8th International Workshop on Sustainable Road Freight

The Centre For Sustainable Road Freight

Predictive powertrain control with connectivity to improve efficiency & emission for heavy duty trucks

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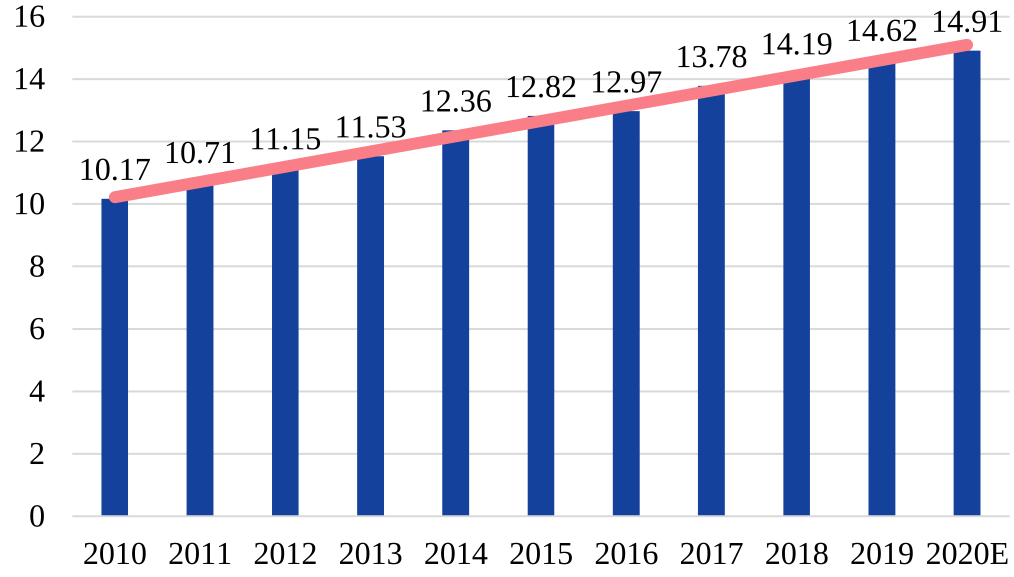
Chen's group

Content

Background

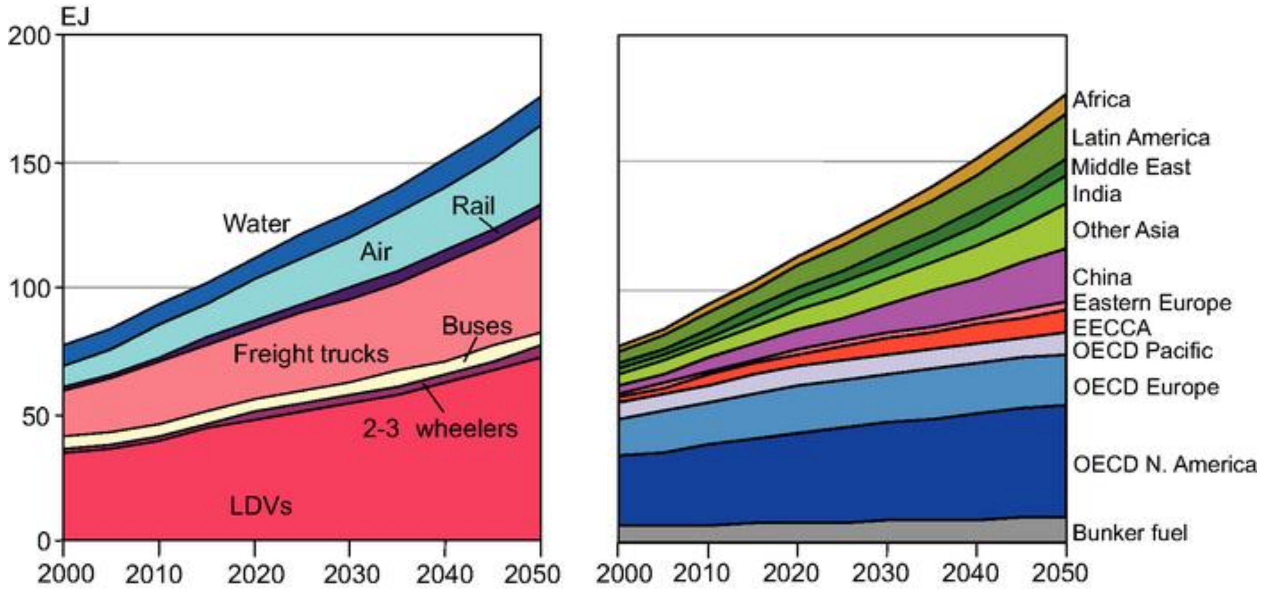
■ **Much more energy consumed due to the increasing number of vehicles**

➢ 2010-2020 World Vehicle Parc (Unit: 100M)



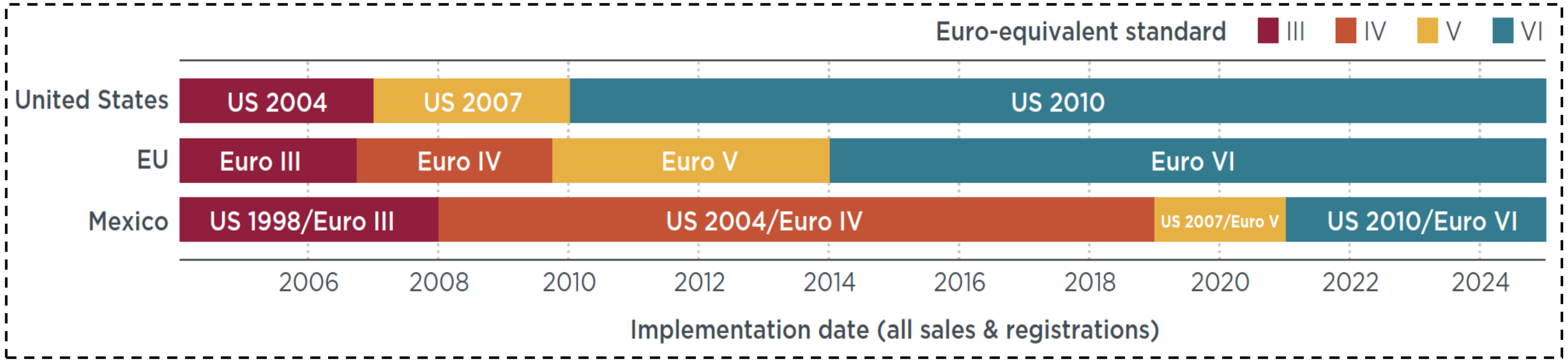
≈1.5B

➢ Energy demand is increasing

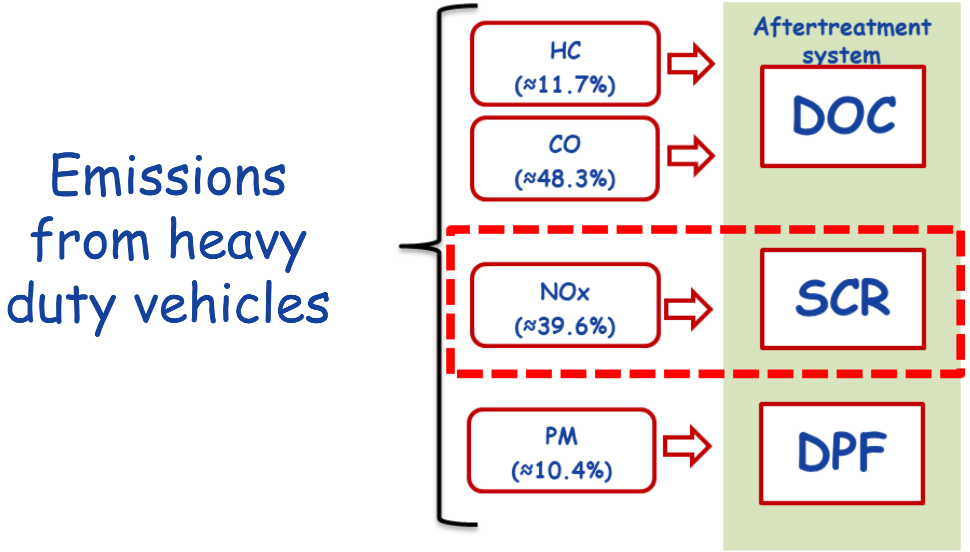


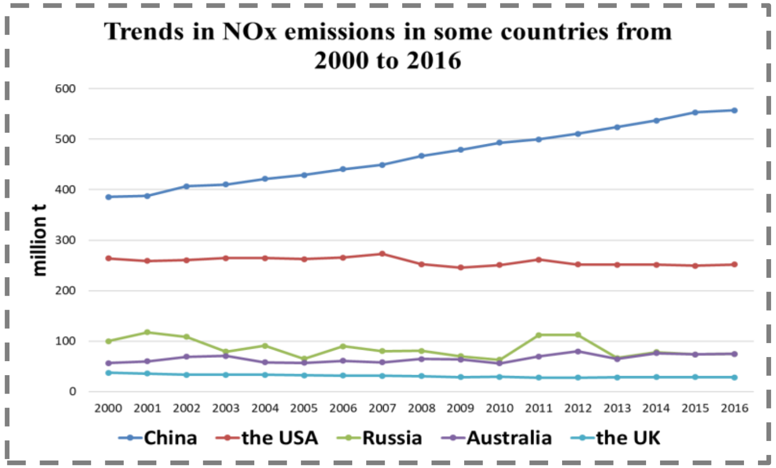
Background

■ Emission is more serious and regulations is more strict



■ Emission reduction is urgent, especially the NOx





⇨

Acid Rain

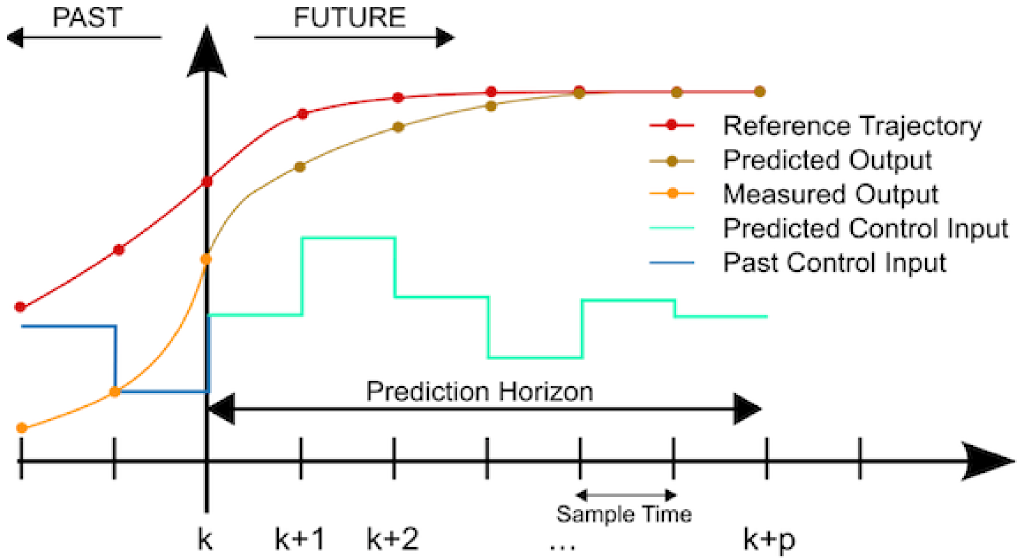
Photochemical Smog

Methemoglobinemia

Background

- Connectivity brings more data

- Predictive Control is the best fit for powertrain with connectivity

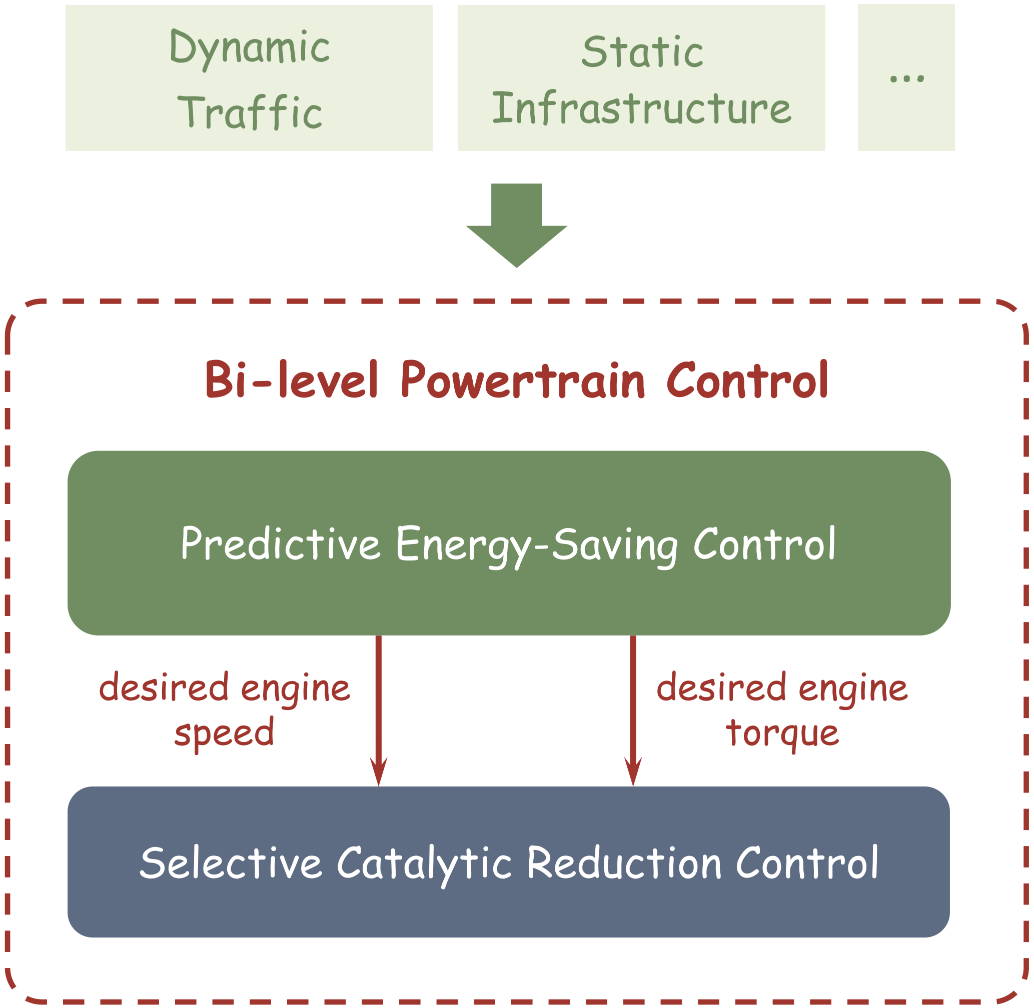


is potentially able to improve the efficiency and reduce emissions

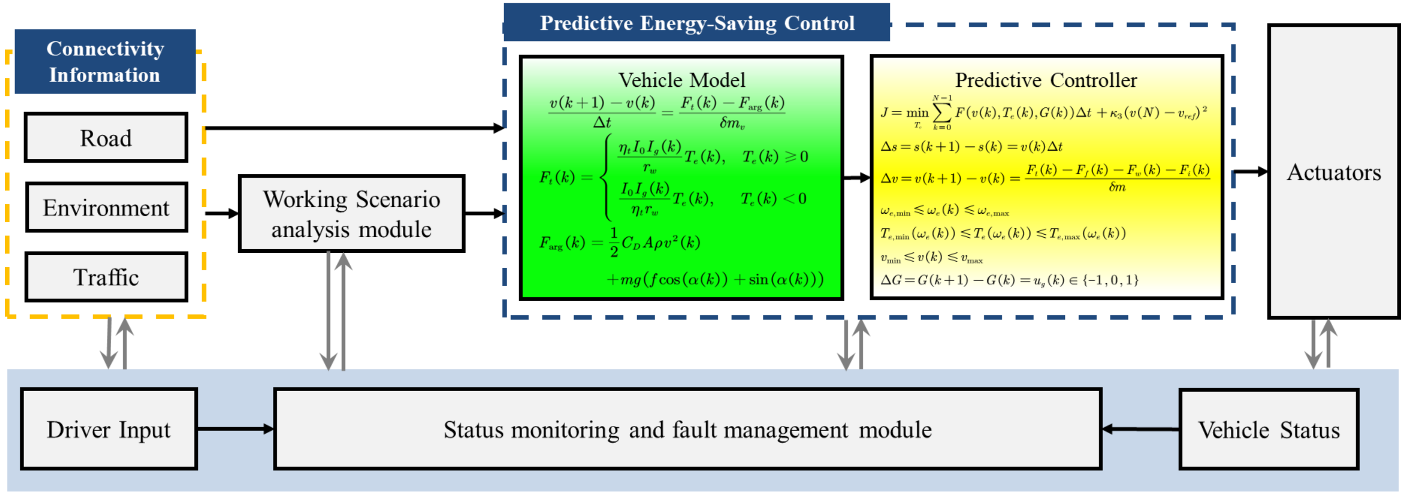
Predictive Powertrain Control with Connectivity

■ Predictive Powertrain Control

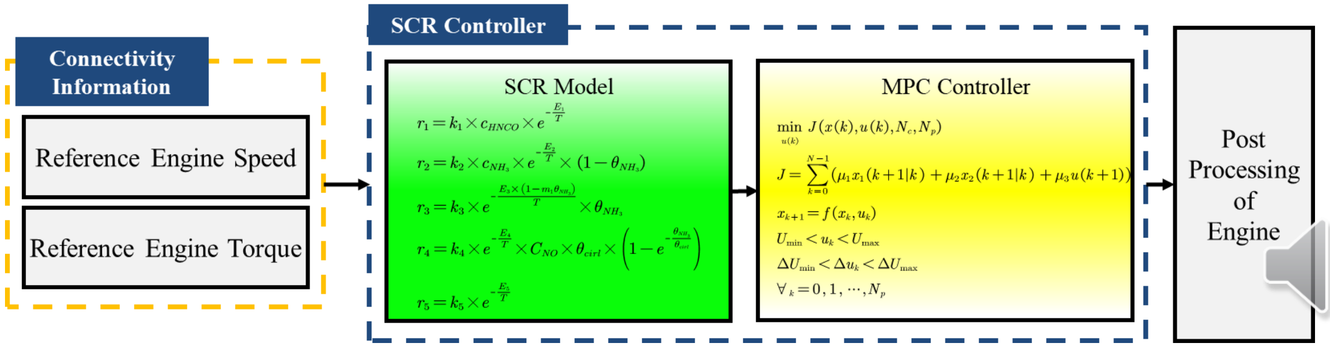
Connectivity Information



Predictive Energy-Saving Control (PESC)



Selective Catalytic Reduction Control (SCRC)



Predictive Powertrain Control with Connectivity

■ Tianlong Qijian Heavy-Duty Truck @Dongfeng

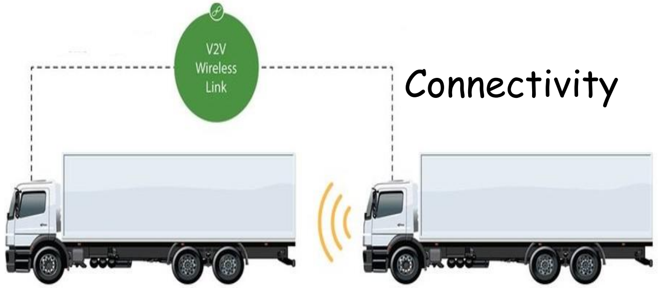
Parameters	Value	Units
Vehicle mass	49000	kg
Transmission eff.	0.98	-
Max engine torq.	2650	Nm
Frontal area	4.2	M^2
Air drag co.	0.5	-
Tire radius	526.7	mm

■ Scenario #1

Available data:

- Road Slope
- Road Curvature
- Speed Limit
- Desired Speed: 80km/h

■ Scenario #2



Available data

- Preceding Vehicle Speed

Predictive Powertrain Control with Connectivity

Powertrain Model

Drivetrain longitudinal dynamics

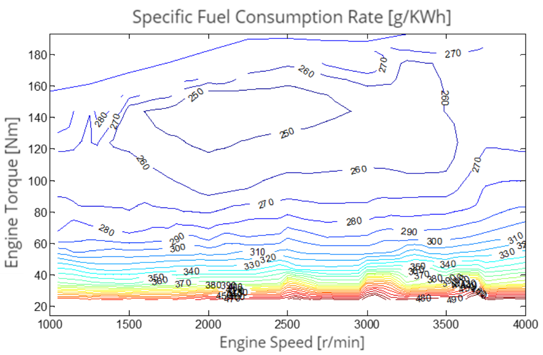
$$\frac{v(k+1)-v(k)}{\Delta t}=\frac{F_t(k)-F_{\arg}(k)}{\delta m_v}$$

$$F_t(k)=\begin{cases}\dfrac{\eta_t I_0 I_g(k)}{r_w}T_e(k), & T_e(k)\geqslant 0\\[2ex] \dfrac{I_0 I_g(k)}{\eta_t r_w}T_e(k), & T_e(k)<0\end{cases}$$

$$F_{\arg}(k)=\frac{1}{2}C_D A\rho v^2(k)$$

$$+mg(f\cos(\alpha(k))+\sin(\alpha(k)))$$

Fuel consumption rate



$$Q_f=Q_{BSFC}(T_e,\omega_e)P_e$$

$$Q_f=\sum_{i=0}^{2}\sum_{j=0}^{2}\iota_{i,j}T_e^i\omega_e^i$$

SCR Model

Chemical reaction rate within SCR

$$r_1=k_1\times c_{HNCO}\times e^{-\frac{E_1}{T}}$$

$$r_2=k_2\times c_{NH_3}\times e^{-\frac{E_2}{T}}\times(1-\theta_{NH_3})$$

$$r_3=k_3\times e^{-\frac{E_3\times(1-m_1\theta_{NH_3})}{T}}\times\theta_{NH_3}$$

$$r_4=k_4\times e^{-\frac{E_4}{T}}\times C_{NO}\times\theta_{cirl}\times\left(1-e^{-\frac{\theta_{NH_3}}{\theta_{cirl}}}\right)$$

$$r_5=k_5\times e^{-\frac{E_5}{T}}$$

SCR dynamics

$$\begin{cases}\dot{C}_{NO_x}=EF_V\times\dot{C}_{NO_x,in}-4r_4-EF_V\times\dot{C}_{NO_x}\\ \dot{C}_{NH_3}=EF_V\times\dot{C}_{NH_3,in}+r_1-r_2+r_3-EF_V\times\dot{C}_{NH_3,out}\\ \dot{\theta}=(r_2-r_3+4\times r_4-4\times r_5)/\theta_{\max}\end{cases}$$

Predictive Powertrain Control with Connectivity

Optimal Control Problem for PESC

Objective Function

$$J = \min_{T_e} \sum_{k=0}^{N-1} F(v(k), T_e(k), G(k))\Delta t + \kappa_3 (v(N) - v_{ref})^2$$

$$F(v(k), T_e(k), G(k)) = Q_f(k) + \kappa_1 (v(k) - v_{ref})^2 + \kappa_2 P(k)$$

$Q_f(k)$: Fuel Consumption $\kappa_1 (v(k) - v_{ref})^2$: Speed Tracking

$\kappa_2 P(k)$: Driving Comfort $\kappa_3 (v(N) - v_{ref})^2$: Terminal Constraints

Variable State Constraints

$$\Delta s = s(k+1) - s(k) = v(k)\Delta t$$

$$\Delta v = v(k+1) - v(k) = \frac{F_t(k) - F_f(k) - F_w(k) - F_i(k)}{\delta m}$$

$$\omega_{e,\min} \leqslant \omega_e(k) \leqslant \omega_{e,\max}$$

$$T_{e,\min}(\omega_e(k)) \leqslant T_e(\omega_e(k)) \leqslant T_{e,\max}(\omega_e(k))$$

$$v_{\min} \leqslant v(k) \leqslant v_{\max}$$

$$\Delta G = G(k+1) - G(k) = u_g(k) \in \{-1, 0, 1\}$$

Optimal Control Problem for SCR

Objective Function

$$\min_{u(k)} J(x(k), u(k), N_c, N_p)$$

$$J = \sum_{k=0}^{N-1} (\mu_1 x_1(k+1|k) + \mu_2 x_2(k+1|k) + \mu_3 u(k+1))$$

x_1: SCR outlet NO_x concentration

x_2: SCR outlet ammonia concentration

u: Ammonia coverage ratio

μ_1, μ_2, μ_3: weighting factors

Variable State Constraints

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

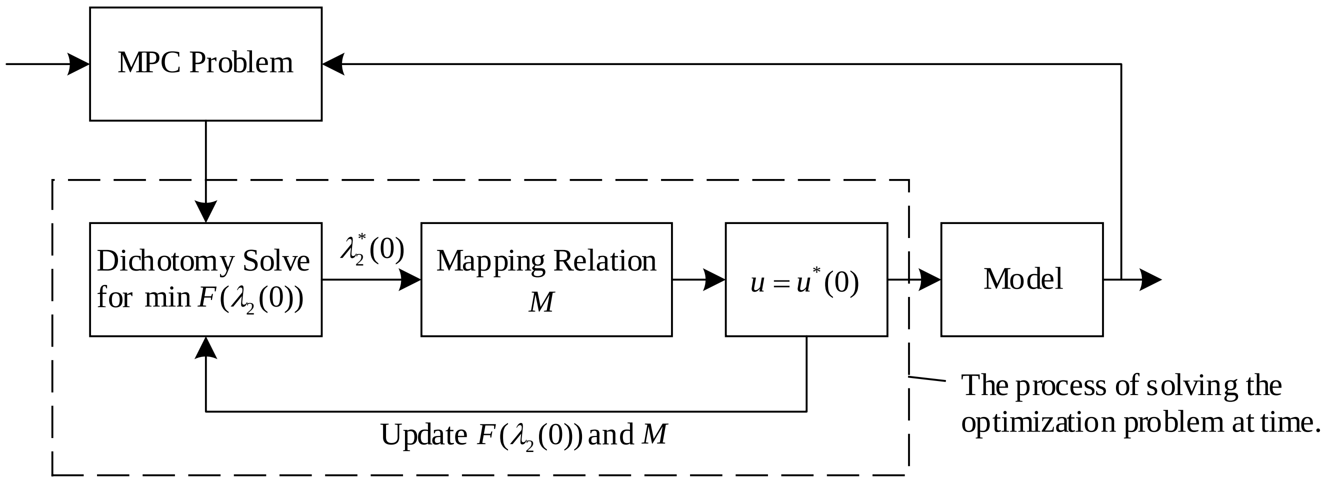
$$U_{\min} < u_k < U_{\max}$$

$$\Delta U_{\min} < \Delta u_k < \Delta U_{\max}$$

$$\forall_k = 0, 1, \cdots, N_p$$

Predictive Powertrain Control with Connectivity

■ Numerical Solution of Optimization Problems



Mapping from the initial covariate $\lambda_2(0)$ to the terminal covariate function $F(\lambda_2(0))$

$$\boxed{\lambda_2(0), x(0) \Rightarrow u(0) \Rightarrow \lambda_2(1), x(1) \Rightarrow u(1) \Rightarrow \cdots \lambda_2(k), x(k) \Rightarrow u(k) \cdots \Rightarrow \lambda_2(N), x(N) \Rightarrow F(\lambda_2(0))}$$

$$\{\lambda(0), x(0)\} \Rightarrow u(0) \Rightarrow \{\lambda(1), x(1)\} \Rightarrow u(1) \Rightarrow \cdots$$
$$\Rightarrow \{\lambda(k), x(k)\} \Rightarrow u(k) \Rightarrow \cdots \Rightarrow \{\lambda(N), x(N)\}$$

$$H(k) = \rho_1(k)T_e^2(k) + \rho_2(k)T_e(k) + \rho_3(k)$$
$$= \rho_4(k)v_e^2(k) + \rho_5(k)v_e(k) + \rho_6(k)$$

$$\lambda(N) = 2\kappa(v(N) - v_{ref})$$

Solving the optimal terminal covariate $\lambda(N)$ iteratively using the dichotomous method

$$\lambda(N) - 2\kappa(v(N) - v_{ref}) \le \varepsilon$$

Reverse Mapping

Optimal initial covariance $\lambda(0)$ and the corresponding $T_e^{opt}(0)$

Given the initial value of a covariate $\lambda(0)$, the corresponding terminal value of the covariate $\lambda(N)$ can be obtained along the necessary conditions and the optimal control law. The optimal problem is transformed into a problem of solving equations by finding the optimal initial covariates $\lambda(0)$ that satisfy the terminal necessary conditions

Predictive Powertrain Control with Connectivity

■ Consider 5 Combinations of Control Schemes

Baseline Controller (BC)

- Without connectivity
- Only tracking the desired velocity

BC with SCRC

- Baseline Controller with a typical industrial feedforward SCR controller

Predictive Energy Saving Controller (PESC)

- Have access to information via connectivity
- Consider both fuel saving and speed tracking

PESC with SCRC

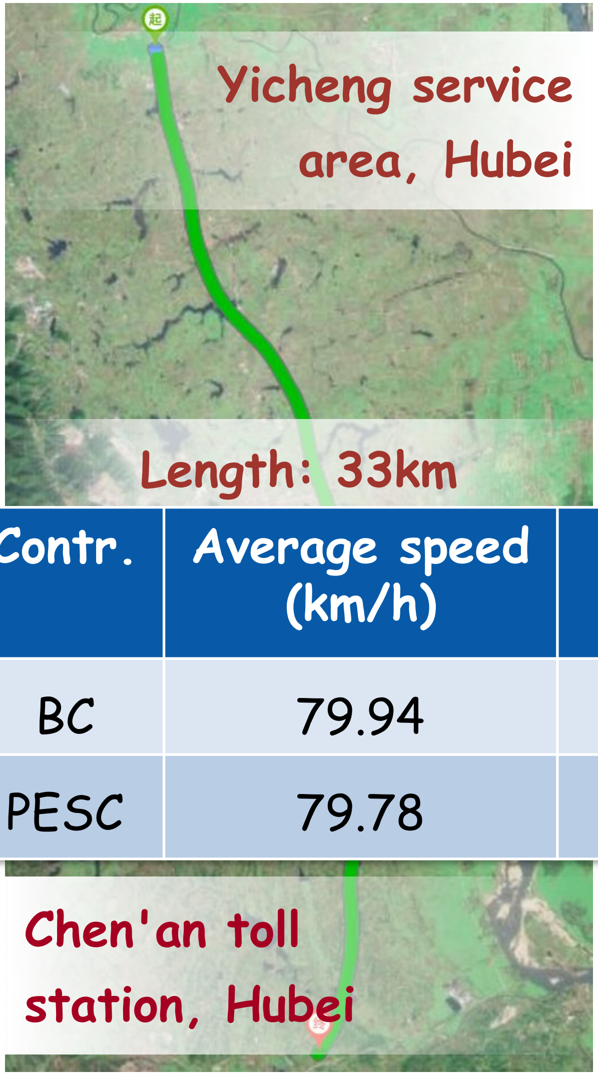
- PESC with a typical industrial feedforward SCR controller

PESC with PSCRC

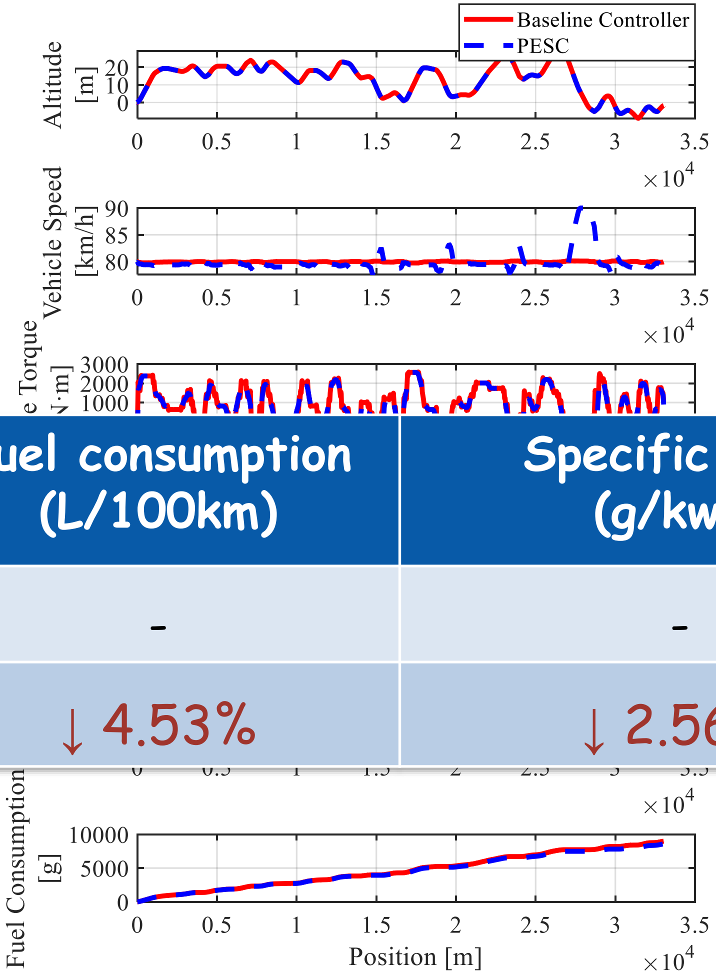
- PESC with the proposed predictive SCRC

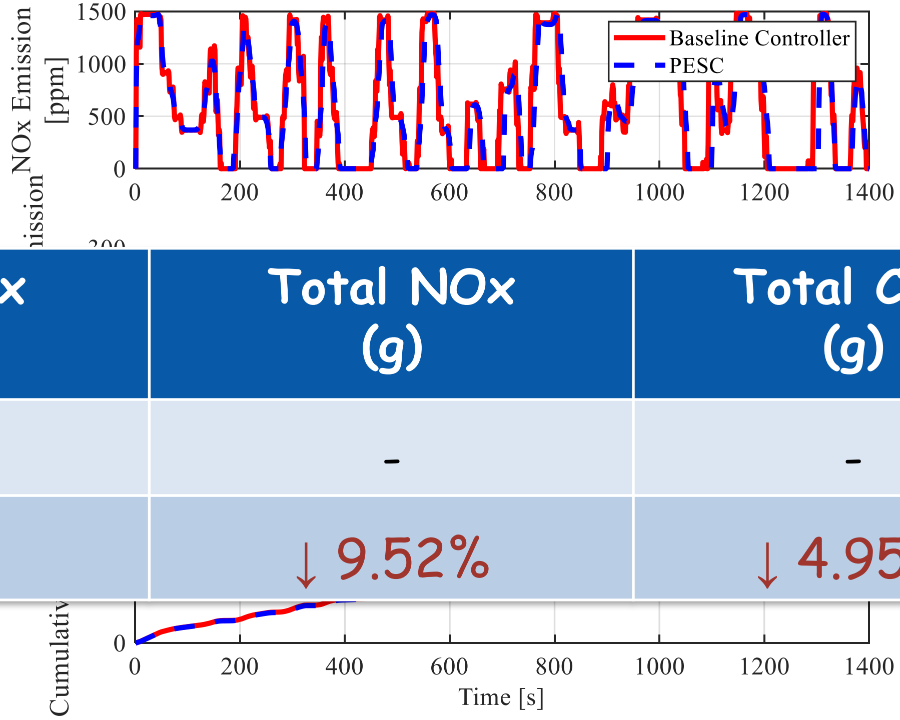
Predictive Powertrain Control with Connectivity

■ Simulation Results of Scenario #1



➢ Energy Saving



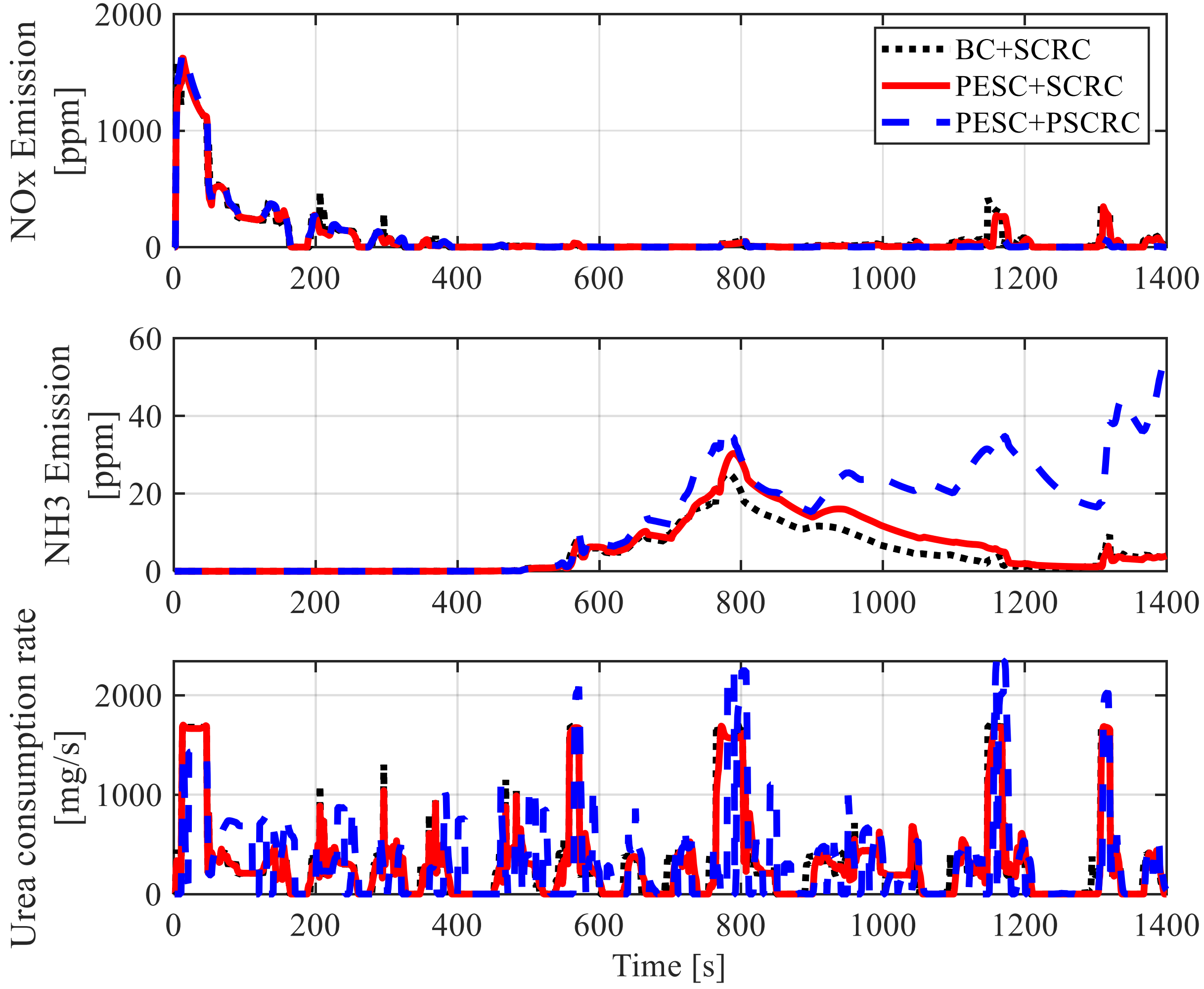


Contr.	Average speed (km/h)	Fuel consumption (L/100km)	Specific NOx (g/kwh)	Total NOx (g)	Total CO2 (g)
BC	79.94	-	-	-	-
PESC	79.78	↓ 4.53%	↓ 2.56%	↓ 9.52%	↓ 4.95%

➢ Original Emission Reduction

Predictive Powertrain Control with Connectivity

■ Simulation Results of Scenario #1



Controller	Total NOx (g)	Urea Consumption (g)
BC + SCRC	-	458.43
PESC + SCRC	↓ 7.37%	445.65

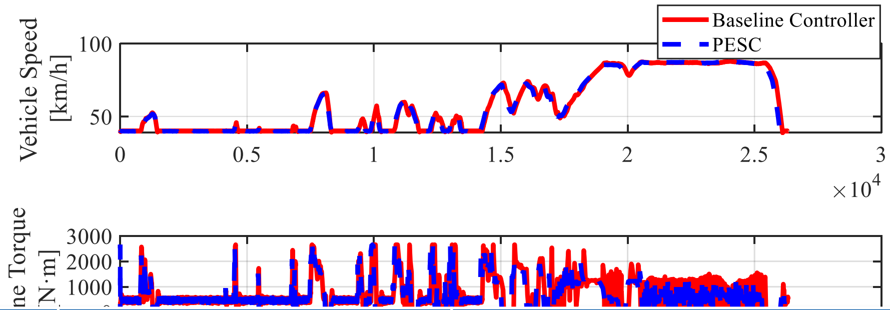
Controller	Total NOx (g)	Urea Consumption (g)
PESC + SCRC	-	445.65
PESC + PSCRC	↓ 5.62%	458.46

Controller	Total NOx (g)	Urea Consumption (g)
BC + SCRC	-	458.43
PESC + PSCRC	↓ 12.58%	458.46

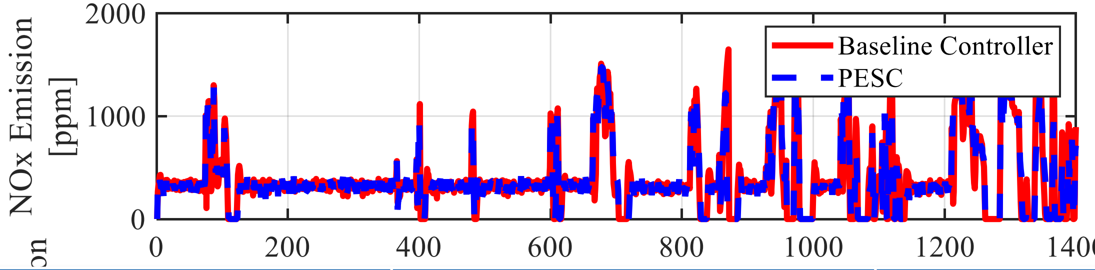
Predictive Powertrain Control with Connectivity

■ Simulation Results of Scenario #2

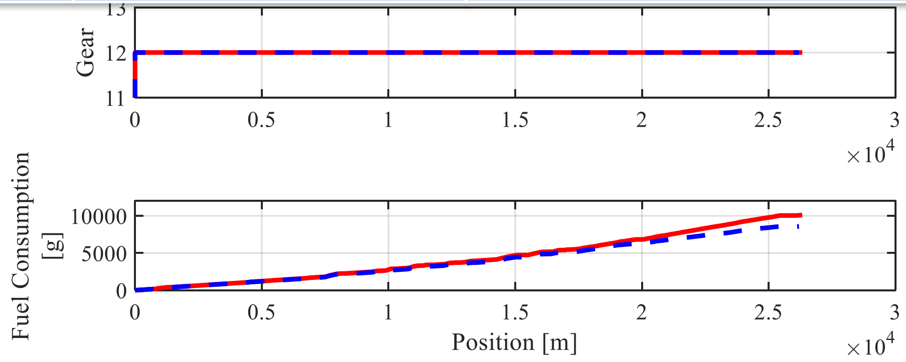
➤ Energy Saving

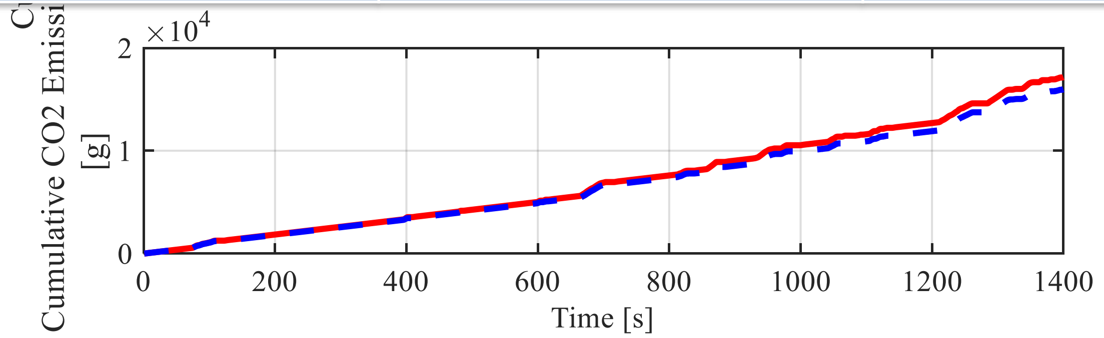


➤ Original Emission Reduction



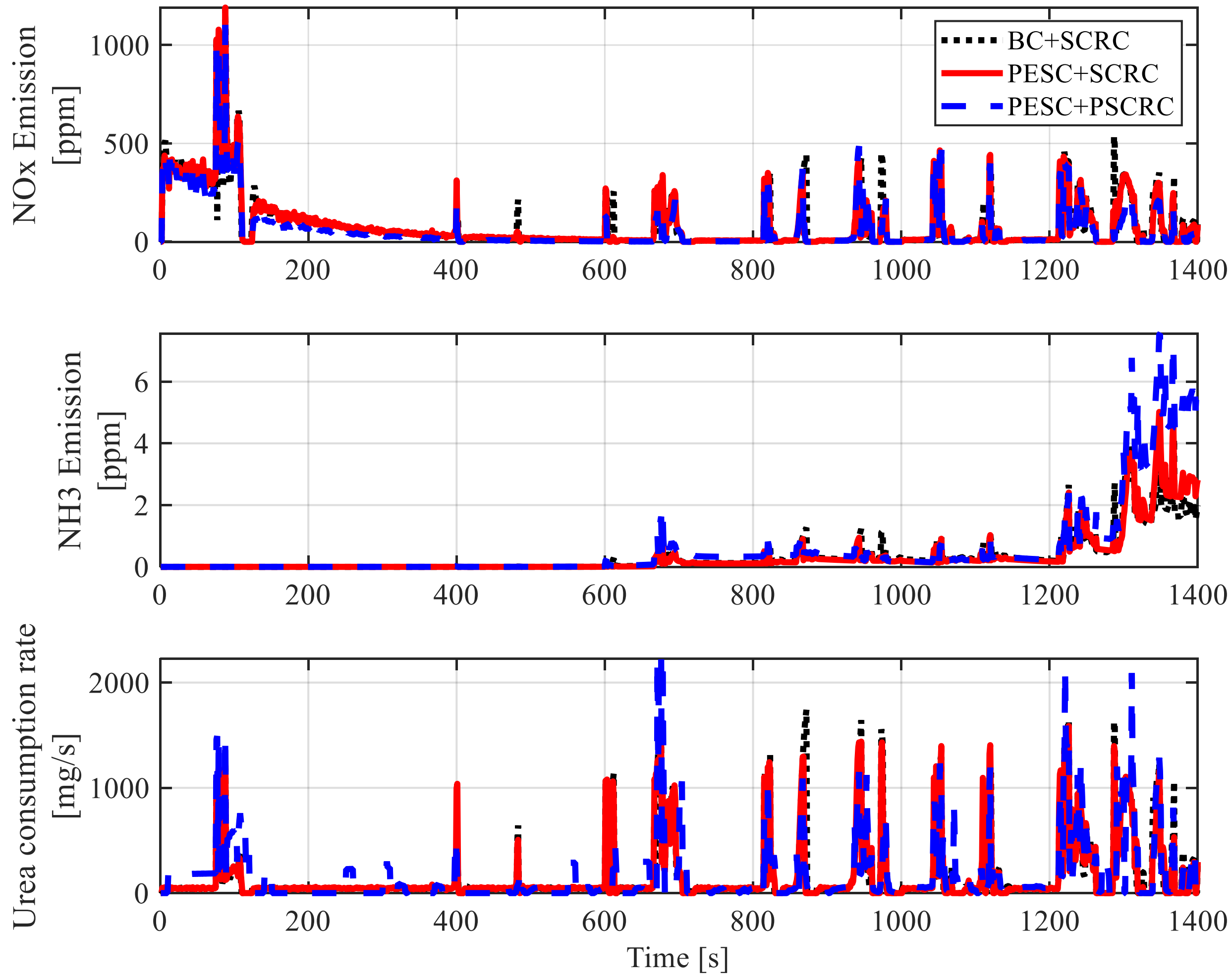
Contr.	Average speed (km/h)	Fuel consumption (L/100km)	Specific NOx (g/kwh)	Total NOx (g)	Total CO2 (g)
BC	52.65	-			-
PESC	52.4	↓ 14.7%	↓ 1.48%	↓ 8.65%	↓ 6.92%





Predictive Powertrain Control with Connectivity

■ Simulation Results of Scenario #2



Controller	Total NOx (g)	Urea Consumption (g)
BC + SCRC	-	217.07
PESC + SCRC	↓ 7.68%	218.07

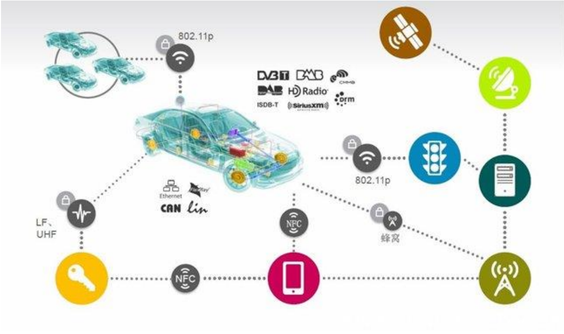
Controller	Total NOx (g)	Urea Consumption (g)
PESC + SCRC	-	218.07
PESC + PSCRC	↓ 22.98%	217.07

Controller	Total NOx (g)	Urea Consumption (g)
BC + SCRC	-	217.07
PESC + PSCRC	↓ 28.9%	217.07

Conclusions

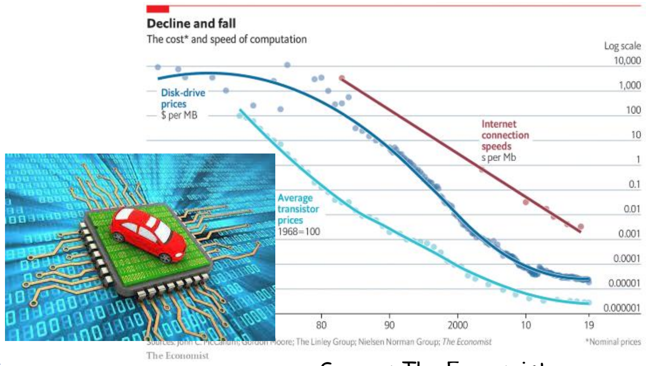
■ What can powertrain control do with the connectivity?

More Information via V2X



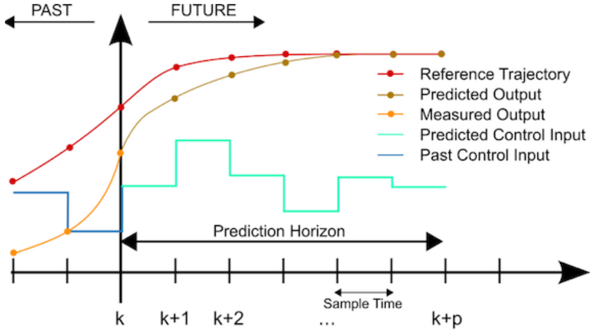
Source: https://www.icauto.com.cn

Lower computing costs



Source: The Economist

Well-established Theory



Application of advanced control algorithm e.g. MPC is possible

Safer, more energy efficient, more environmentally friendly, more comfortable ...

- Predictive cruise control
- Predictive energy management for HEVs
- Predictive battery management
- Predictive engine management
- Predictive emission control for trucks…

Thank you!