Empa
Materials Science and Technology

The particle-NOx trade-off: Two decades of diesel converter technologies have not settled both issues

20th ETH conference on Combustion Genereated Nanoparticles

Zürich, June 13-16, 2016

First of all: congratulations to the 20th anniversary

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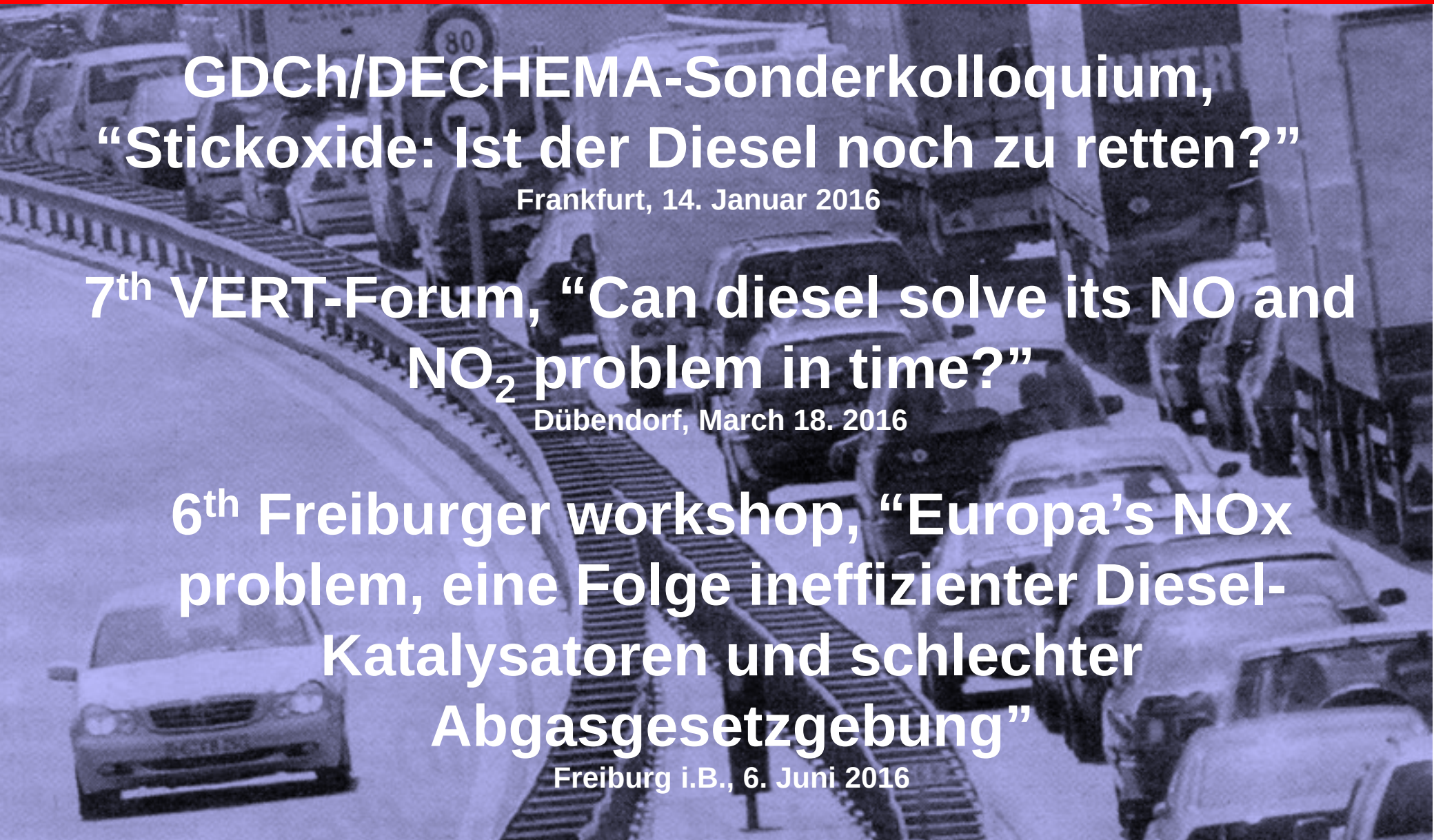
The particle-NOx trade-off: Two decades of diesel converter technologies have not settled both issues



GDCh/DECHEMA-Sonderkolloquium, “Stickoxide: Ist der Diesel noch zu retten?”

Frankfurt, 14. Januar 2016

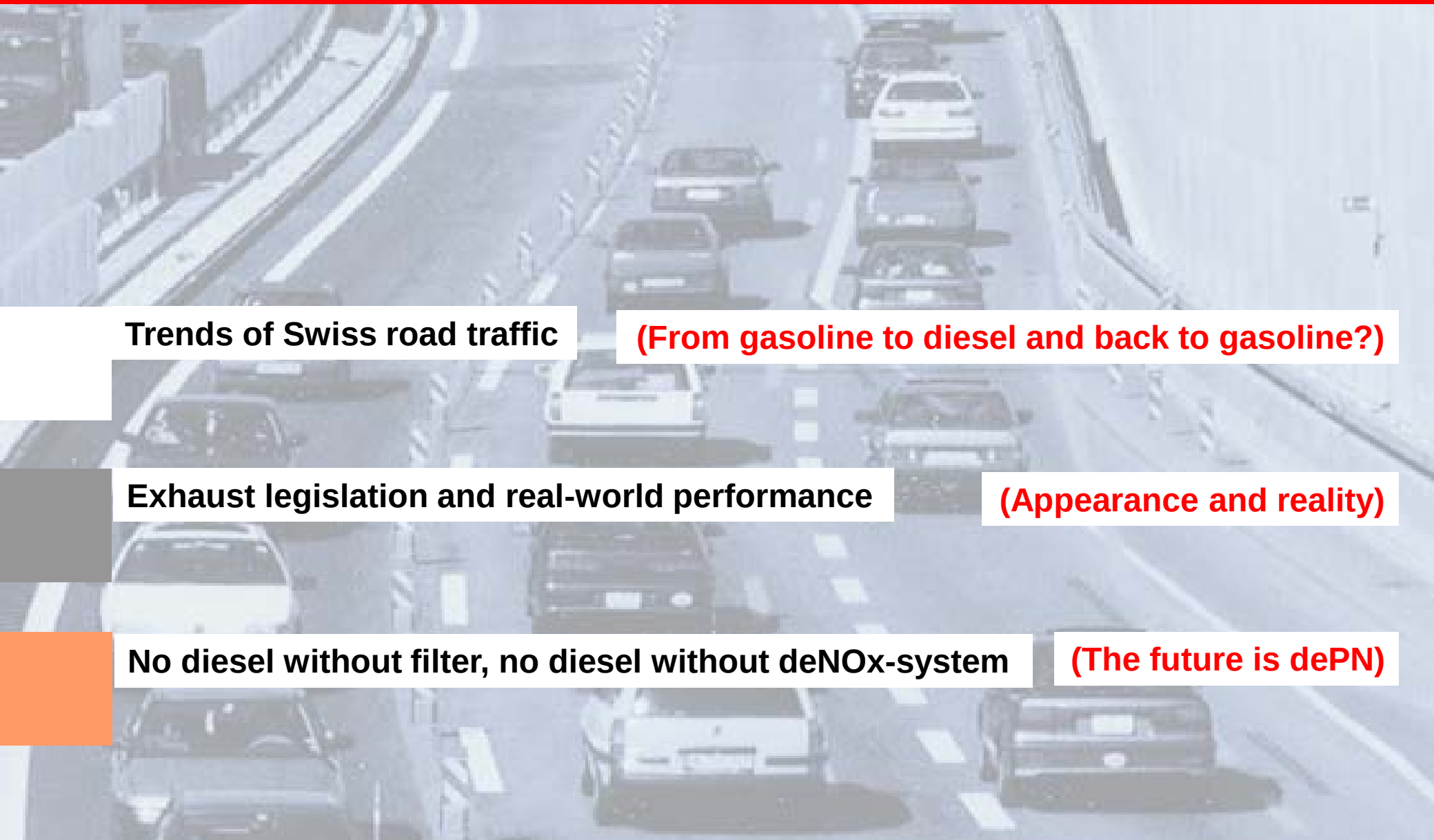
7th VERT-Forum, “Can diesel solve its NO and NO_2 problem in time?”

Dübendorf, March 18. 2016

6th Freiburger workshop, “Europa’s NOx problem, eine Folge ineffizienter Diesel-Katalysatoren und schlechter Abgasgesetzgebung”

Freiburg i.B., 6. Juni 2016

The particle-NOx trade-off: Two decades of diesel converter technologies have not settled both issues



Trends of Swiss road traffic (From gasoline to diesel and back to gasoline?)

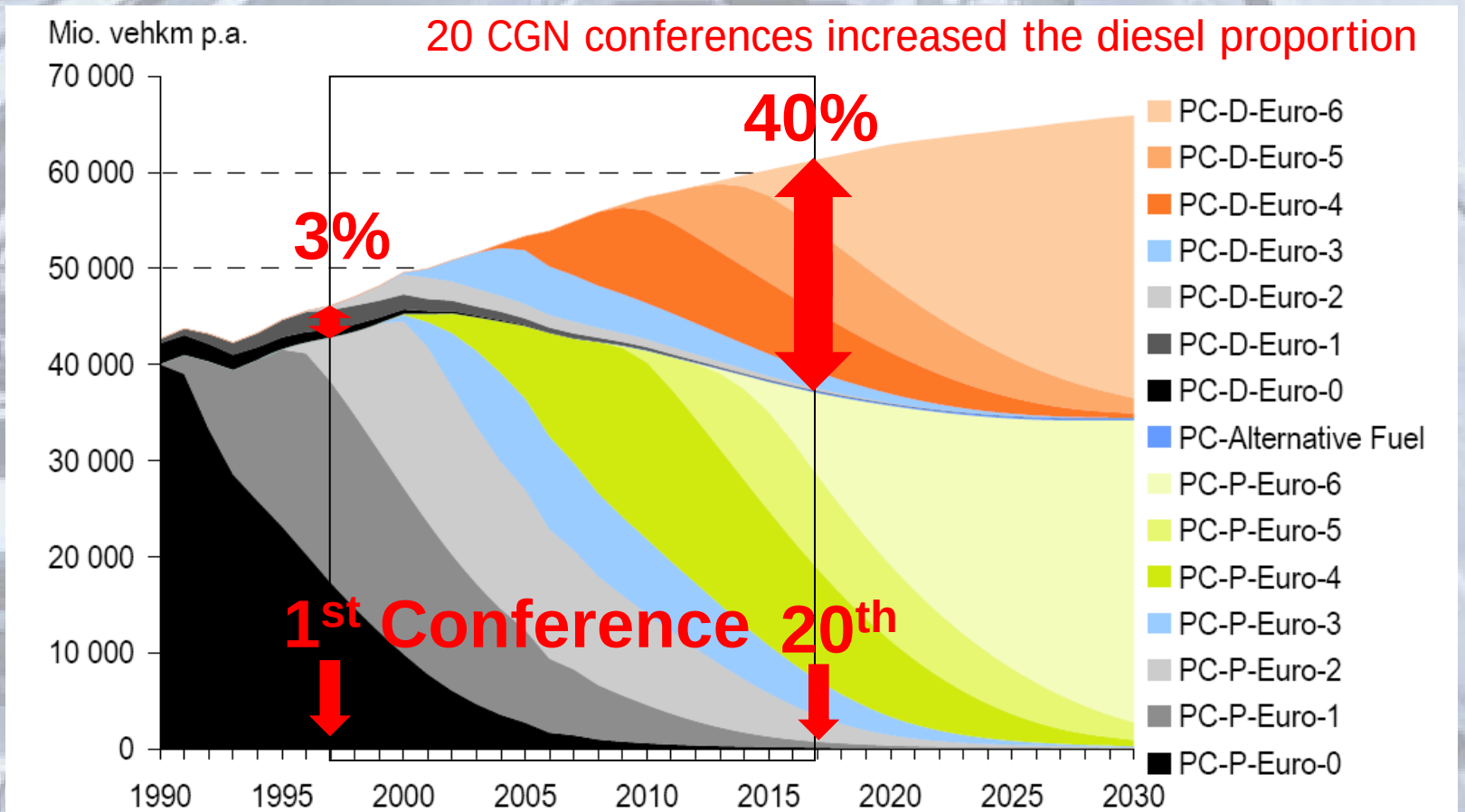
Exhaust legislation and real-world performance (Appearance and reality)

No diesel without filter, no diesel without deNOx-system (The future is dePN)

Swiss road traffic

The first CGN conference at this location held in 1997

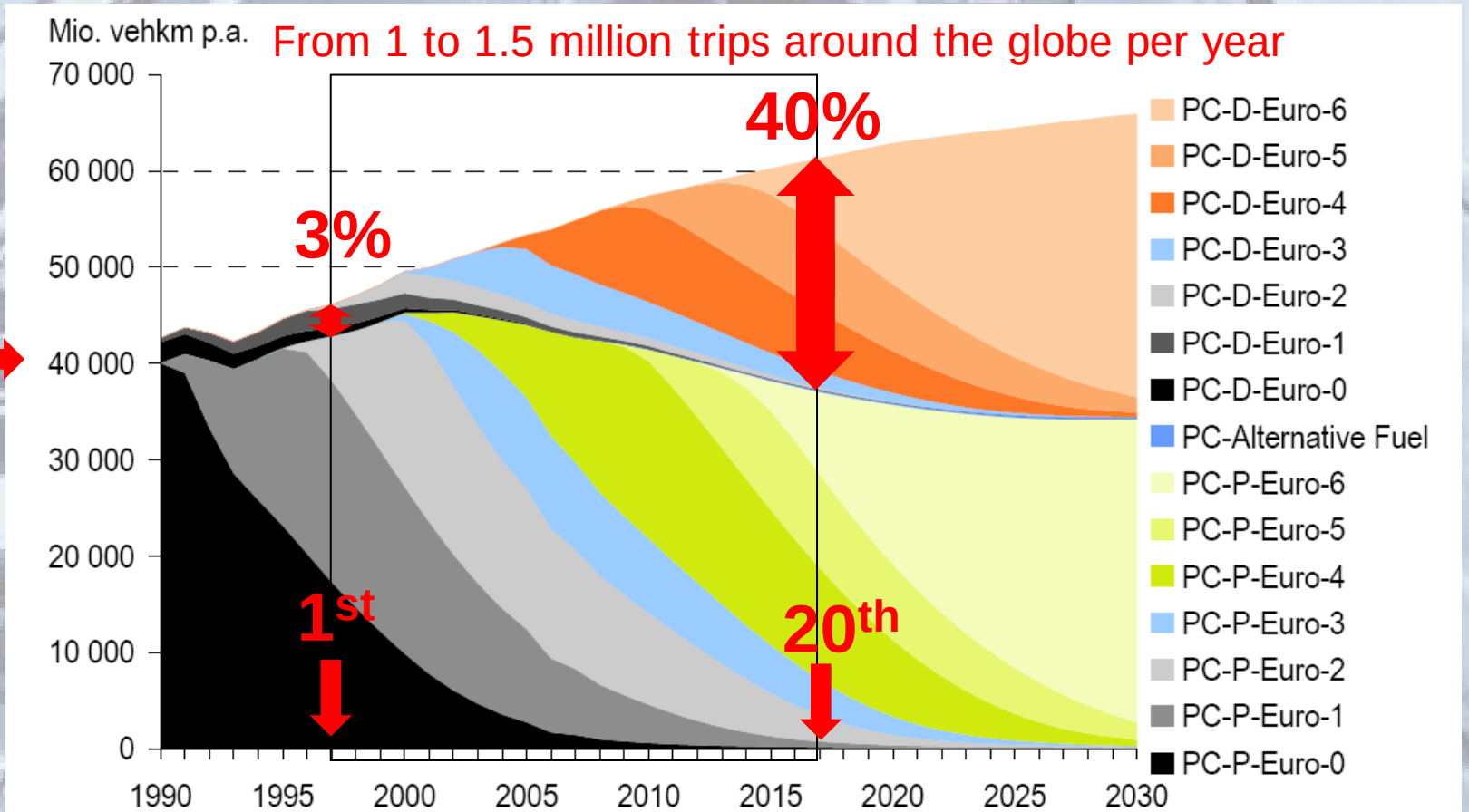
Driving distance per vehicle class (million km/y)



Swiss road traffic

From 3% diesel pc in 1990 to 40% in 2016: diesel on the rise, alternatives <1%!

Driving distance per vehicle class (million km/y)



Swiss road traffic

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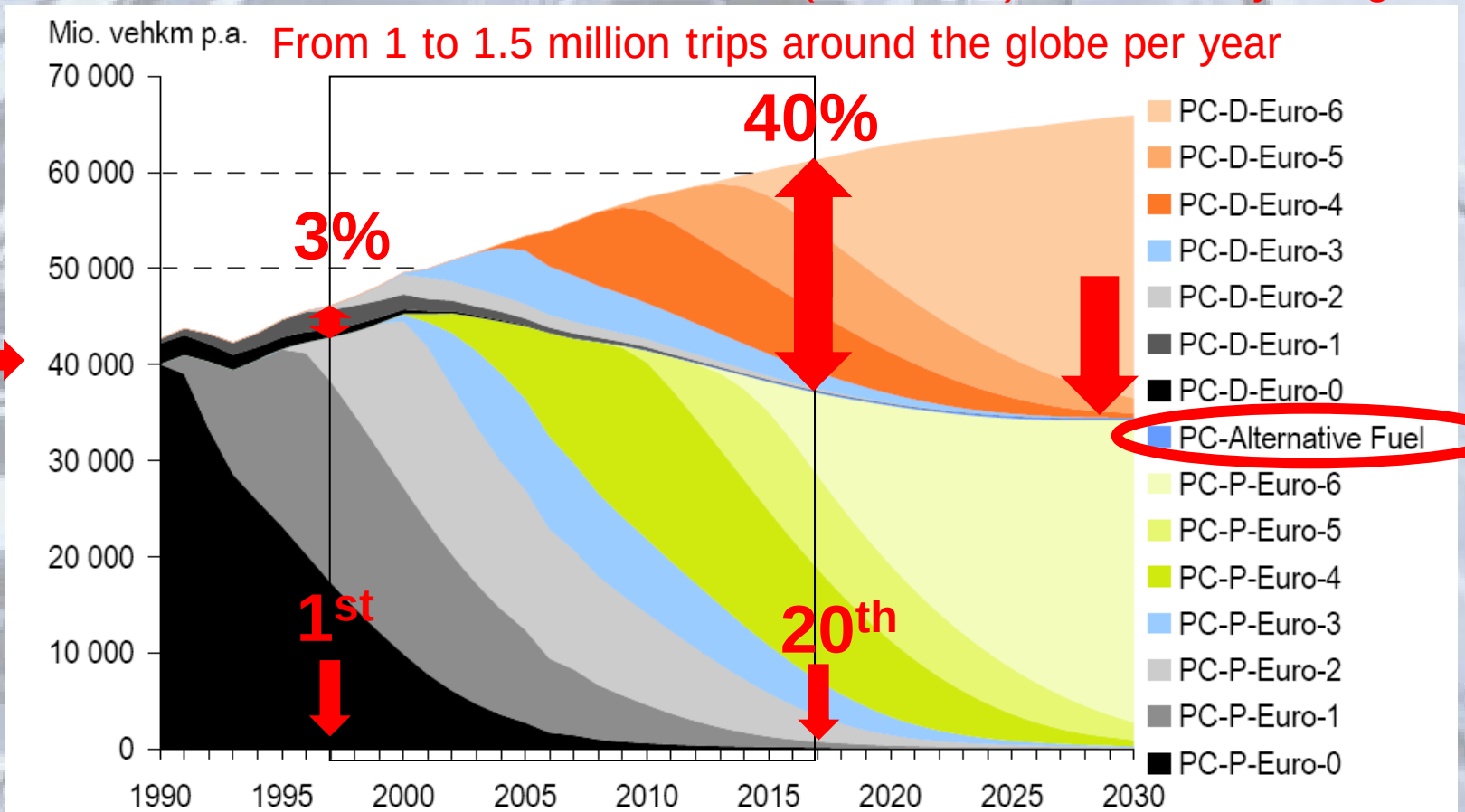
Driving distance per vehicle class (million km/y)

Not much low carbon fuels (CH4 & H2) or e-mobility in sight

From 1 to 1.5 million trips around the globe per year



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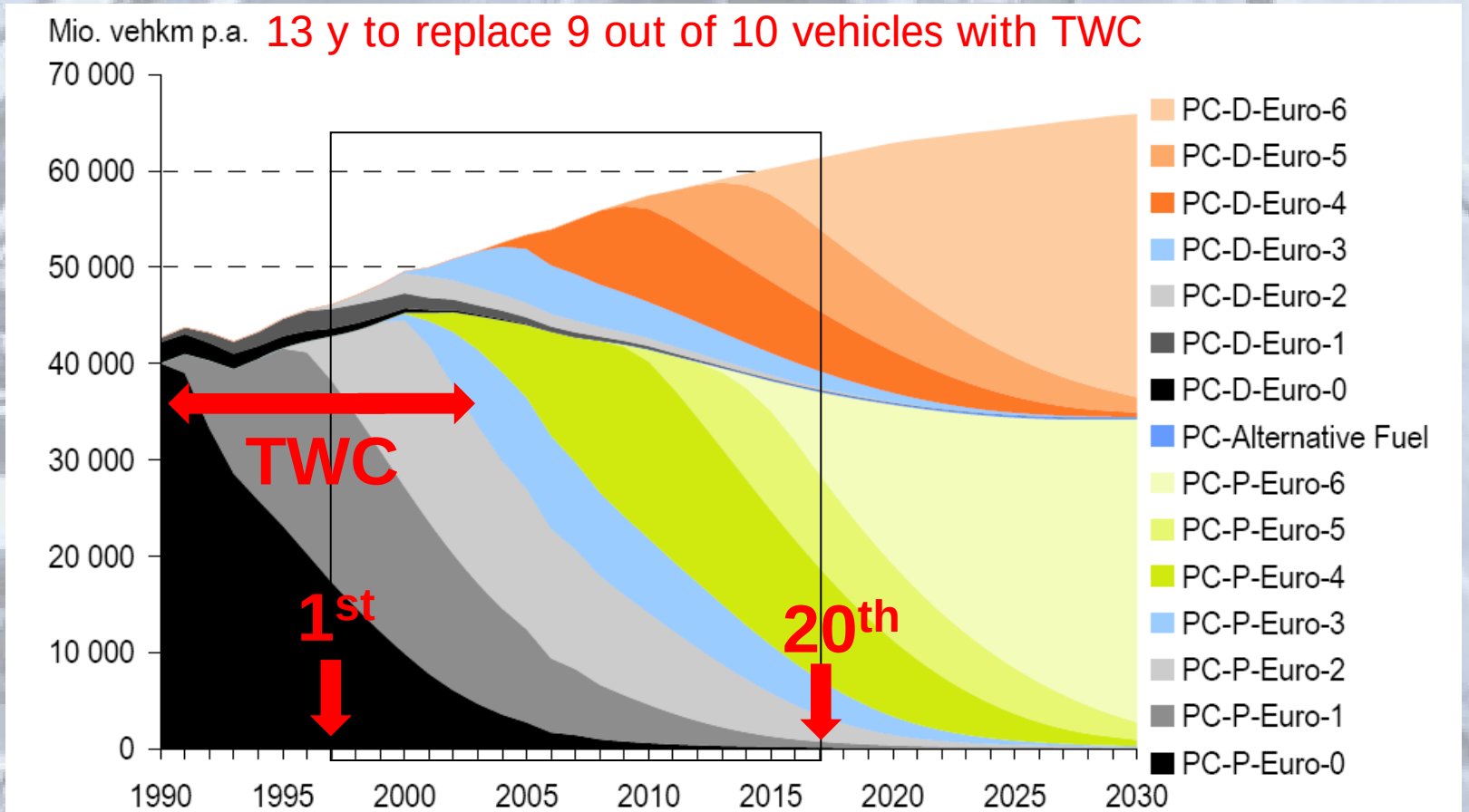

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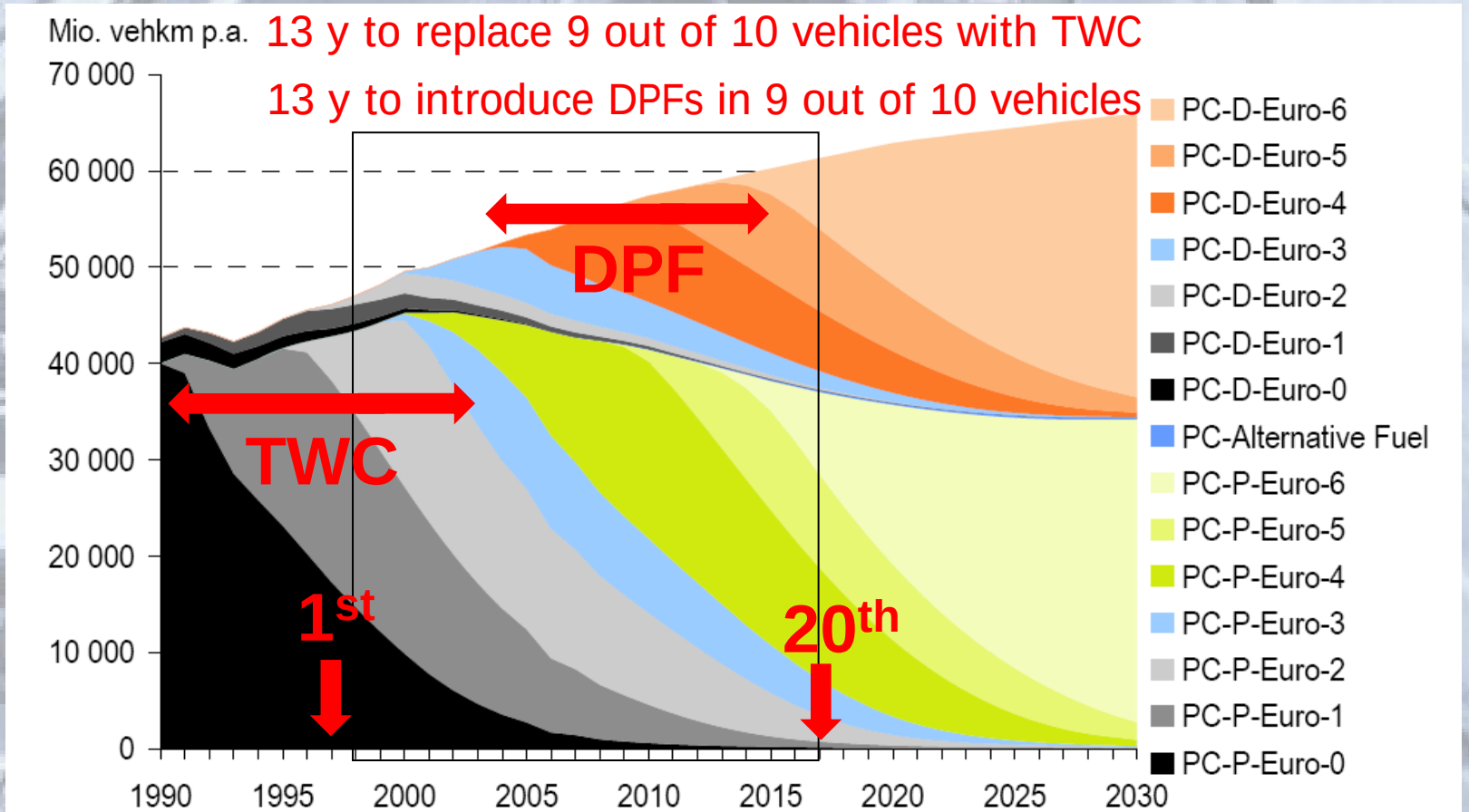
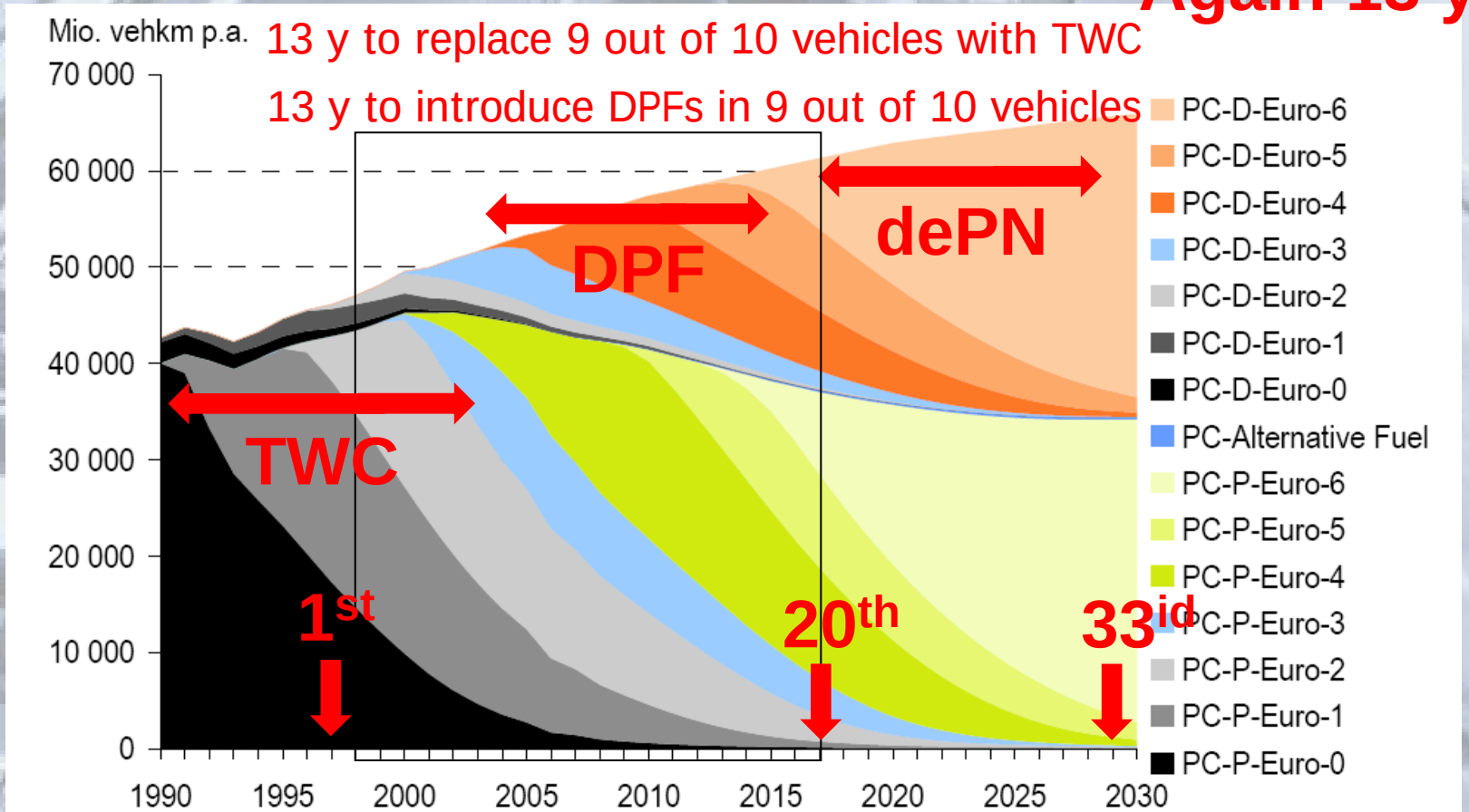


Swiss road traffic

From 3% diesel pc in 1990 to 40% in 2016: diesel on the rise, alternatives <1%!

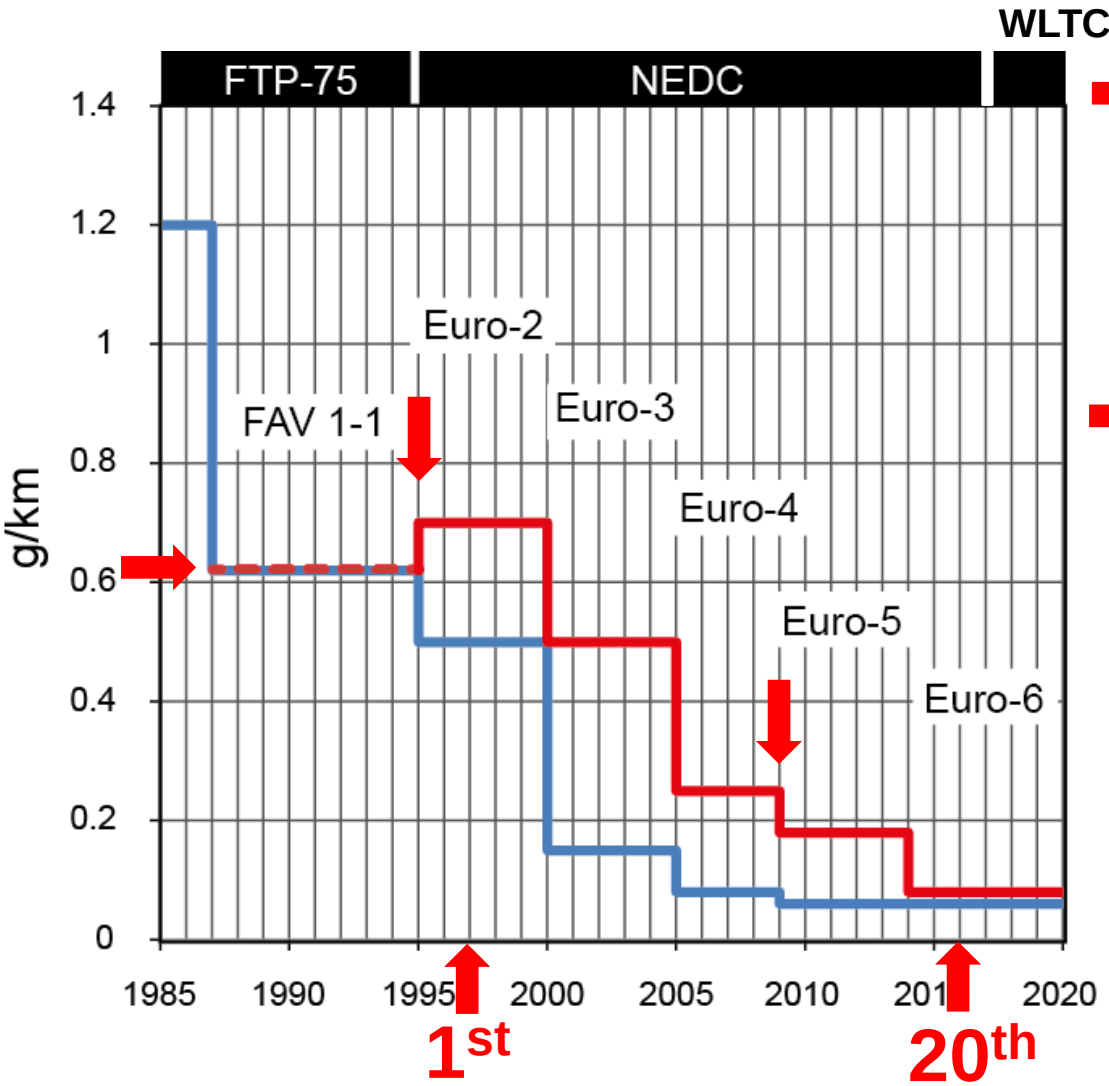
Driving distance per vehicle class (million km/y)

Again 13 years?



Legislation and reality

Since 1995 NOx limits in CH and Europe are based on EDC!



Before 1995 CH and US

- NOx limit technology independent

(0.65 g/km both for diesel & gasoline)

- transient cycle (FTP75)

After 1995 Europe favored diesel

- Higher NOx limits for diesel

- Static cycle (EDC)

- PN limit in 2009 (Euro-5)

(6x10e11 #/km, ca. 1 Billion #/km)

More diesel cars in Europe's cities

- Increased NO_2 emissions

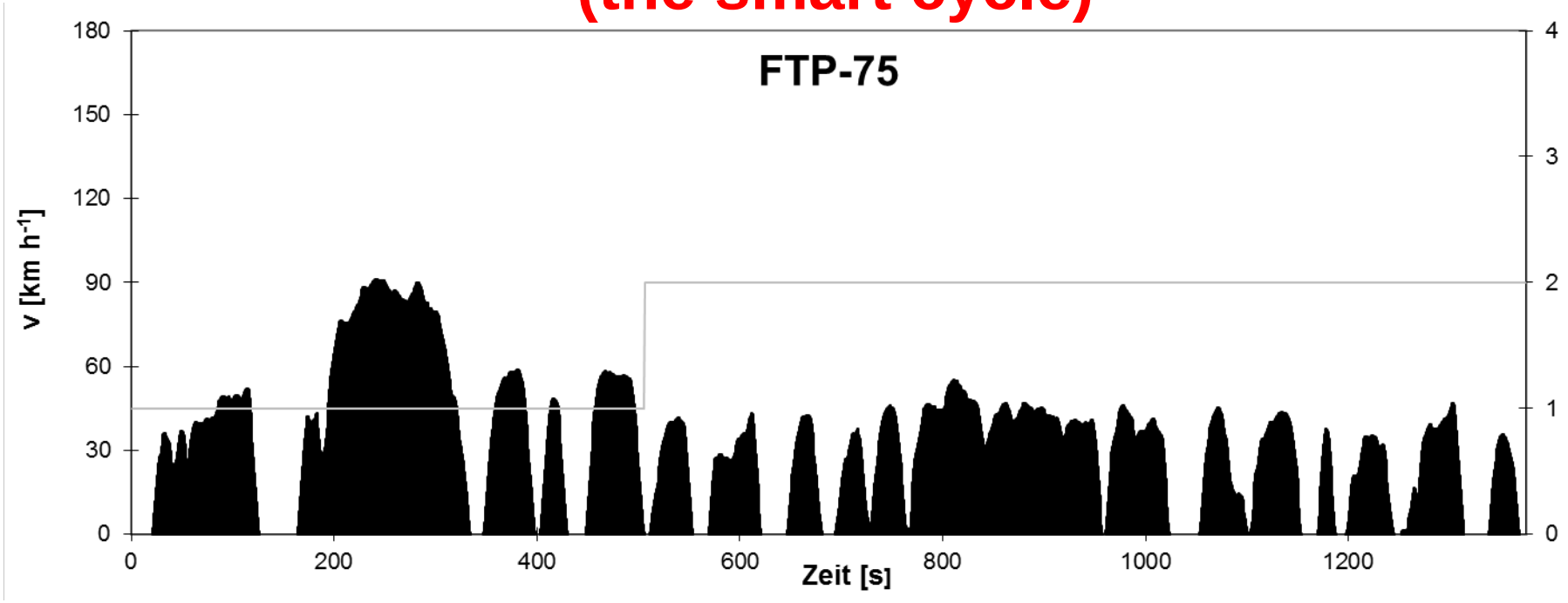
- Increase of PN emissions

Useful and other driving cycles

Transient urban driving with cold start and stop-&-go

The US FTP-75, valid also in CH until 1995

(the smart cycle)



Real-world driving cycle, realistic driving pattern

Consequence: Converters are tested under road-like conditions

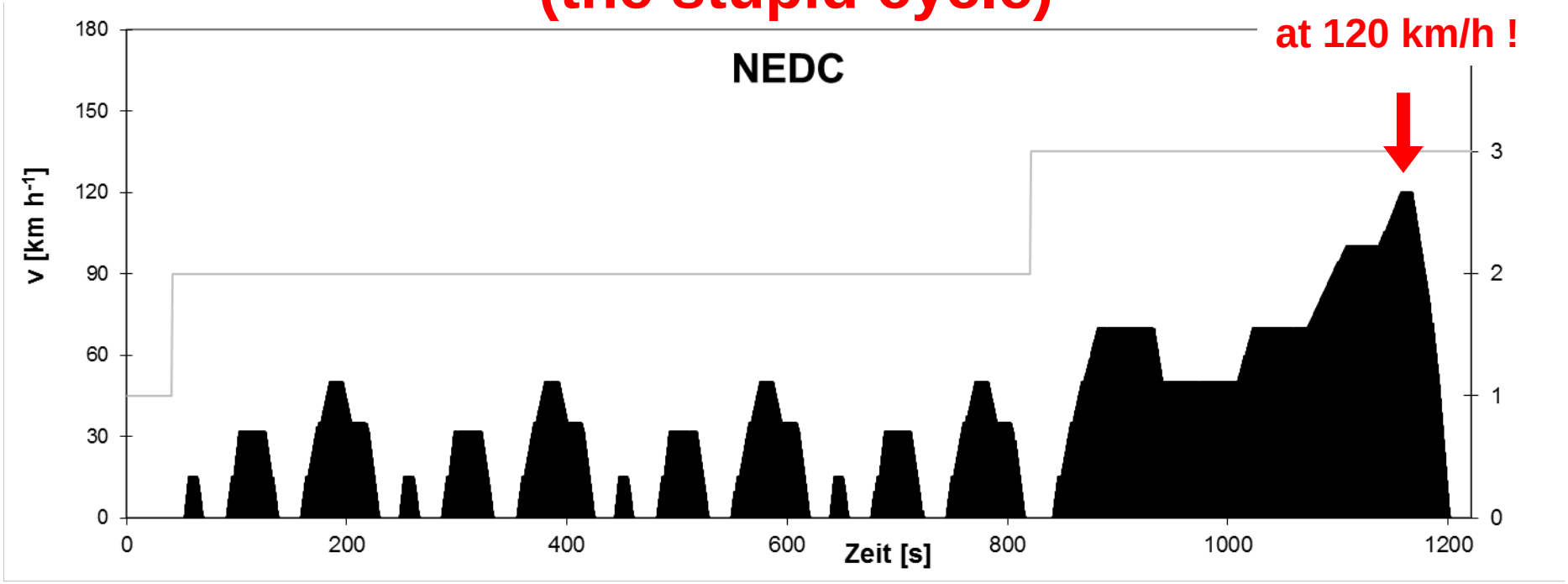
Useful and other driving cycles

Low engine load, fewer load changes, moderate acceleration, even without cold start

The EDC, valid in CH from 1995

(the stupid cycle)

5 seconds at 120 km/h !



The outcome of a bureaucrat?

Consequence: Converters are tested at low loads, quasi-stationary

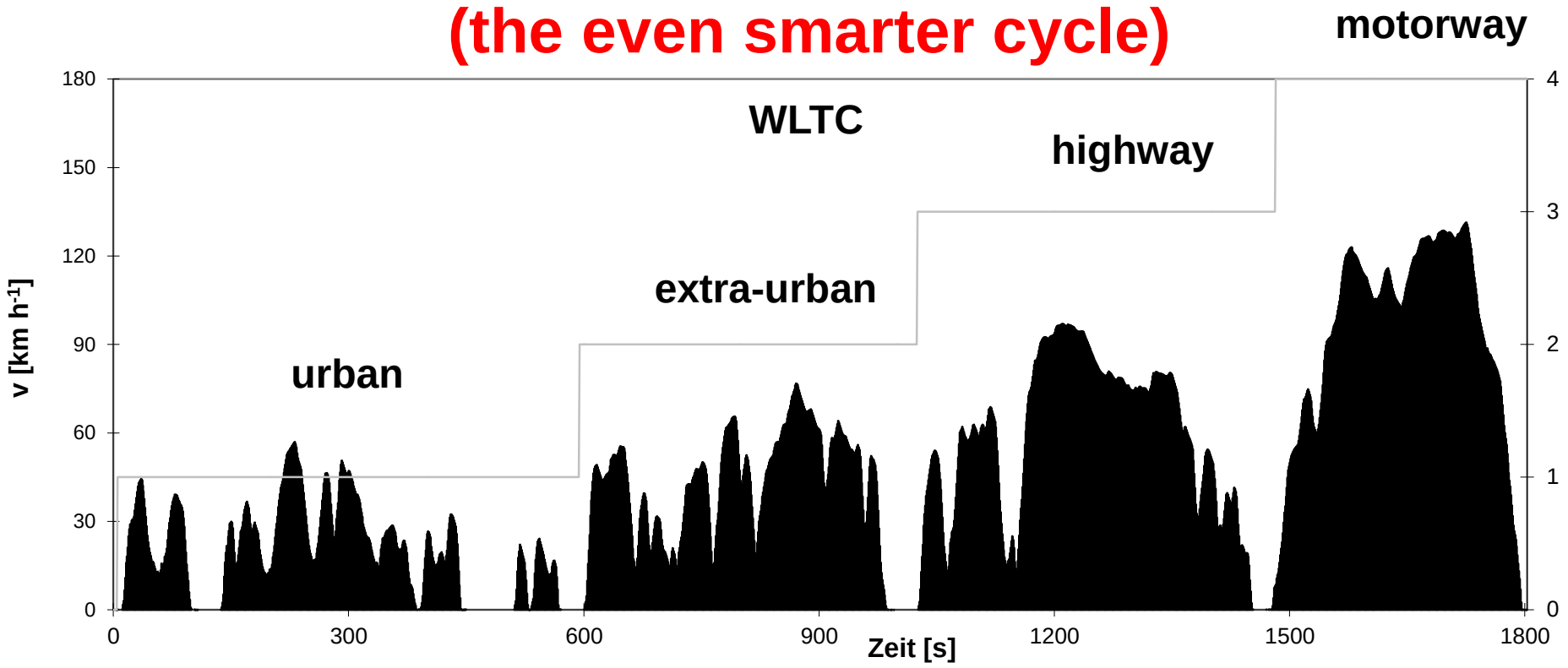
Useful and other driving cycles

Lots of transients, with cold start, motorway and some stop-&-go

The WLTC, from 2017 on

>100 s >120 km/h !

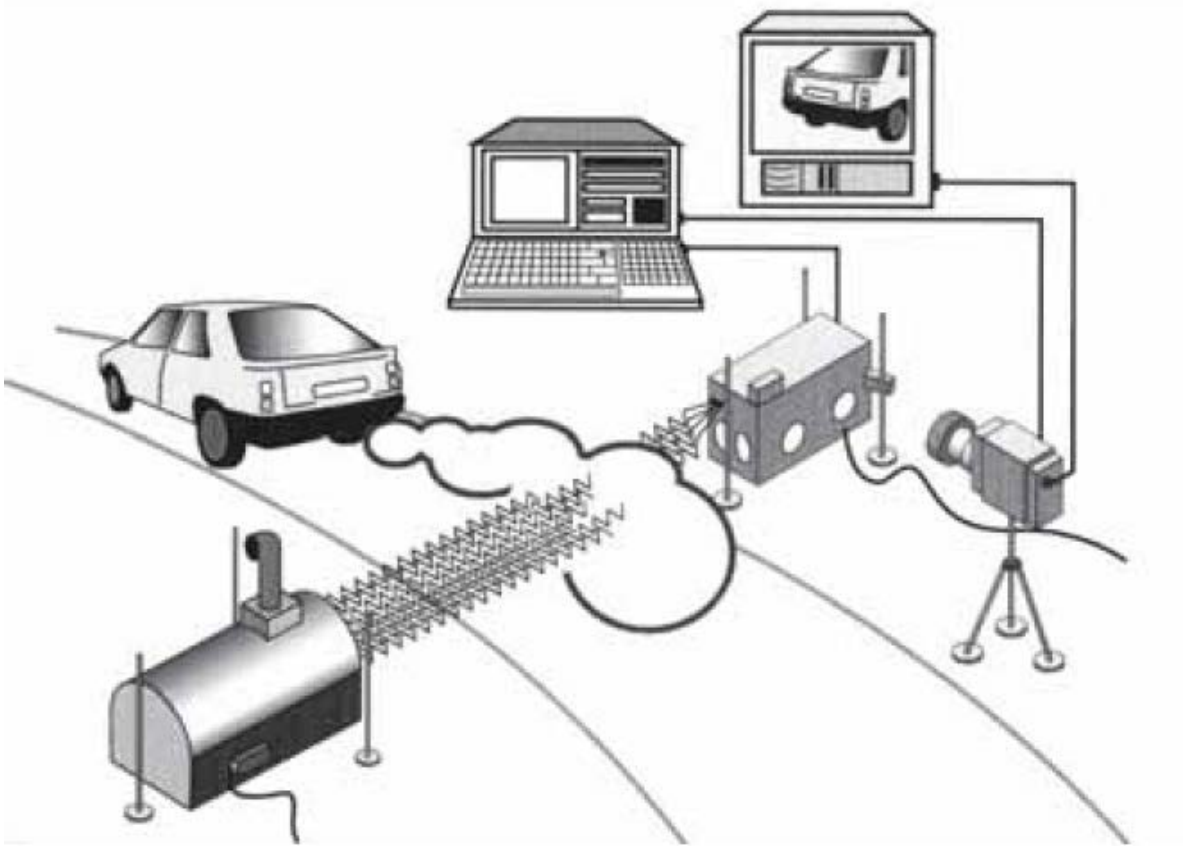
(the even smarter cycle)



There's hope, that 40 years after the FTP-75 Europa is getting a transient cycle too!

From chassis dynamometers to on-road measurements

For example with an FT-IR at the curbside



- Remote Sensing

- Emissions of individual vehicles

- NO, CO, HC, CO_2

- 15 years, 500’000 vehicles

- Licence plate recognition

- Technology assignment

- Detection of high emitters

- Field inspection and control

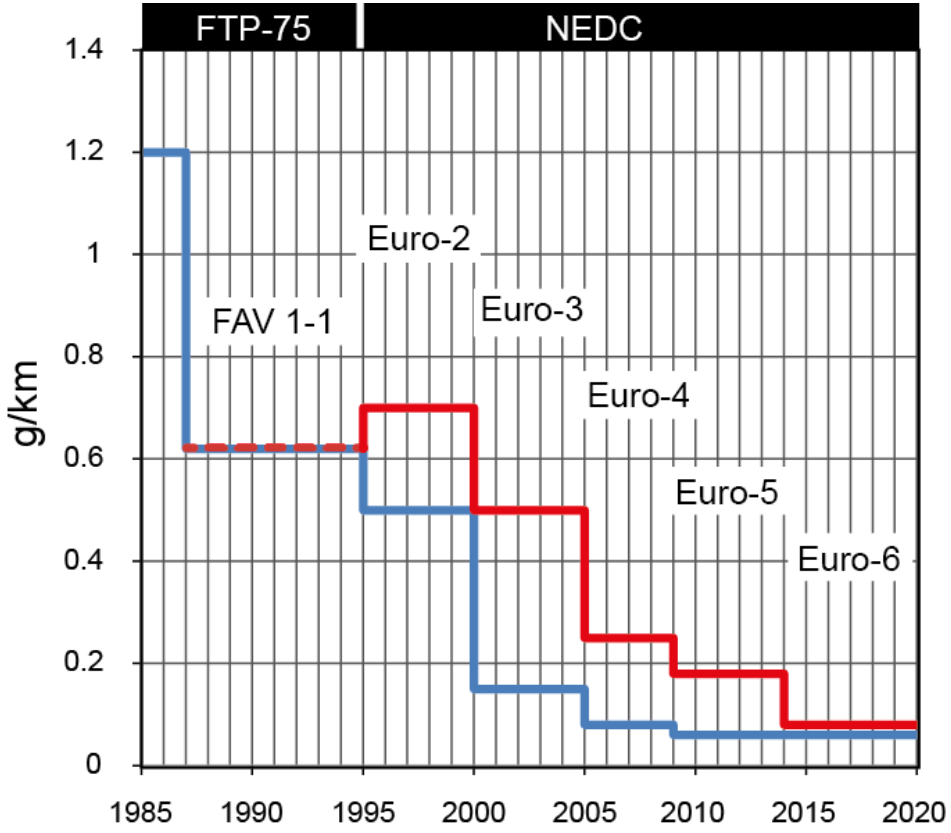
Gian-Marco Alt, Michael Götsch, Valentin Delb, AWEL, Zürich

Chen & Borken-Kleefeld Atm. Env. **2014**, 88, 157-164

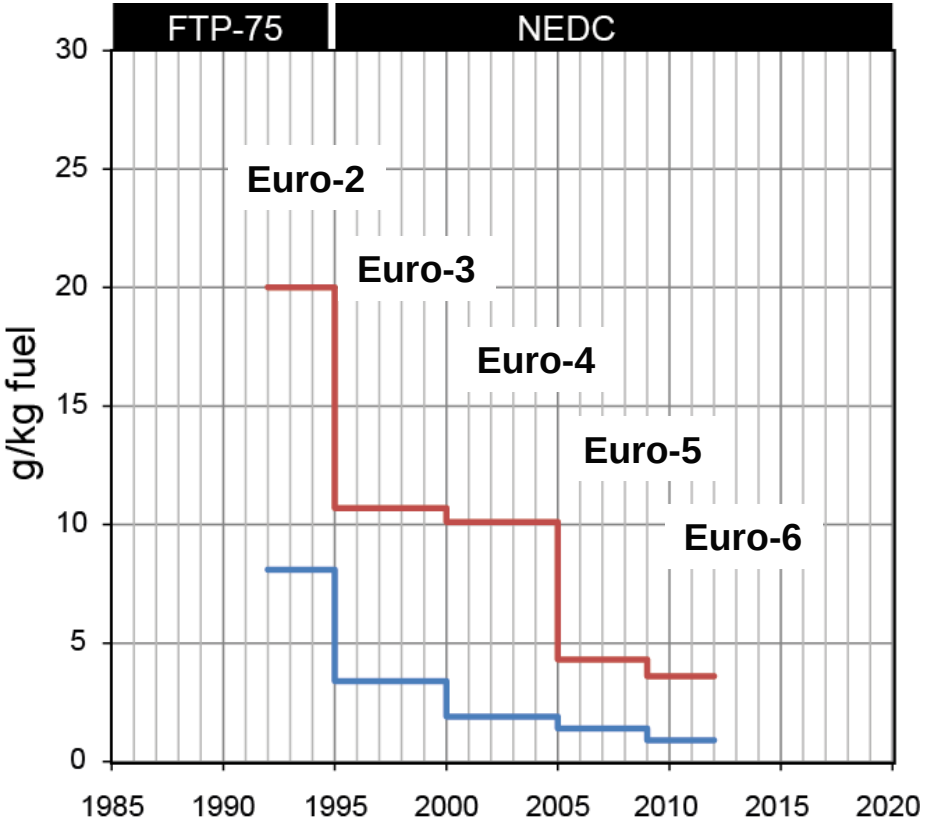
Exhaust regulation and reality

NOx emission limits in CH and Europe

Related to distance (g NOx/km)



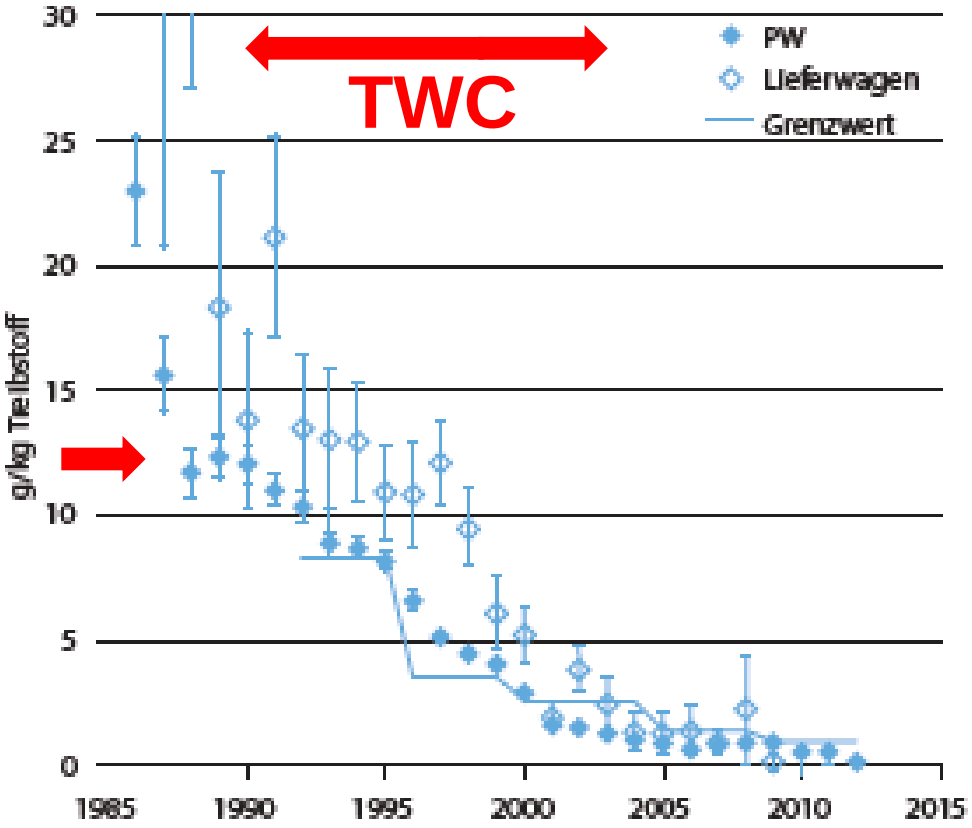
Consumption-related (g NOx/kg fuel)

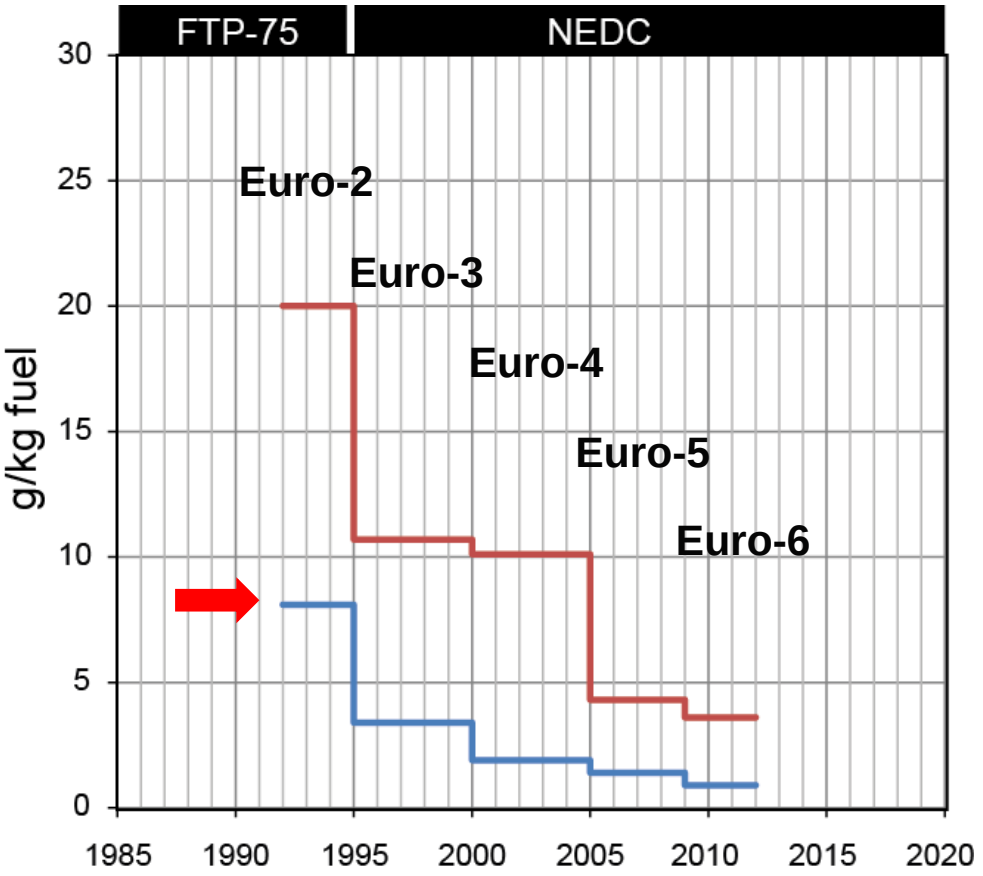


From chassis dynamometers to on-road measurements

NOx-emissions followed the prescribed limits (from 11 to <1 g/kg in 20 y)

NOx-emissions of gasoline cars





DeNOx-technologies of gasoline vehicles (TWCs) are active, also on roads

From chassis dynamometers to on-road measurements

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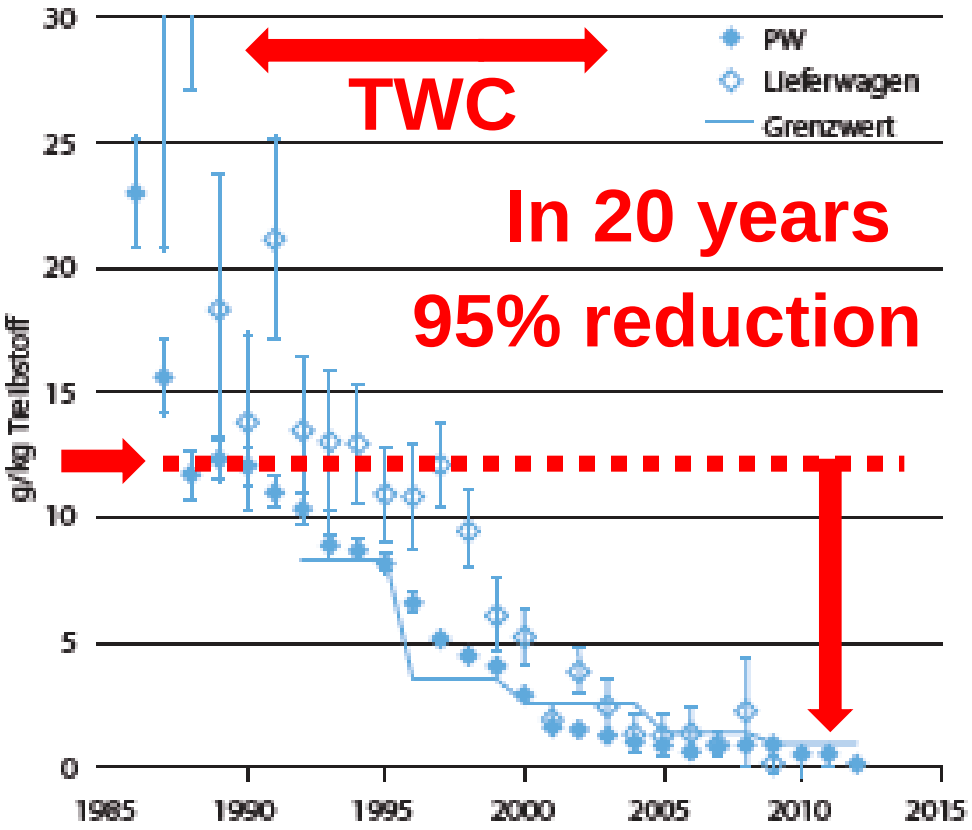
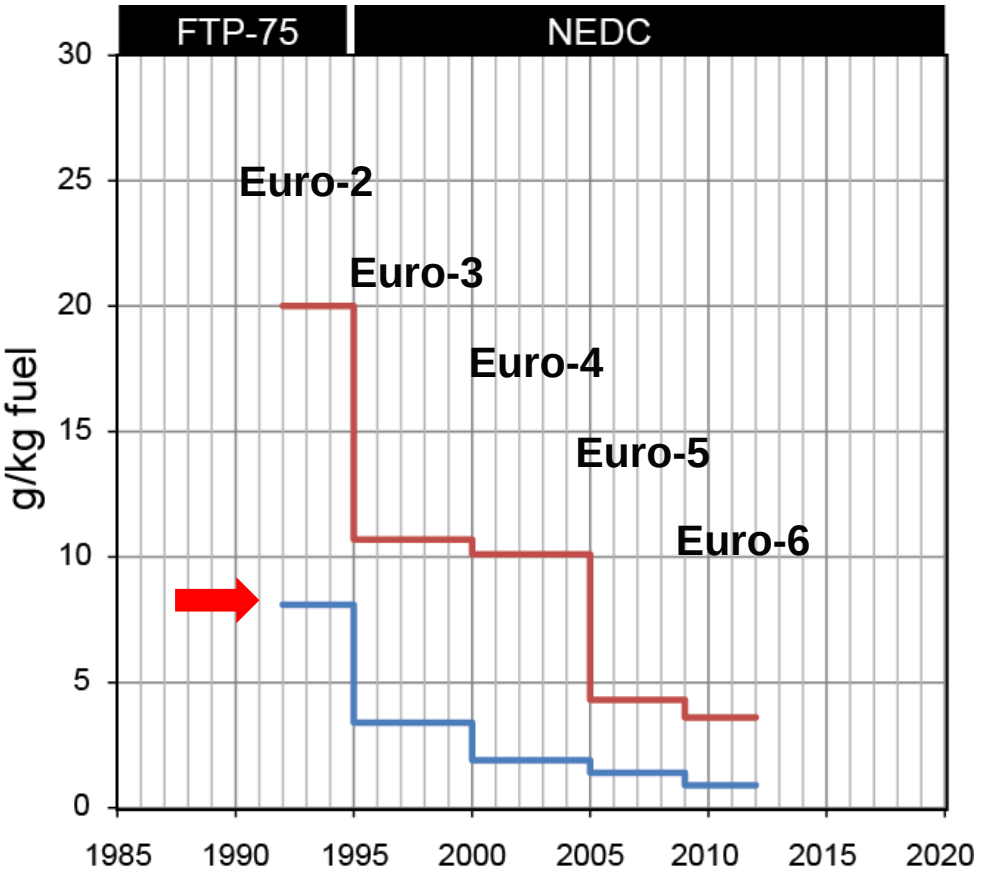


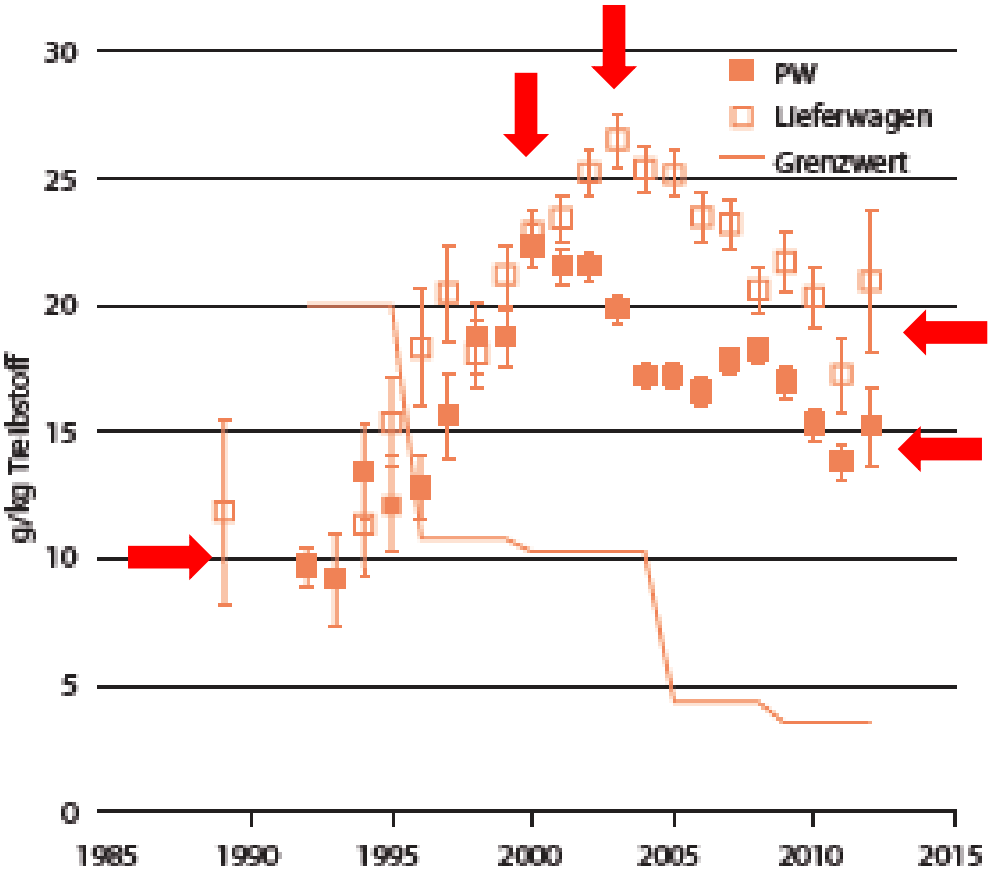


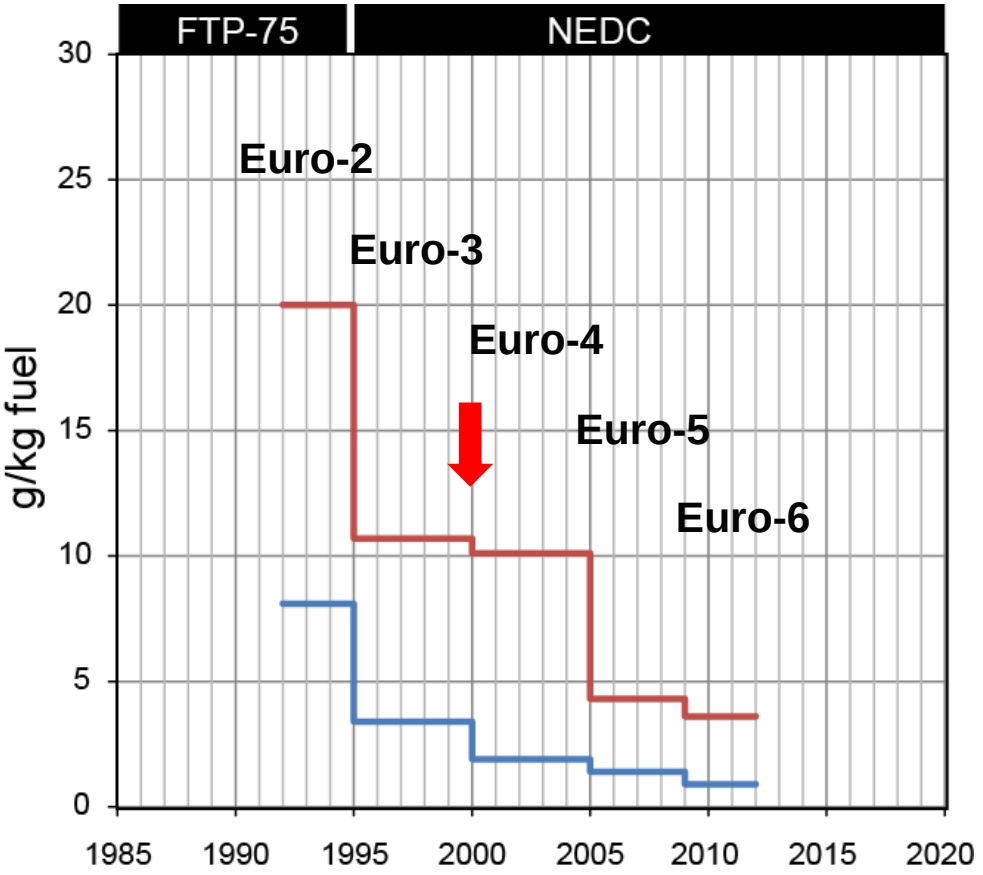
DeNOx-technologies of gasoline vehicles (TWCs) are active, also on roads

From chassis dynamometers to on-road measurements

NOx-emissions of diesel PC and LDV even got worse (from 10 in 1990 to 20 g/kg in 2000)

NOx-emissions of diesel-vehicles





Converter-technologies for diesel vehicles are not deNOx active

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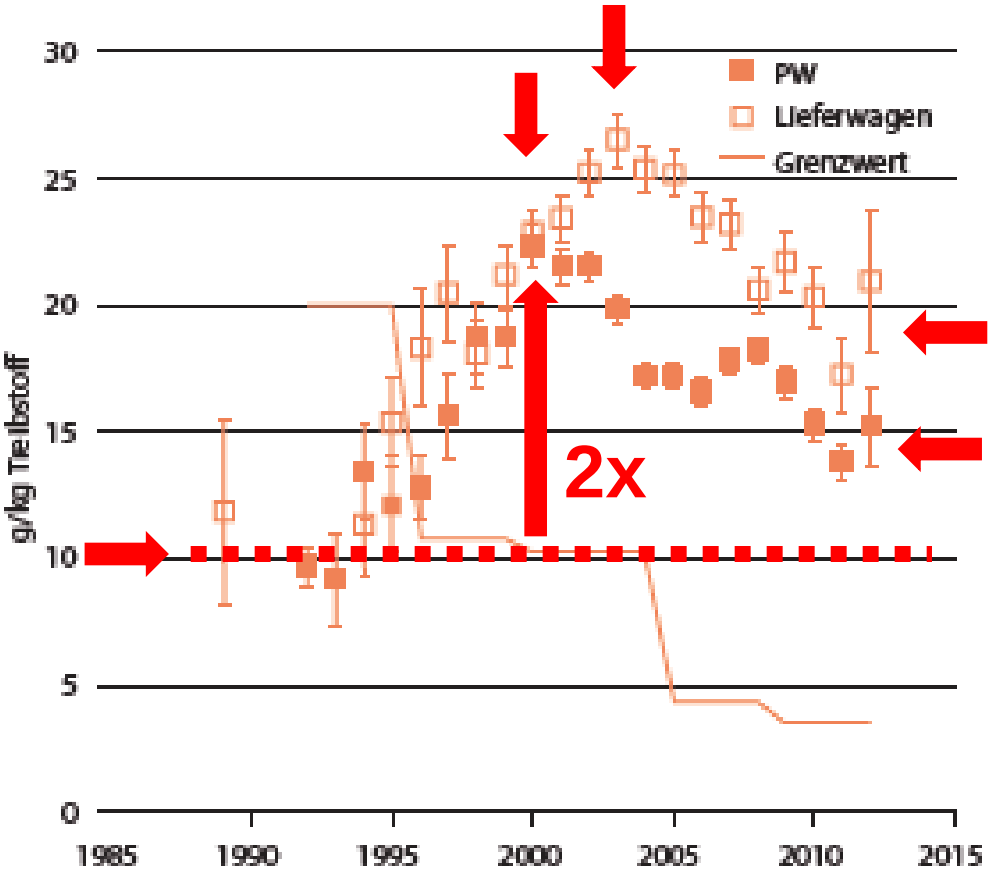
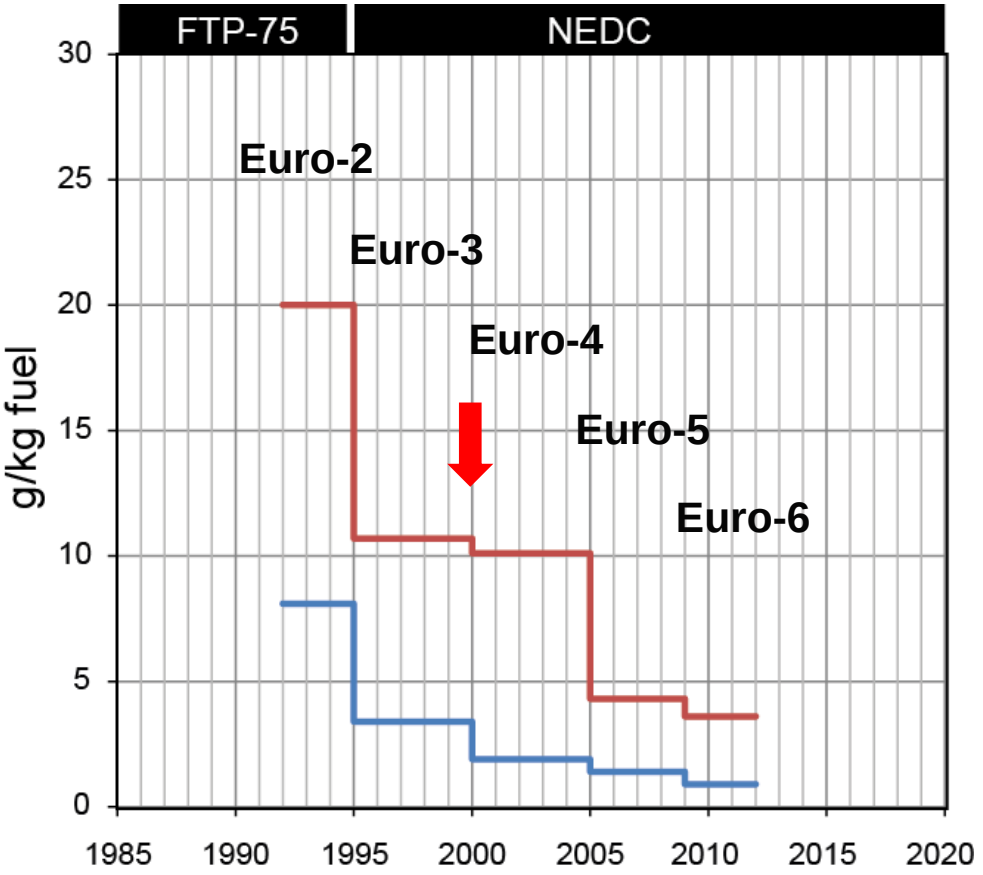




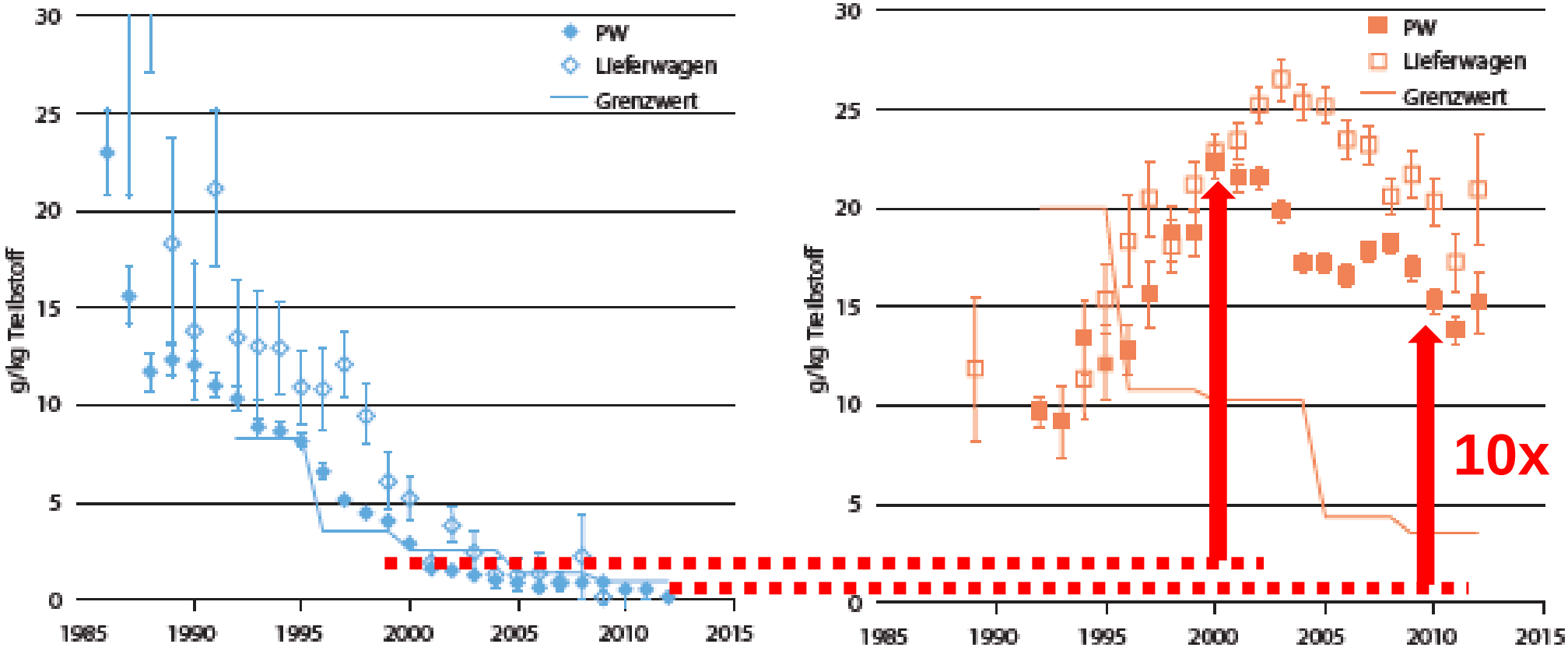
Converter-technologies for diesel vehicles are not deNOx active

From chassis dynamometers to on-road measurements

Appearance and reality are far apart! Diesel NOx 10x higher than gasoline vehicles

NOx-emissions of gasoline- & diesel-vehicles

The NOx-problem of diesel-PCs & LDVs is 20 years old – that's the scandal



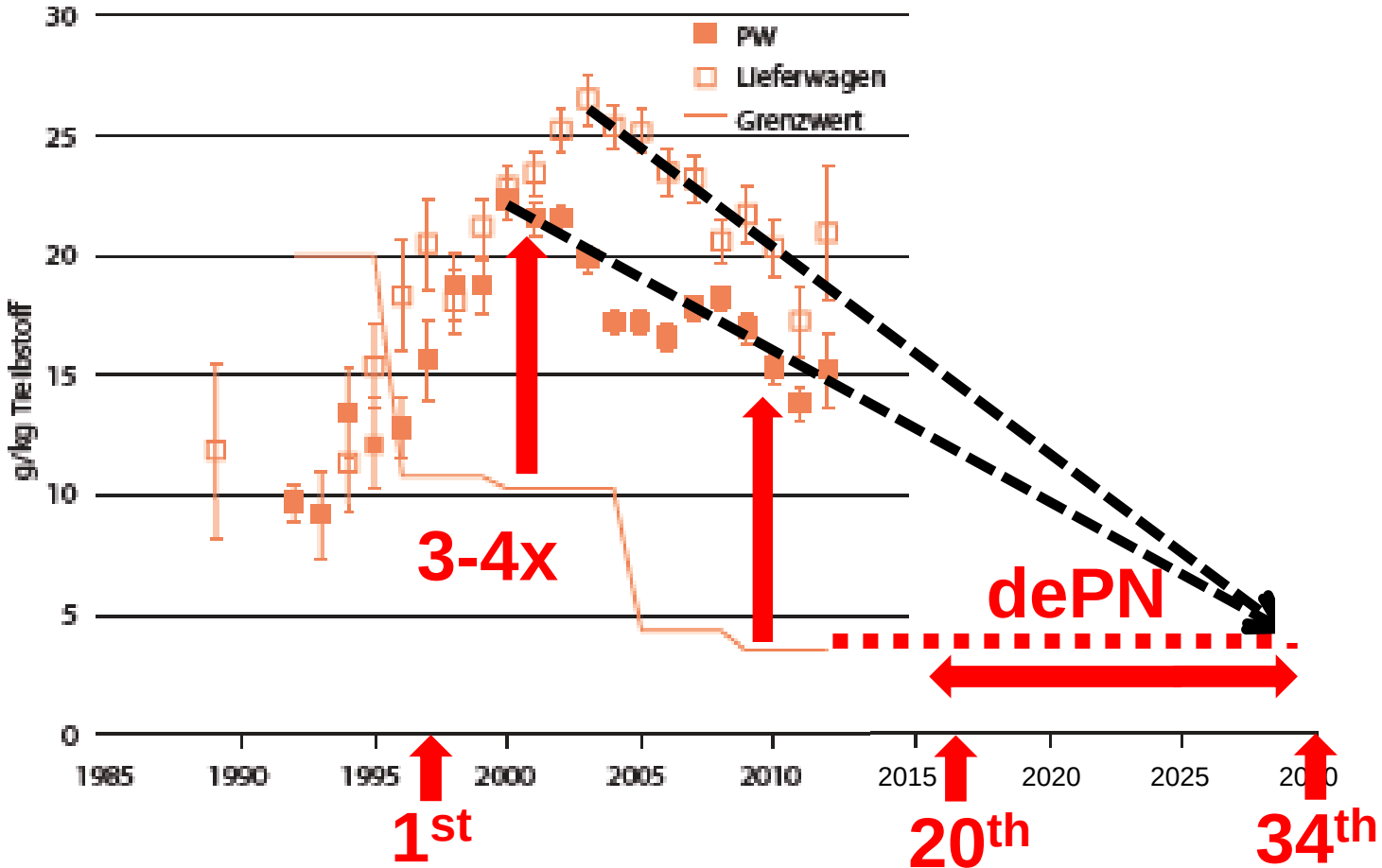
Chen & Borken-Kleefeld Atm. Env. **2014**, 88, 157-164

Can diesel solve its NO and NO_2 emission problem in time?

Appearance and reality are far apart! Another 15 years to wait?

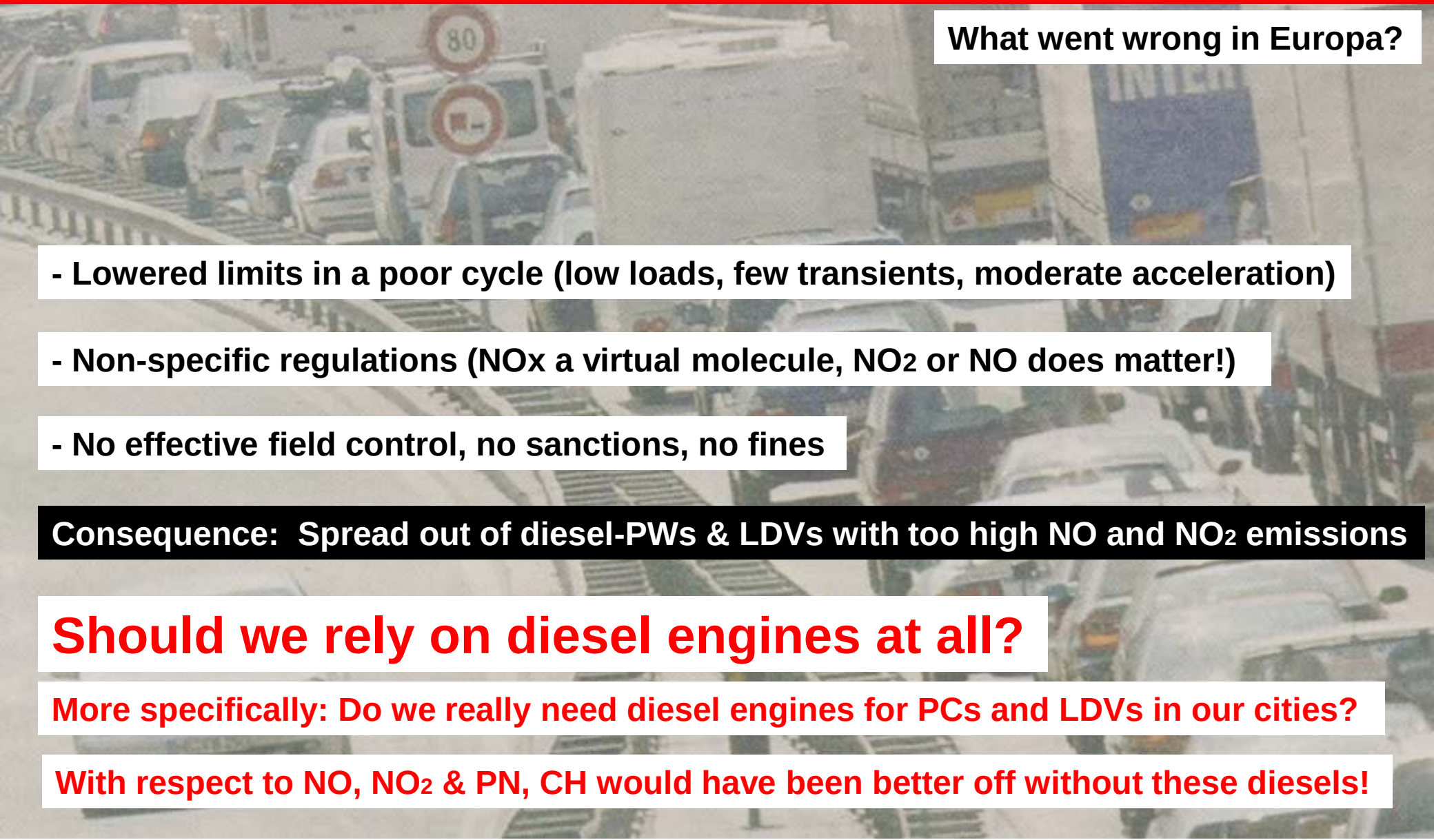
NO_x-emissions of diesel-vehicles

The NO_x-problem of diesel-PCs & LDVs is 20 years old – that's the scandal



Is it really 2030 when diesel PC and LDV reach the Euro-6 level?

Exhaust regulation and reality



What went wrong in Europa?

- Lowered limits in a poor cycle (low loads, few transients, moderate acceleration)

- Non-specific regulations (NOx a virtual molecule, NO_2 or NO does matter!)

- No effective field control, no sanctions, no fines

Consequence: Spread out of diesel-PWs & LDVs with too high NO and NO_2 emissions

Should we rely on diesel engines at all?

More specifically: Do we really need diesel engines for PCs and LDVs in our cities?

With respect to NO, NO_2 & PN, CH would have been better off without these diesels!

Exhaust regulation and reality

But

Diesel engines move the world

Heavy duty vehicles
construction, mining &
farming machinery
>90 % diesel

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Passenger cars and
light duty vehicles
EU: ~42 % diesel
CH: ~40 % diesel
US: ~3 % diesel

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Ships
>95 % diesel

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We have to, they are all around us!

Ships
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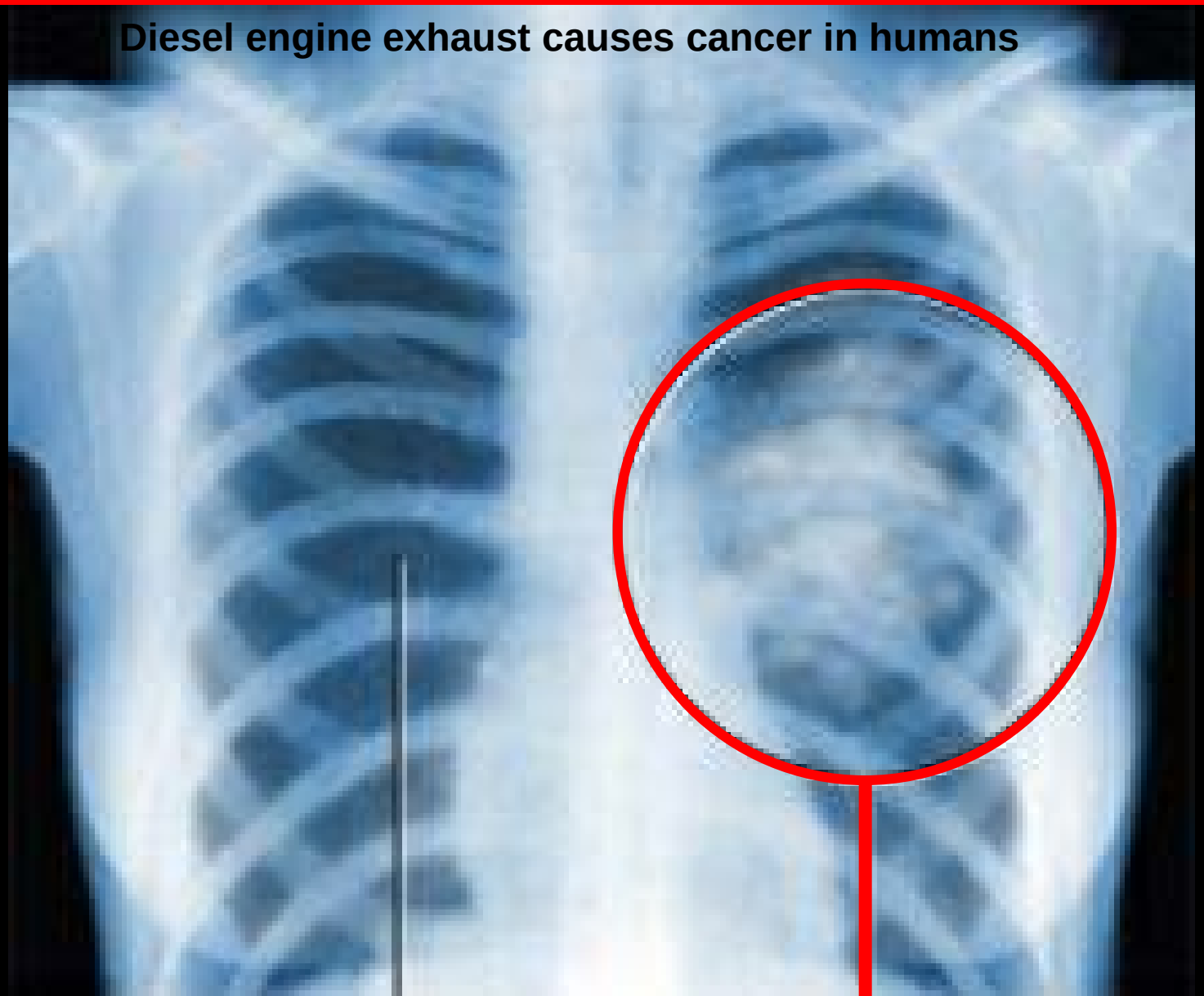
Locomotives
EU: ~55 % Diesel

World Health Organization, IARC
Diesel engine exhaust: A group 1 carcinogen

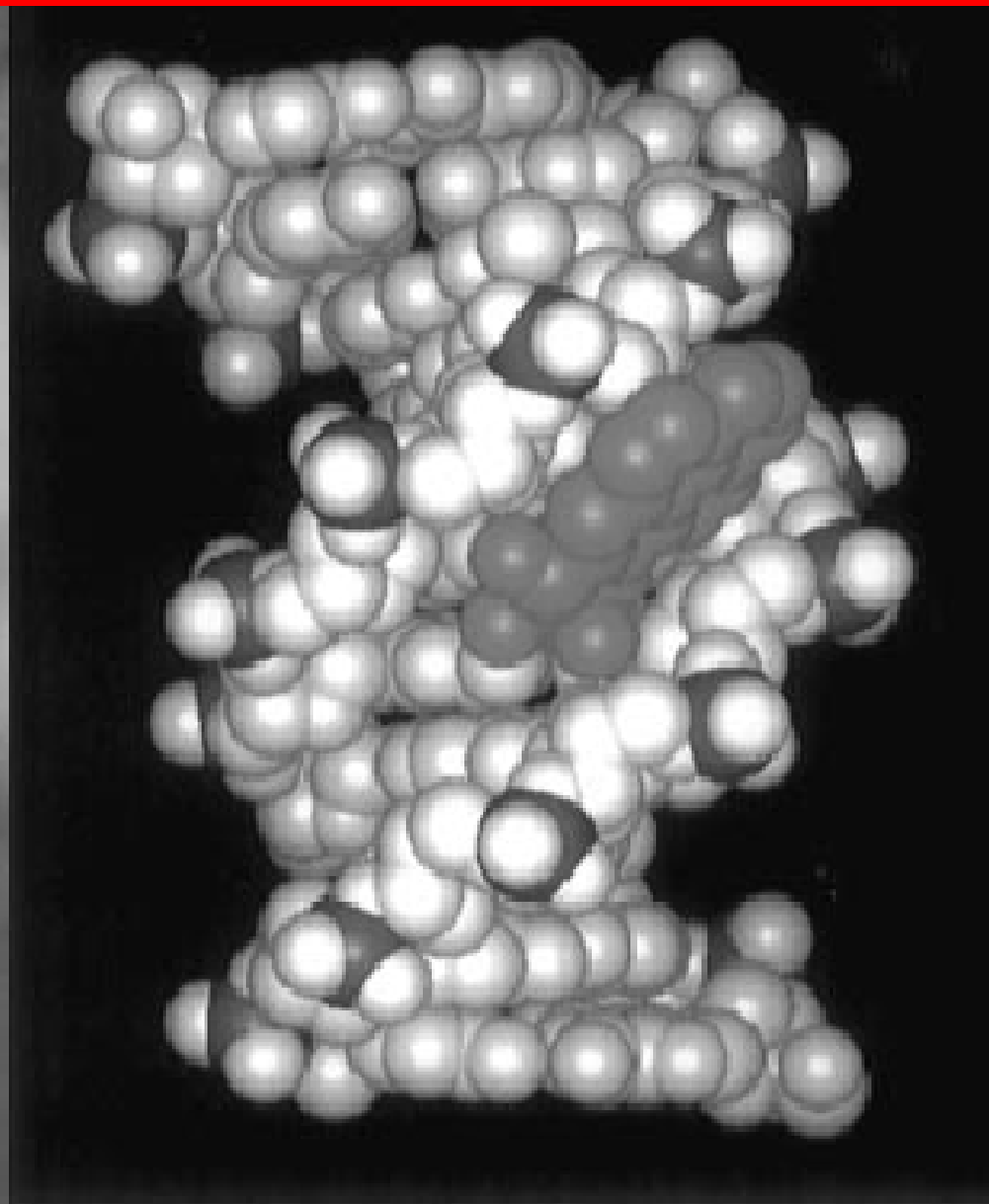


Adverse health effects of diesel exhaust

How about genotoxic compounds?

Problem 1: Genotoxicity

- Diesel exhaust is genotoxic (it contains mutagenic and carcinogenic compounds)



Adverse health effects of diesel exhaust

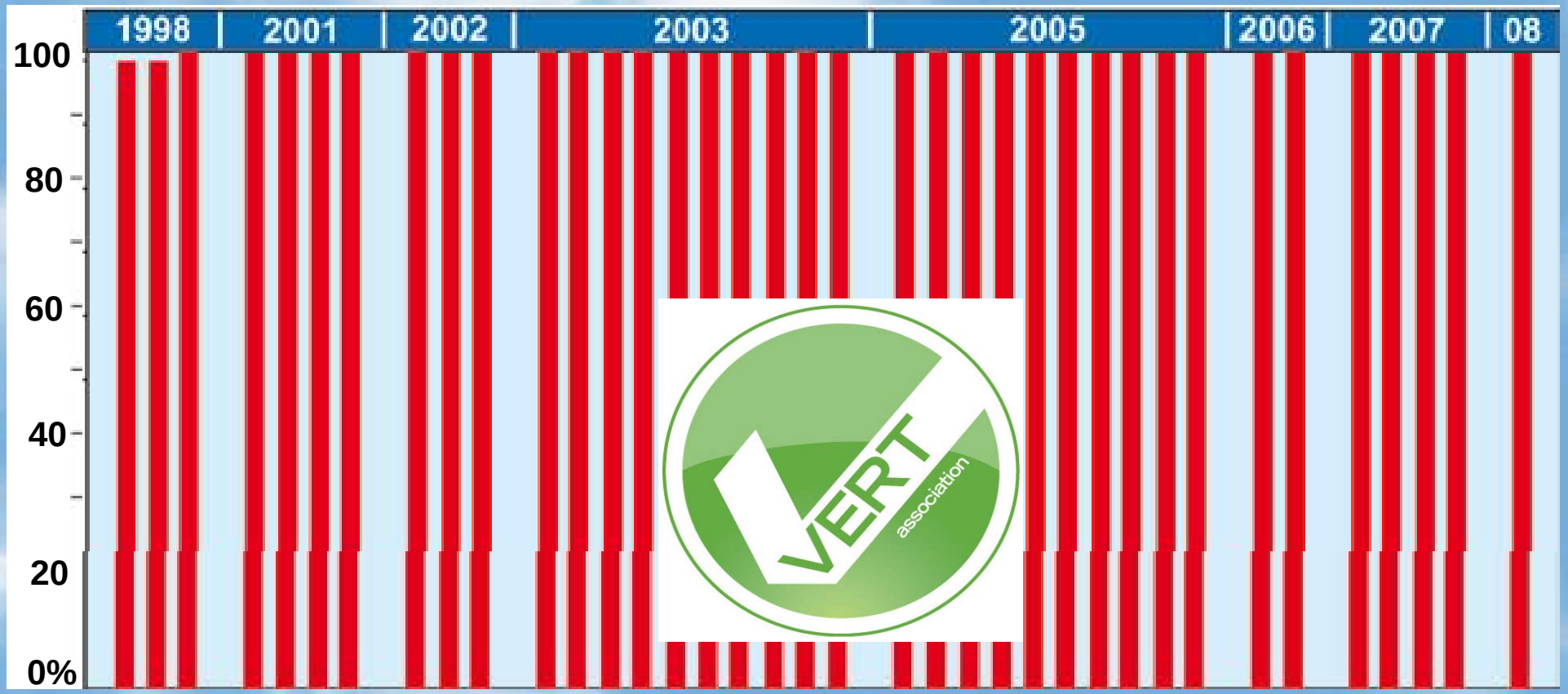
Problem 2: Trojan horse effect

- Nanoparticles penetrate cell membranes (alveoli, placenta, blood cells) acting like a Trojan horse transporting toxic compounds into cells

Trojan horse, Harbour of Canakkale, Turkey

Catalytic DPFs, BAT since 1998

more than 50 VERT-tested DPFs are on the market (ready to be used).



Mayer et al. MTZ, **2009**, 70, 72-79

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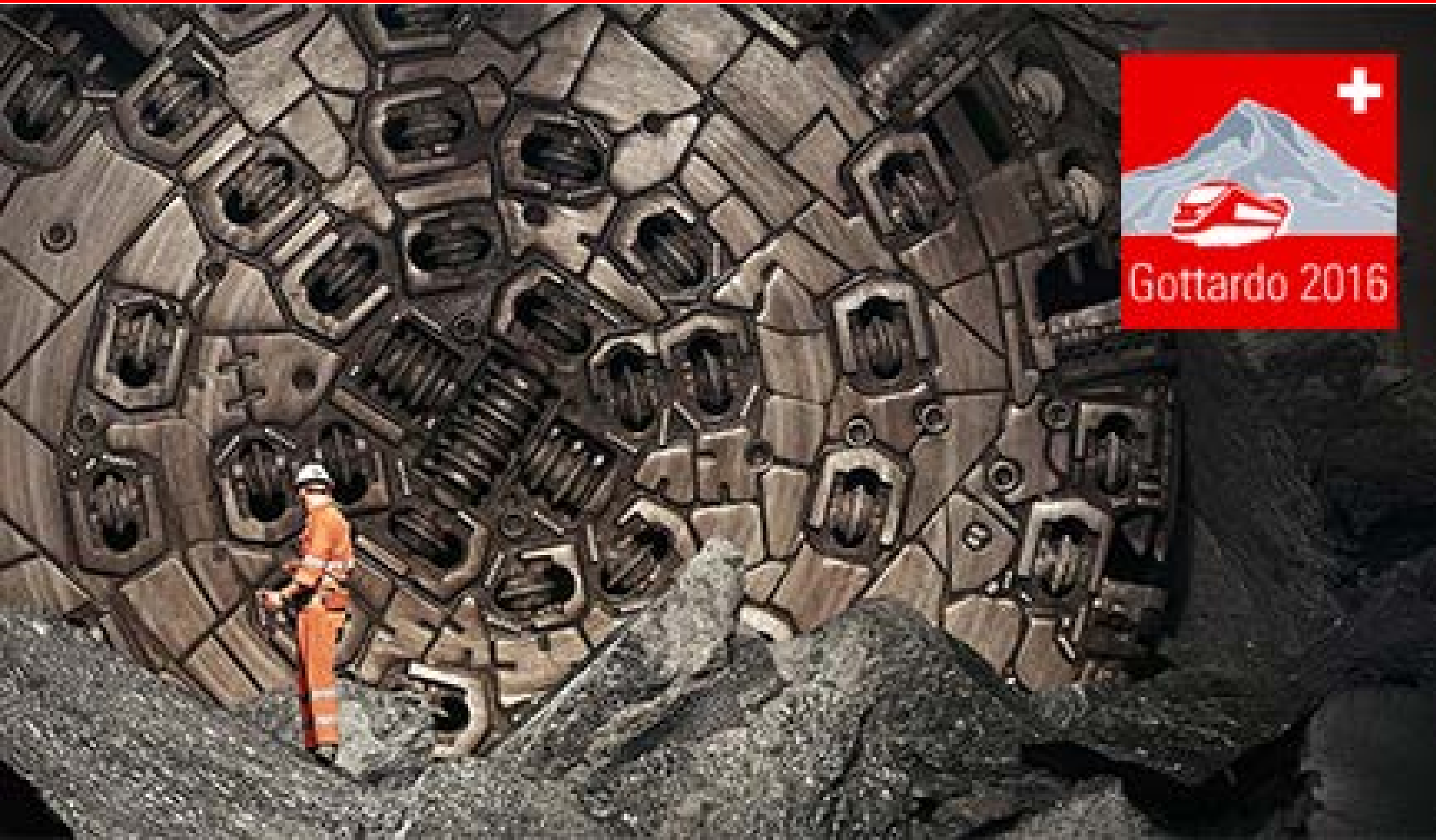
NEAT – the longest railway tunnel of the world
Was built with VERT/LRV-approved DPFs



NEAT – if DPFs work in these tunnels they'll also work in all other applications

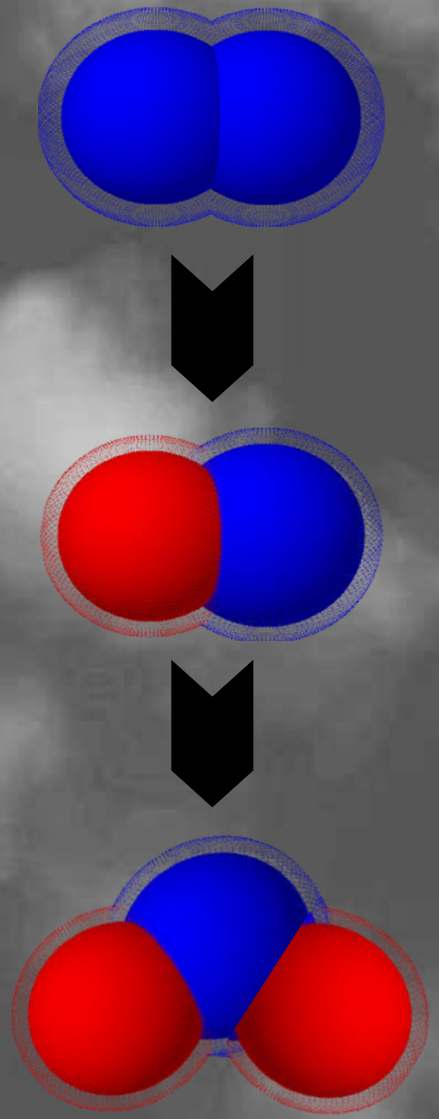
NEAT – the longest railway tunnel of the world
Was built with VERT/LRV-approved DPFs

Adverse health effects of diesel exhaust

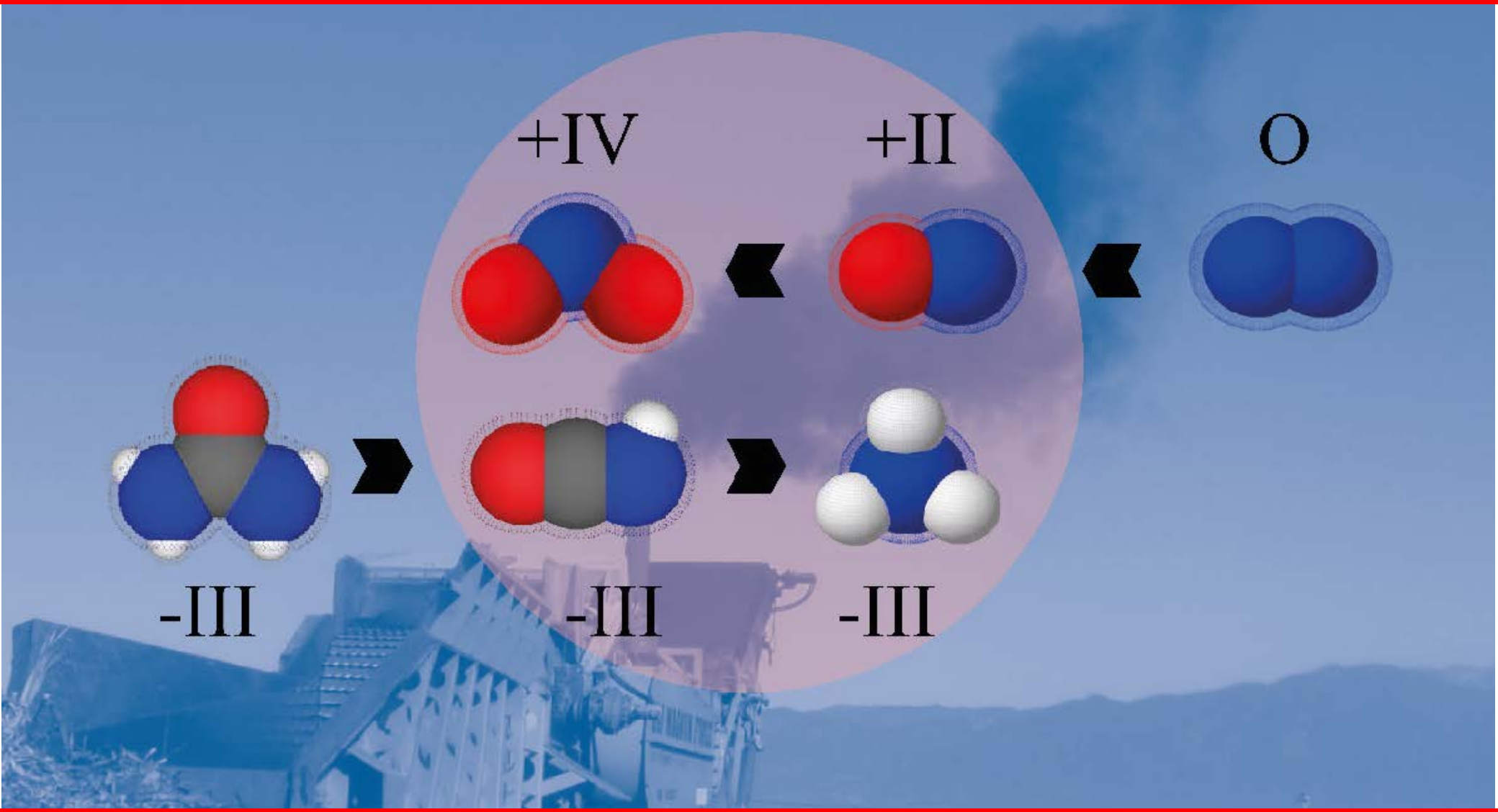
Problem 3: Reactive nitrogen compounds

- NO_2 highly toxic (acute and chronic) (induces oxidative stress, inflammation chronic obstructive pulmonary disease)
- Diesel vehicles with DOCs and hox-DPFs substantially increased NO_2 emissions

No diesel without efficient deNOx system!



Urea-based SCR

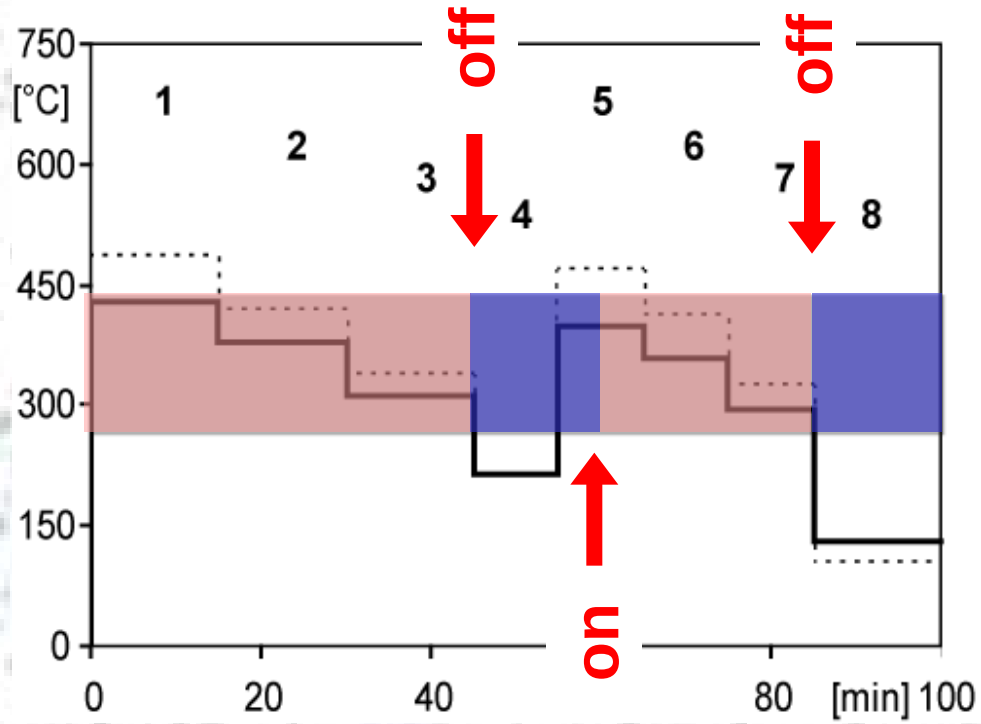


Currently the most efficient deNOx system for diesel engines

Exhaust temperatures in the ISO.8178/4 C1 cycle

The urea-based deNO$_x$-system is active only for about 60-80% of the operating time

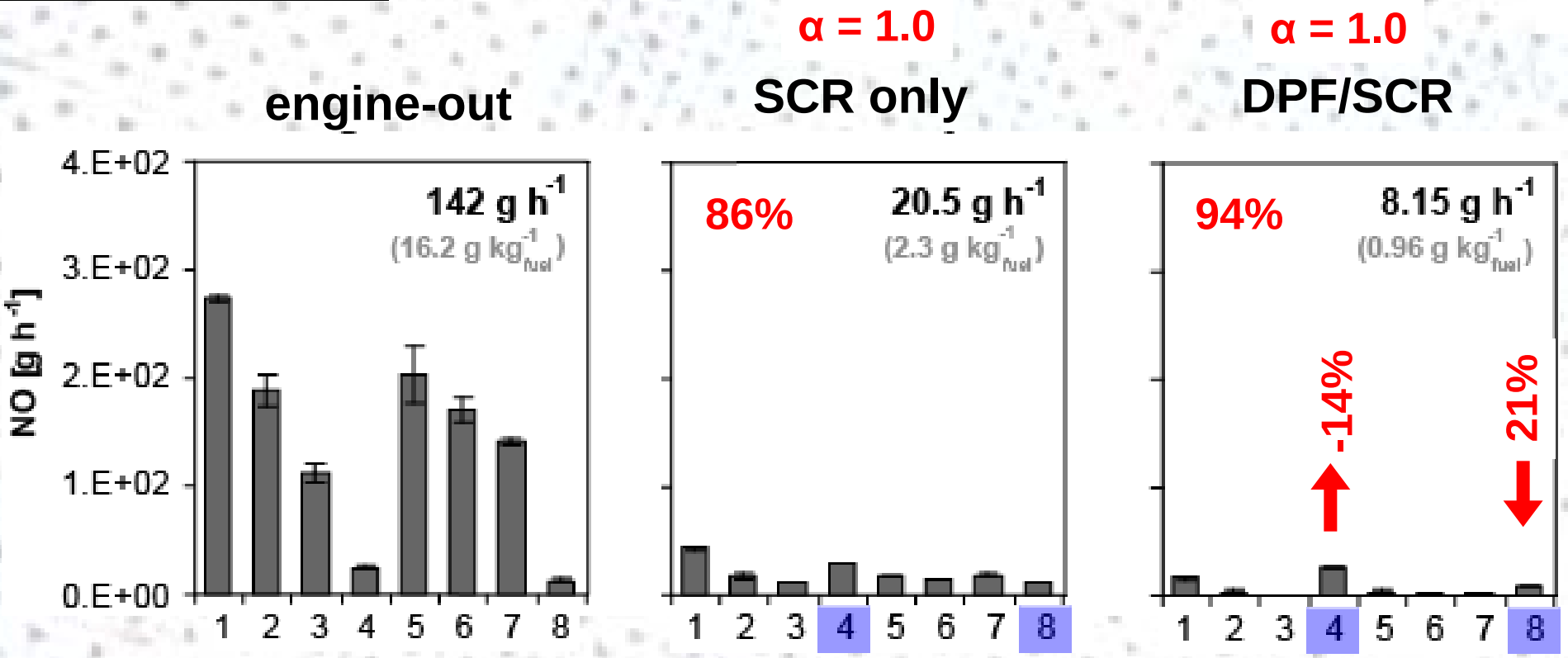
DeNO$_x$-system active >200°C



$DeNO_x$ Efficiencies: A best case scenario

High NO conversion efficiencies can be achieved at alpha = 1.0!

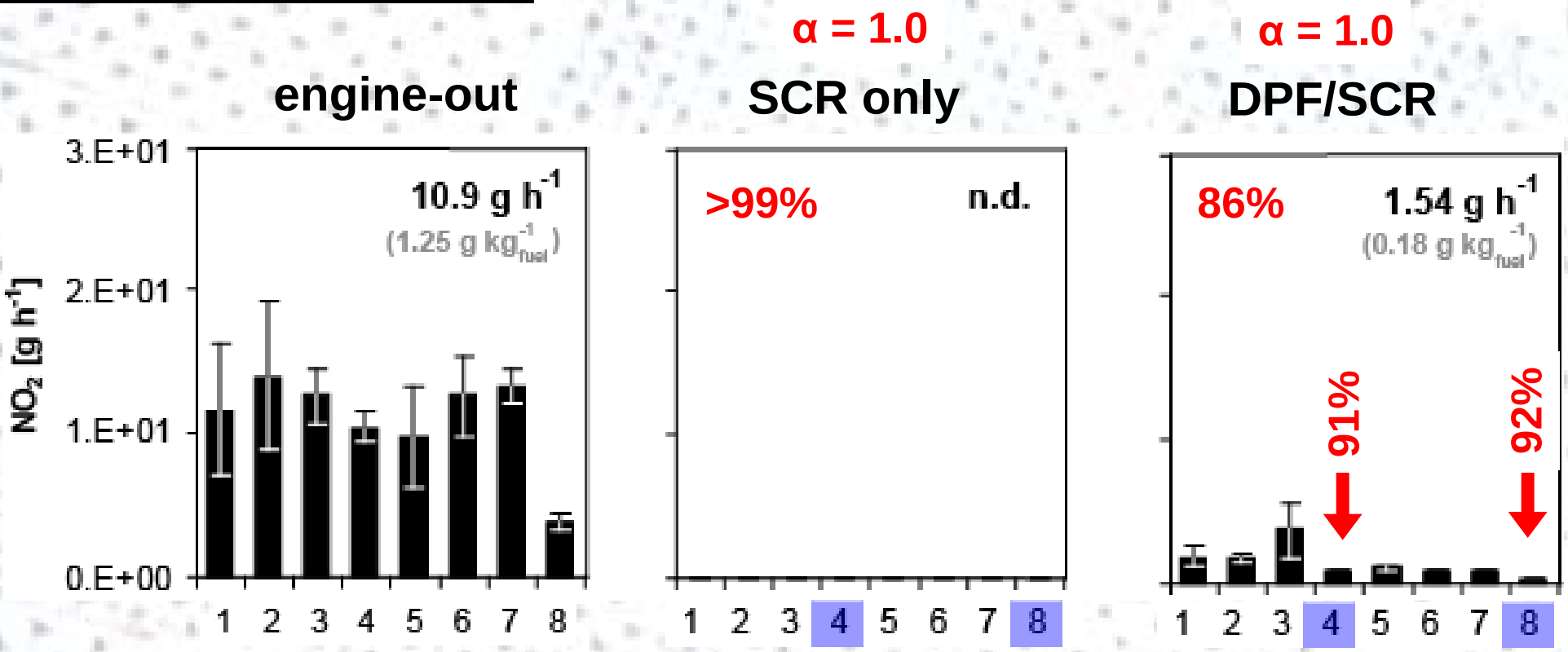
Nitric oxide (NO)



$DeNO_x$ Efficiencies: A best case scenario

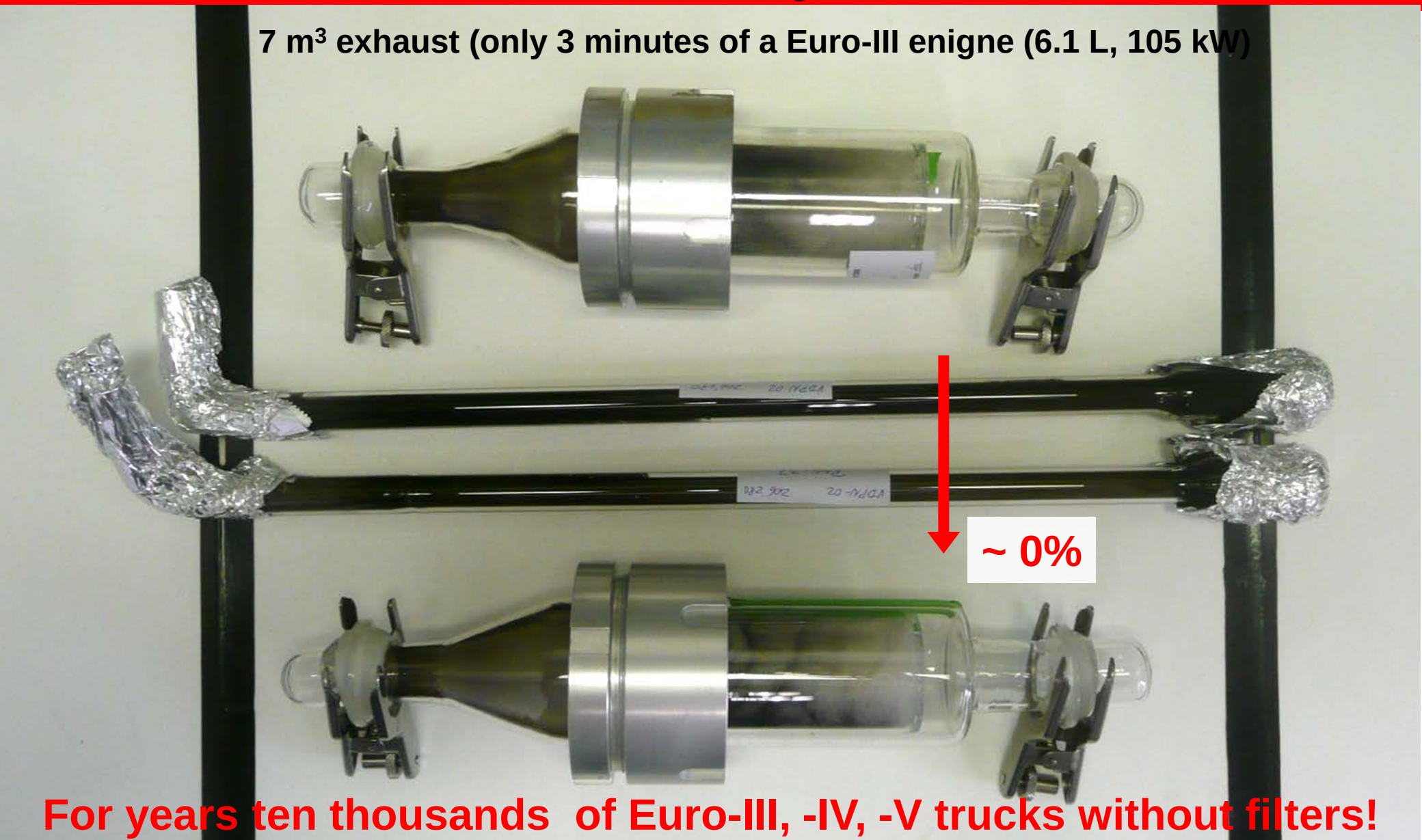
High $deNO_2$ efficiencies can be achieved at alpha = 1.0!

Nitrogen dioxide (NO_2)



~3% NO_2 und 97% NO Anteile

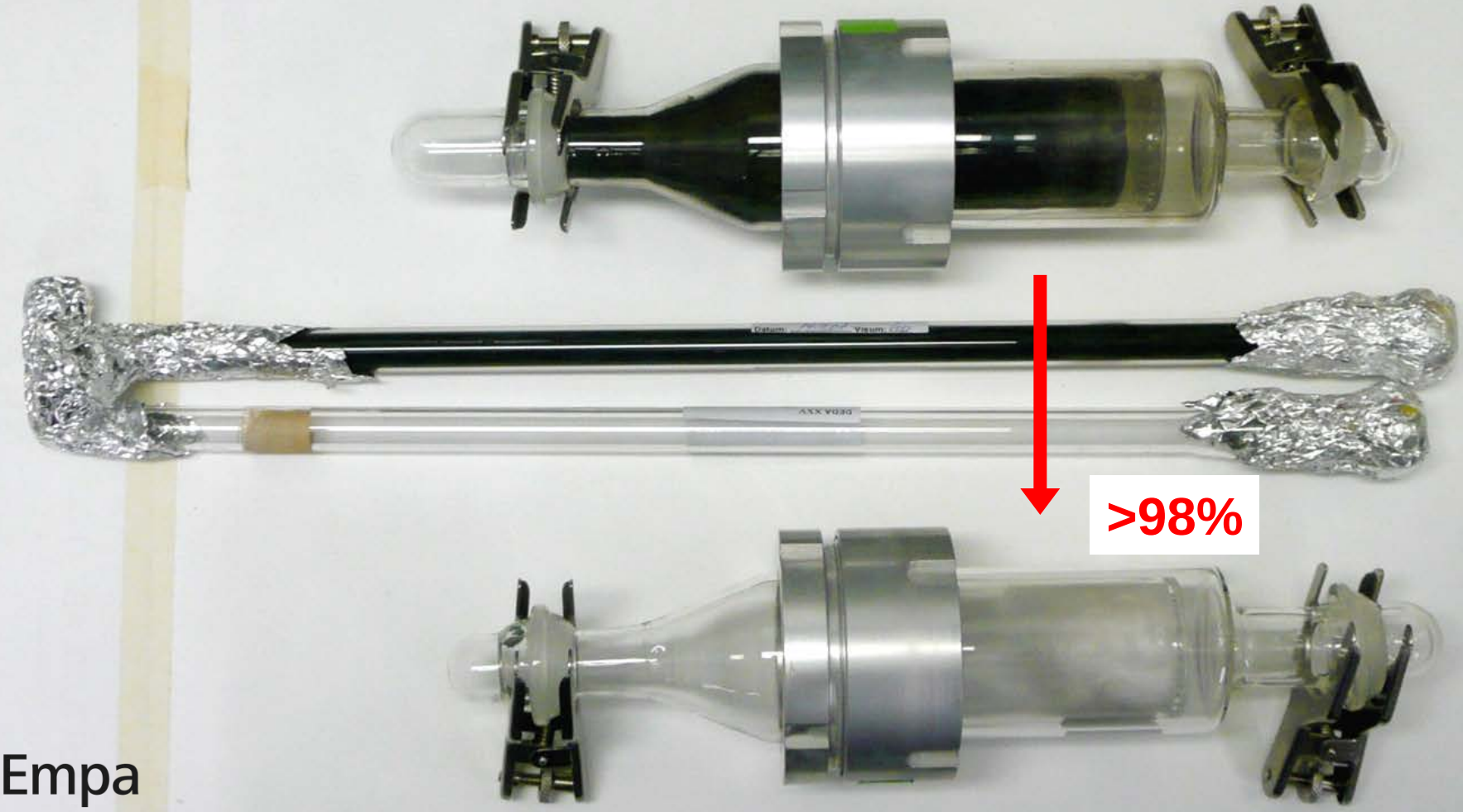
The visible effect of an SCR-system



For years ten thousands of Euro-III, -IV, -V trucks without filters!

The visible effect of an efficient DPF

About 7 m^3 of exhaust (3 min operating time of a 3.0 Liter Euro-III engine (100 kW)



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Summary

- The NO and NO_2, problem of diesel vehicles is 20 years old!
- No more particle-NOx trade-off, no more either/or policy
- No diesel without filter, no diesel without deNOx!

The future is dePN, but there's lot's of work ahead of us!

May be we also invite those to this conference that work on the NOx problem,
or those studying NOx-related toxicology,
or those developing NOx abatement technologies

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Outlook

Some suggestions to do better in the future

- test new technologies in advance (by independent bodies)
- develop specific regulations for NO, NO_2, NH_3, HNCO
- protection from toxic secondary pollutants
- incentives for efficient converter technologies (best available technology)
- avoid stupid legislation (e.g. ppm based NH_3 emission limit)

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The DePN - a chemical factory!

we need the diesel, but with efficient deNO_x and filter technologies!

The DePN - a chemical factory!

In other words:
if we can not deliver deNOx technologies that are active in real world, diesel vehicles will not be tolerated in our cities even though they are equipped with high quality filters!

we need the diesel, but with efficient deNO$_x$ and filter technologies!

Can diesel solve its NO and NO_2 emission problem in time?

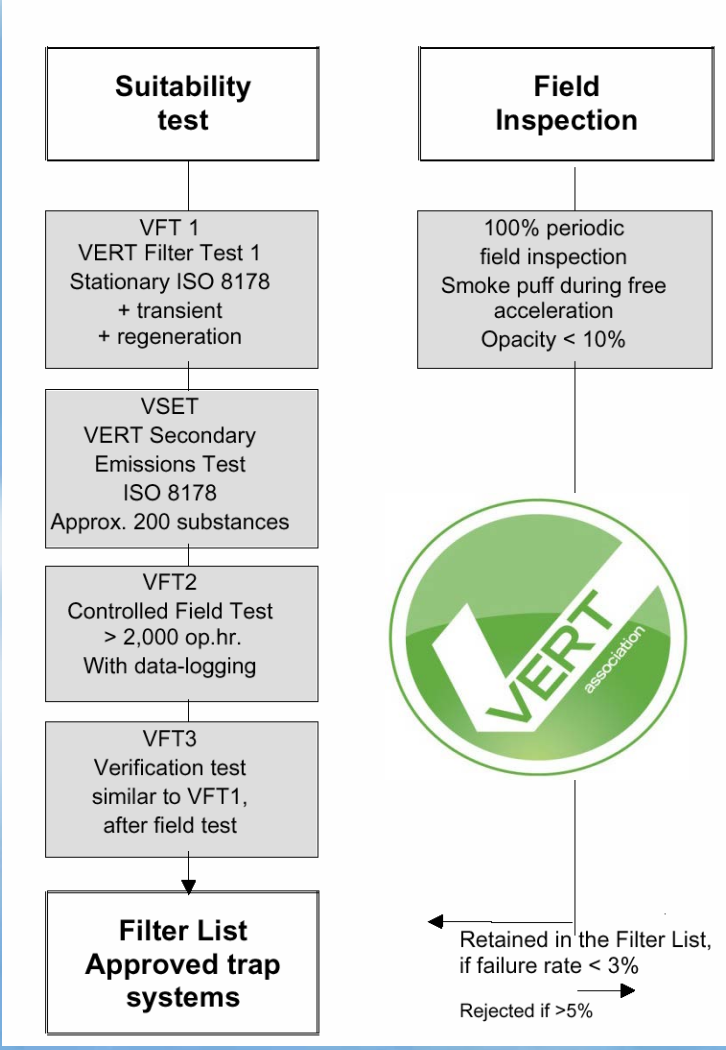
VERT should proceed and recommend the use of high quality dePN systems?

Requirements for VERT approved systems

Approved dePN systems should:

- lower genotoxic compounds (a.m.a.p.)
- reduce PM- & PN-emissions (>98%)
- reduce NO and NO_2 emissions (not defined yet)
- have low risks of secondary emissions
- not increase metal emissions (e.g. catalysts)

we need >90%



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