

# Model-Based Performance Assessment of a Lean-Burn System

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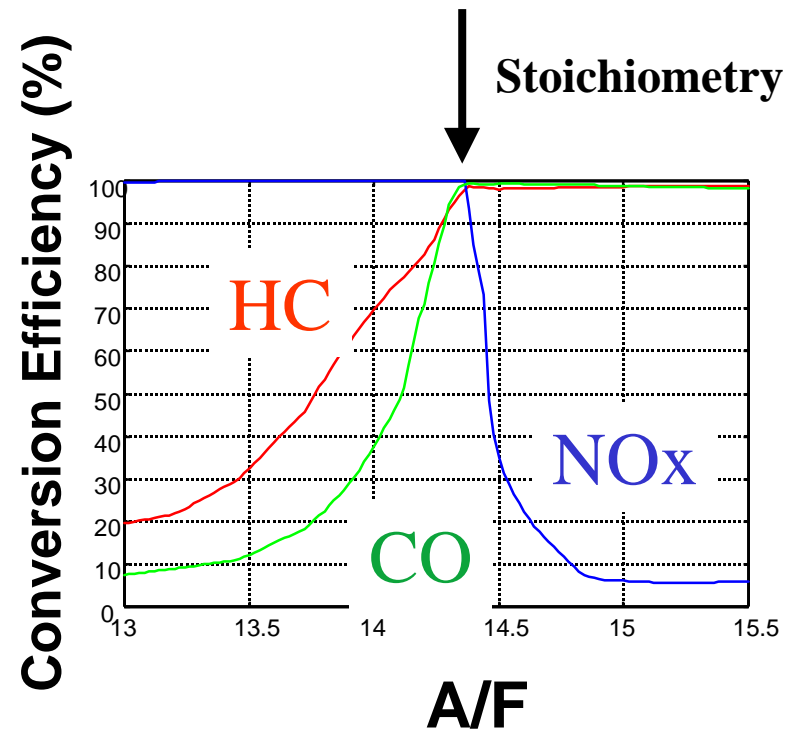
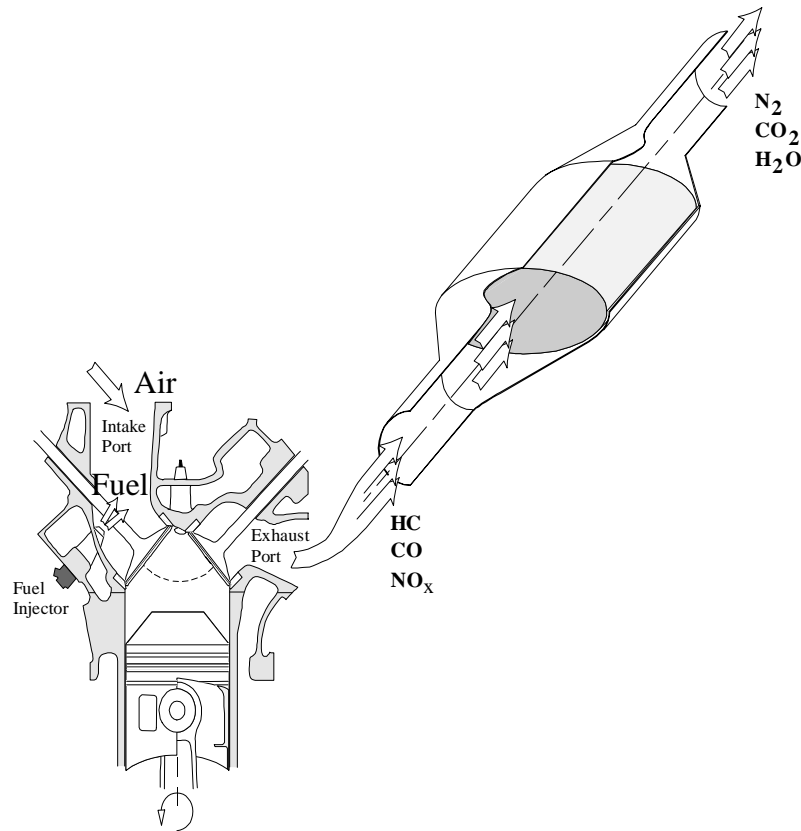
# Acknowledgements

- Erich Brandt
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- Jing Sun
- Yanying Wang

# Outline

- Performance Assessment Problem Statement
- Relevant Models
  - DISC Engine
  - Three-way Catalytic Converter
  - Lean NO<sub>x</sub> Trap
- Results of the Performance Assessment


# Classic Engine and Emissions Treatment System



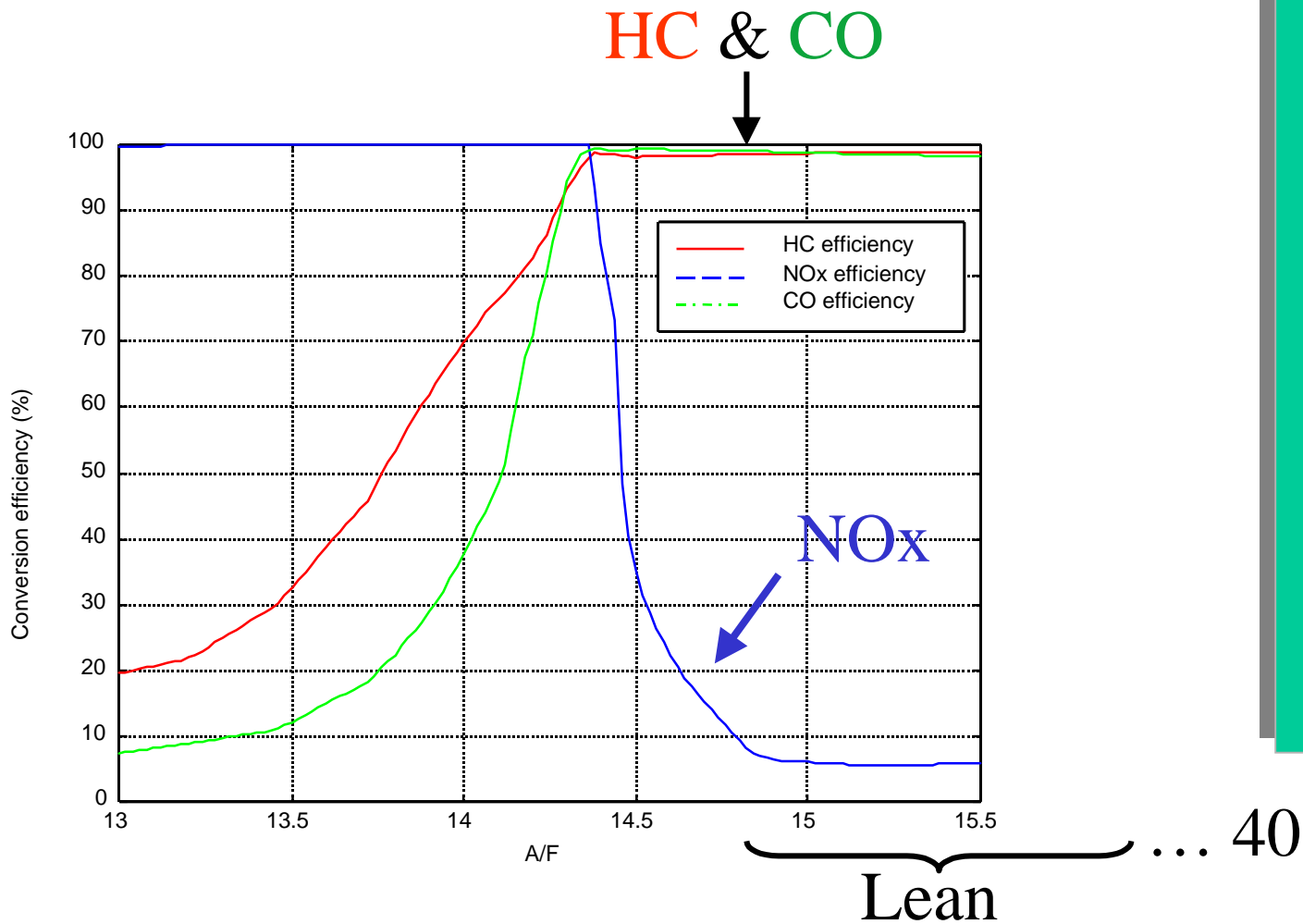
# Remarks

- To-date, we have been able to essentially ignore after-treatment system dynamics in feedback design
- Create an emissions pseudo-objective:
  - maintain A/F at stoichiometry
  - main focus becomes engine dynamics
- Rare exception: feedback of post-TWC A/F

# Lean Burn Basics

- Fuel economy  run SI engine like a diesel:
  - reduce pumping losses with high manifold pressure
  - requires combustion of high air fuel ratios
  - stratified charge engines: 40:1 A/F
- Must also worry about emissions
  - HC & CO easy
  - NO<sub>x</sub> hard!

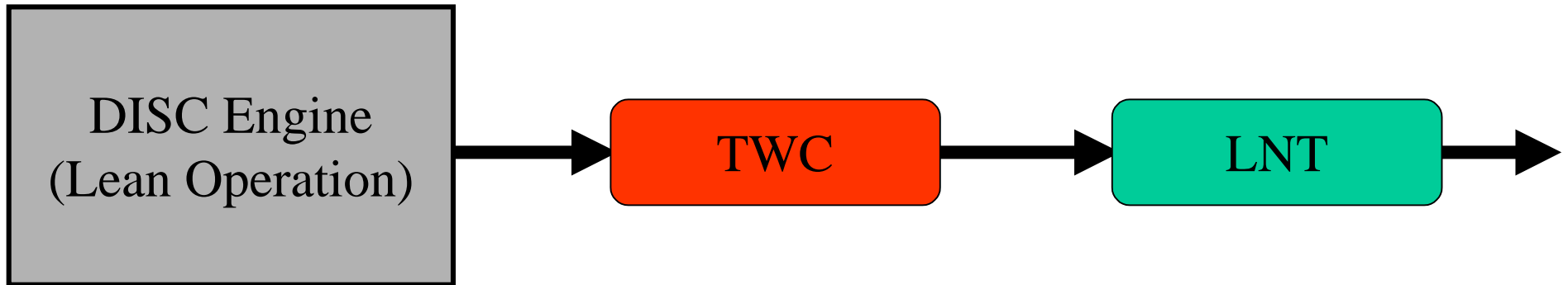
# TWC Alone Inadequate for Treating NOx in Lean Operation



Poor NOx conversion for lean mixtures

Must do something else!

# Potential Solution: Lean NOx Trap



## **LNT Basics:**

- 1) Store NO<sub>x</sub> under lean conditions.... ..until device saturates
- 2) Empty device by reducing NO<sub>x</sub> under rich conditions
- 3) Thus, even for constant “speed and load”, steady state system operation unlikely to be acceptable!

# Goal: Make Initial Performance Assessment w/o Assembling the Overall System

- Evaluation of fuel economy versus NO<sub>x</sub> emission trade-off
  - intrinsically a dynamic problem
  - evaluate over an emission test cycle, for example
  - determine how to operate the system (e.g., when to purge?)
  - assess relative effects of component parameters
    - size
    - temperature sensitivity, etc.

# Approach

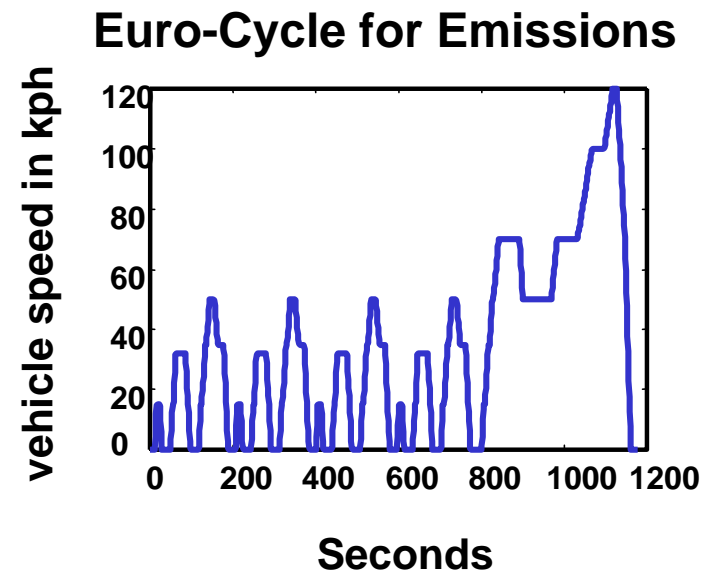
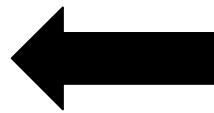
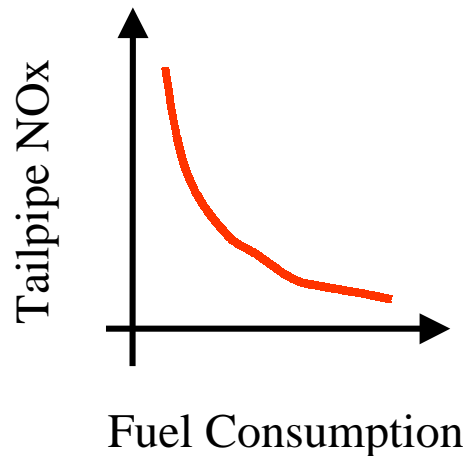
- Dynamic Models

- DISC engine
- TWC
- LNT

+

- Dyn. Prog.

+



**Later step:** approximate the optimal control by a causal feedback ....

# Engine Model

- 1.8 L, Direct Injection, Stratified Charge
  - homogeneous mode: from 12:1 to 20:1 (A/F)
  - stratified mode: from 25:1 to 40:1 (A/F)
- Model built in standard fashion
  - regression against steady state mapping data
  - insertion of dynamic elements
    - intake manifold
    - EGR
    - fuel injection timing delays
    - transport delays

# Engine Model (cont.)

- Inputs:
  - throttle
  - fuel
  - EGR
  - spark
- Injection timing was fixed
- Primary Outputs:
  - torque
    - brake & indicated
  - manifold pressure
  - in cylinder A/F, etc.
  - emissions
    - HC
    - NO<sub>x</sub>
    - CO
    - feedgas temperature

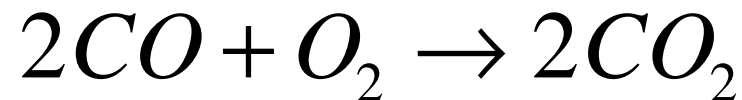
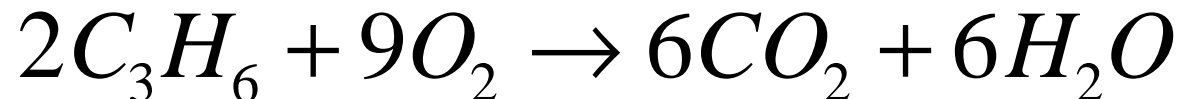
# Control-Oriented TWC Model

- Steady-state conversion efficiency curves are like the steady-state gain of the system
- Would like to get a good approximation of a “time constant” of the TWC
- Possible approaches
  - deduce from existing PDE models
  - measure “it” in a dynamometer test cell
  - propose a phenomenological mechanism/model and fit to data

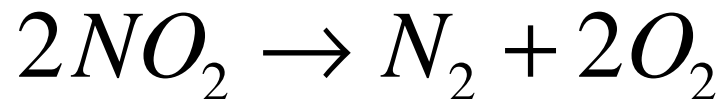
# TWC Basic Chemistry

(in the Presence of Pd, Rh and/or Pt)

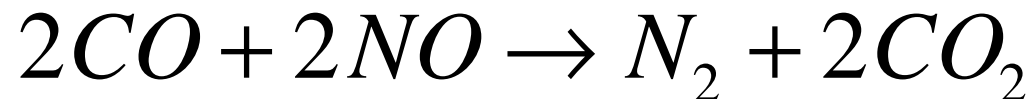
- Typical Oxidation Reactions



- Typical Reduction Reactions

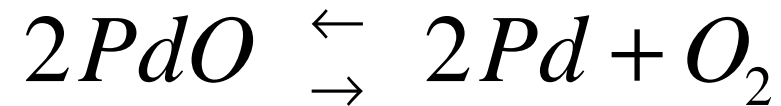


- Combined



# TWC Basic Chemistry (cont.)

- Additional key reactions

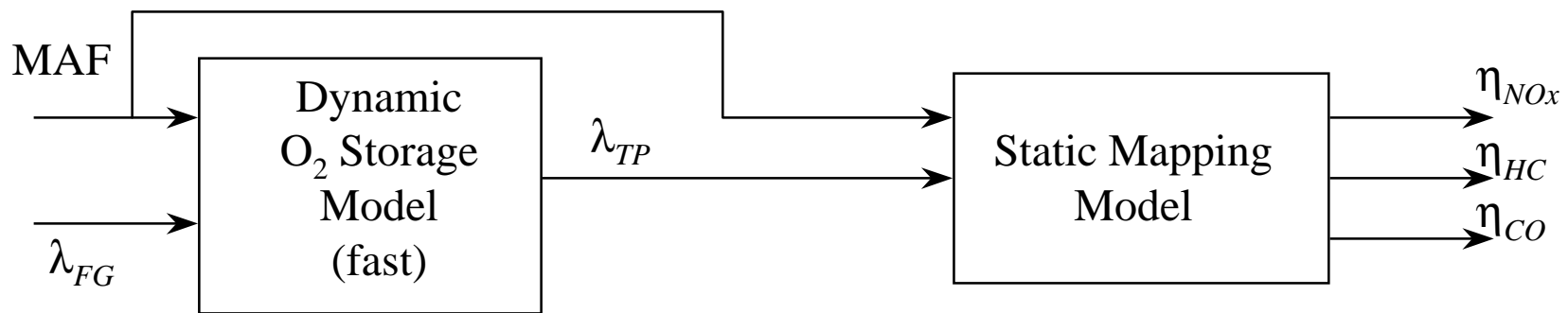


- Referred to as ‘oxygen storage’

# Phenomenological Basis for Model

- **Observation:** A/F through TWC can change only through oxidation and/or reduction reactions
- **Hypothesis:** “time constant” of A/F is rough indicator of “time constants” of underlying chemistry
- **Idea:** Dynamic conversion efficiencies can be approximated by applying standard TWC static curves to A/F at output of TWC

# Phenomenological Model Structure for Dynamic TWC (Warm)



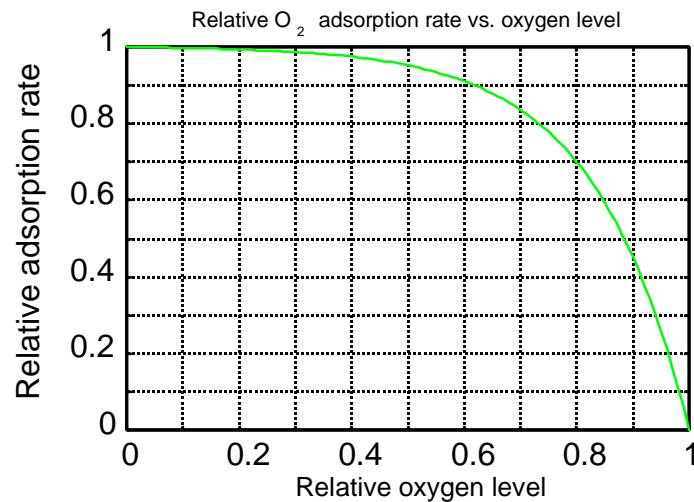
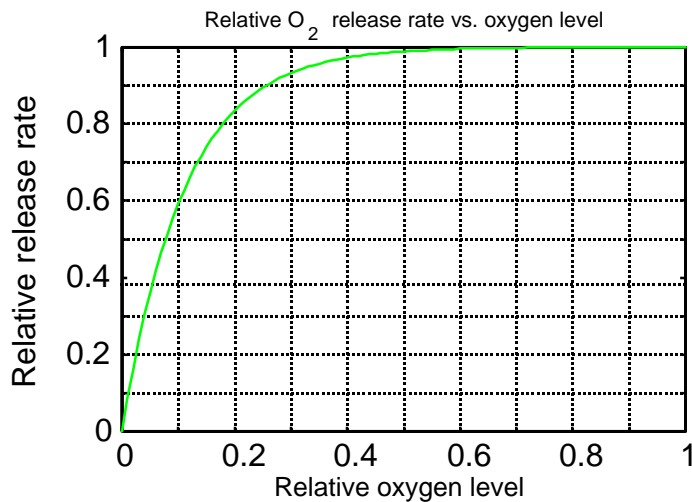
- Accurate to within experimental error on dynamic emission measurements
- Motivates development of a dynamic A/F model for TWC [Shafai et al. (1996)]

# Oxygen Storage Sub-model

“sticking”  
fraction

Oxygen excess/deficit

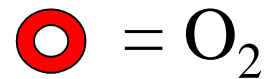
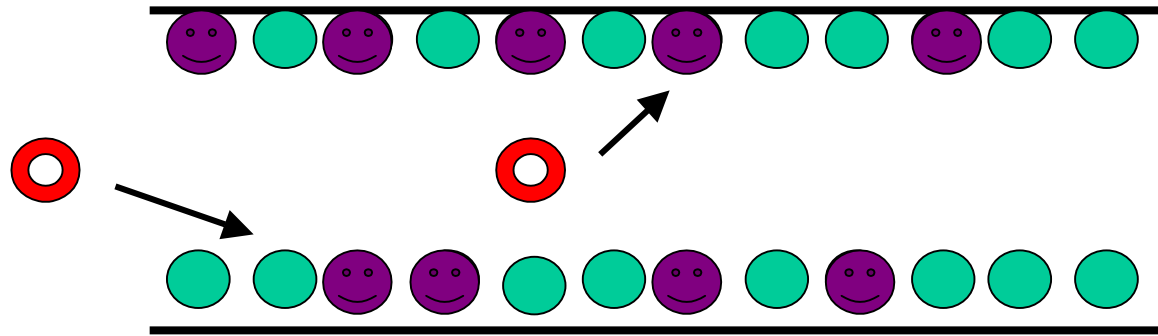
$$\dot{\Theta} = \begin{cases} \frac{1}{C} \times \rho(\lambda_{FG}, \Theta, MAF) \times 0.21 \times MAF \times \left(1 - \frac{1}{\lambda_{FG}}\right) & 0 \leq \Theta \leq 1 \\ 0 & \text{otherwise} \end{cases}$$



$$\Theta = \text{Relative O}_2 \text{ level}$$

$$\lambda_{TP} = \lambda_{FG} + (\text{O}_2 \text{ storage effect})$$

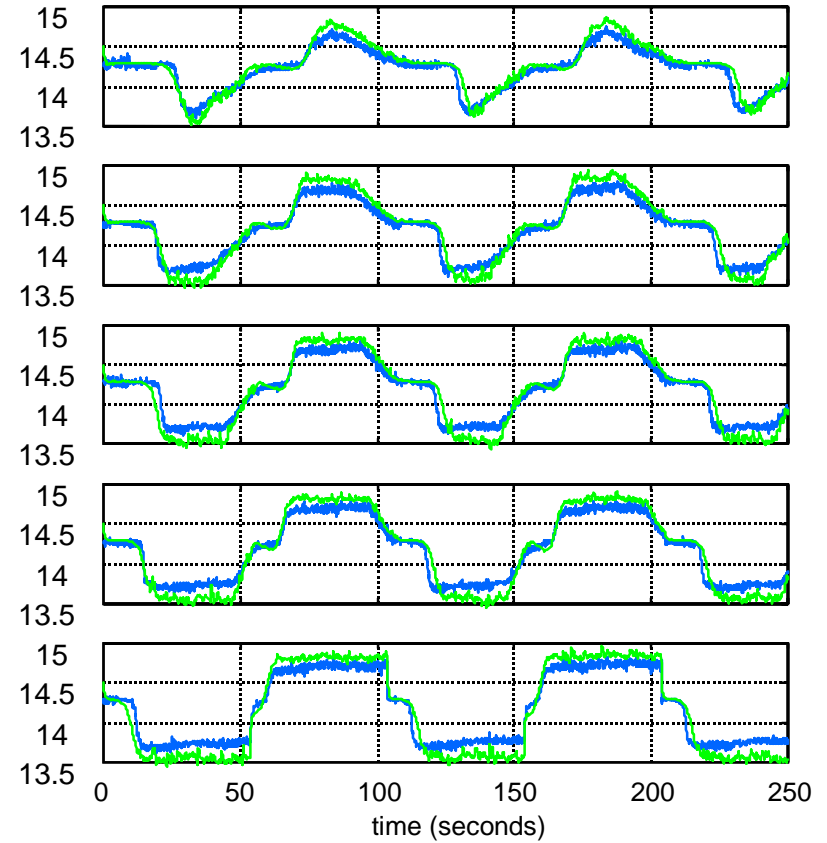
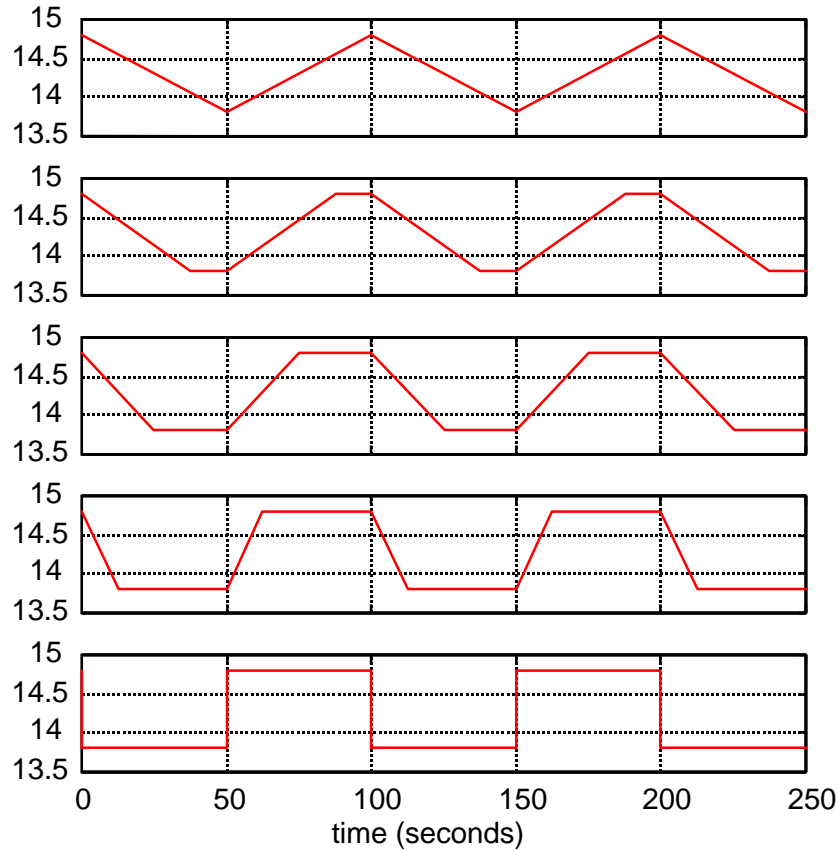
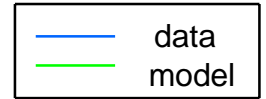
# Storage and Release Rates Depend on Number of Available Pd or Ce Sites



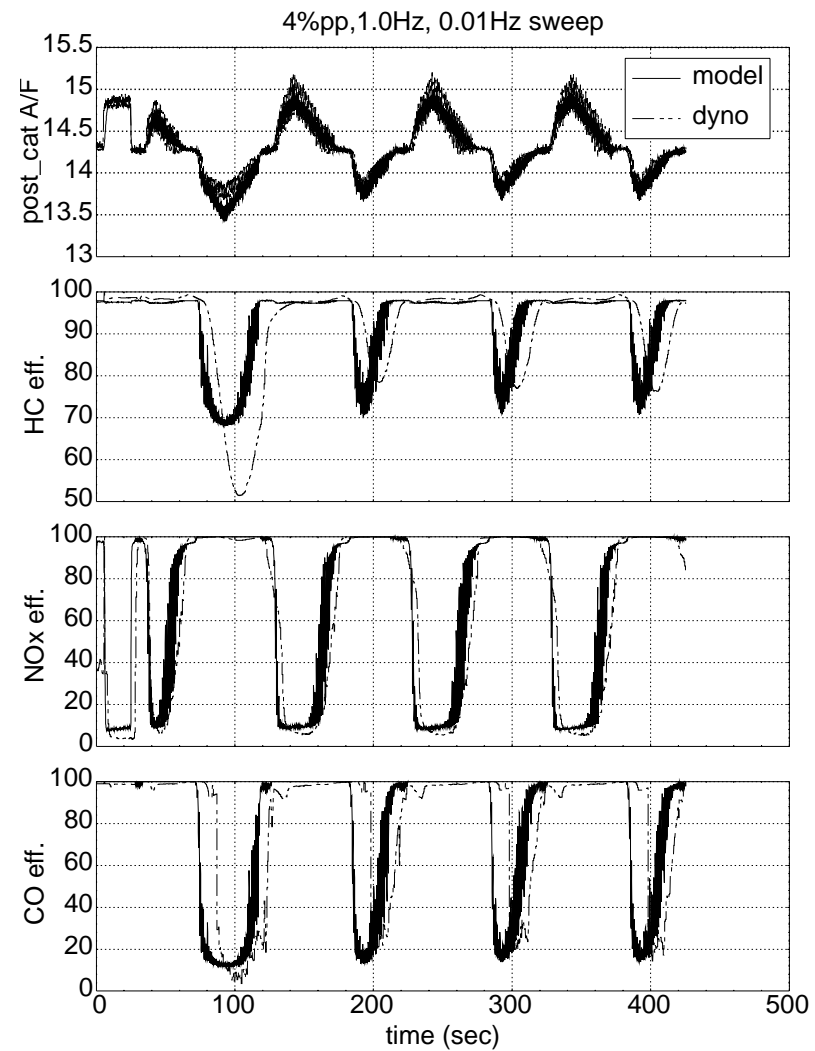
# Dynamic A/F Validation

Sample feedgas A/F input

Tailpipe A/F

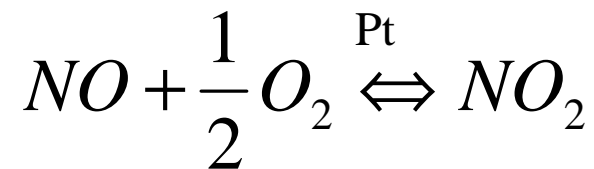


# Dynamic Emissions Validation



# LNT Storage Chemistry

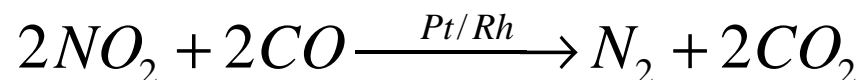
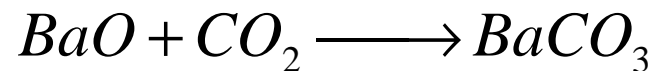
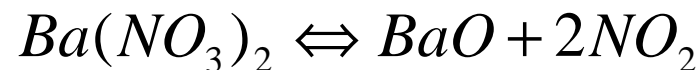
- Under lean conditions, NO is oxidized to NO<sub>2</sub> in the gas phase over platinum.
- The resulting NO<sub>2</sub> is adsorbed on barium carbonate surface as barium nitrate.



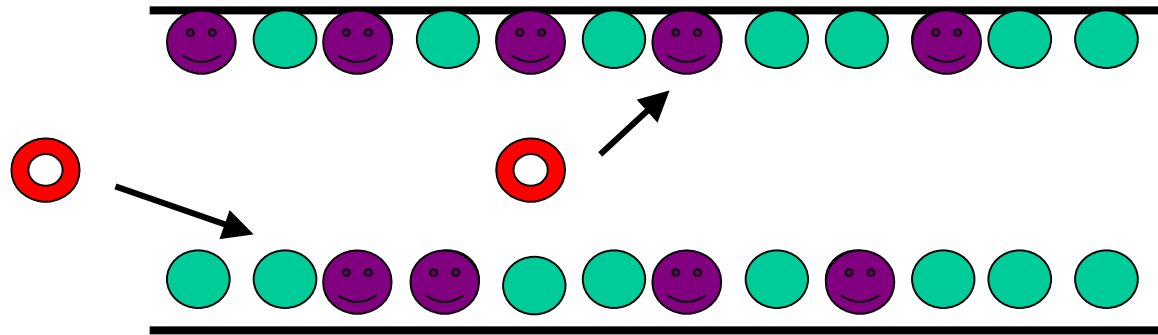
**Surface saturates and must be renewed....by running rich (purging)!**




# LNT Purge Chemistry

- At rich air fuel ratios, the adsorbed barium nitrate is released from the trap as barium oxide.
- In the presence of reducing agents (such as CO, HC and H<sub>2</sub>) and the platinum/rhodium catalyst, the NO<sub>x</sub> is converted to nitrogen.



# Key Feature: State Dependent Storage Efficiency



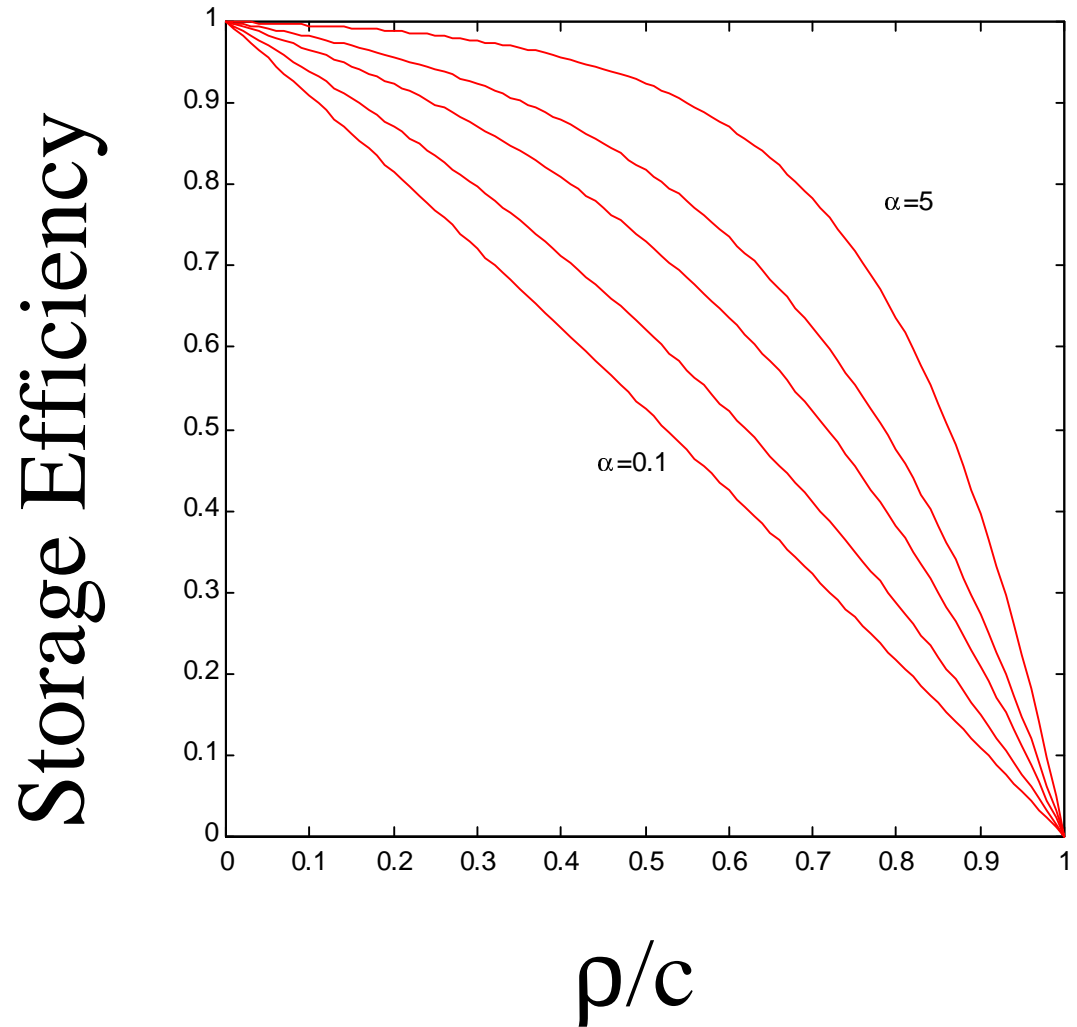
-  =  $\text{NO}_x$
-  =  $\text{BaCO}_3$
-  =  $\text{Ba}(\text{NO}_3)_2$

“Probability of sticking” depends of how full the trap is

# Storage efficiency versus the ratio of trap state to capacity

$$\varepsilon(x) = \frac{e^{\alpha x} - e^{\alpha}}{1 - e^{\alpha}}$$

$$x = \rho/c$$



# Nomenclature for Trap Model

- $\lambda$  relative air fuel ratio of exhaust entering the LNT
- $\rho$  mass of NO<sub>x</sub> stored in the LNT (g)
- $c$  maximum capacity of the LNT (g)
- $\dot{N}O_x$  and  $\dot{C}O$  flow rates of NO<sub>x</sub> and CO into LNT (g/s)
- $\beta$  is the reduction rate of NO<sub>x</sub> in the LNT (fraction)
- $\mu$  is the maximum empty trap storage efficiency (fraction)
- $\gamma$  moles of CO needed to reduce one mole of NO<sub>x</sub>

# Phenomenological Trap Model

## “Mass Balance”

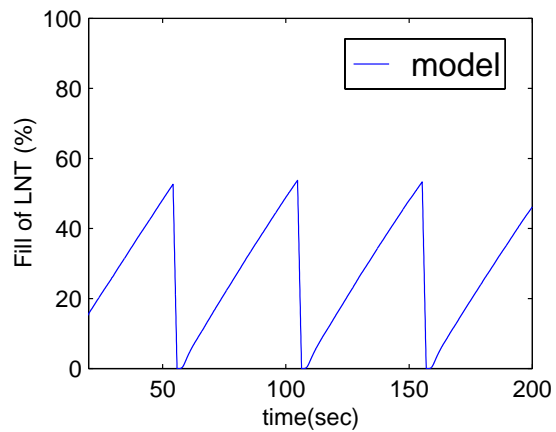
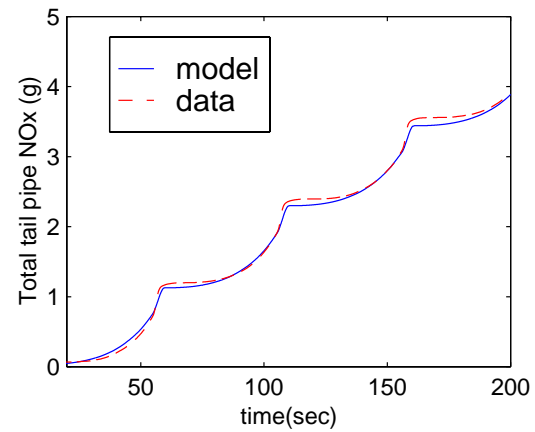
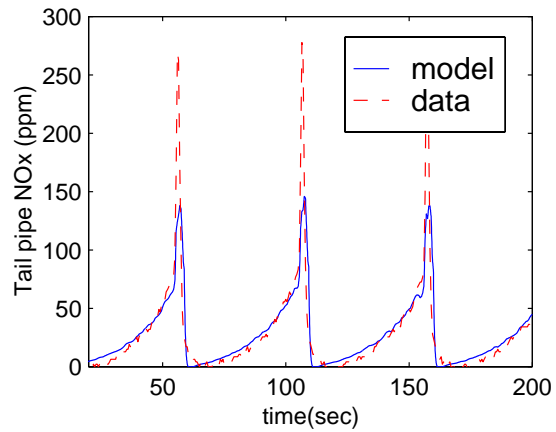
$$\frac{d\rho}{dt} = \begin{cases} f_L(\rho, \dot{NO}_x, c) & \lambda \geq 1 \text{ \& } 0 \leq \rho \leq c \\ f_R(\rho, \dot{CO}) & \lambda < 1 \text{ \& } 0 \leq \rho \leq c \\ 0 & \text{otherwise} \end{cases}$$

$$f_L(\rho, \dot{NO}_x, c) = (1 - \beta) \times \dot{NO}_x \times \mu \times \varepsilon(\rho / c)$$

$$f_R(\rho, \dot{CO}) = -\gamma \times \dot{CO}$$

$$y = \begin{cases} (1 - \beta) \times (\dot{NO}_x - f_L(\rho, \dot{NO}_x, c)) & \lambda \geq 1 \\ 0 & \lambda < 1 \end{cases}$$

# Model versus Data



Not a measurable quantity

# Qualitative Analysis

- Time-scales
    - LNT nominally 30 sec to 1 minute to “fill”; 1 to 3 seconds to “purge”
    - TWC nominally a few secs to “empty-fill”
    - Intake manifold nominally 4 to 6 engine revolutions to “empty-fill”, or 100 ms
- ⇒ Dynamics of exhaust system are dominant
- ⇒ Can start with a static engine model
- ⇒ Optimization complexity determined by exhaust system models

# Optimization Problem

- Overall Model of Engine + Exhaust System

$$x_{k+1} = f(x_k, u_k)$$

$$u = \begin{cases} \text{throttle} \\ \text{fuel} \\ \text{spark} \\ \text{EGR} \\ \dots \end{cases}$$

- Cost

$$J = \sum_{k=1}^N g(x_k, u_k)$$

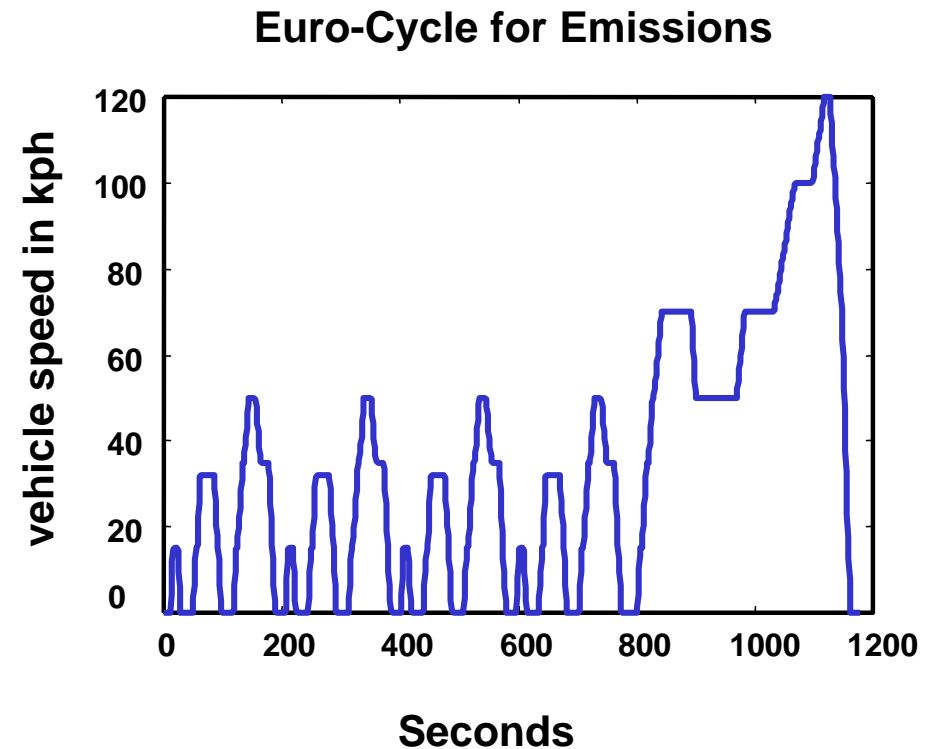
$$g(x_k, u_k) = \text{fuel}_k + \mu \text{NOx}_k$$

# Optimization Problem (cont)

$$\min_{u_k} J = \sum_{k=1}^N g(x_k, u_k)$$

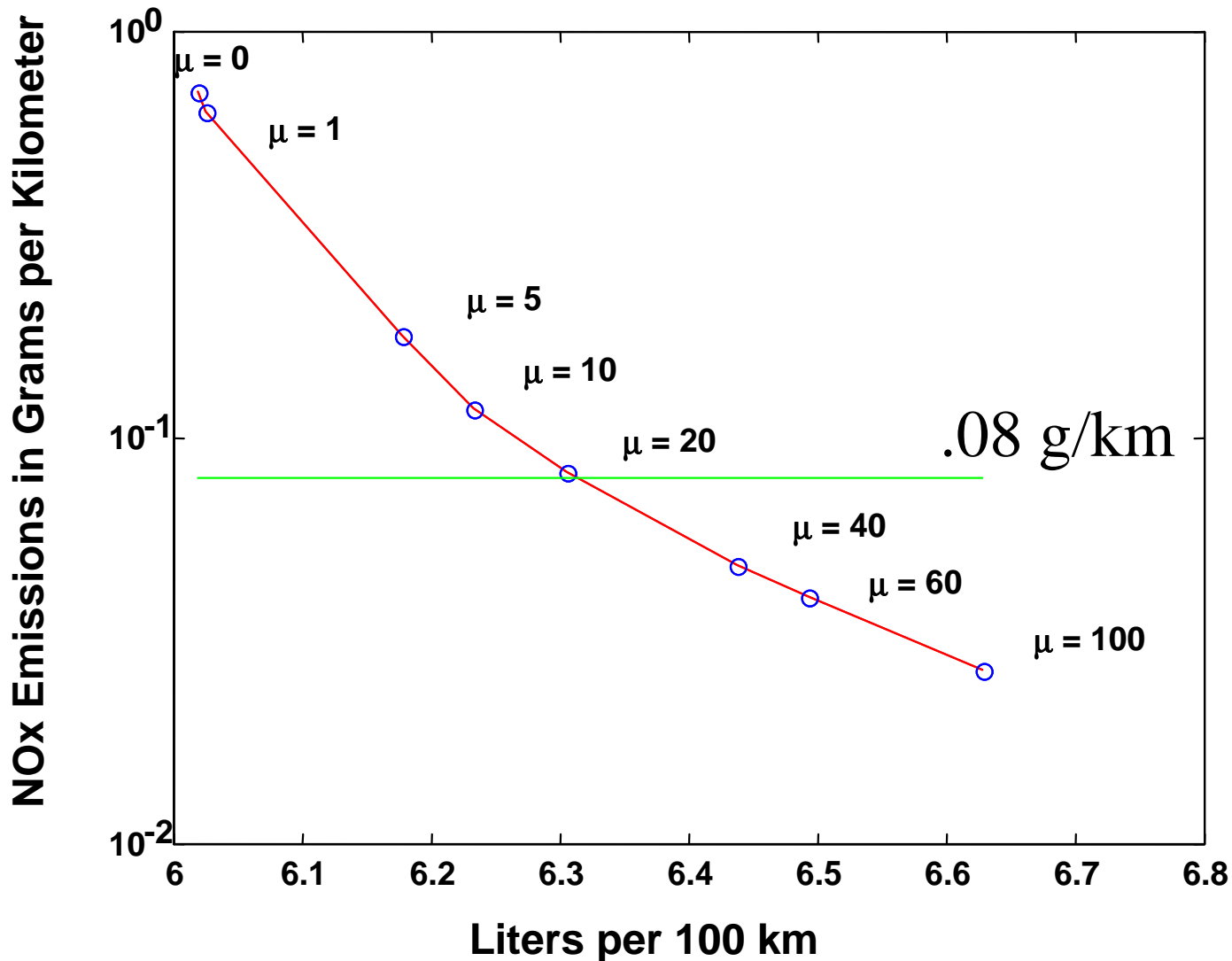
## Subject to:

- Physical limitations on actuators, states ....
- Drive a given emissions cycle (Euro-Cycle)



# Nominal Trade-off Curve

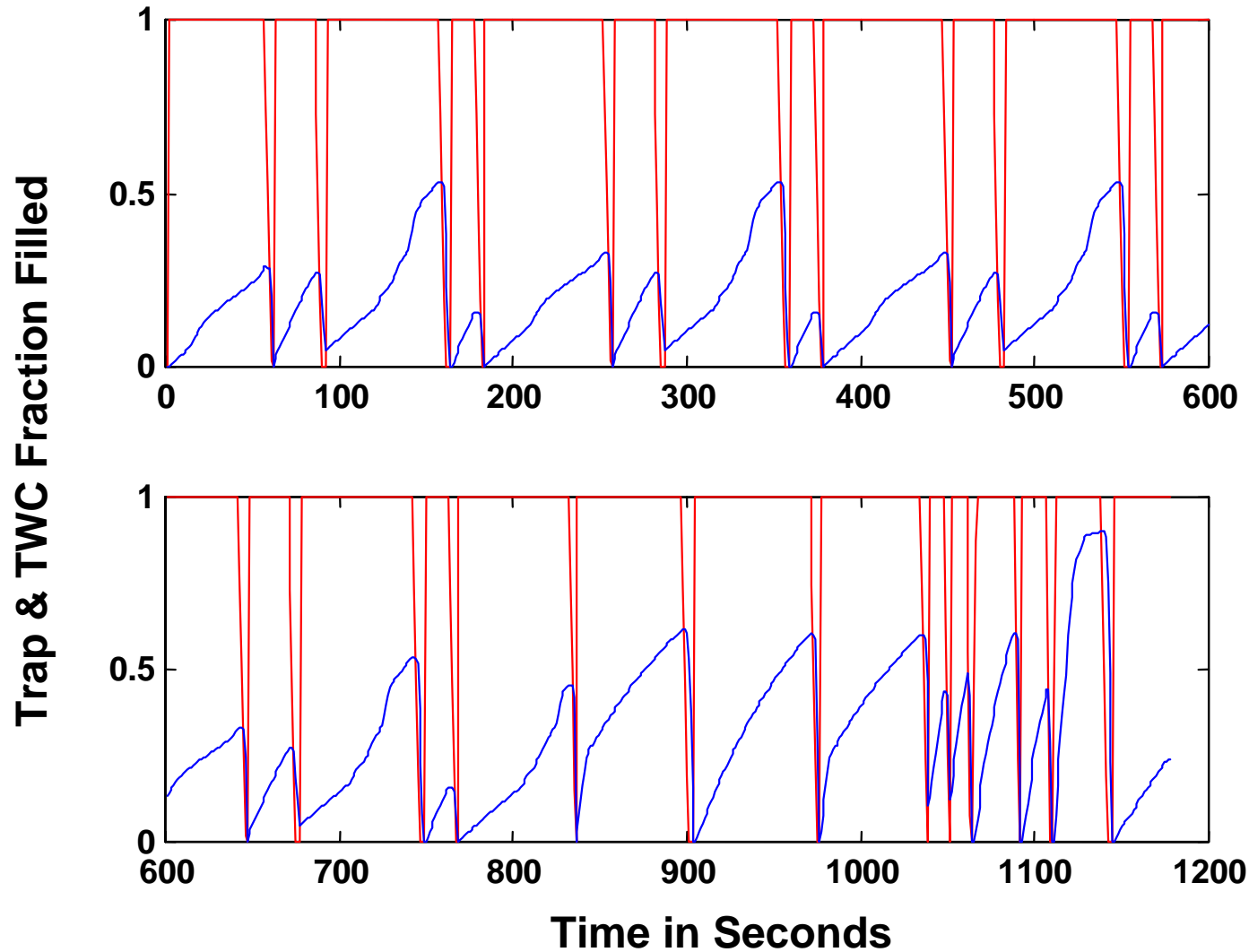
DP Solution: 1.8L DISC on Euro Cycle



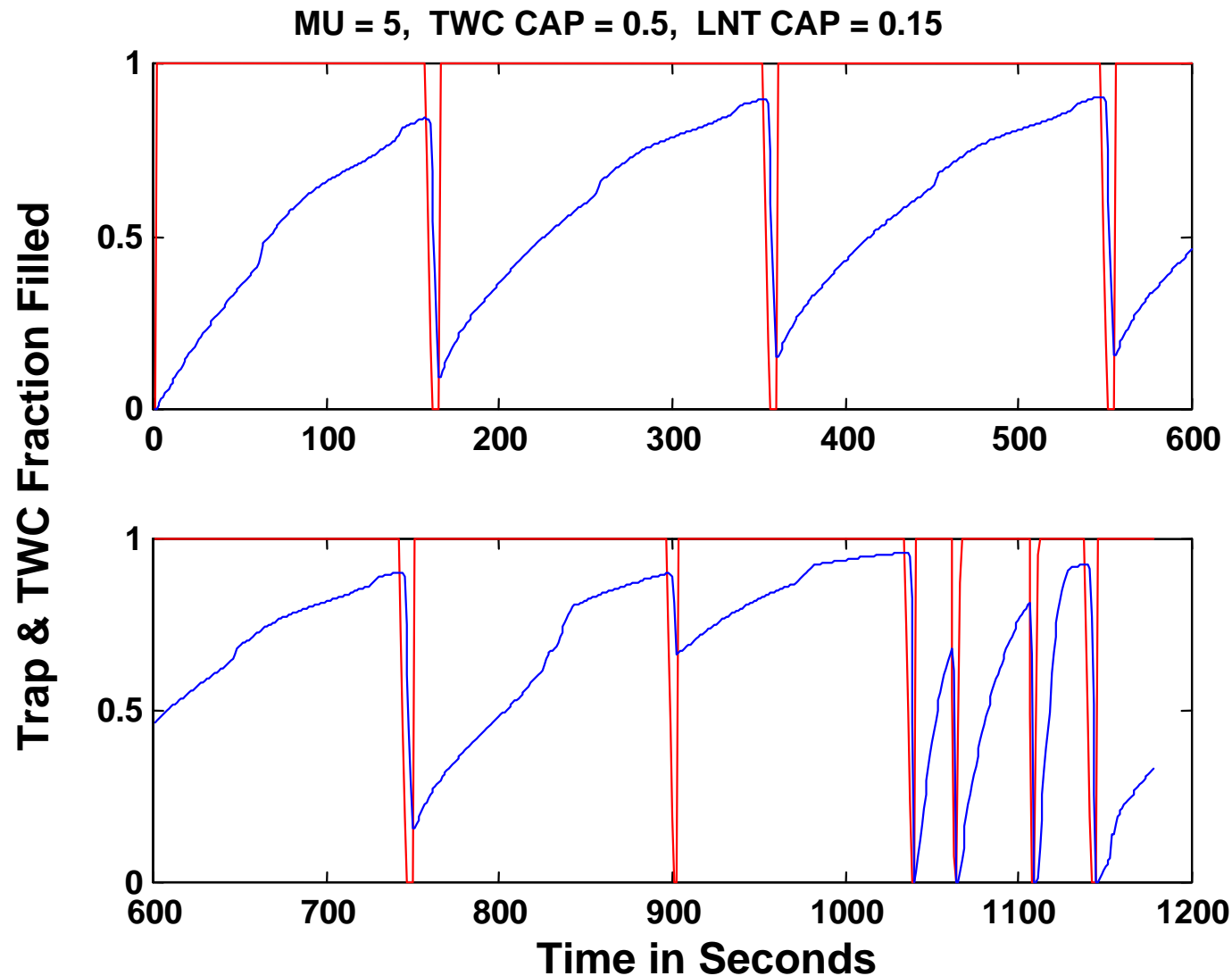
TWC Cap = 0.5 g  
LNT Cap = 0.15g  
FE = 6.3 l/100 km  
= **37.3** mpg

# Nominal Optimal Dynamic Response

MU = 20, TWC CAP = 0.5, LNT CAP = 0.15

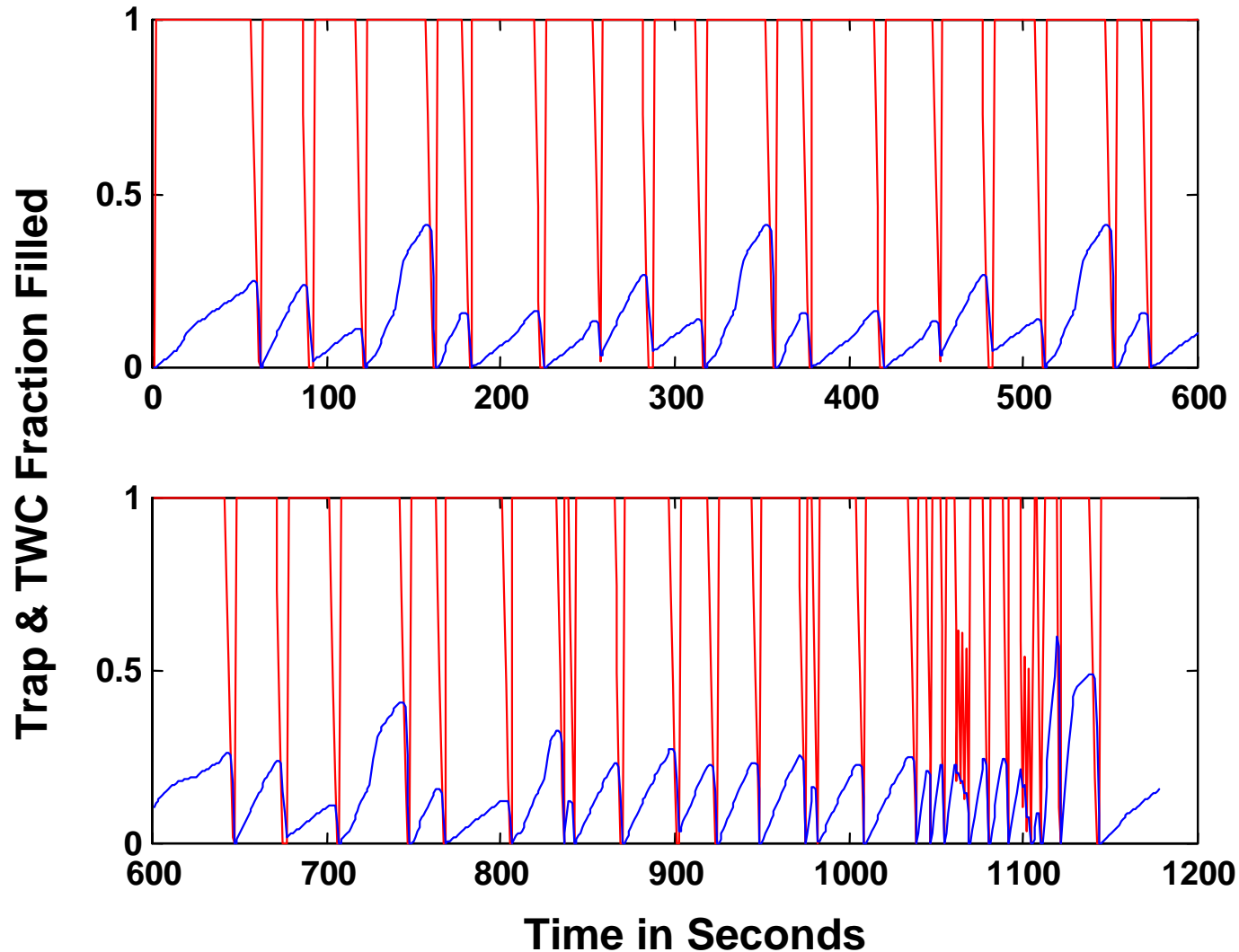


# High Fuel Economy Dynamic Response (infrequent purging)

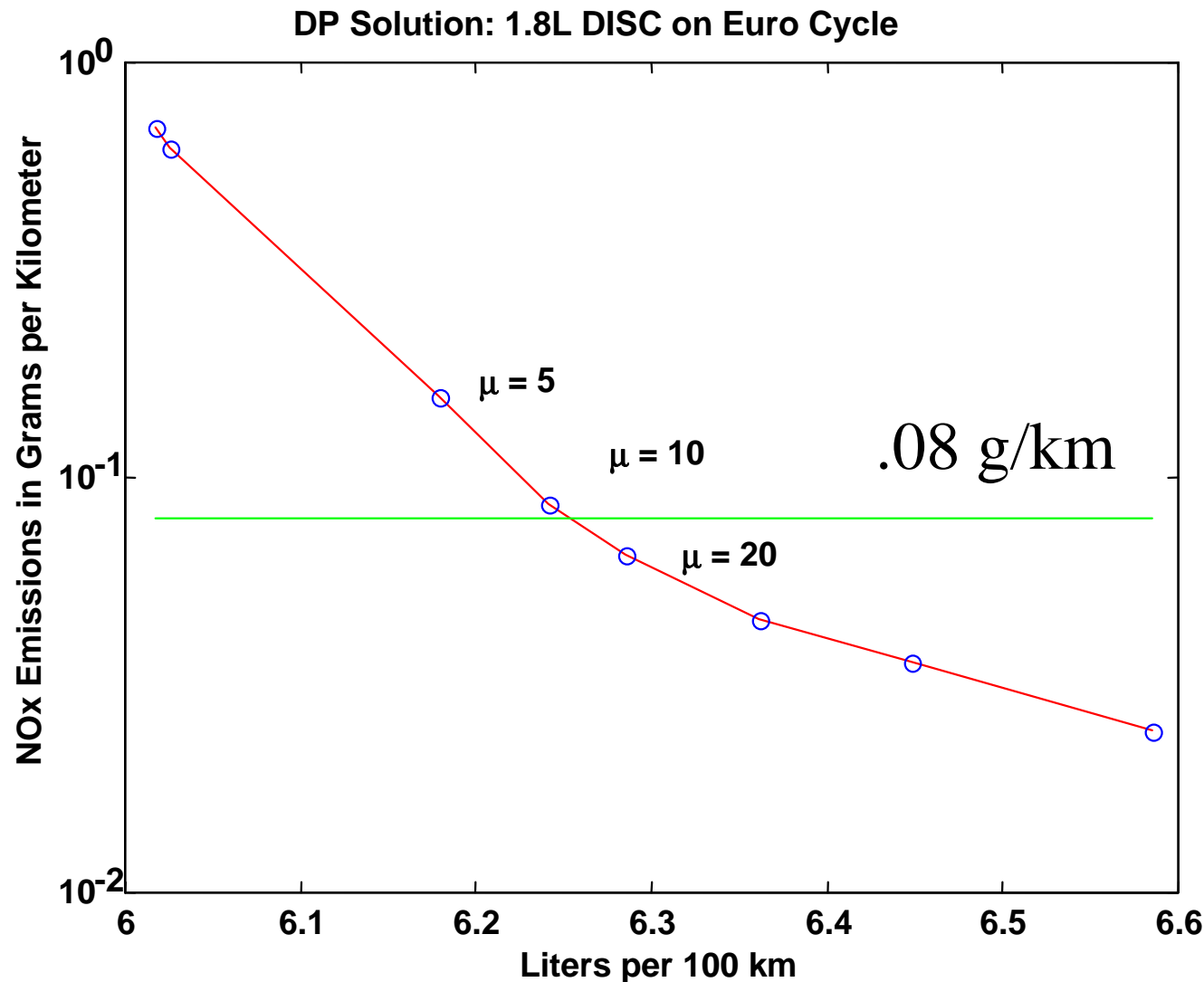


# Lower NO<sub>x</sub> Dynamic Response ( more frequent purging )

MU = 60, TWC CAP = 0.5, LNT CAP = 0.15



# Trade-off Curve w/ 200% LNT Cap.

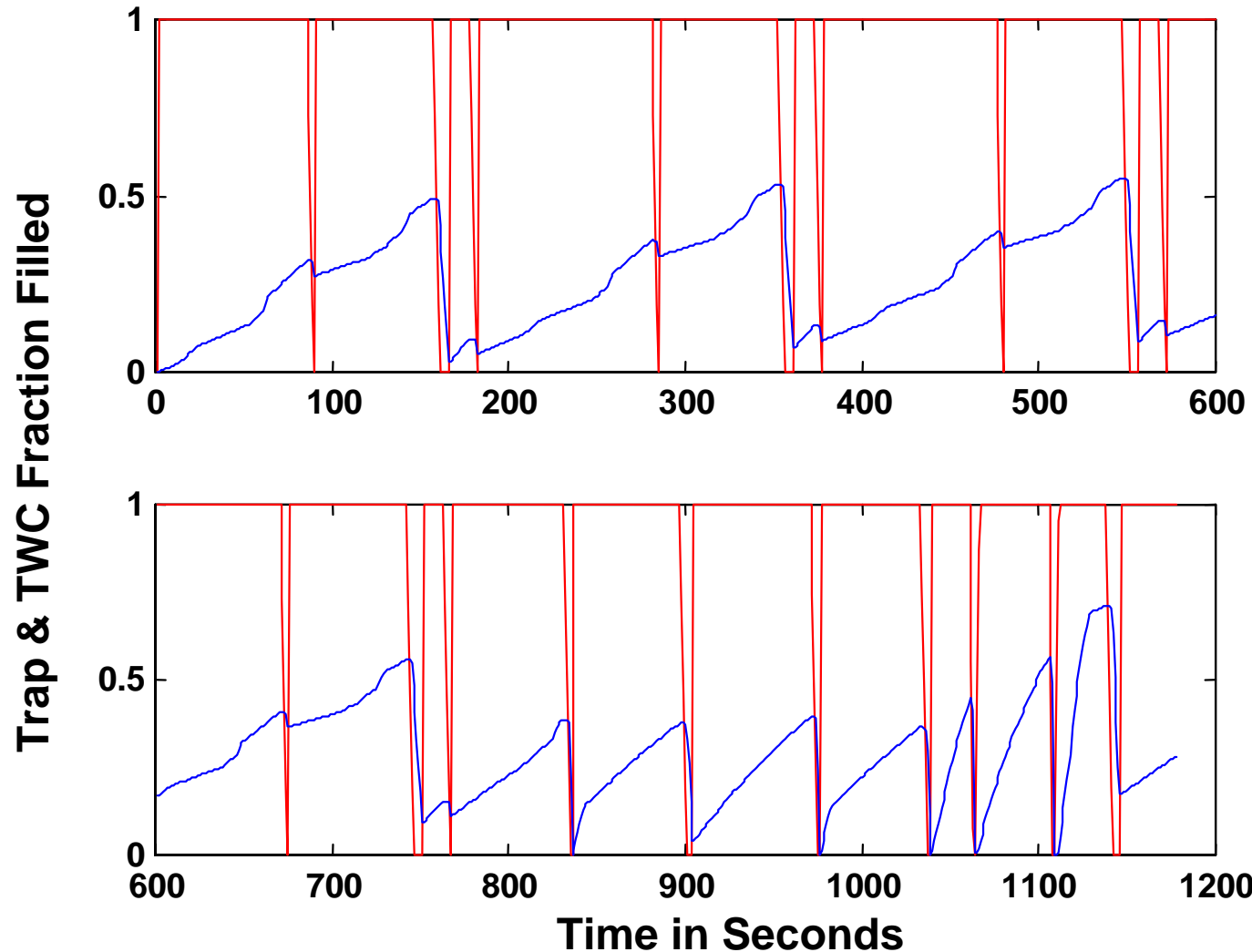


TWC Cap = 0.5 g  
LNT Cap = 0.3g  
FE = 6.25 l/100 km  
= **37.6 mpg**

Nominal = **37.3 mpg**

# Optimal Dynamic Response w/ 200% LNT Capacity

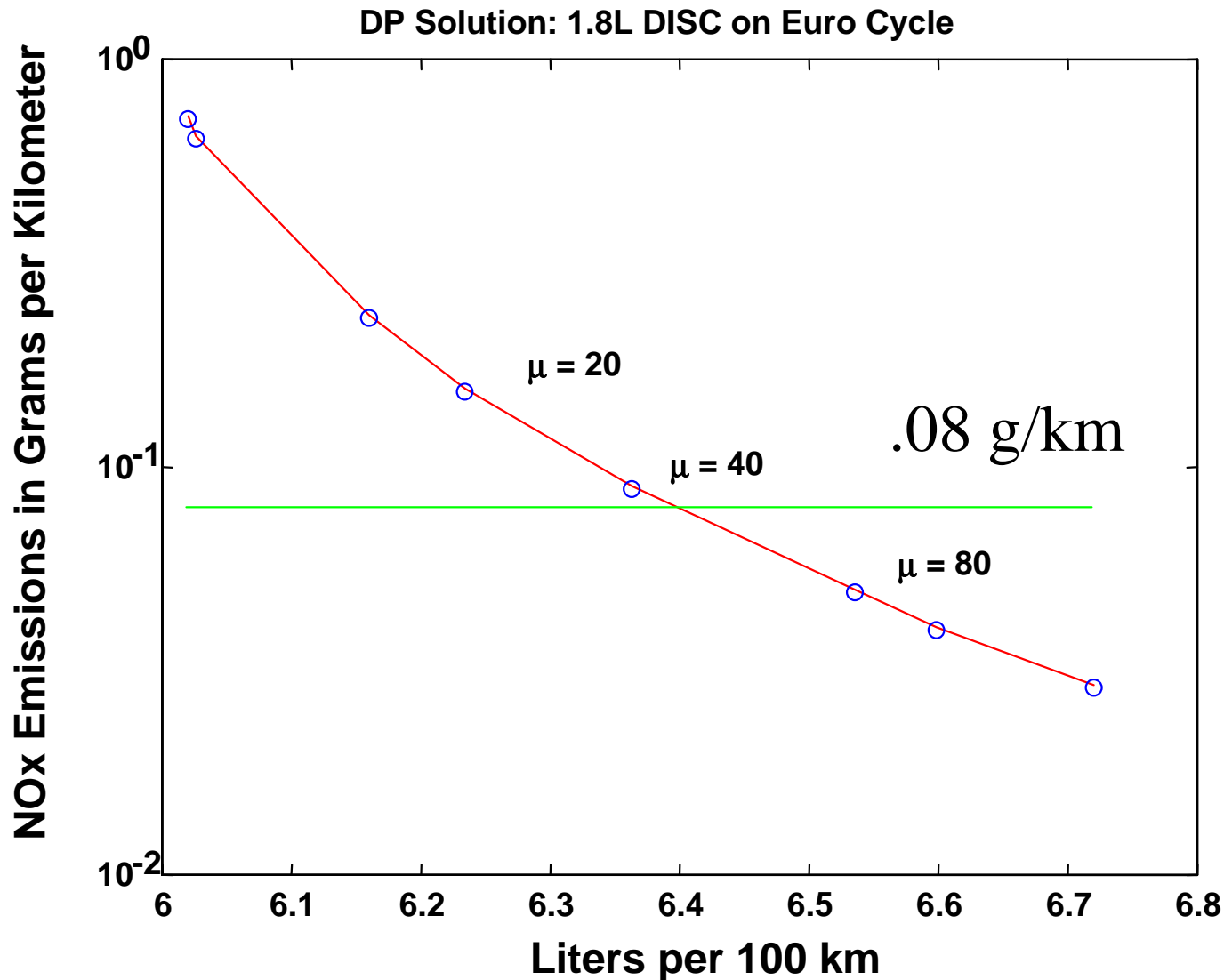
MU = 10, TWC MAX = 0.5, LNT MAX = 0.3



# Remarks

- Doubling the LNT capacity has improved the fuel economy by less than 1%
- However, it has yielded an ‘easier’ closed-loop purge control problem
  - less frequent purging
  - less sensitive to errors in the purge time schedule

# Trade-off Curve w/ 50% LNT Cap.

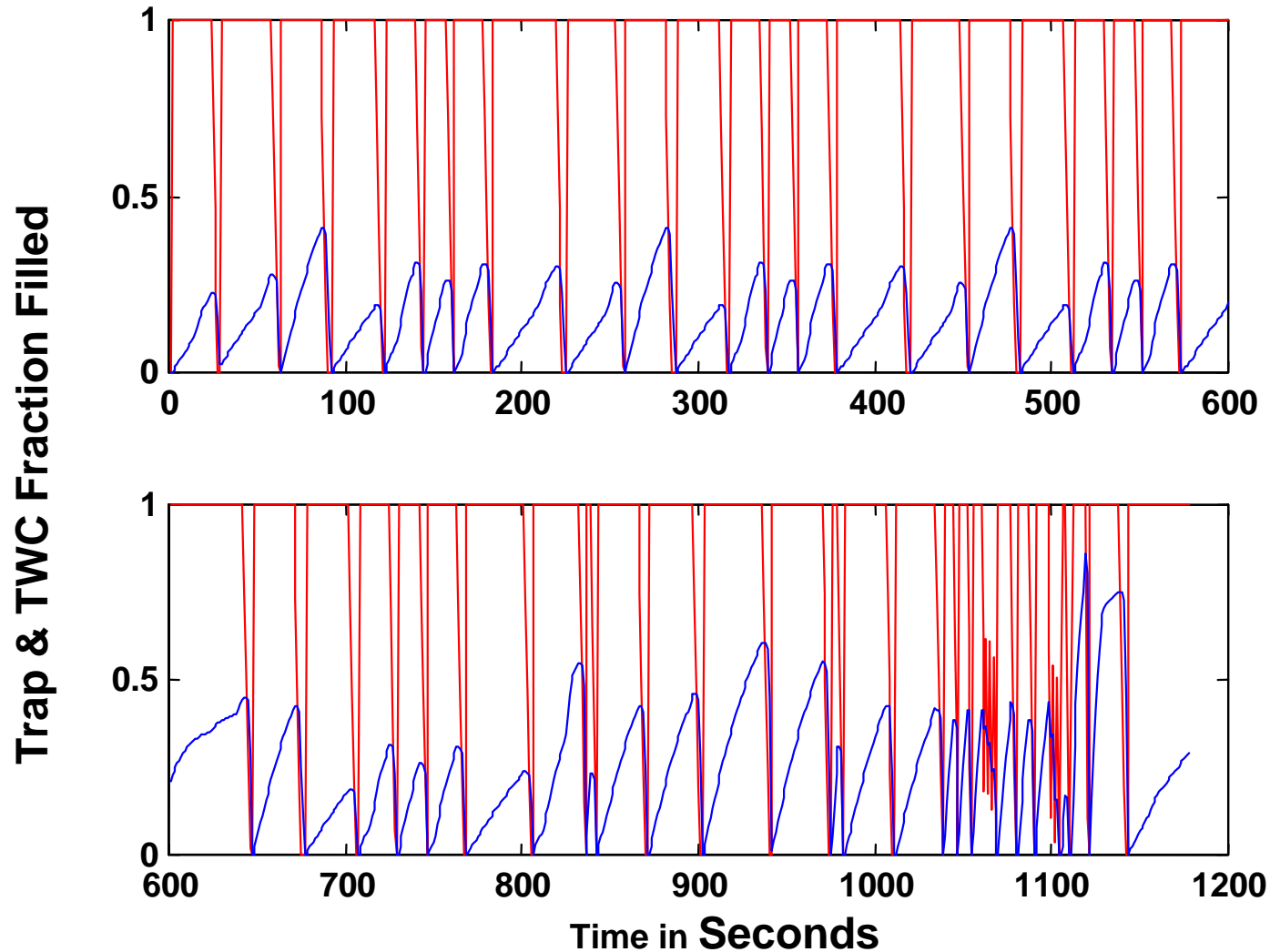


TWC Cap = 0.5 g  
LNT Cap = 0.075 g  
FE = 6.54 l/100 km  
= **36.0 mpg**

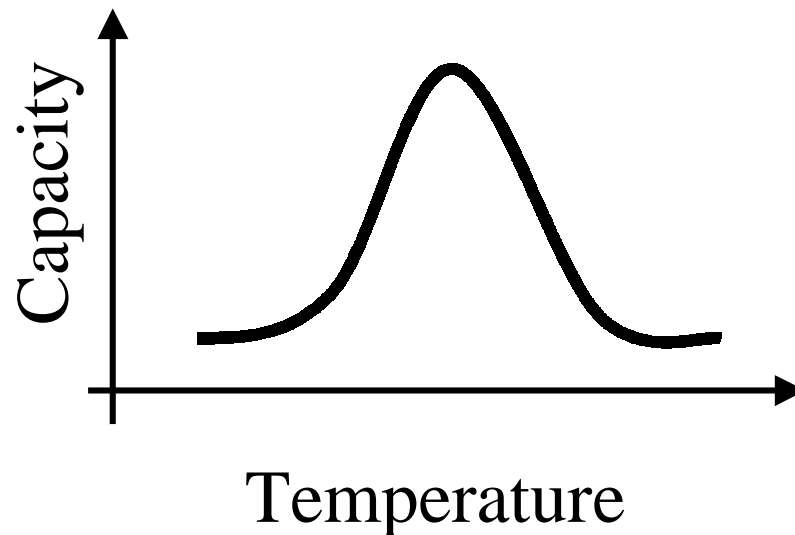
Nominal = **37.3 mpg**

# Optimal Dynamic Response w/ 50% LNT Capacity

MU = 40, TWC CAP= 0.5, LNT CAP = 0.075

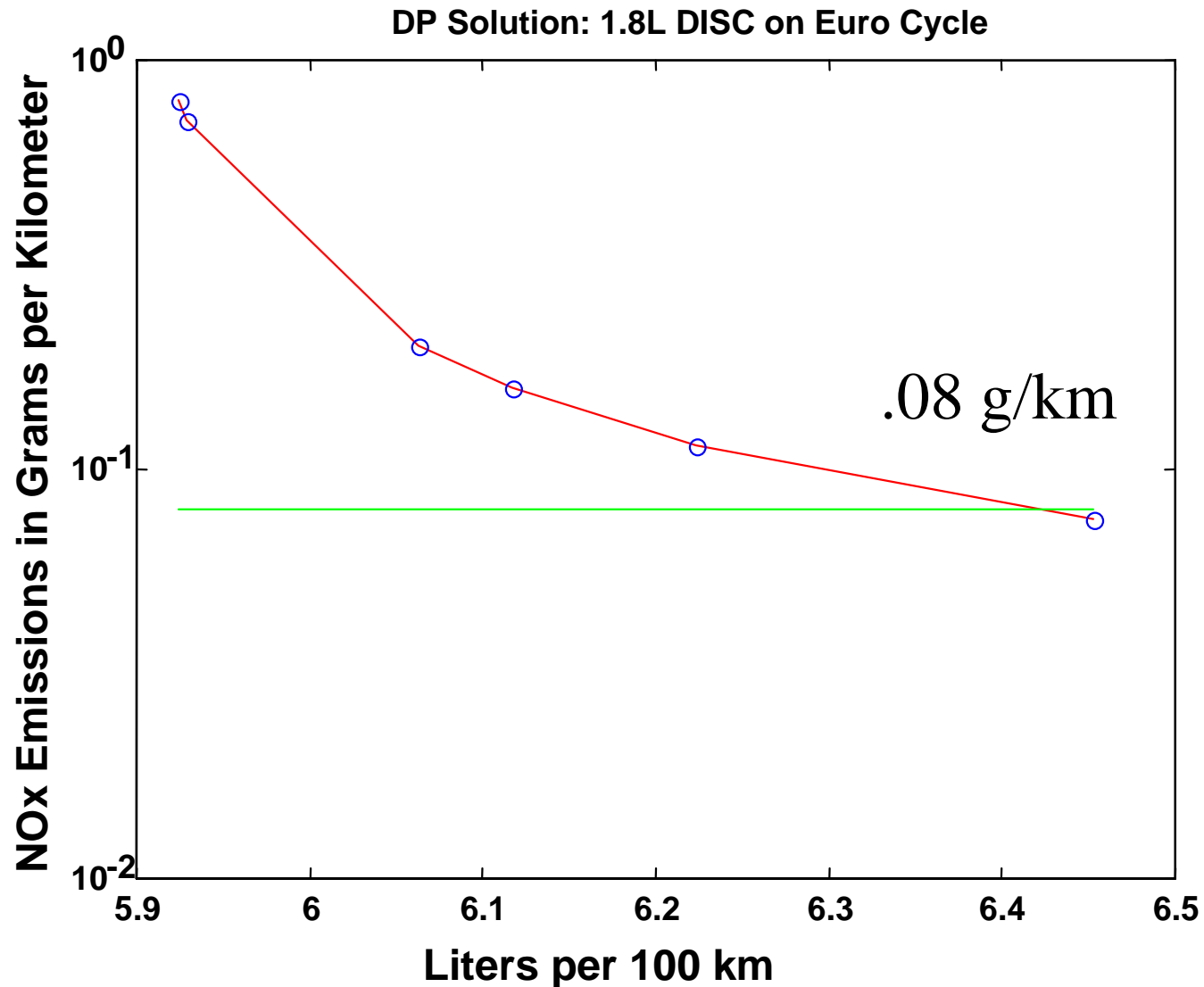


# Temperature Dependence in LNT Performance



- Trap capacity and storage rate depend on temperature
- Will assess impact on performance

# Trade-off Curve w/ Temp. Model



TWC Cap = 0.5 g  
LNT Cap = 0.15 g  
FE = 6.41 l/100 km  
= **36.7 mpg**

Nominal = **37.3 mpg**

# Remarks

- Capacity of trap becomes low in many sections of the Euro-cycle due to temperature variations
  - idles
  - high torque output
- This cannot be easily off-set through feedgas temperature management via spark, for example
- Loss of trap capacity due to temperature is very significant over the Euro-cycle
- Purge control will probably require LNT temperature sensing.

# Conclusions

- Rapid development process requires technology assessment prior to full hardware build-ups
- A model based performance assessment of a lean burn system was undertaken here
  - models were developed separately and in parallel
  - exhaust system models were a key component
  - optimization based methods allows one to systematically sort through dynamic performance issues ...
  - ... if you can determine a low dimensional set of dominant dynamics