyle\sum_j \delta(i,j,k_1) = \sum_j \delta(i,j,k_2) = 1 \tag{3}$$

(i.e., lane k_1 and lane k_2 are both exclusive lanes for the same movement)

and $y_{i,k_1} \ge \min_{k_2} y_{i,k_2}$,

$$\forall k_1, k_2 \text{ that satisfies } \sum_j \delta(i,j,k_1) > 1, \sum_j \delta(i,j,k_2) = 1$$

$$\text{and } \forall j, \delta(i,j,k_2) \le \delta(i,j,k_1)\,; \tag{4}$$

(i. e., lane $k1$ is a shared lane and lane $k2$ is any exclusive lane with common moveme along lane $k1$)

$$\sum_j f(i,j,k) = 1, \qquad \text{for any } k = 1, \ldots, N_i^A \tag{5}$$

$$0 \le f(i,j,k) \le \delta(i,j,k), \qquad \text{for any } k = 1, \ldots, N_i^A, j = 1, \ldots, N_T. \tag{6}$$

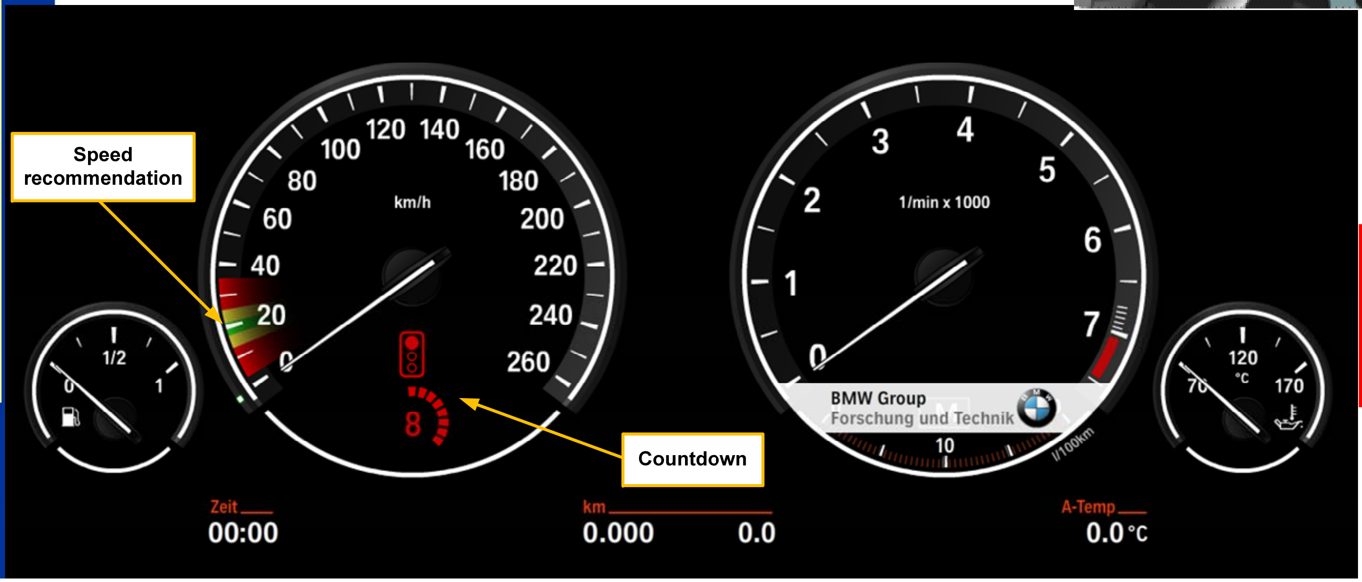
Eco-Driving

Messages

"Here I am"

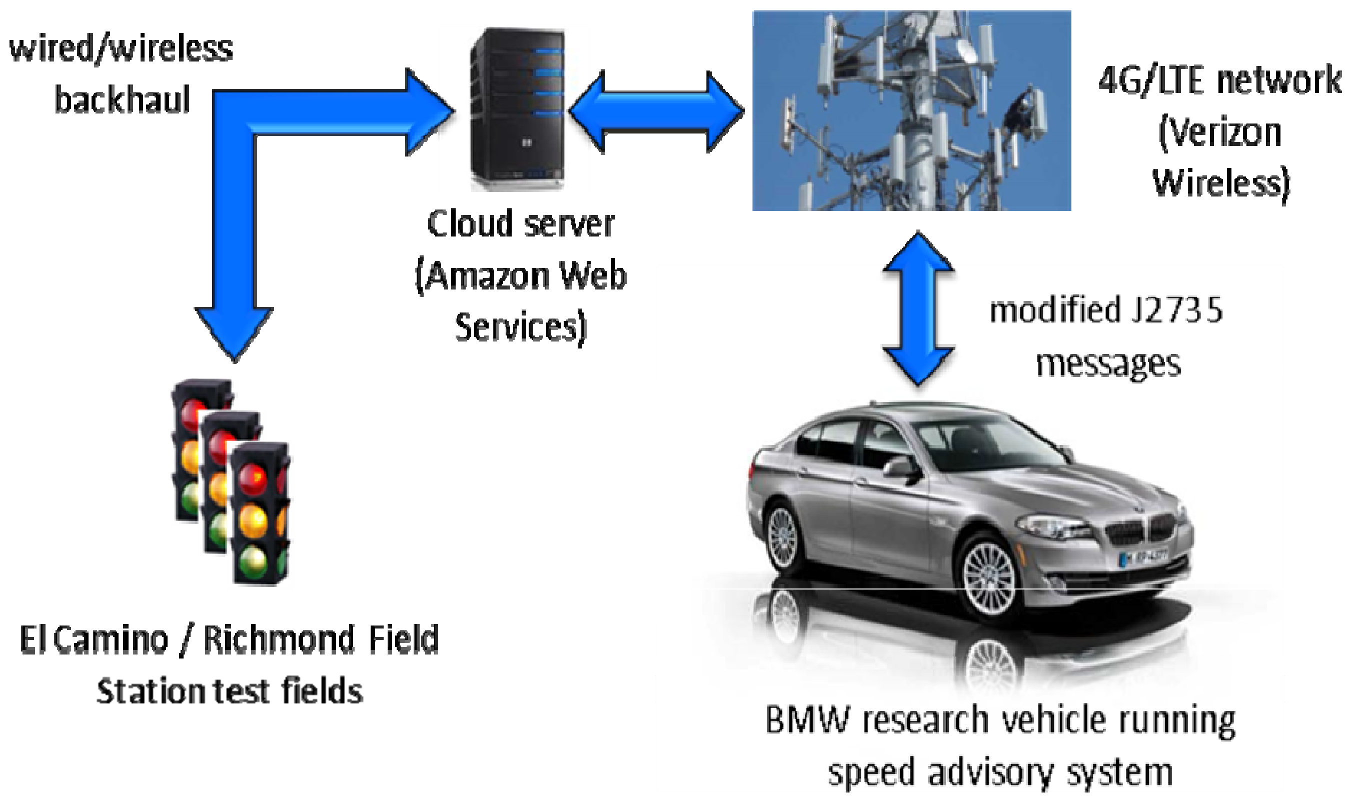
Signal Phase & Timing (SPaT)

Application: Dynamic Speed Advisory (source: UC & BMW)

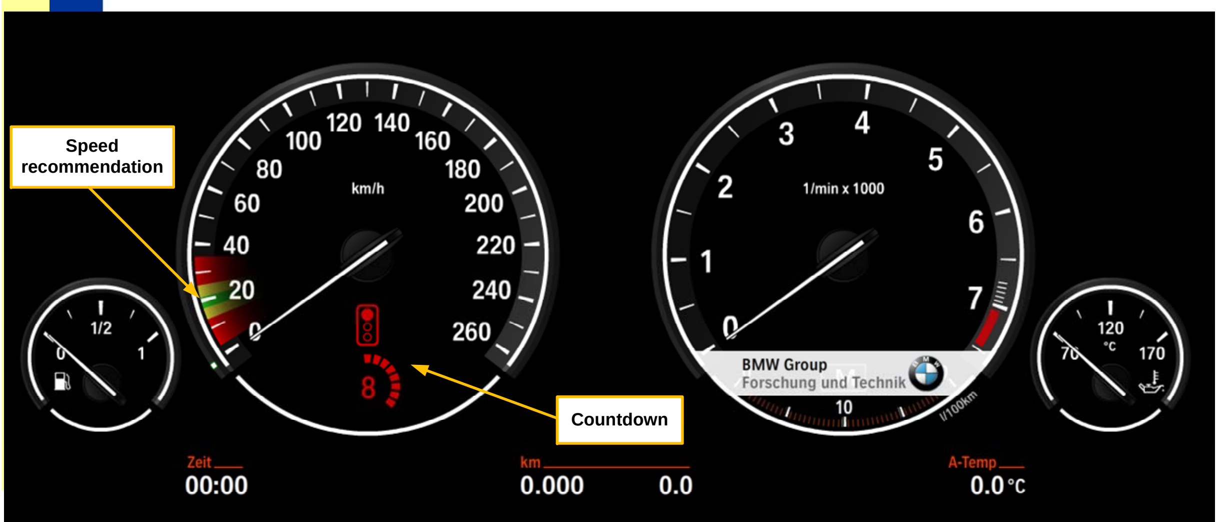


14% Reduction in Fuel Use

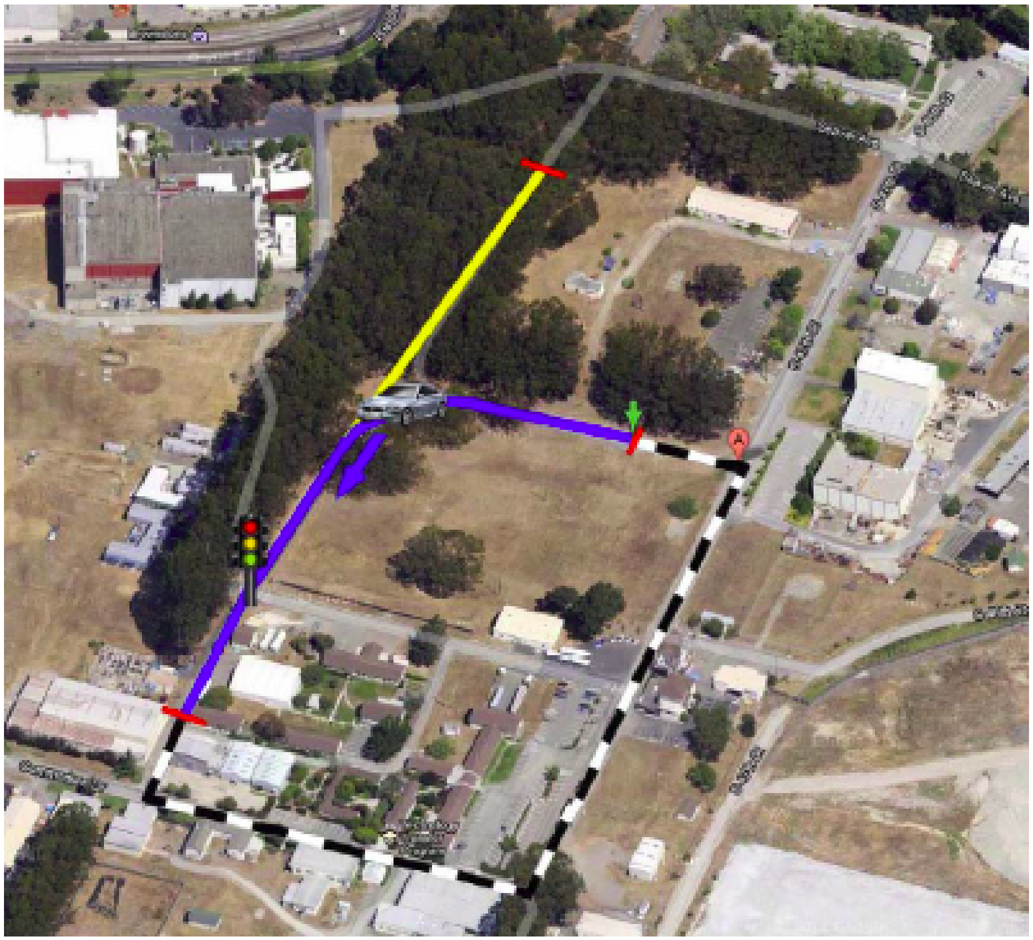
Communication System



BMW Research Vehicle



Test Field Setup



→ due to GPS positioning problems, the yellow leg is unusable

→ data gathering for blue leg only

Length of test section: 320 m (1050 ft)

Speed limit: 25 mph

Default Signal Timing: 60 sec cycle
(30 sec green; 3 sec yellow; 27 sec red)

All data is gathered from the vehicles CAN buses, e.g. consumption from digital motor management.

4G/LTE communication link, 1Hz update frequency.

Scenarios

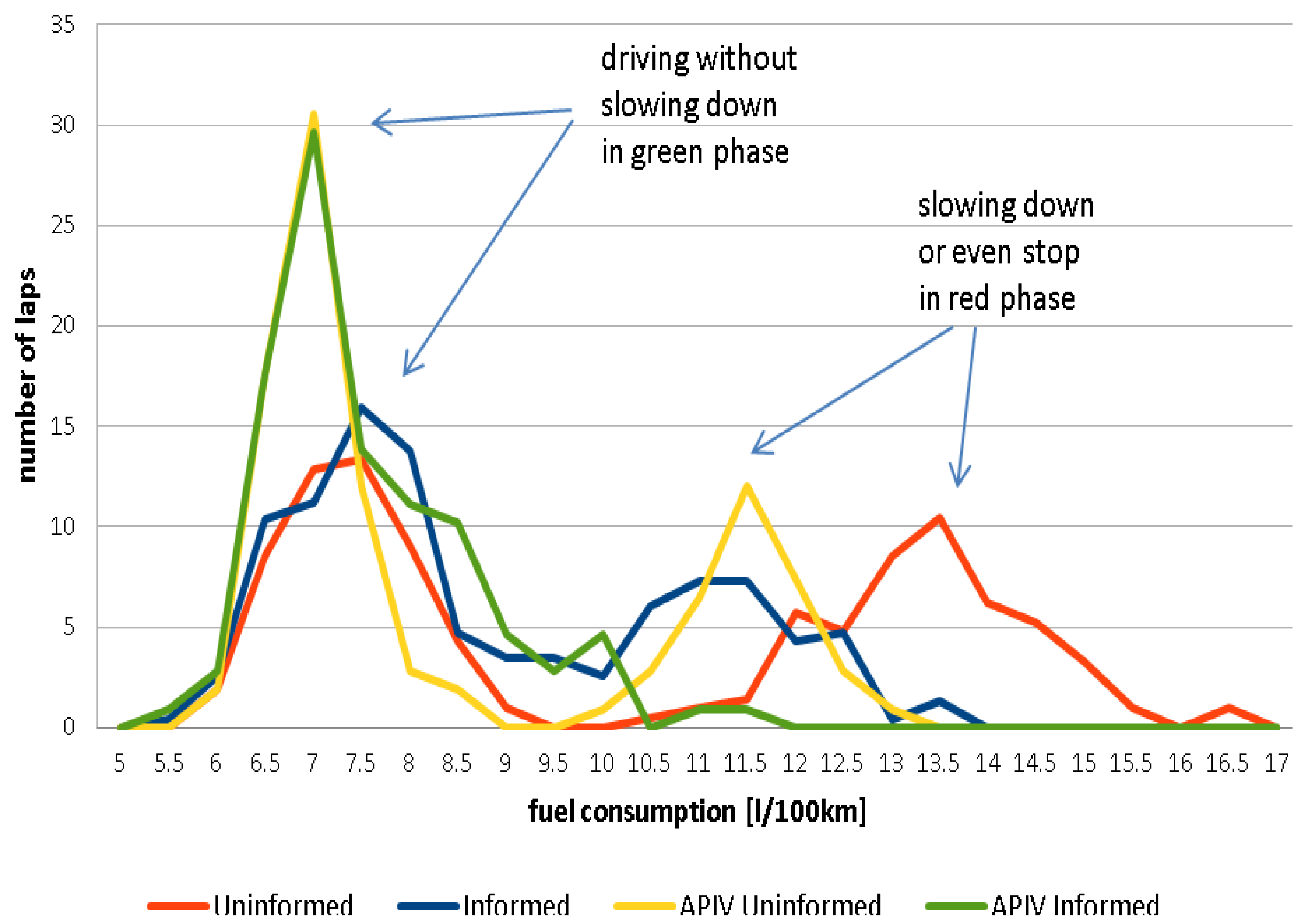
1. Uninformed Driver (Baseline Scenario) — n=270
    - drive without speed recommendation
    - driver behaves economic reasonable

2. Informed Driver — n=292
    - follow speed-recommendation

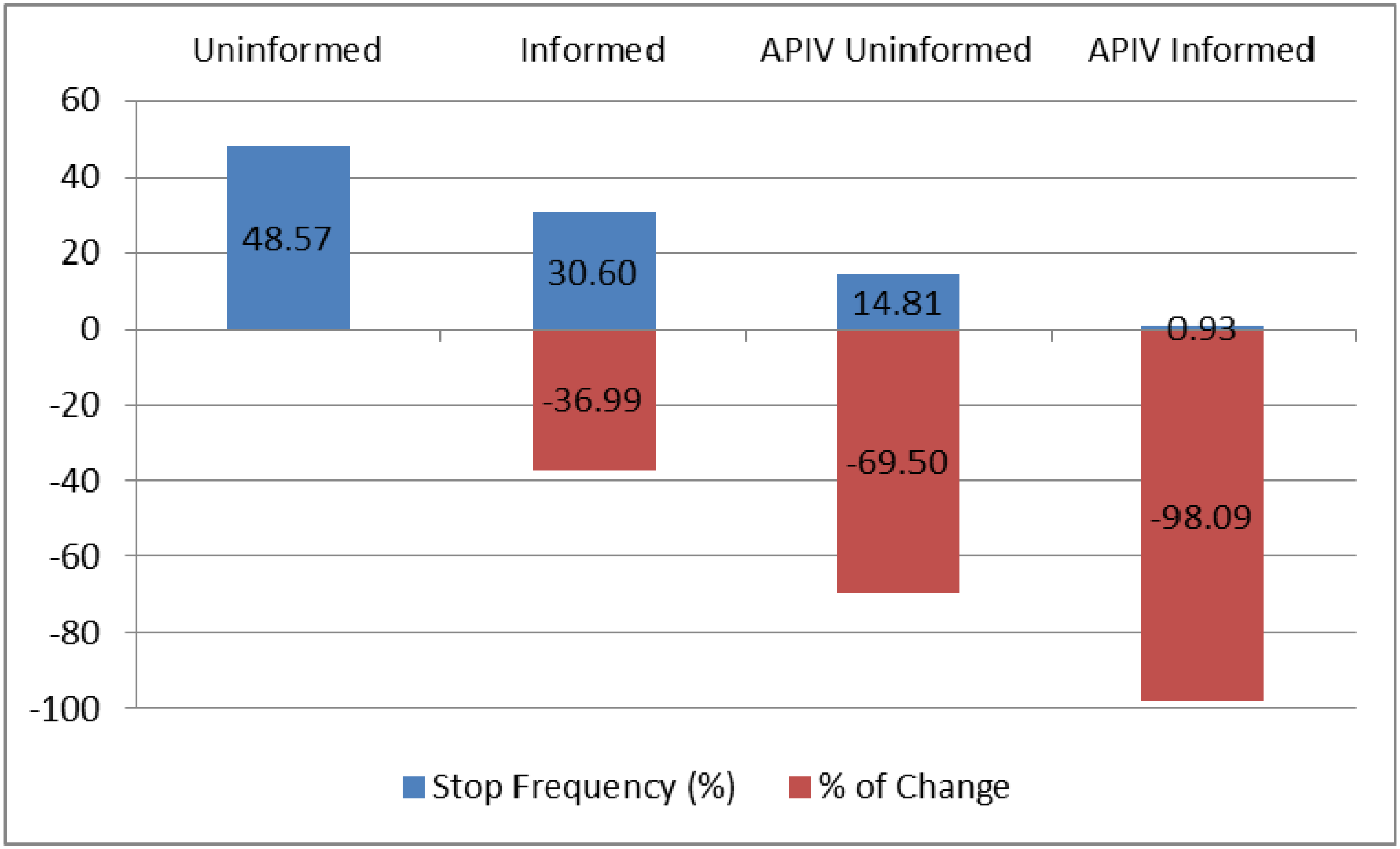
3. APIV (Adaptive Priority for Individual Vehicle) & Uninformed Driver — n=108
    - drive without any speed recommendation
    - intersection adapts timing with individual vehicle priority

4. APIV & Informed Driver — n=108
    - drive with speed-recommendation
    - intersection adapts timing with individual vehicle priority

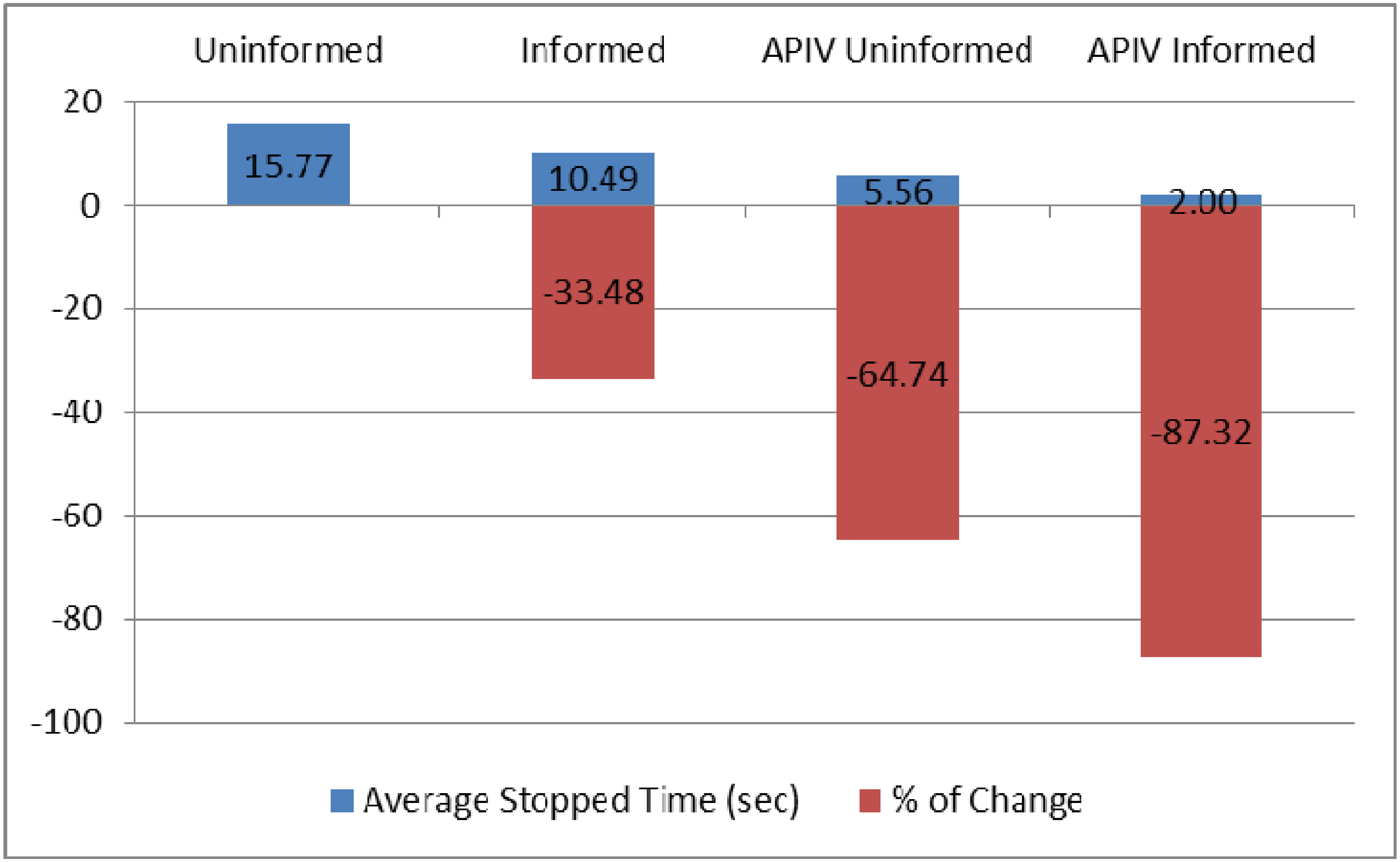
RFS Testing: Test Results (3)



RFS Testing: Test Results (3)

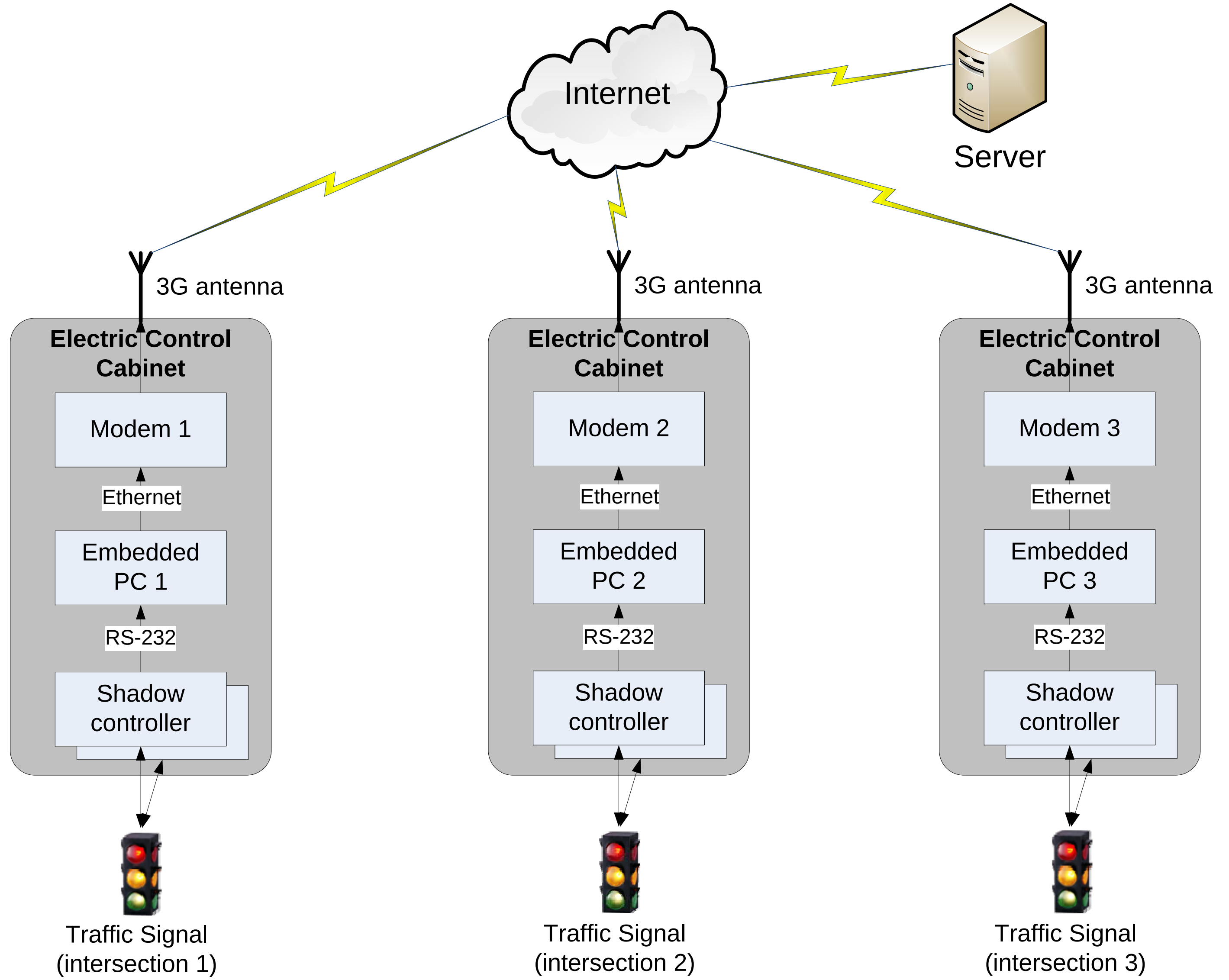


RFS Testing: Test Results (4)



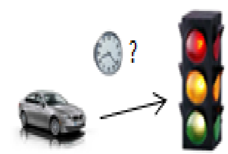
Field Test: El Camino Real

El Camino Real Setup



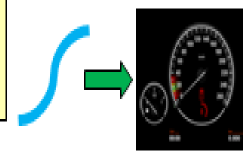
Algorithm Overview (1)

1. Select best arrival time
   or
   decide to stop at intersection

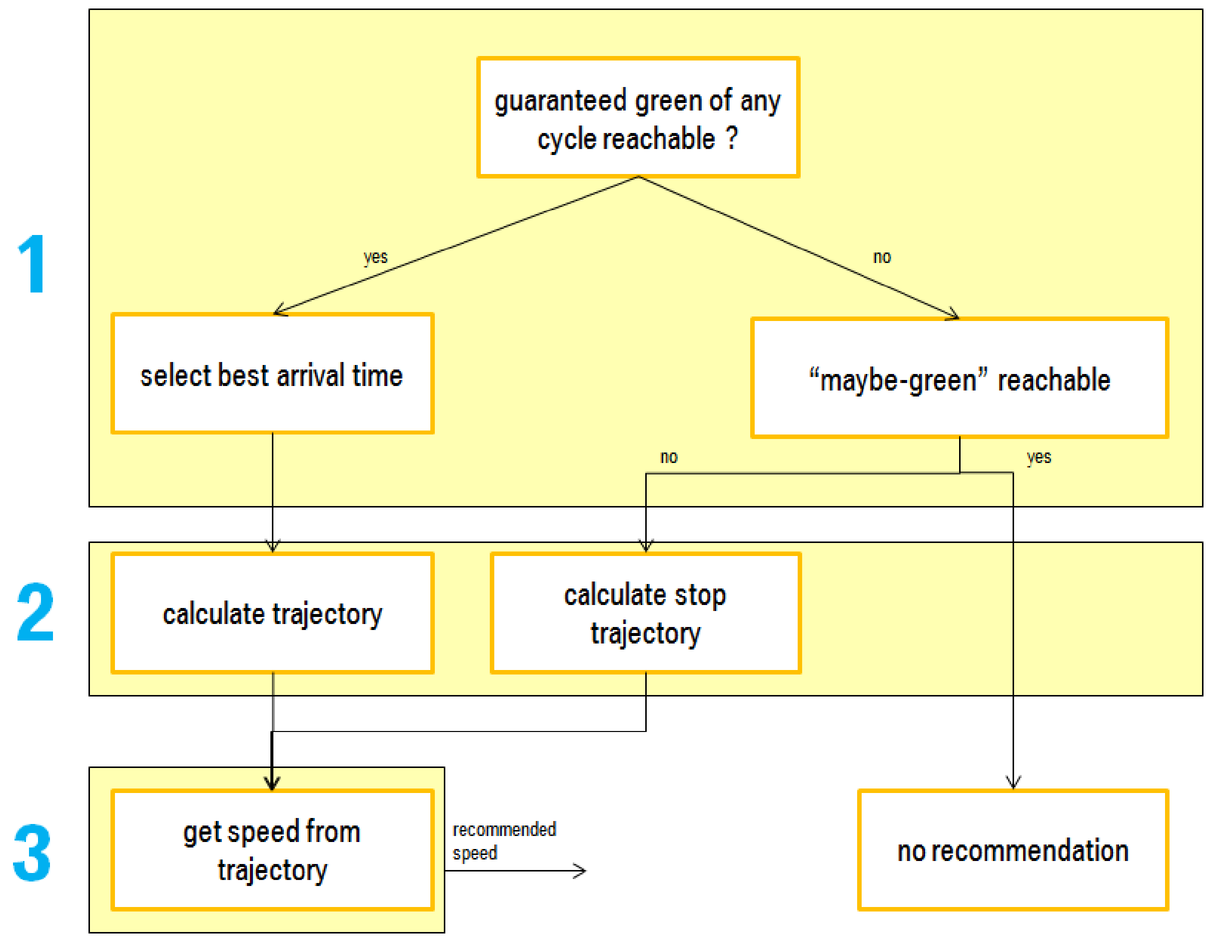


2. Calculate speed trajectory

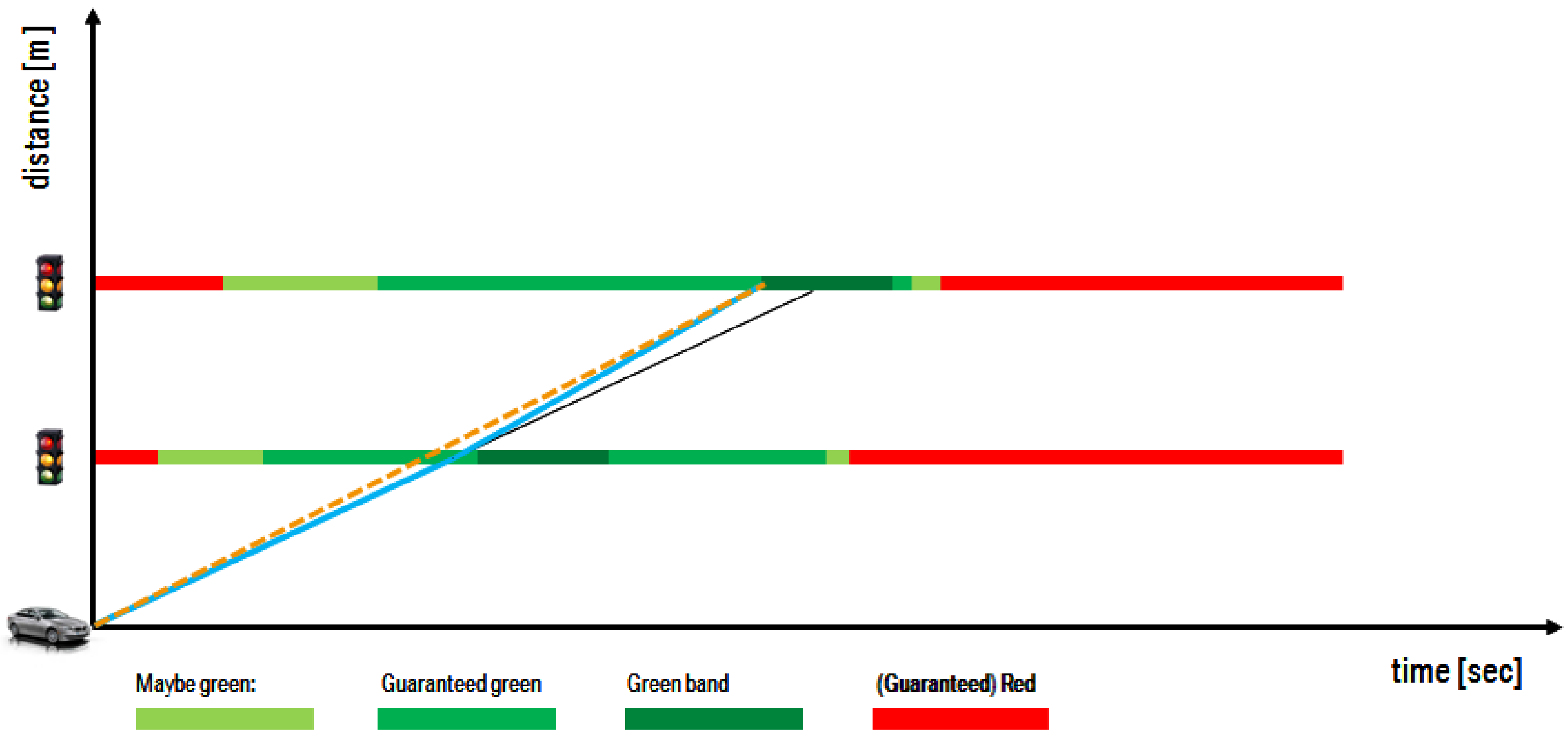
3. Get speed recommendation from trajectory



Algorithm Overview (2)

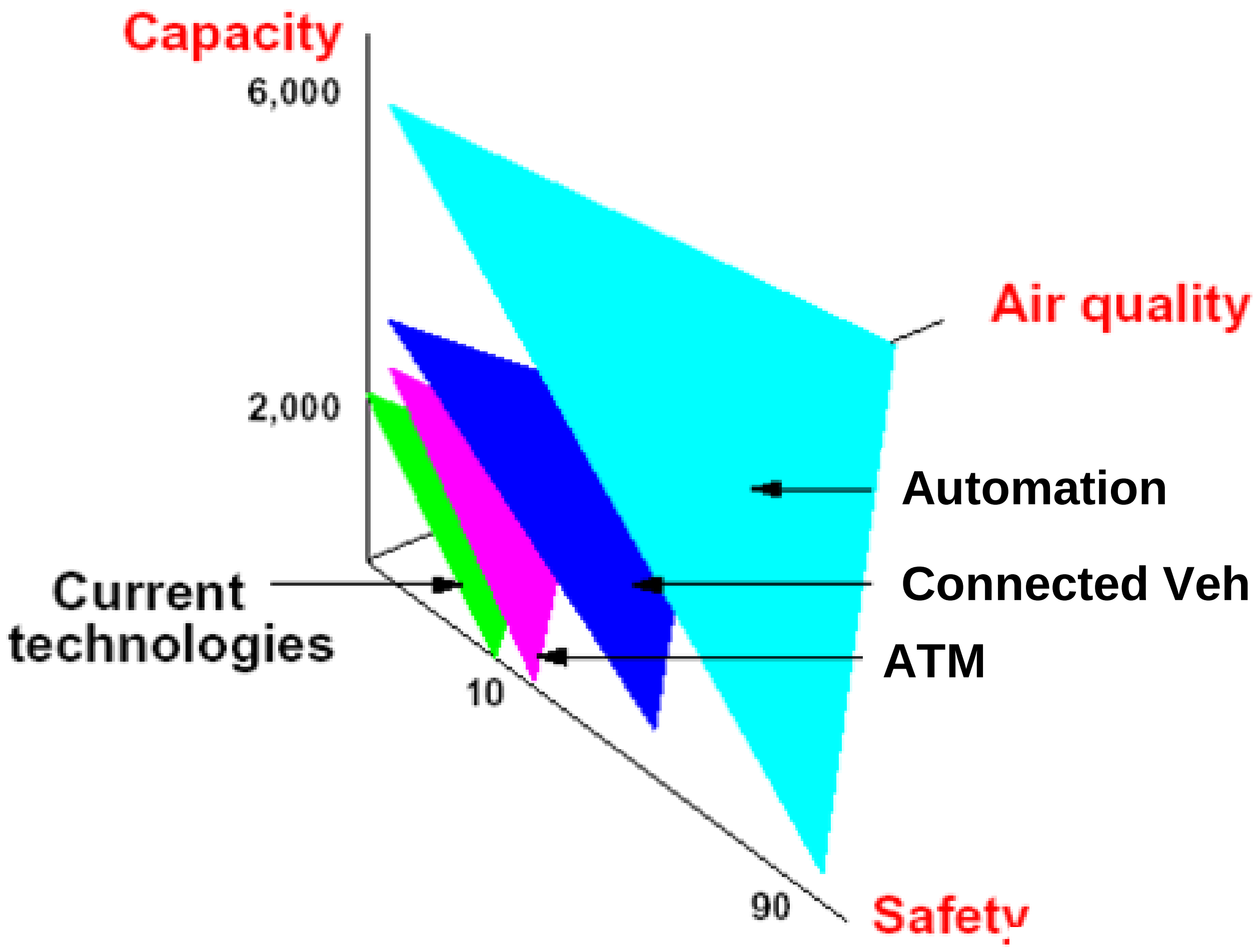


Challenges



Speed recommendation changes at intersection

Looking Ahead



Background: Initial Deployment Plans