Innovative ITS Approaches for Control of Large-Scale Urban Networks

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Introduction

❑ Despite continuous efforts in the field of traffic control, traffic congestion in urban road networks persists and extends around the globe.

❑ Congestion(↘) { road capacity (supply) ↗ ; traffic demand ↘ }

❑ Road capacity (↗) ⇒ traffic management and signal control

❑ **Practicable** and **efficient** signal control under saturated traffic conditions remains a challenge.

❑ *"No current generally available tool is adequate for optimizing [signal] timing in congested conditions"* (FHWA, 2008).

Introduction

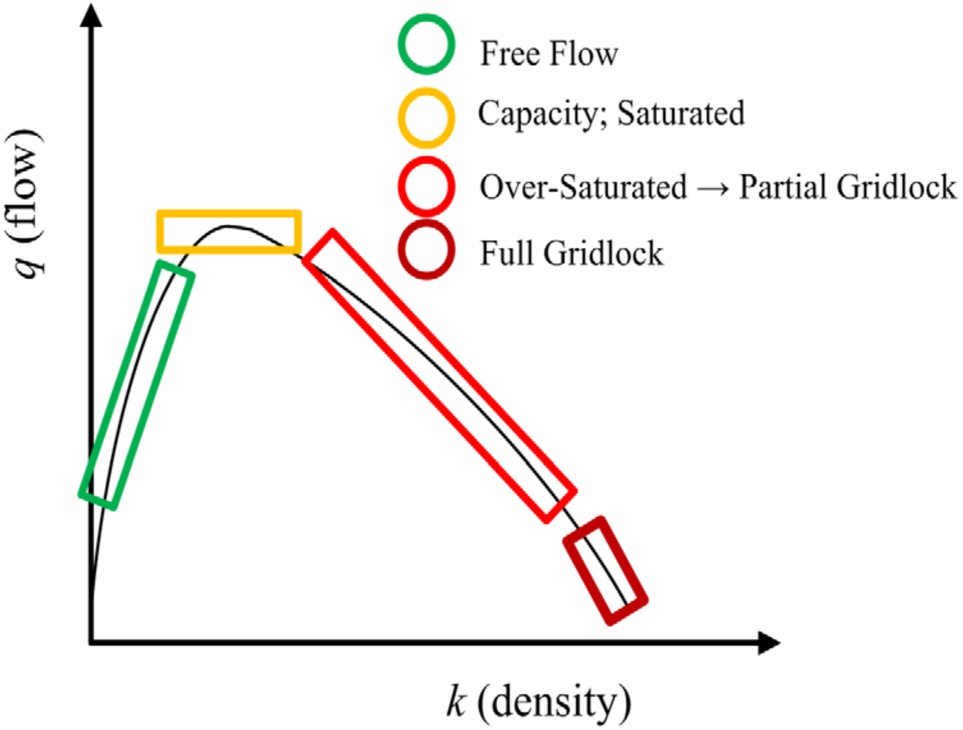
Gating Control??

- Holding traffic back (via prolonged red phases at traffic signals) at the perimeter or upstream of the zone to be protected from **over-saturation**

- **Gating :**
  - Practical tool against **over-saturation**
  - Usually employed in an ad hoc way
  - Based on engineering judgment and manual fine-tuning
  - May lead to insufficient or unnecessarily strong gating actions

Network or Macroscopic Fundamental Diagram (NFD or MFD)

Verification by real data: Geroliminis & Daganzo, 2008



1. Under-saturated; minimize delays!
2. Saturated: maximize capacity!
3. Oversaturated: queue management, gating!
4. Blocked: call the police or walk home!

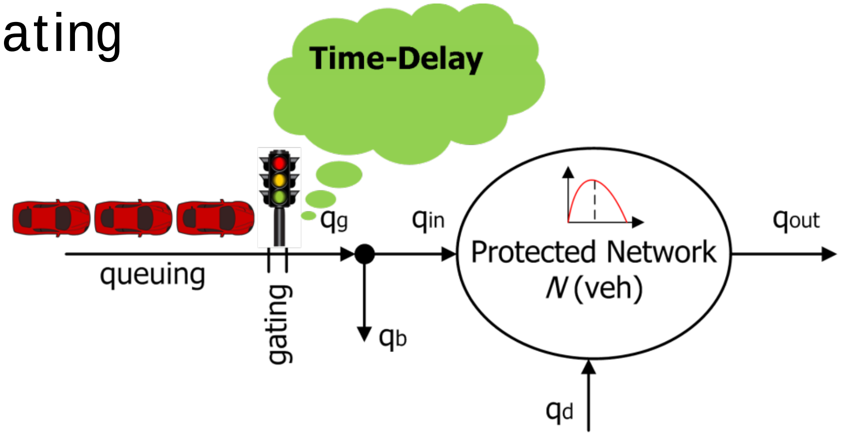

seen on phun.org

Combining Gating With NFD

- Protected Network (PN) via gating

$$q_{in}(t) = \beta q_g(t-\tau)$$

$$\dot{N}(t) = q_{in}(t) + q_d(t) - q_{out}(t)$$



- According to NFD, if *N* grows beyond certain limits ⇒ PN **exit** flow (↘)

- Via gating, PN can be **protected** from link queue **spillovers** and **gridlocks**

Operational NFD

- *Operational* NFD: based on measurements/ estimates, rather than exact knowledge,
- at links $\mathbb{M} \subseteq \mathbb{Z}$, where $z \in \mathbb{M}$ (complete NFD) or $\mathbb{M} = \mathbb{Z}$ (reduced NFD)
- y-axis: Total Travel Distance (TTD)

$$TTD(k) = \sum_{z \in \mathbb{M}} \frac{T \cdot q_z(k) \cdot L_z}{T} = \sum_{z \in \mathbb{M}} q_z(k) \cdot L_z$$

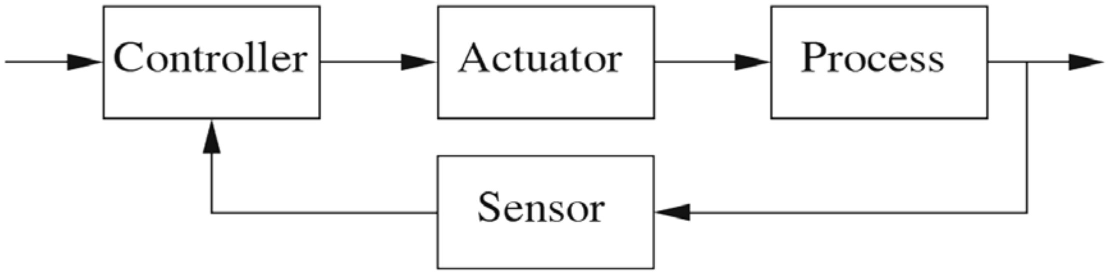
(where k =1,2,... are signal cycles)

- x-axis: Total Time Spent (TTS)

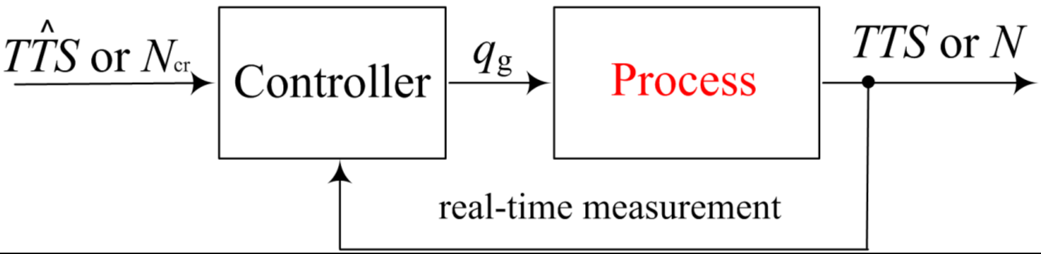
$$TTS(k) = \sum_{z \in \mathbb{M}} \frac{T \cdot \hat{N}_z(k)}{T} = \sum_{z \in \mathbb{M}} \hat{N}_z(k) = \hat{N}(k)$$

$$\hat{N}_z(k) = L_z \cdot \frac{\mu_z}{100\lambda} \cdot o_z(k-1)$$

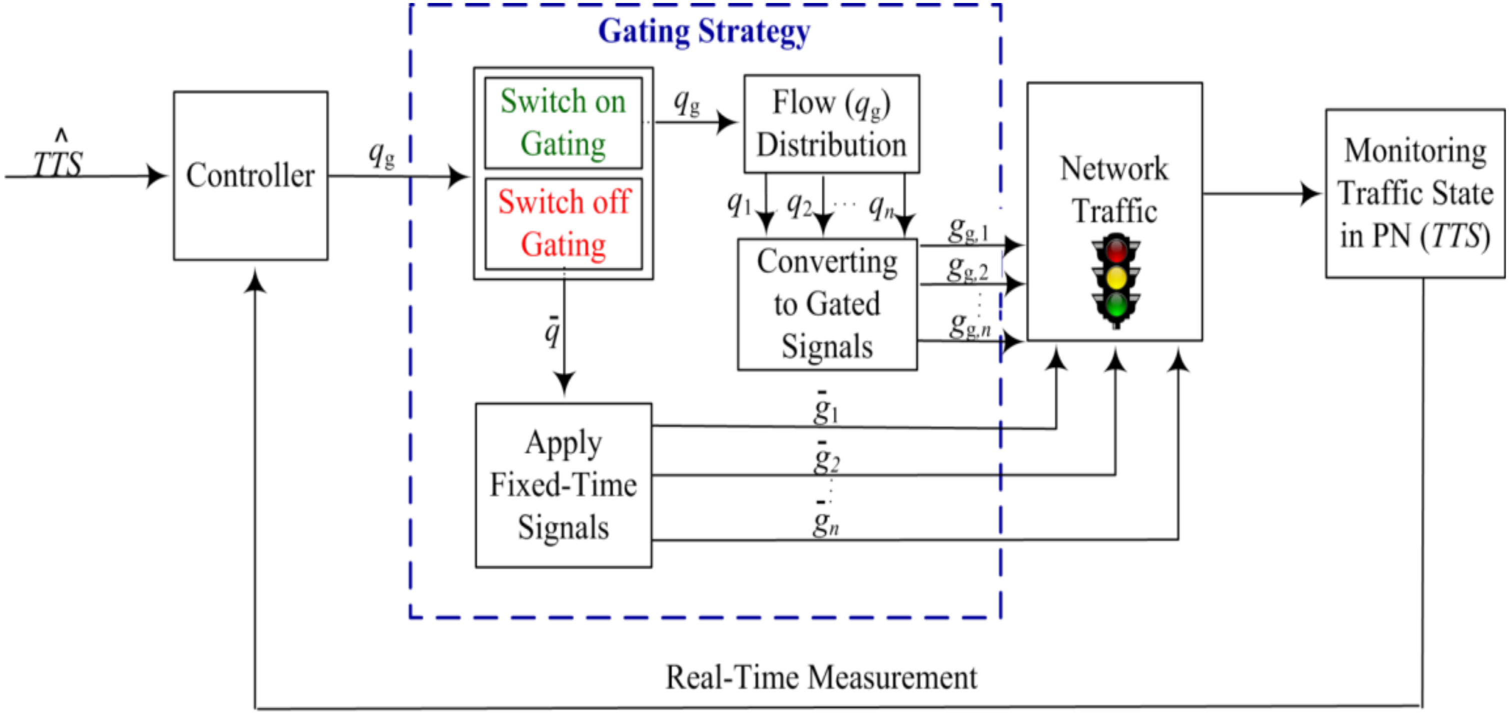
Typical Feedback Loop



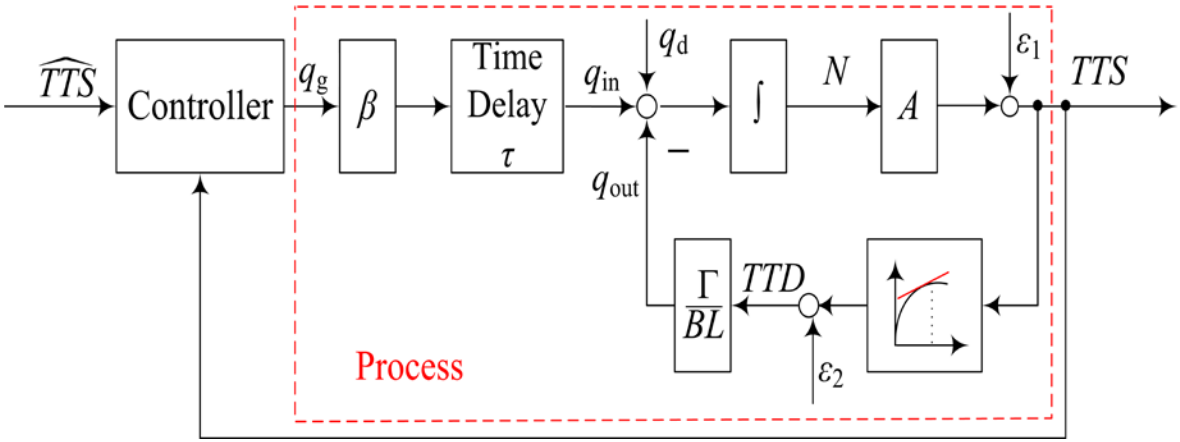
- ❑ SISO system is a simple control system with one input and one output
- ❑ Actuator is the device that can influence the controlled variable of the process (In traffic; actuator: traffic light, control variable: *TTS*)
- ❑ Sensor: measures the control variable (in Traffic Control: detectors)



Feedback Gating Traffic Control Scheme



Time-Delayed Feedback gating



$$\frac{d}{dt}\left(TTS(t)\right) = \left(\beta q_g(t-\tau) + q_d(t) - \frac{\Gamma}{BL} F\left[TTS(t)\right]\right) \cdot A + \varepsilon(t)$$

- If gating applied at the border of PN $\Rightarrow$ $\tau = 0$ & $q_g = q_{in}$

Time-delayed nonlinear first-order dynamic system

Time-Delayed Feedback gating

- The model can be linearized around an optimal steady state that is within the maximum throughput region of NFD

Linearized System: $$\frac{d}{dt}(\Delta TTS) = \left(\Delta q_{\mathrm{g}} + \Delta q_{\mathrm{d}} - \frac{\Gamma \bar{F}'}{BL}\Delta TTS\right) \cdot A + \varepsilon$$

- The continuous-time state equation of the PN may be directly translated in discrete-time

$$\Delta TTS(k+1) = \mu \cdot \Delta TTS(k) + \zeta \cdot \Delta q_{\mathrm{in}}(k-m) + \gamma \cdot \Delta d(k)$$

Where $\Delta TTS = TTS - T\hat{T}S,\ \Delta q_g = q_g - \bar{q}_g,\ m \triangleq time - delay$

Parameters μ, ζ , m can be obtained from using time-series of (q_g , *TTS*)-measurements via model identification (e.g. least-square method) around the critical *TTS*-range.

Controller

- A proportional-integral-type (PI) **feedback controller** is suitable

$$q_g(k) = q_g(k-1) - K_{\mathrm{P}}\left[TTS(k) - TTS(k-1)\right] + K_{\mathrm{I}}\left[T\hat{T}S - TTS(k)\right]$$

- Flow, constrained by pre-specified **minimum** and **maximum** K_{P} and K_{I} gain values

- Flow splitting if multiple gating links: Various policies, queue management (this work, based on link saturation flow)
- Conversion of flows to gating signals (appropriate modification of fixed plans)

Controller Gain Values

The z-transform function of the process and controller:

$$P(z) = \frac{\zeta}{z^m (z-\mu)} \qquad C(z) = \frac{z \cdot (K_P + K_I) - K_P}{z-1} = K' \cdot \left(\frac{z - \frac{K_P}{K'}}{z-1} \right) \qquad K' = K_P + K_I$$

By closing the loop with *C* (controller) and *P* (process):

$$F_C = \frac{C(z) \cdot P(z)}{1 + C(z) \cdot P(z)} = \frac{K' \cdot \left(\frac{z - \frac{K_P}{K'}}{z-1} \right) \cdot \left(\frac{\zeta}{z^m \cdot (z-\mu)} \right)}{1 + K' \cdot \left(\frac{z - \frac{K_P}{K'}}{z-1} \right) \cdot \left(\frac{\zeta}{z^m \cdot (z-\mu)} \right)}$$

Using control laws, simplified to:

$$\Downarrow$$

$$F_C = \frac{K'\zeta}{z^m (z-1) + K'\zeta}$$

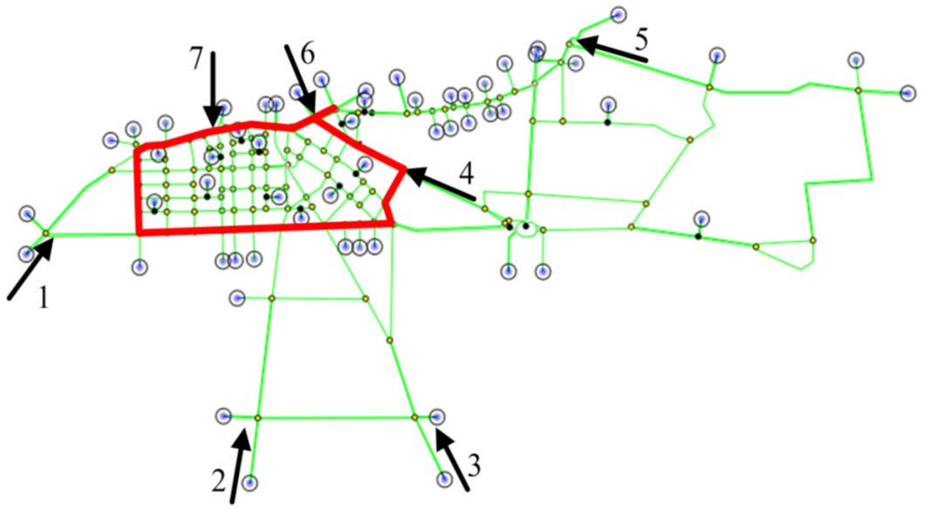
Applying the design rules of (Papageorgiou and Messmer, 1985)

Controller Gain Values

- ready design of a PI regulator

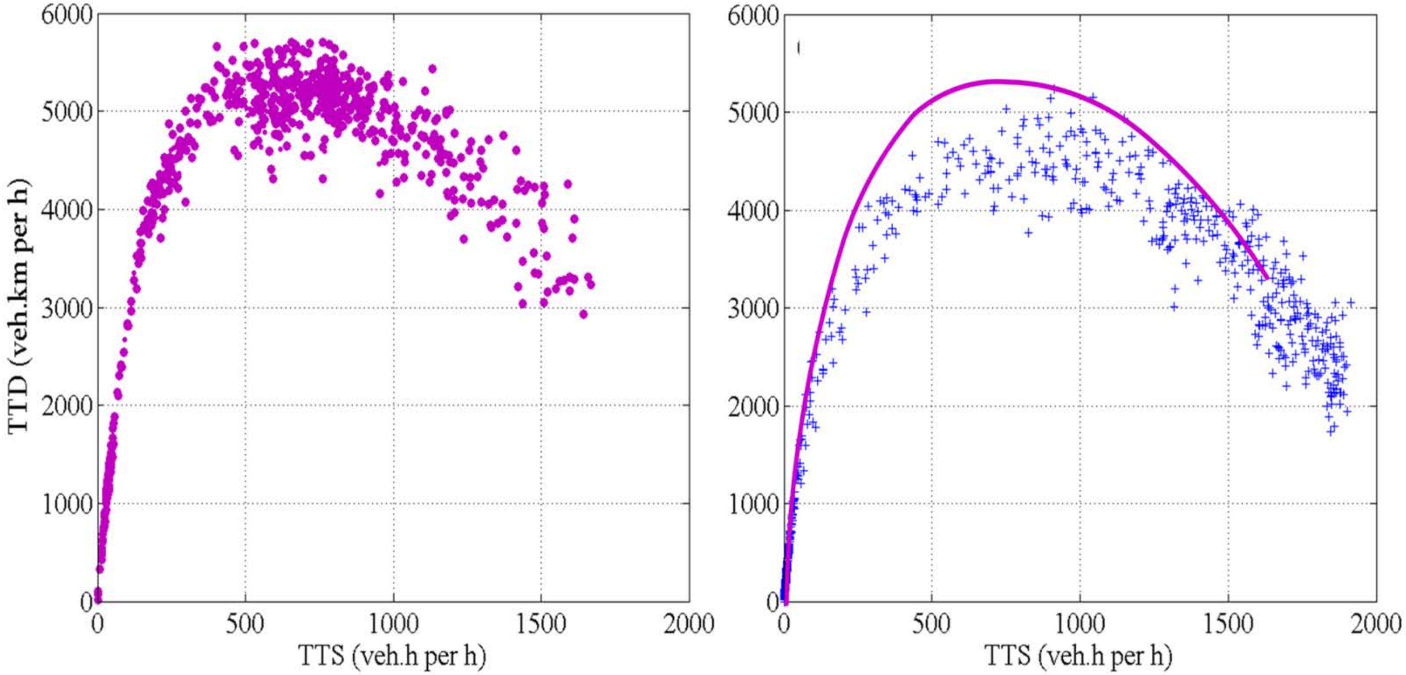
m	K_P	K_I
0	μ/ζ	$(1-\mu)/\zeta$
1	$\mu/(3\zeta)$	$(1-\mu)/(3\zeta)$
2	$\mu/(5\zeta)$	$(1-\mu)/(5\zeta)$
3	$\mu/(6\zeta)$	$(1-\mu)/(6\zeta)$
>3	$\mu/(2m\zeta)$	$(1-\mu)/(2m\zeta)$

Chania (Greece) Urban Network



- Microscopic simulator AIMSUN applied.
- Realistic O-D demands and dynamic traffic assignment (DTA) based routing (4h simulation)
- In the middle of every link inside PN, a loop detector has been installed

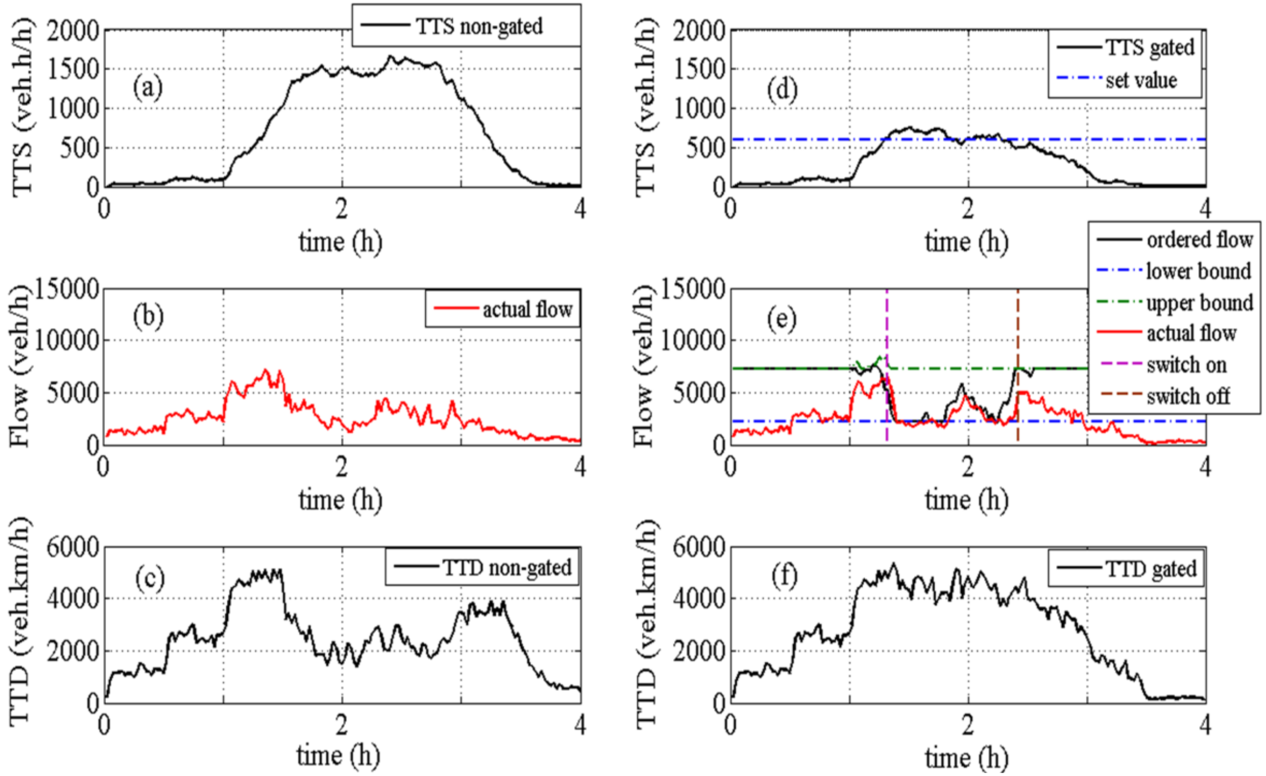
Simulation Result: NFD



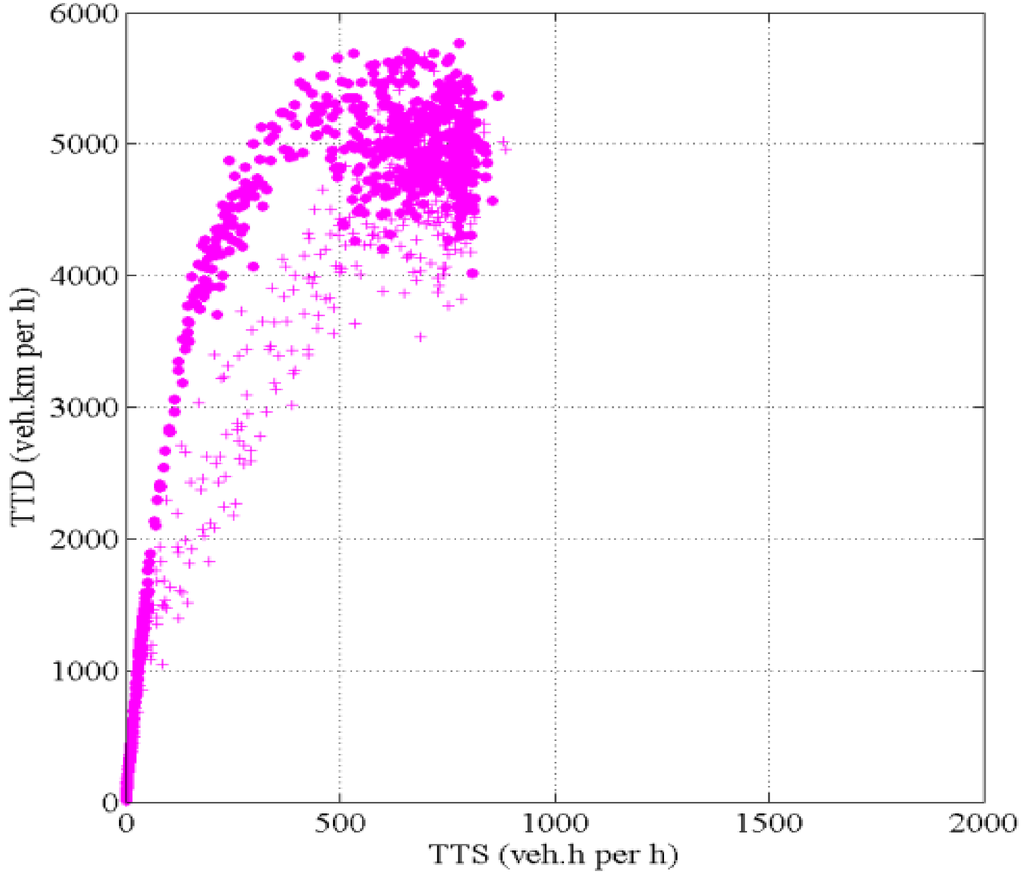
- **Maximum** *TTD* values in the diagram occurs in a *TTS* region of 600 to 800 veh·h per h

Control Results (90s Control Step)

Gating $T\hat{T}S = 750, K_p = 10, K_I = 3, m = 3, \mu = 0.7692, \zeta = 0.0128$

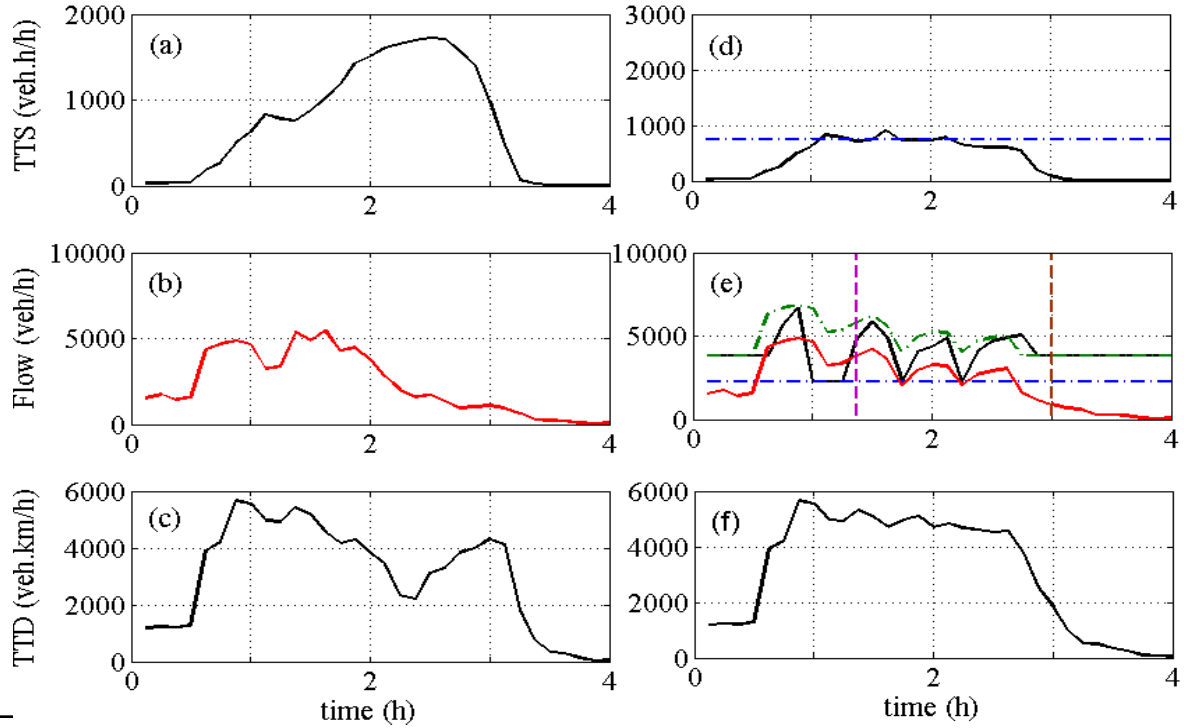


NFD after Gating Control



Time-Delayed Gating with Higher Control Step (450s)

Gating $\hat{TTS} = 750, K_p = 65, K_I = 20, m = 3, \mu = 0.760, \zeta = 0.011$

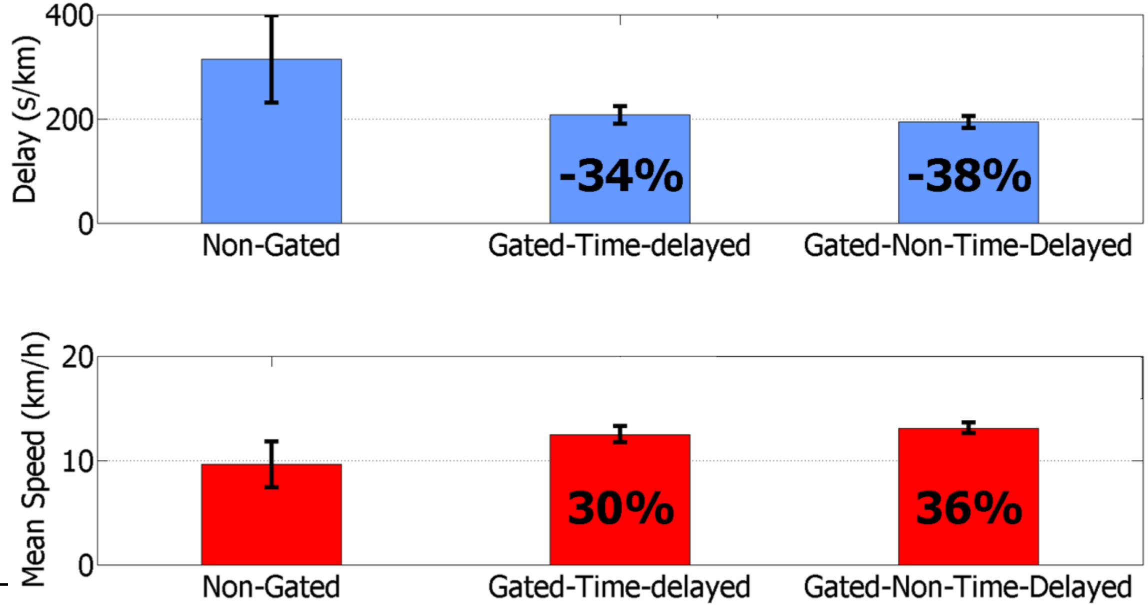


Network-Wide Performance Indexes

15 replications per control scenario

Performance indexes (whole network, 4h)

- Average vehicle delay per km
- Mean speed



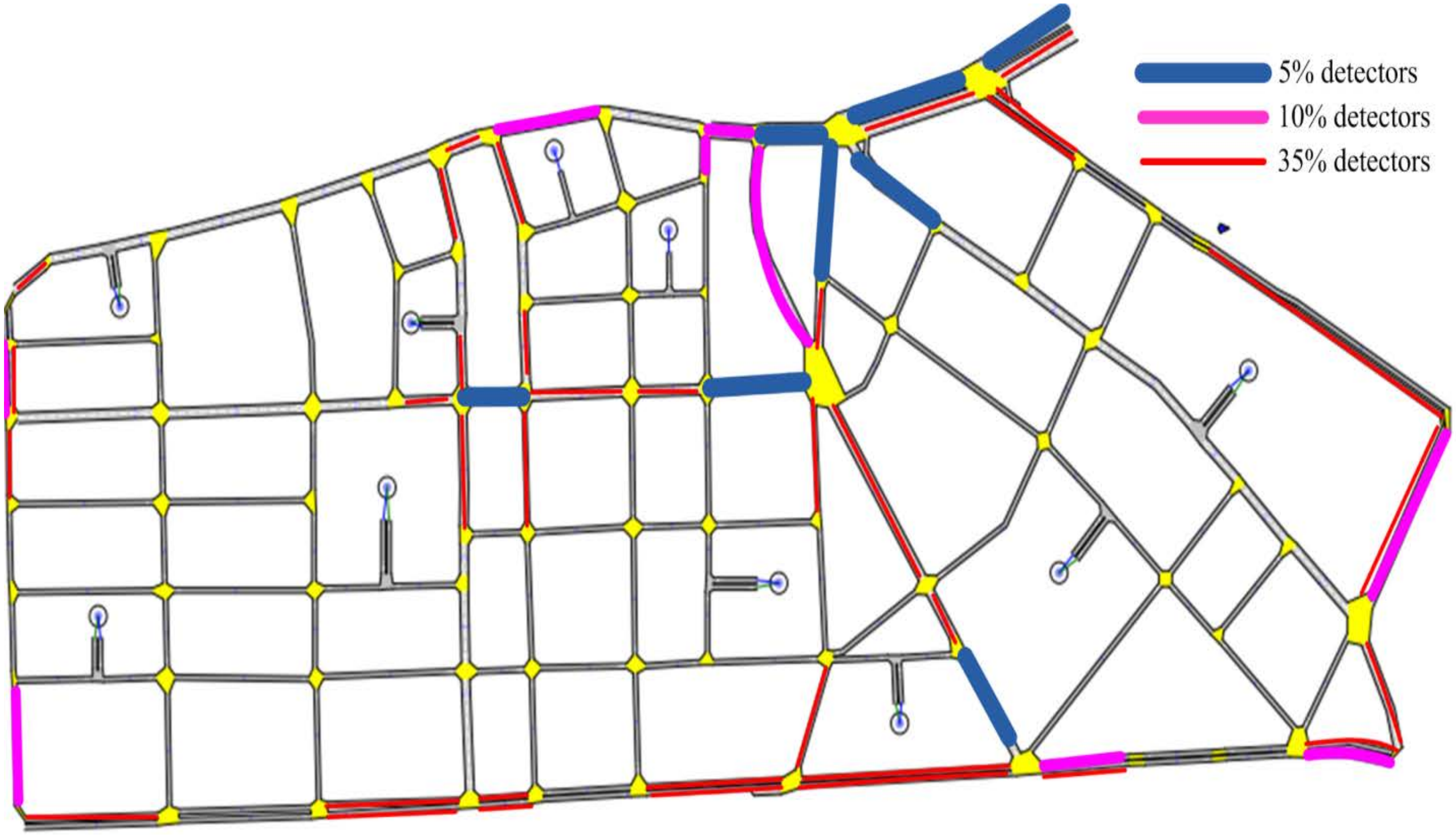
Reduced NFD

Measurements:

- Four groups of measurements collected from:
  - each and every link inside PN (100% of all)
  - signal-controlled links inside PN (35% of all)
  - proportions of controlled links in PN:
    - 10% of all
    - 5% of all

- Selection of links: critical links where congestion starts spreading

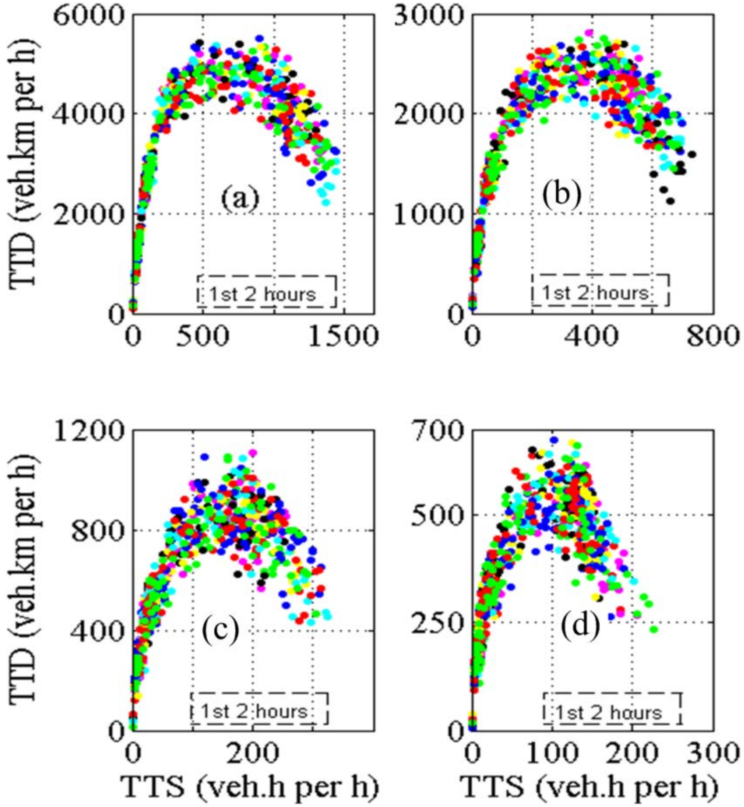
Measurement Location



Reduced NFD

100%

35%

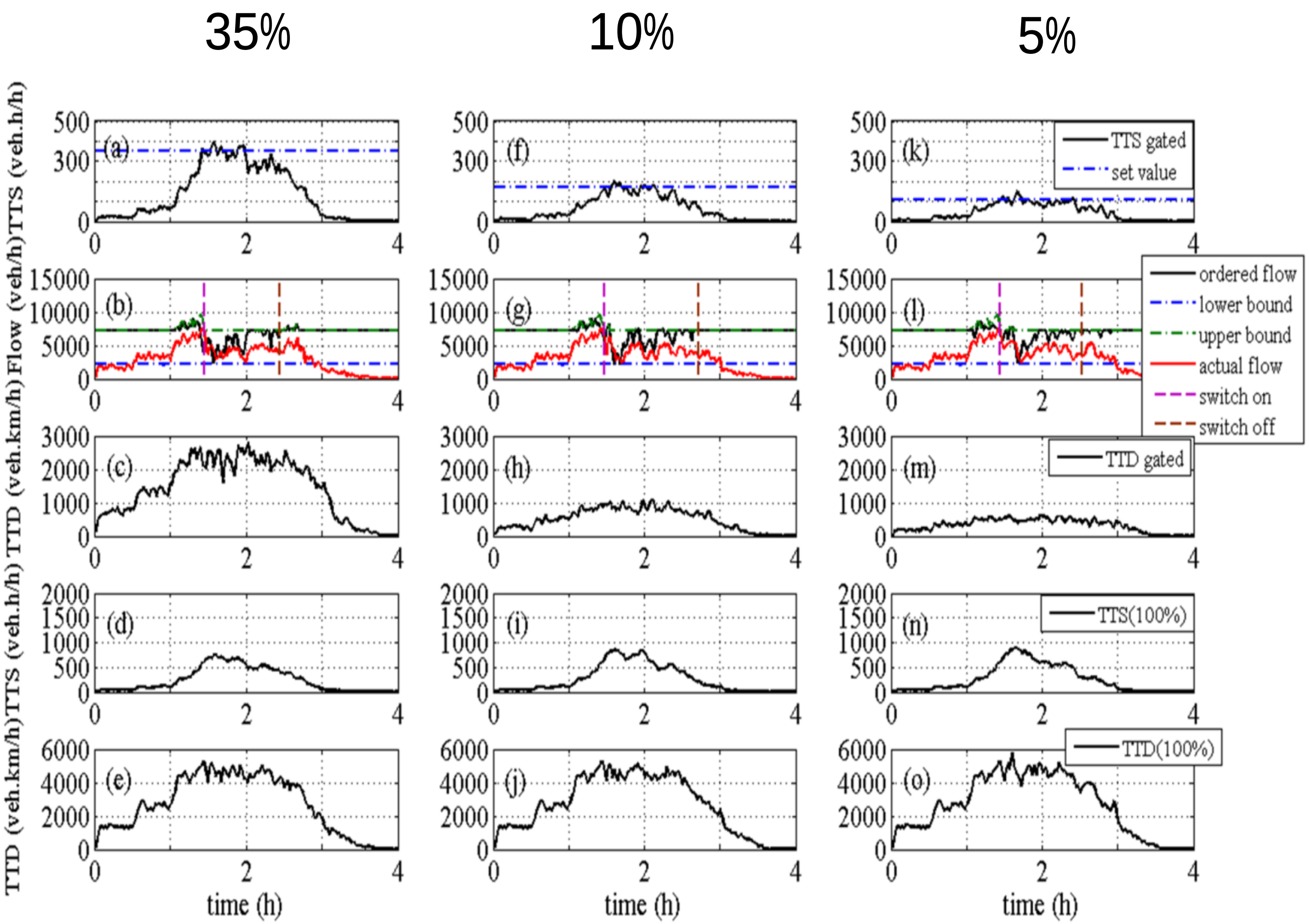


10%

5%

- When *TTS(100%)* in its **critical** range, *TTS(x%)* is in its own **critical** range

Control Results

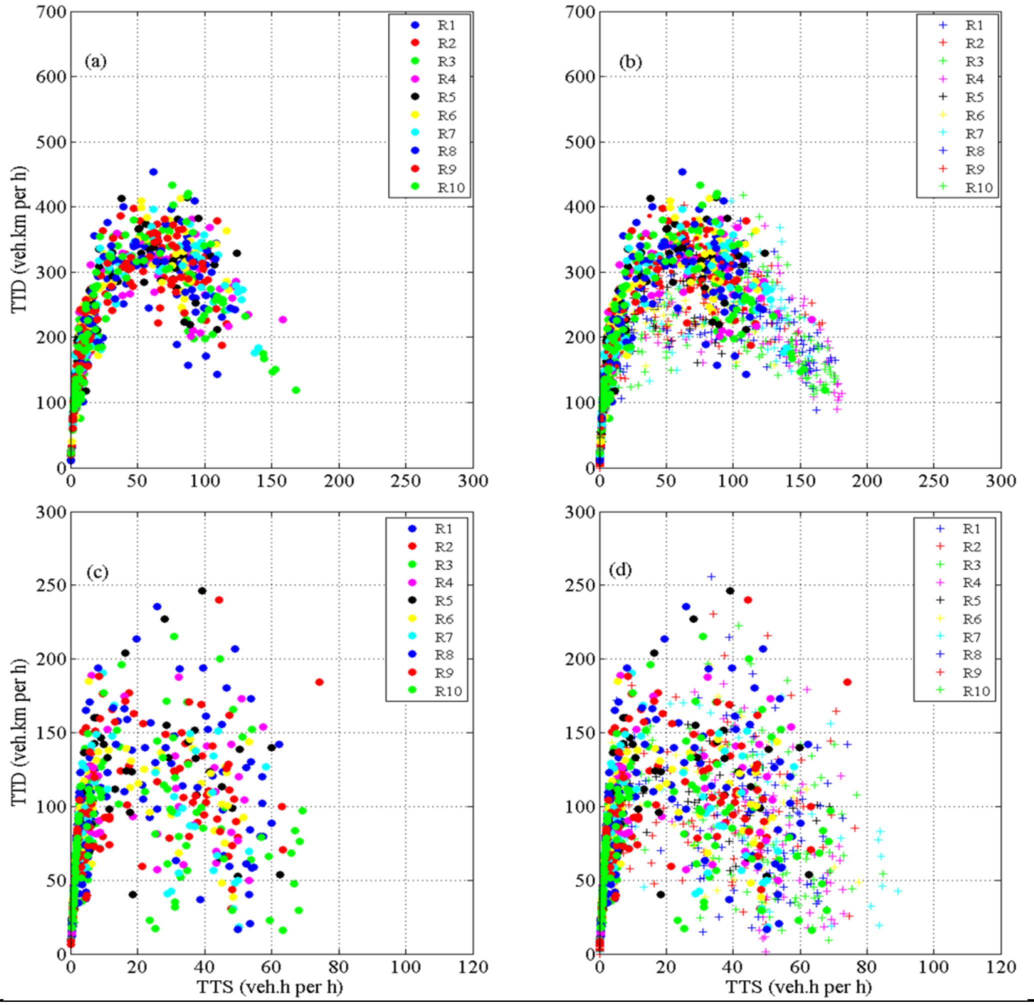


Critical Links

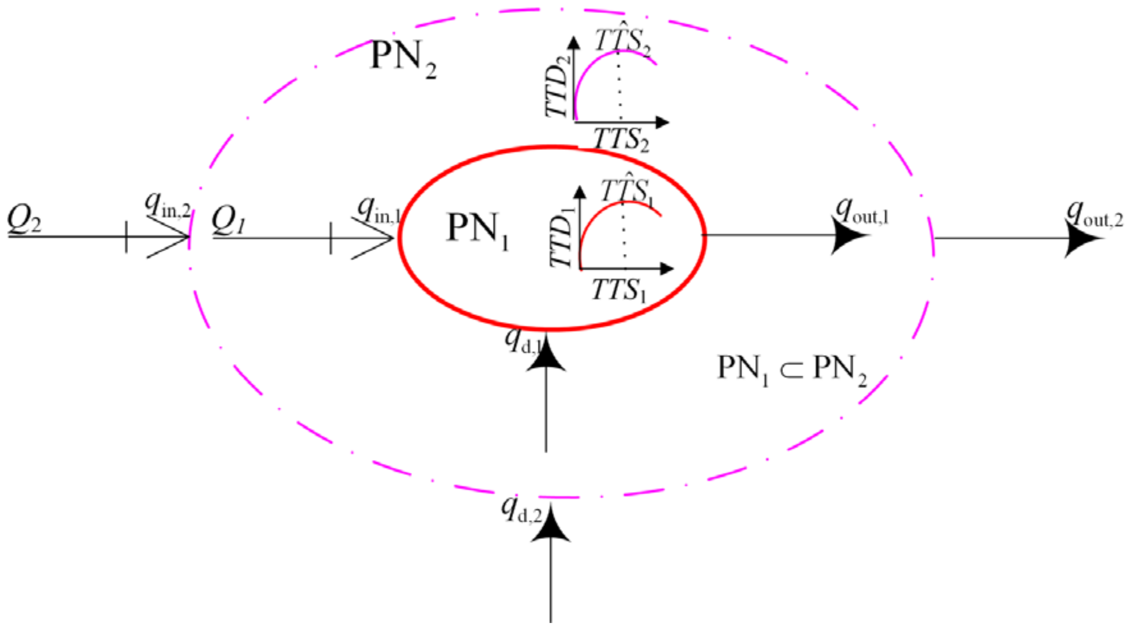
5% measurements:
4 early-congested
4 late-congested

maximum-*TTDTTS*-range of [50-90]

5%: 8 late-congested



Multiple Concentric Gating



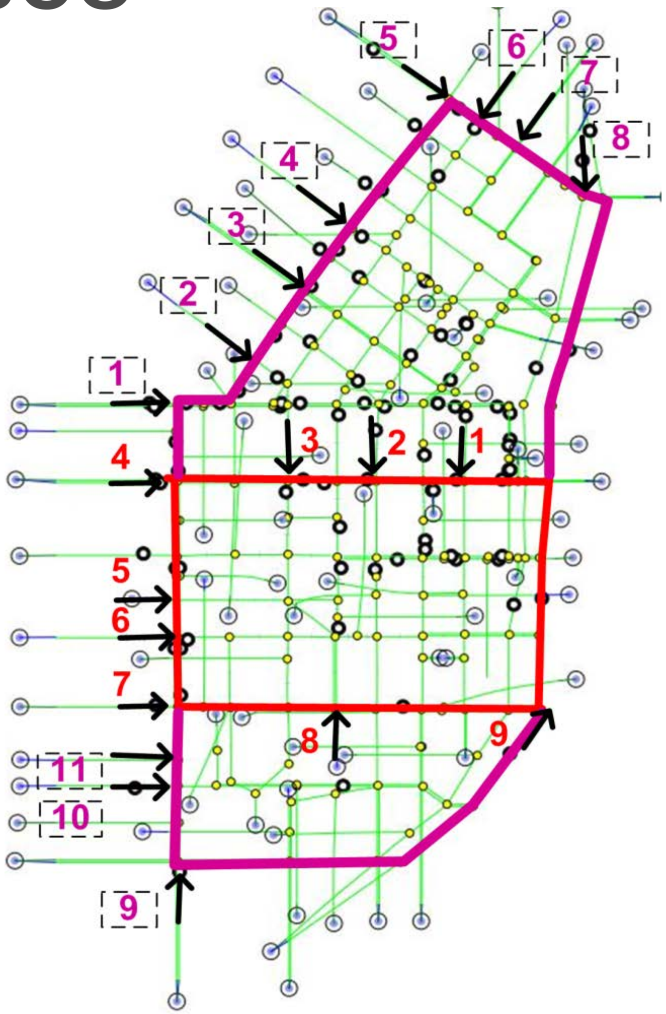
- After the first core of congestion formed, **red perimeter** activated
- If **small** proves unsuccessful to mitigate the congestion, **big** activated additionally

Test-bed: San Francisco

- Large-scale urban network ⟹ heterogeneous spatial distribution of congestion ⟹ different regions may not reach the critical accumulation (NFD) simultaneously

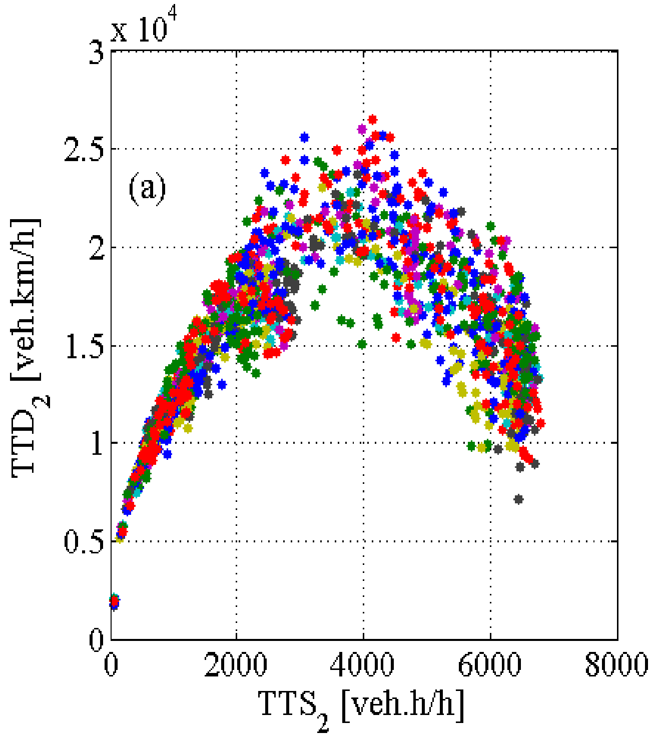
⇓

- **Red border: first** protected network (PN1)
- Pink Border: **second** protected network (PN2), OVERAL NETWORK
- measurements collected every 60s (shortest cycle of the traffic lights inside the whole network)
- 5-hour simulation

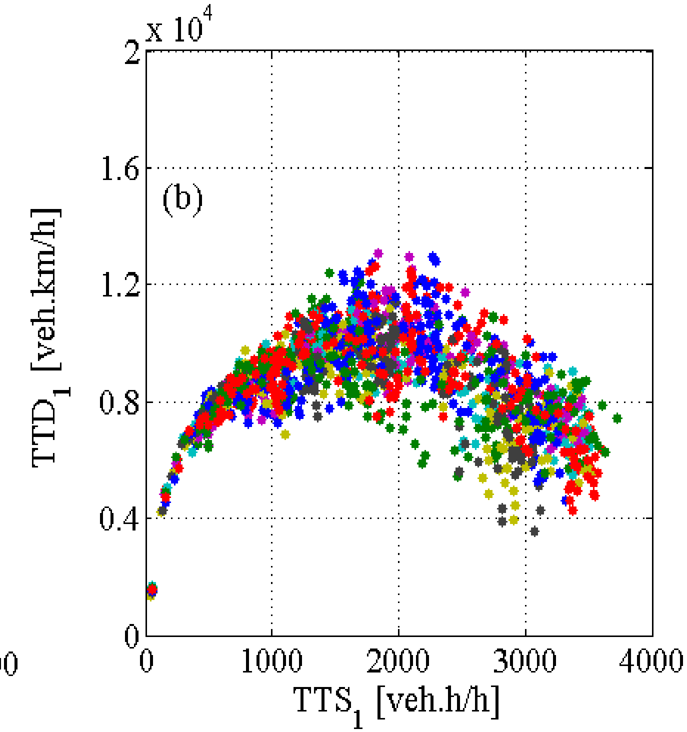


NFDs

NFD for **PN2**
maximum-*TTDTTS*-range of [3500-4000]



NFD for **PN1**
maximum-*TTDTTS*-range of [1700-2000]

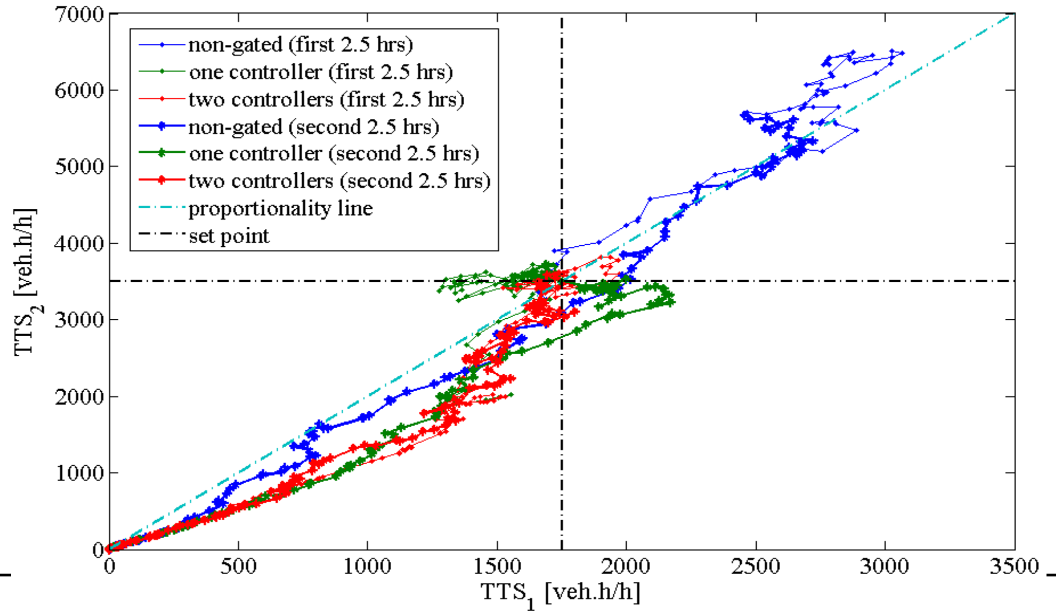


Results: Multiple Concentric

Improvements: No gating (NG); Single Controller (SC); Two Controller (TC)

	TTS/TTD (s/km)			Improvement (%)	
	NG	SC	TC	SC	TC
Avg.	1369	1227	1166	10.01	14.39
COV	0.09	0.05	0.04	-	-

	Delay (s/km)			Improvement (%)	
	NG	SC	TC	SC	TC
Avg.	563	442	414	21.15	26.24
COV	0.08	0.05	0.04	-	-

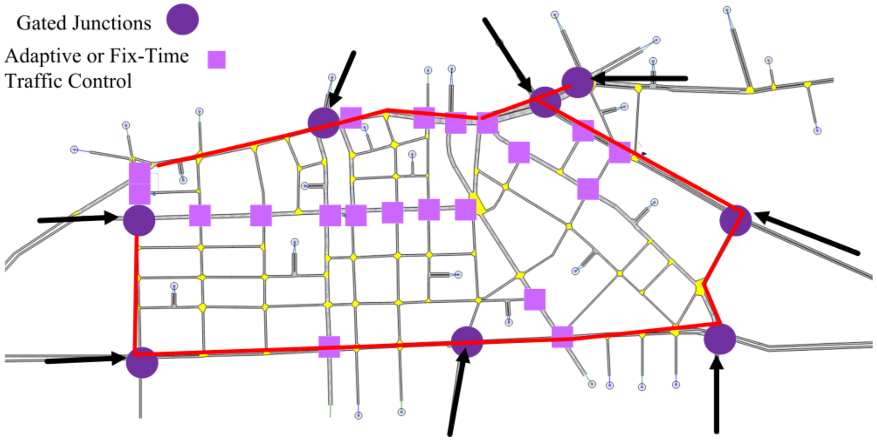


Combining Gating and Traffic Responsive Strategies

Two adaptive traffic control strategies:

- Modified SCATS
- Volume-based traffic responsive control strategies

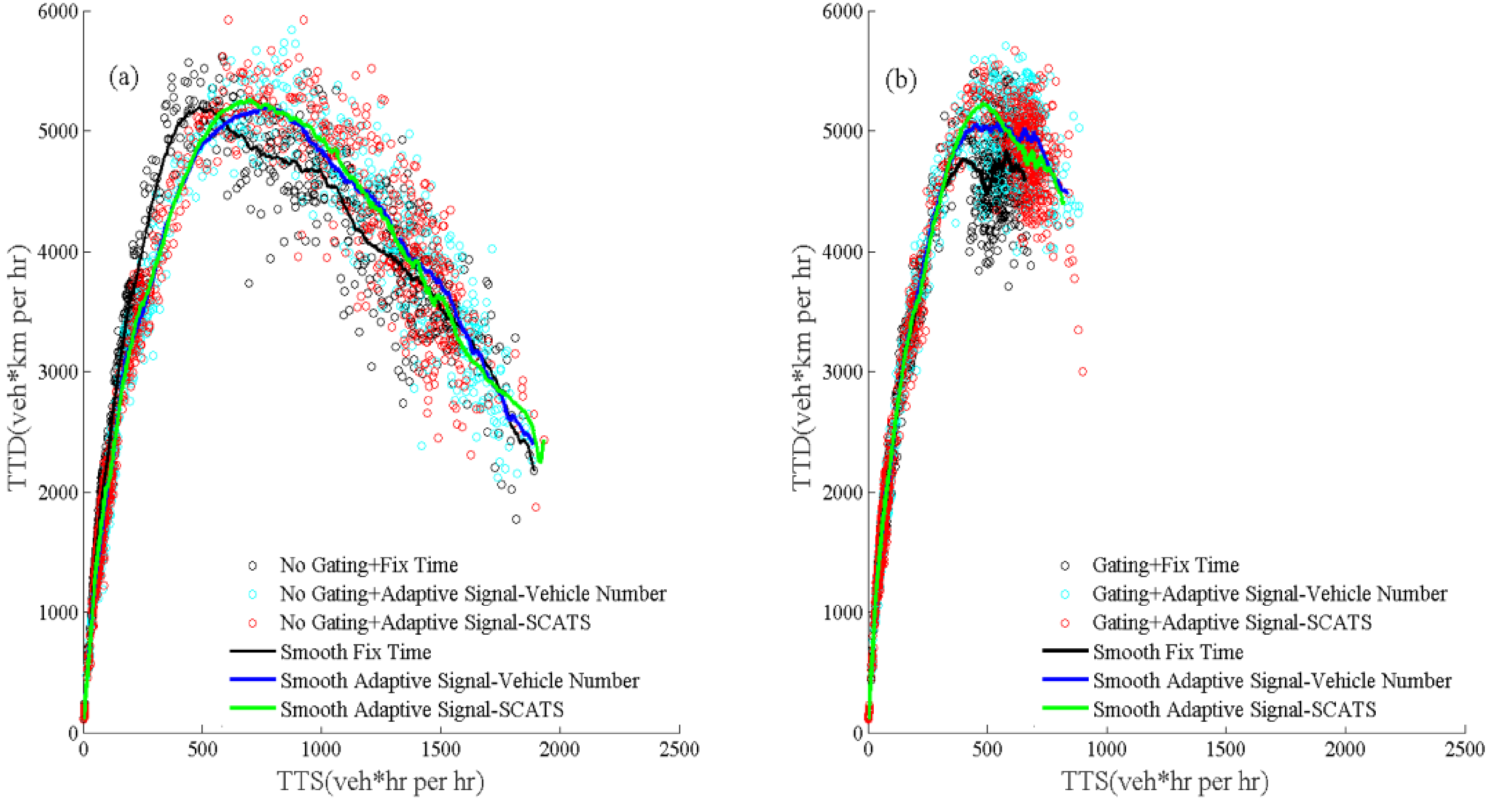
Gating or Perimeter Control



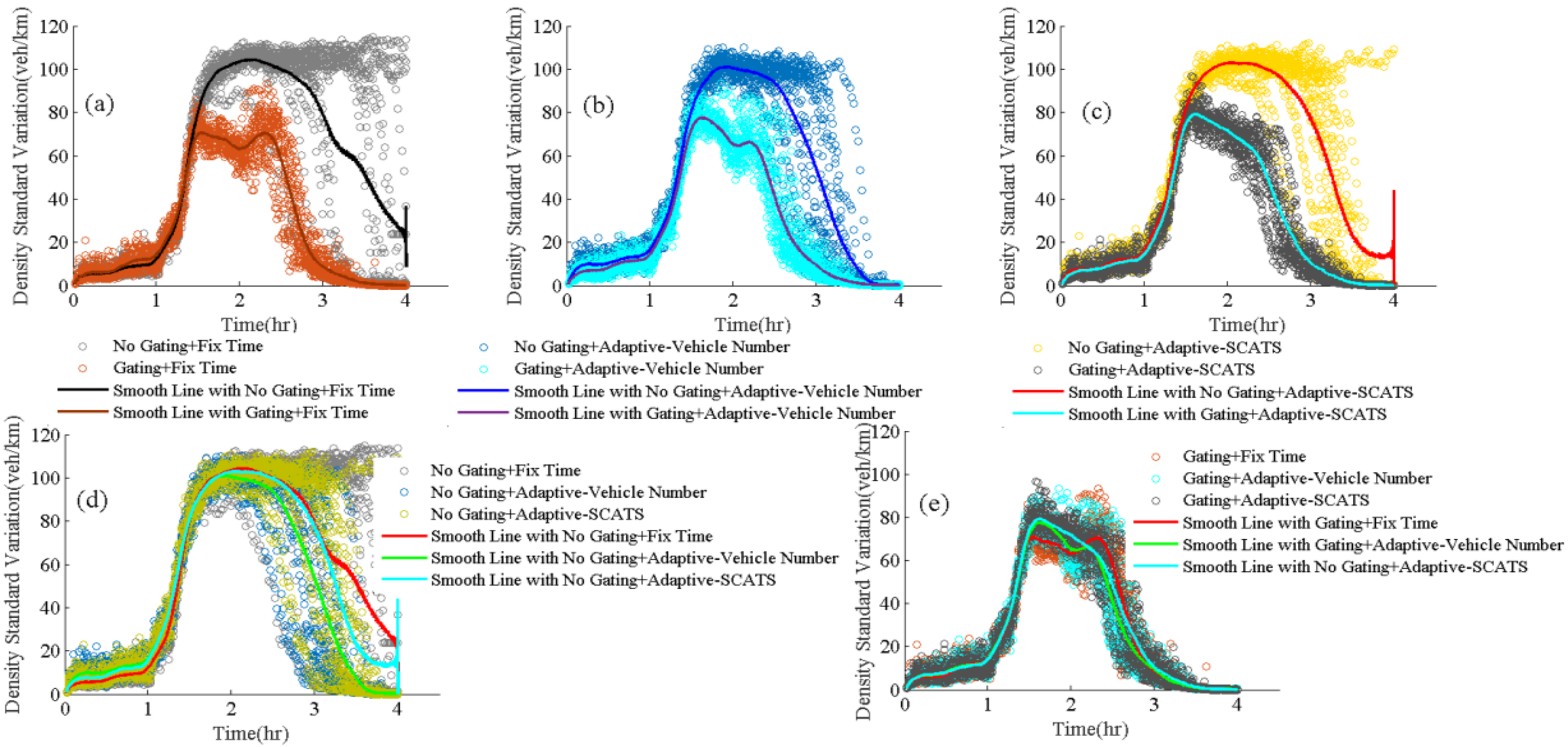
Control Scenarios

- ***Scenario 1***: (no-gating) the traffic lights in the PN are controlled applying fix-time control signal plan.
- ***Scenario 2***: (no-gating) “volume-based” traffic responsive control strategy is implemented to control all the traffic lights within PN.
- ***Scenario 3***: (no-gating) adaptive traffic control strategy “modified SCATS” is used for controlling the signalized junctions within PN.
- ***Scenario 4***: Gating at the perimeter and fix-time control inside PN.
- ***Scenario 5***: Gating at the border and “volume-based” for the rest of the traffic lights in the PN.
- ***Scenario 6***: Gating at the boundary and “modified SCATS” within PN.

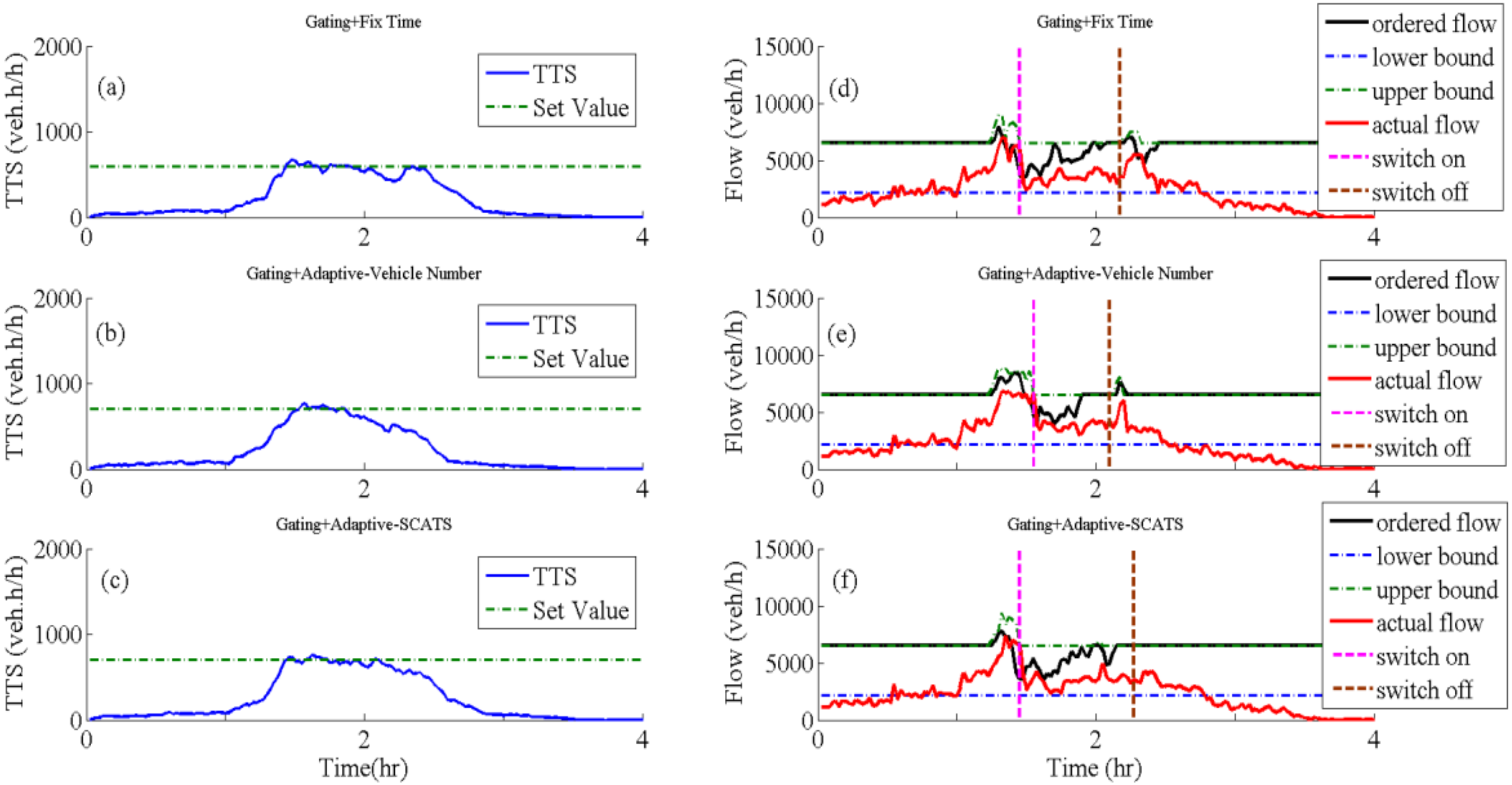
NFDs for Different Control Scenarios



Density Variation in Different Scenarios



Control Results for Six Scenarios



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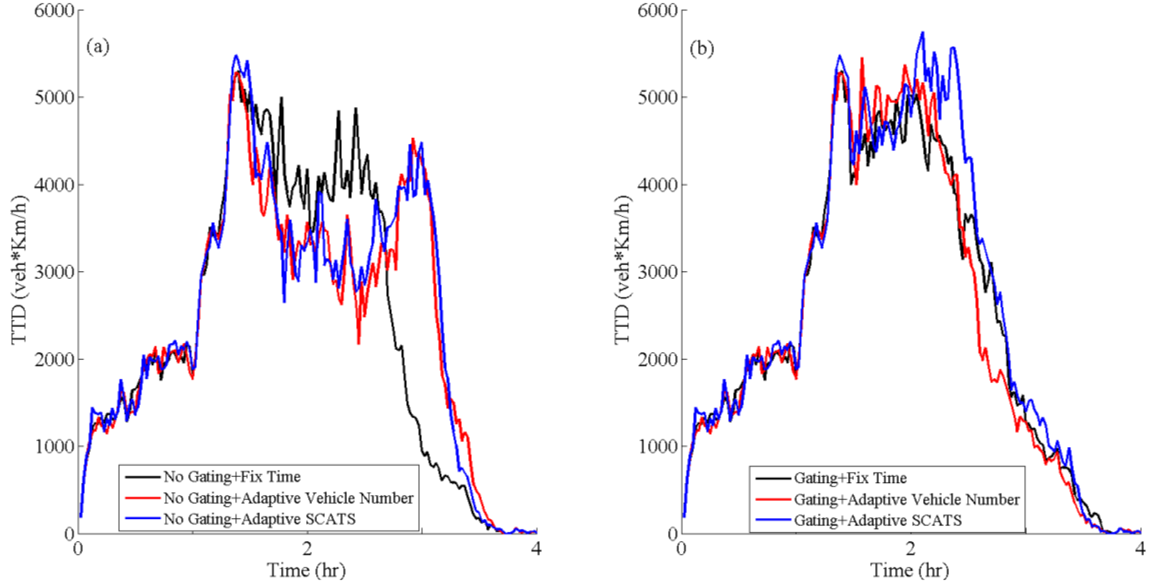

Performance Index	Fix-time	Volume-based	SCATS	Gating + fix-time	Gating + Volume-based	Gating + SCATS
delay (sec/km)	389	294	351	203	193	203
speed(Km/h)	8	10	9	13	14	13
avg. virtual queue (veh)	252	166	204	206	164	194
max virtual queue (veh)	728	696	702	965	808	888
vehicle out	12675	12913	12801	12924	12912	12923

Conclusion and Future Work

- ✓A robust feedback controller, by considering time-delay on the system is designed.
- ✓It is shown that the feedback gating works properly with much longer time-steps.
- ✓Overall performance of the network improved.

- ✓On-going work: comparison and combining with traffic-responsive signal control strategies.
- ✓Future work:
- ✓Queue management at gated links
- ✓Field test

Thanks for listening!

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