Analyses of effects of fuel sulfur content on DPF particle removal efficiency and particle deposition in human lung

Mahdi Doozandegan, Hossein Nemati, **Vahid Hosseini***, Mohammadsaid Saidi

Mechanical Engineering Department
Sharif University of Technology, Tehran, Iran

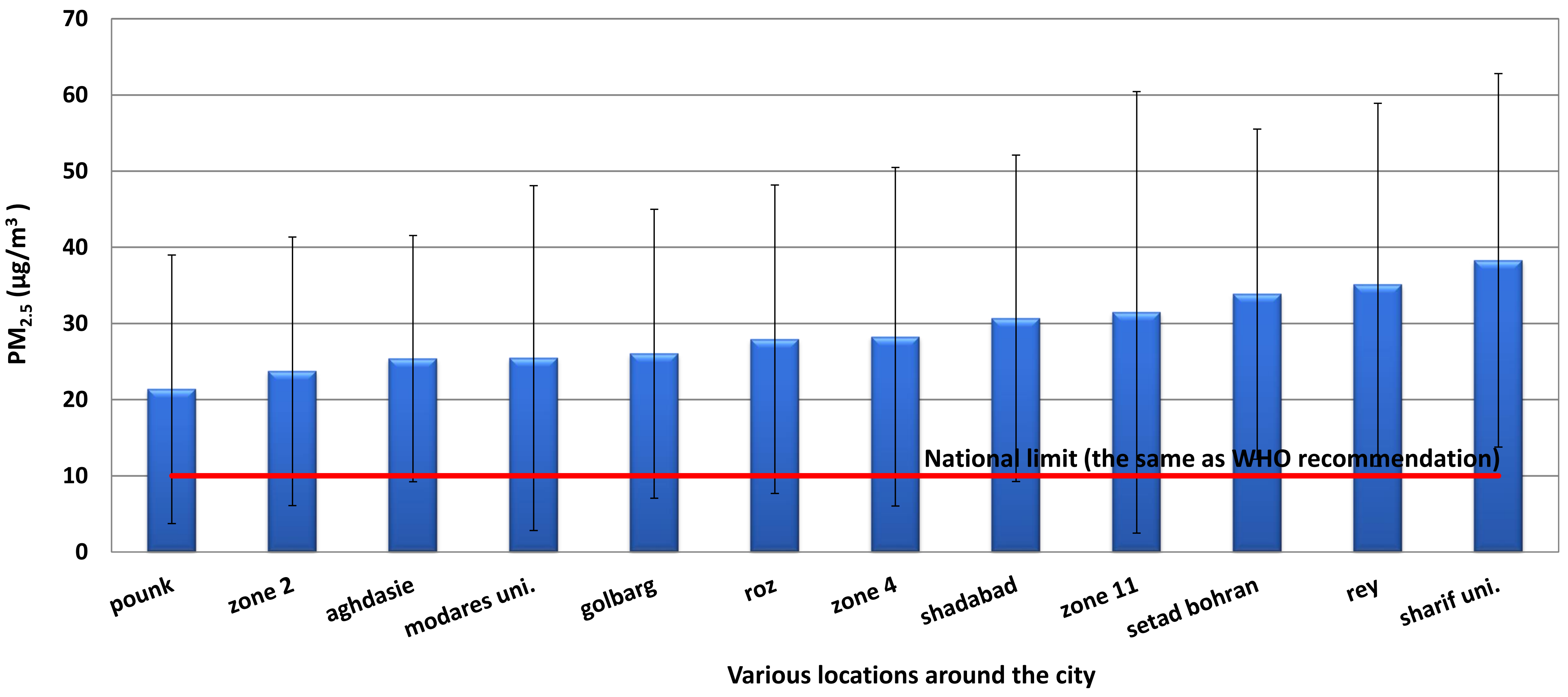
** Presenter and corresponding author*

20th ETH-Conference on Combustion Generated Nanoparticles
June 13th – 16st 2016, Zurich, Switzerland

Tehran Air Quality with respect to Particles

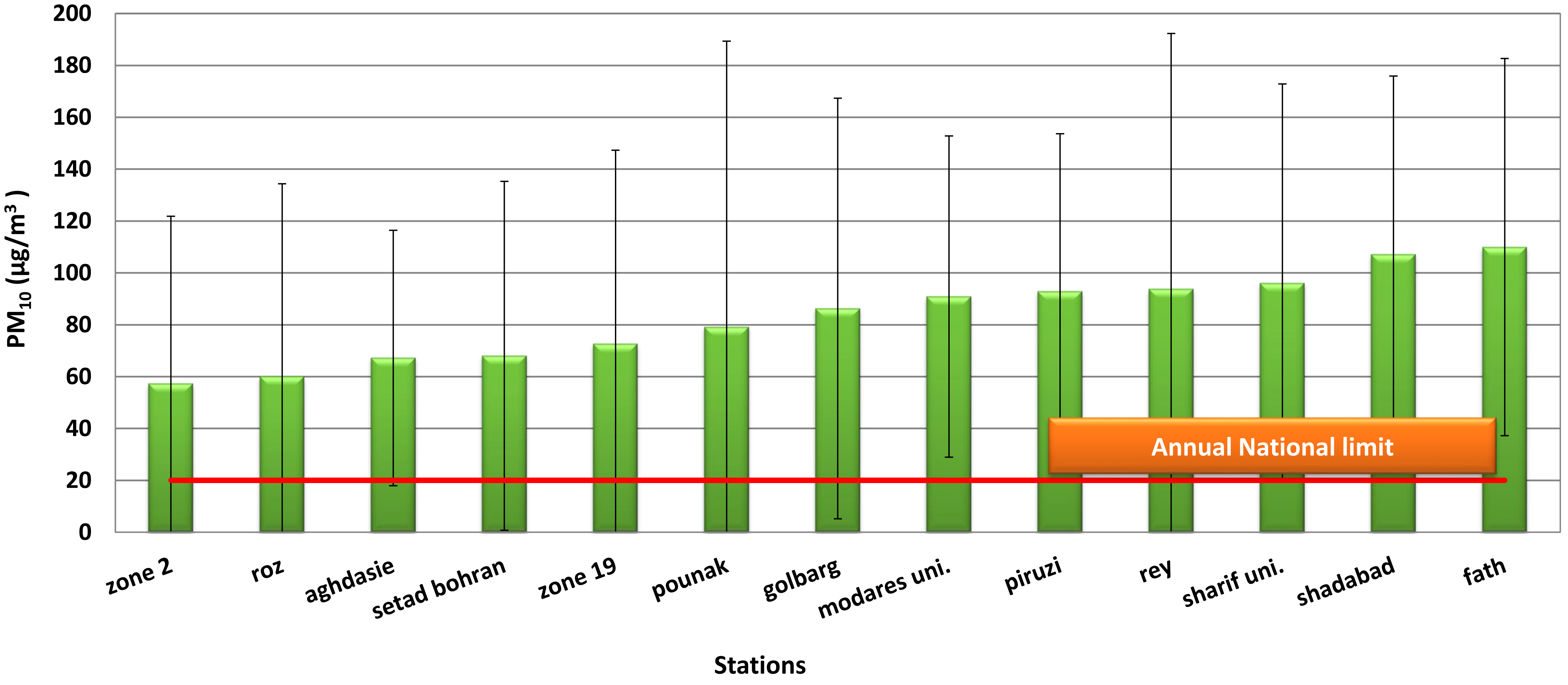
Annual Concentrations of $PM_{2.5}$ in AQCC Stations in the City of Tehran During 21 March 2015 to 19 March 2016

The red line is national standard level



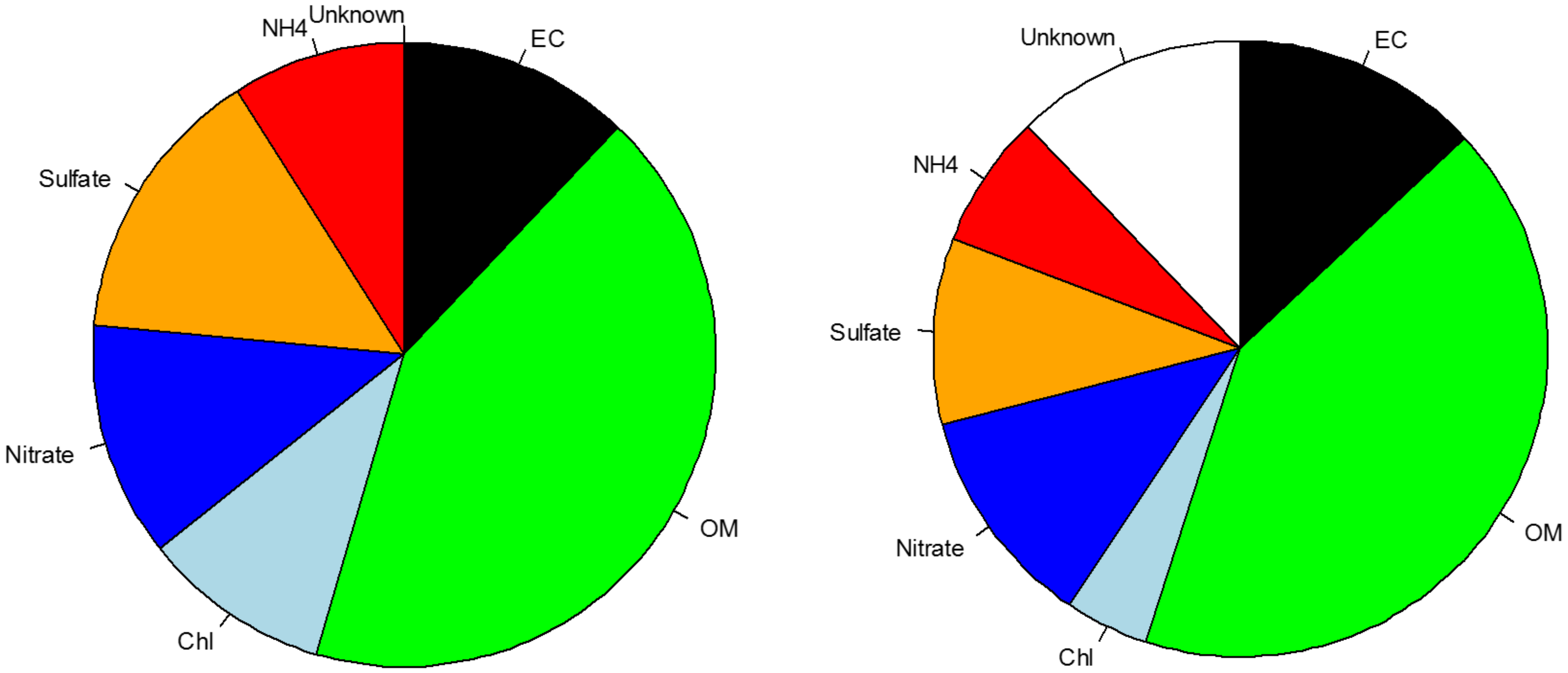
Annual Concentrations of PM_{10} in AQCC Stations in the City of Tehran During 21 March 2015 to 19 March 2016

The red line is national standard level

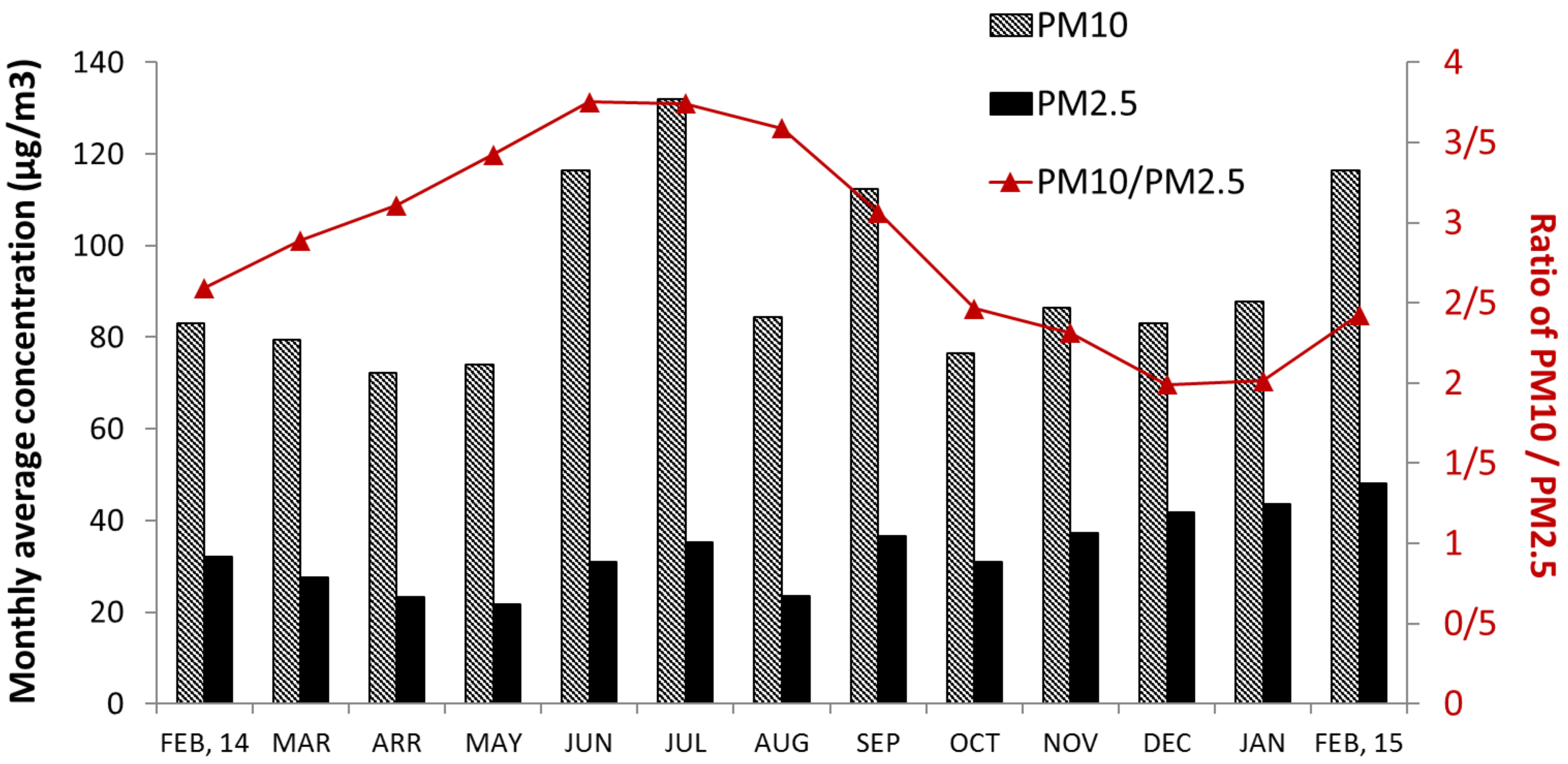


Chemical analysis of PM2.5 in two stations of Tehransar and Aqdasieh stations

Analyses: EMPA laboratory, Zurich, Switzerland

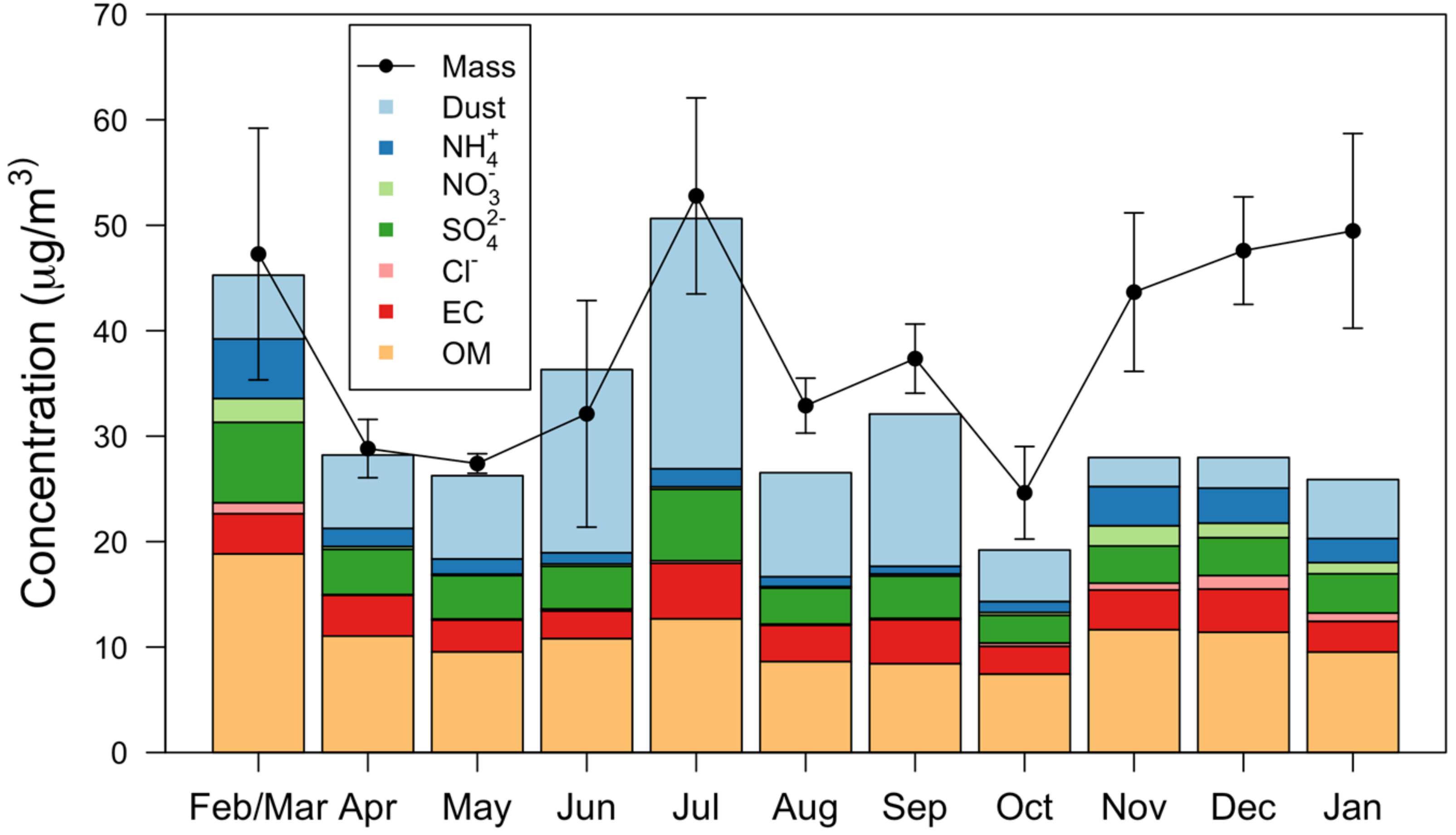


PM10 and PM2.5 during 2014-2015 sampling period



Chemical analyses of PM2.5 samples done by Prof. James Schauer of University of Wisconsin, Madison, USA
Sampling by Prof. Mohammad Arhami of Sharif University

Average composition



Average composition:

Organic matter (**OM**): 28 ± 12%

Dust: 22 ± 19%

Sulfate (**SO_4^{2-}**): 11 ± 6%

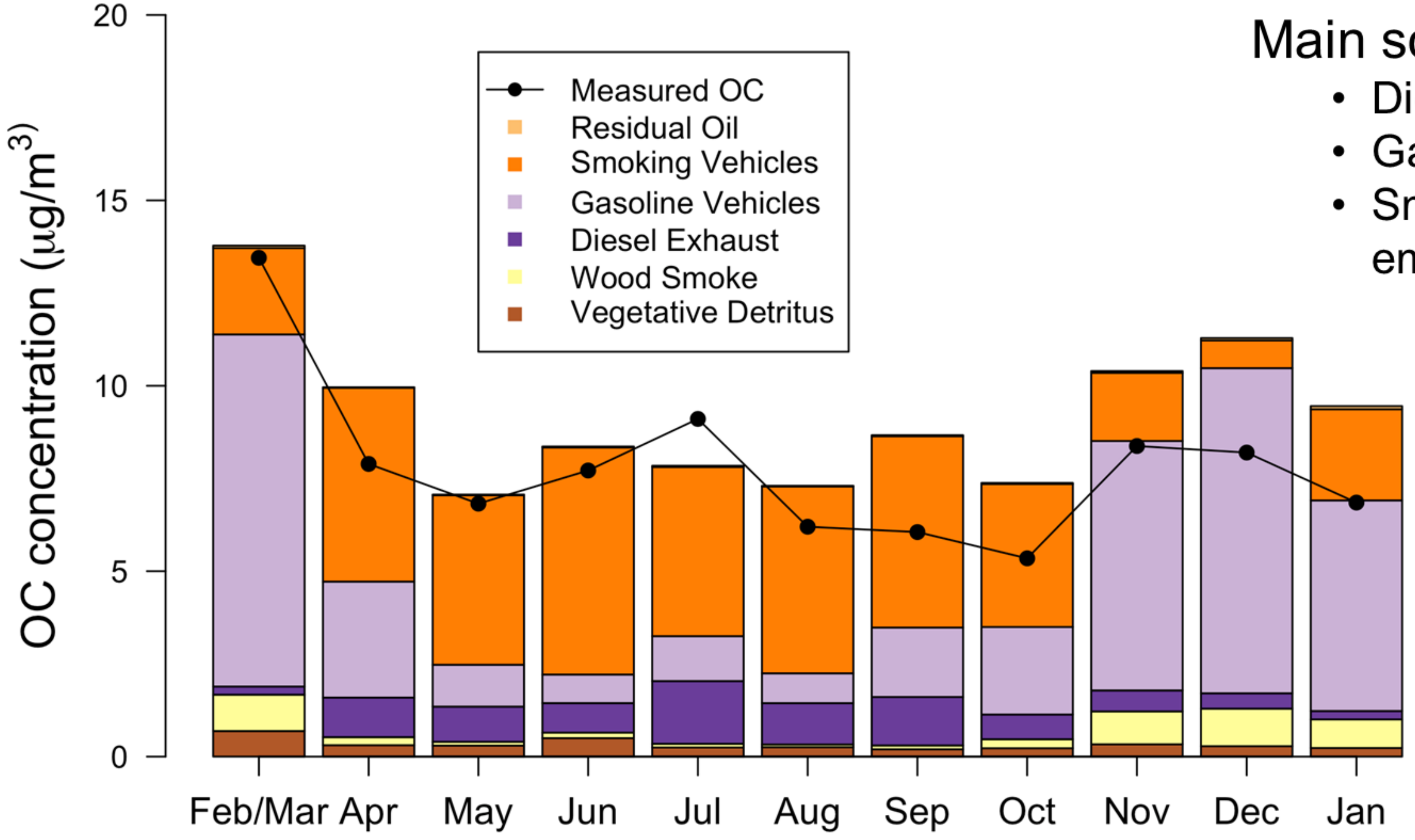
Elemental carbon (**EC**): 9 ± 4%

Ammonium (**NH_4^+**): 6 ± 6%

Nitrate (**NO_3^-**): 2 ± 3%

Chemical analyses of PM2.5 samples done by Prof. James Schauer of University of Wisconsin, Madison, USA
Sampling by Prof. Mohammad Arhami of Sharif University

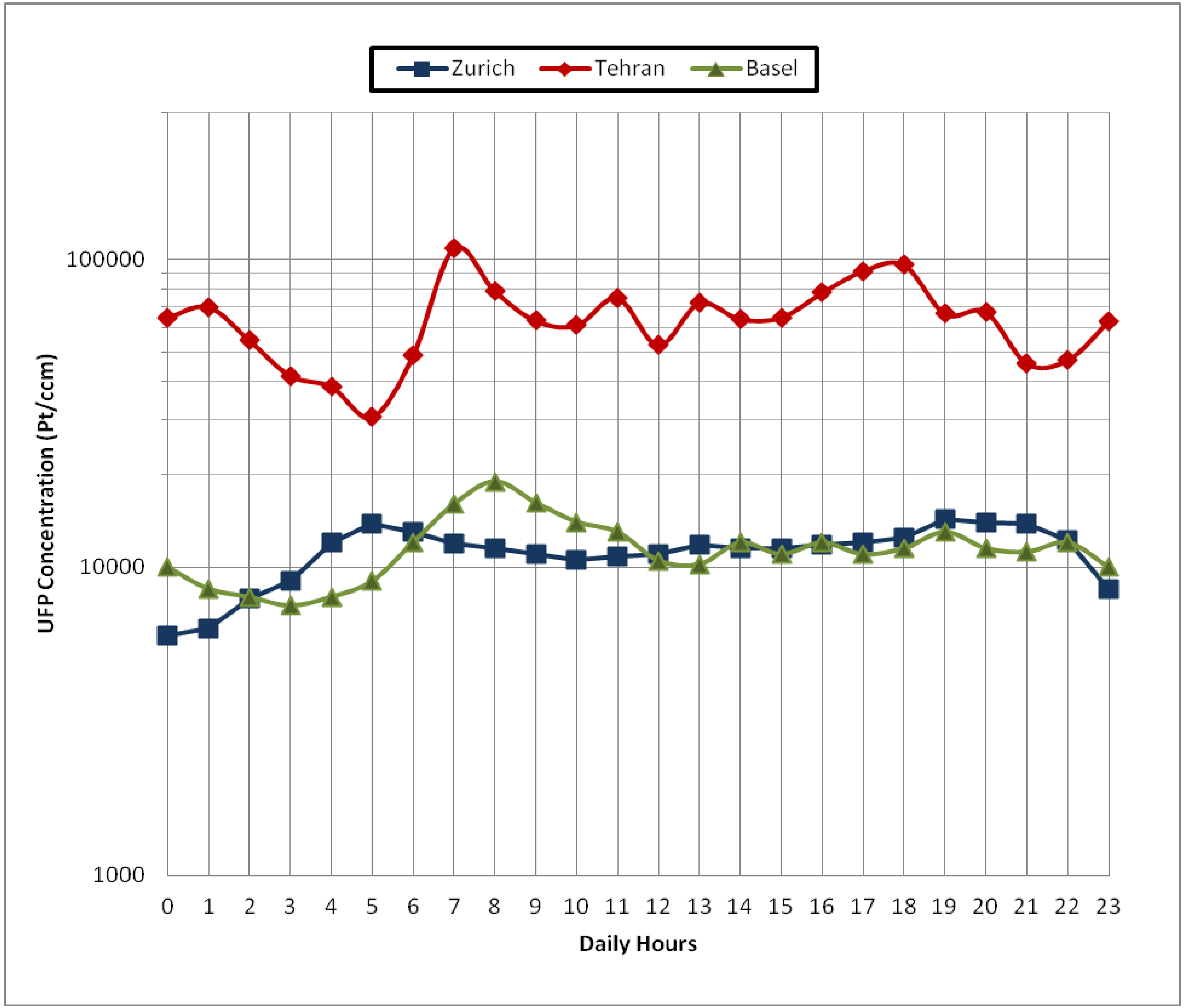
Main sources of OC



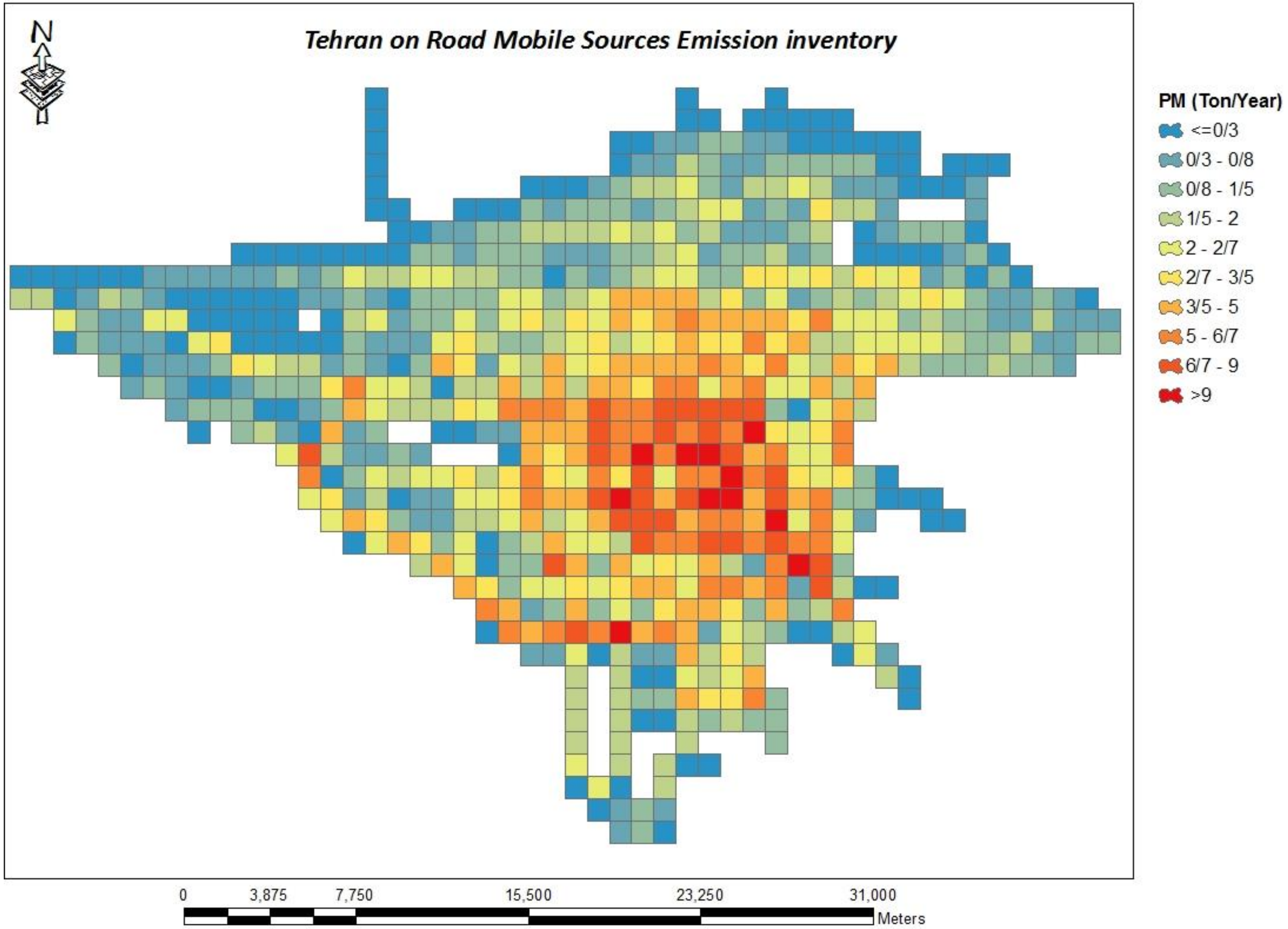
Main source of OC: vehicles
- Diesel
- Gasoline
- Smoking (vehicles without emissions controls)

Chemical analyses of PM2.5 samples done by Prof. James Schauer of University of Wisconsin, Madison, USA
Sampling by Prof. Mohammad Arhami of Sharif University

A Comparison of number of fine particles in Tehran air vs Zurich/Basel



Spatial distribution of annual PM emission from mobile sources



Decisions both at national and local governments

Tehran Municipality

- The issue with particles, especially traffic-generated particles became clear for Tehran Municipality in 2012.
- AQCC was mandated to put together a comprehensive program to reduce combustion generated particles.
- FCE lab of Sharif University was involved on developing the comprehensive plan. VERT was approached in March 2013 for diesel particles mitigating measures.

The big picture

- The target was set to reduce traffic-related particles.
- The program includes:
  - Removal of carburetor gasoline motorcycles
  - Old fleet renewal for public and private sectors diesel vehicles
  - More natural-gas public transit bus introduction to the city
  - Electric bus for BRT lines
  - The very first Tehran LEZ plan with restrictions for carburetor gasoline vehicles
  - Introduction of BAT DPFs for all public transit buses including those with private companies.

Activities at national level

- At national level, a very strong legislation was approved by cabinet to retrofit diesel buses in all major cities of Iran with DPF.
- Plus, starting March 2015 all new diesel vehicles must be equipped with DPF independent of their emission standard limits which is currently Euro-III and Euro-IV.

National legislation for new and used vehicles

Iran legislation to protect the environment [4]

from April 2014

	Activity	Executor	Supervisor	Time plan
1	**Fuel**			
1-2	Distributing Euro 4 fuel and diesel having maximum sulfur content of 40 ppm, in Tabriz (Jul. 23, 2014) in Esfahan and Shiraz (Sep. 23, 2014) , in Ahvaz and Mashhad (Nov. 23, 2014)	Ministry of Oil	Department of Environment	*
1-3	Standardization of fuel, at least in metropolises, according to Euro 4 and Euro 5 standards, and standardization of fuel in power plants based on Supreme Council of Department of Environment's act.	Ministry of Oil	Department of Environment	36 months
2	**Moving vehicle**			
2-1	Replacing public city vehicles' catalyst.	Homeland Ministry(via municipality)	Department of Environment	6 months
2-3	Using particulate filters for diesel heavy-duty vehicles	Homeland Ministry(For urbane public vehicles via municipality) -Ministry of Roads and Transportation	Department of Environment	24 months
4	**New vehicles**			
4-1	Diesel vehicle registration is complete, stipulating that the soot filter is used.	Traffic Police of Iran	Department of Environment	Mar. 21, 2015

National legislation for new and used vehicles

- **<u>A stakeholder process</u>** during 2015 was introduced and during one year, details of the new legislation was discussed and approved as Iran IVa and Iran IVb.
- The legislation is basically at Euro IV level, but requires a closed filter.
- Opposed by a few European manufacturers, the implementation date was delayed to September 2016 for urban vehicles and March 2017 for all vehicles.

Pilot performance and durability tests for the case of Iran

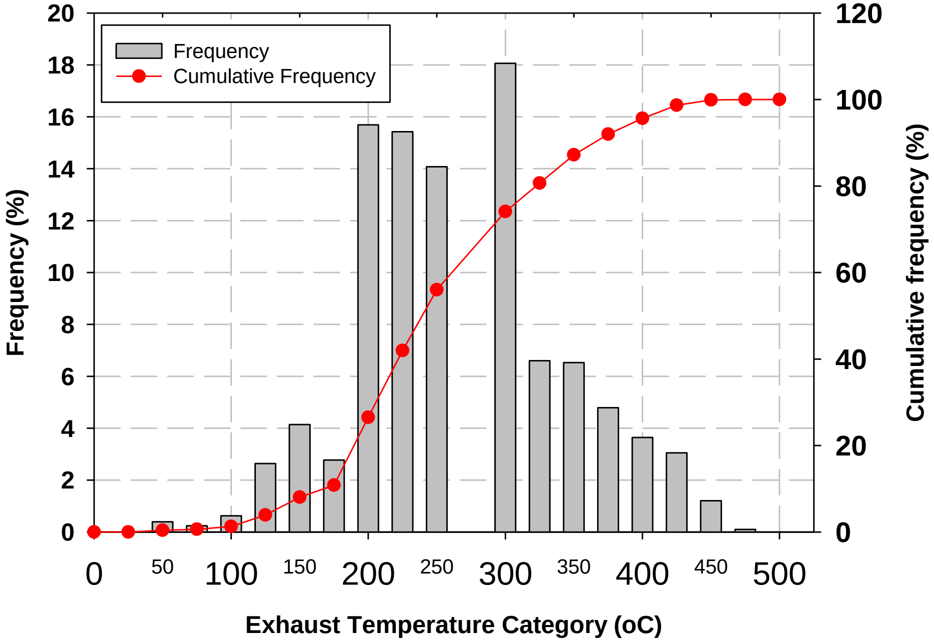
Main concerns

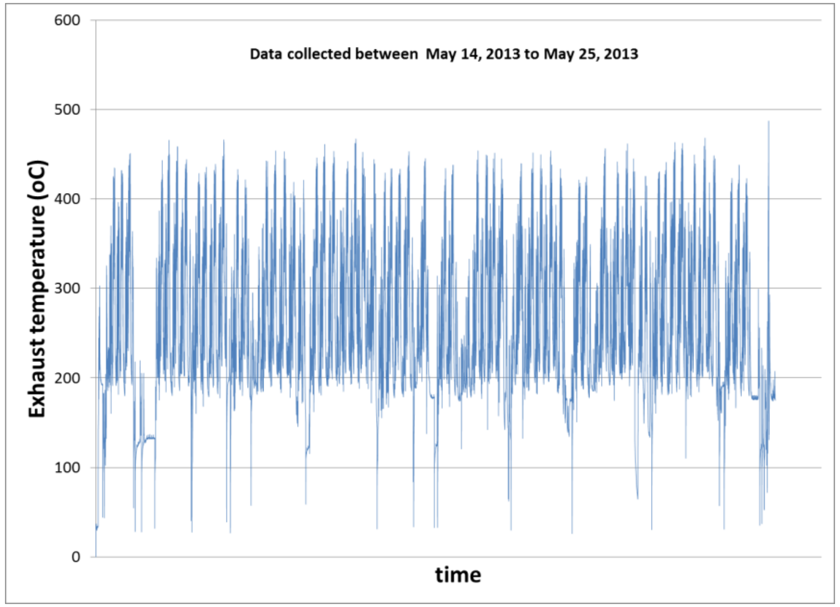
- Low exhaust temperature
- High fuel sulfur content
- High sulfate ash lube oil
- High smoke number and low NOx

Triple-stages pilot program was designed

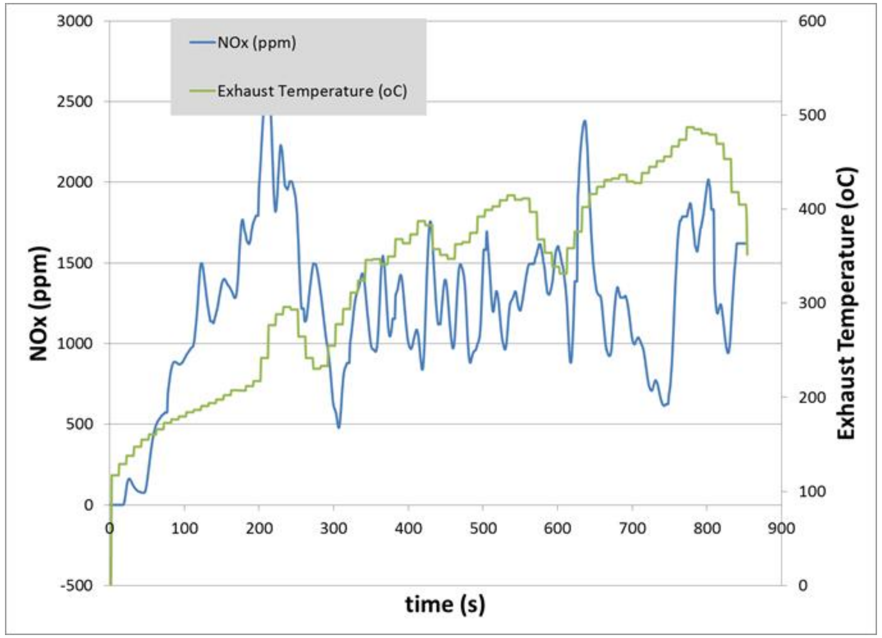
- Stage 1: Selection of candid engine and vehicles, exhaust data gathering
  - MAN articulated buses with Euro II and Euro III engines
- Stage 2: Engine dynamometer tests
  - Daimler OM457 Euro II engine
  - Fuel sulfur : 50 ppm, 229 ppm, 7000 ppm
- Stage 3: Year-long durability tests on buses

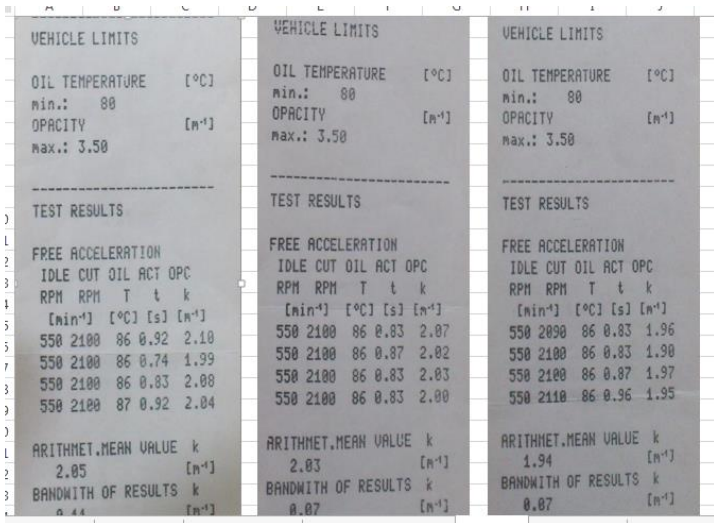
Stage 1: Exhaust temperature analyses of the pilot fleet





Stage 1: NOx and smoke number





VEHICLE LIMITS

OIL TEMPERATURE [°C]
min.: 80
OPACITY [m-1]
max.: 3.50

TEST RESULTS

FREE ACCELERATION

IDLE RPM [min-1]	CUT RPM [min-1]	OIL T [°C]	ACT t [s]	OPC k [m-1]
550	2100	86	0.92	2.10
550	2100	86	0.74	1.99
550	2100	86	0.83	2.08
550	2100	87	0.92	2.04

ARITHMET.MEAN VALUE k [m-1]
2.05
BANDWITH OF RESULTS k [m-1]
0.44

VEHICLE LIMITS

OIL TEMPERATURE [°C]
min.: 80
OPACITY [m-1]
max.: 3.50

TEST RESULTS

FREE ACCELERATION

IDLE RPM [min-1]	CUT RPM [min-1]	OIL T [°C]	ACT t [s]	OPC k [m-1]
550	2100	86	0.83	2.07
550	2100	86	0.87	2.02
550	2100	86	0.83	2.03
550	2100	86	0.83	2.00

ARITHMET.MEAN VALUE k [m-1]
2.03
BANDWITH OF RESULTS k [m-1]
0.07

VEHICLE LIMITS

OIL TEMPERATURE [°C]
min.: 80
OPACITY [m-1]
max.: 3.50

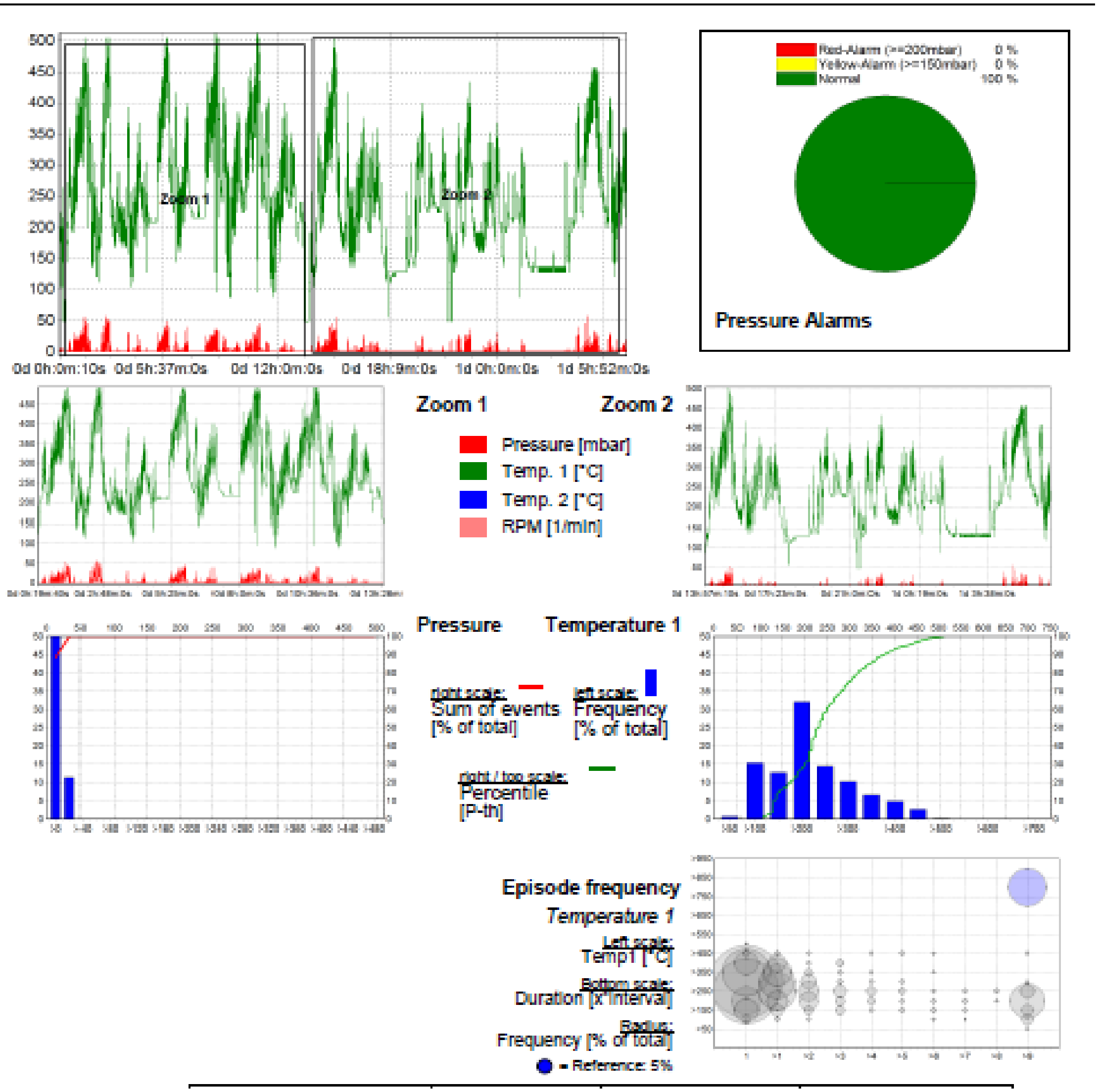
TEST RESULTS

FREE ACCELERATION

IDLE RPM [min-1]	CUT RPM [min-1]	OIL T [°C]	ACT t [s]	OPC k [m-1]
550	2090	86	0.83	1.96
550	2100	86	0.83	1.90
550	2100	86	0.87	1.97
550	2110	86	0.96	1.95

ARITHMET.MEAN VALUE k [m-1]
1.94
BANDWITH OF RESULTS k [m-1]
0.07

Stage 1: Statistical analyses of exhaust temperature and pressure data



Stage 1: Instruments and filters

hugengineering.
Ein Unternehmen der ElringKlinger-Gruppe

HUSS GROUP
We care for air.

bersy
catalysts and exhaust systems

HJS
Emission Technology

BAUMOT

matter aerosol
a testo company

TEHAG

GLOBALMRV
Fuel, Fleet, Emissions Specialists

CPK Automotive
Member of the Heinzmann Group

dinex

PURItech
ABGASTECHNIK – EMISSION TECHNOLOGY

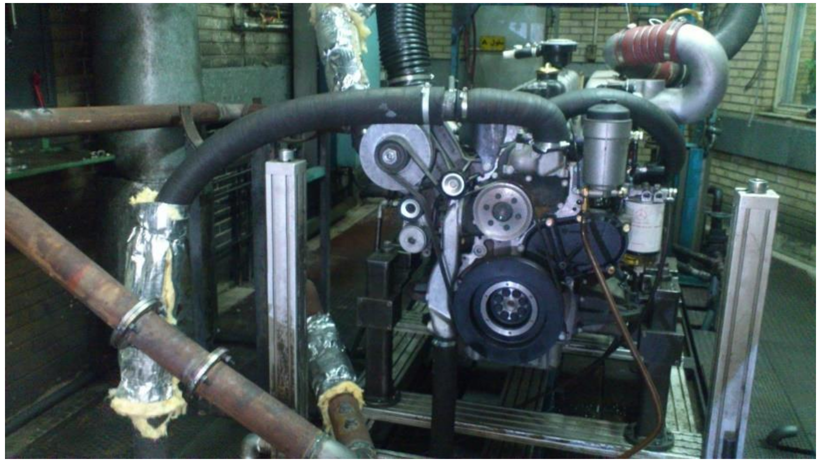
AIRMEEX

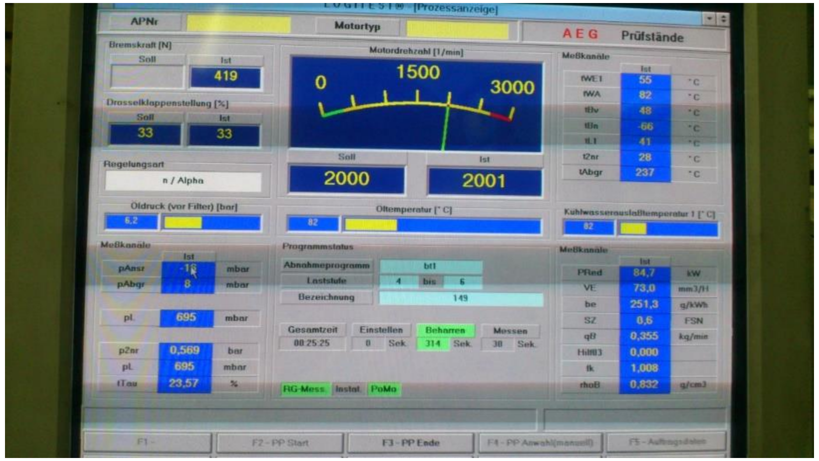
RUNWODA 北京润沃达汽车科技有限公司

Stage 2: engine test cell preparation

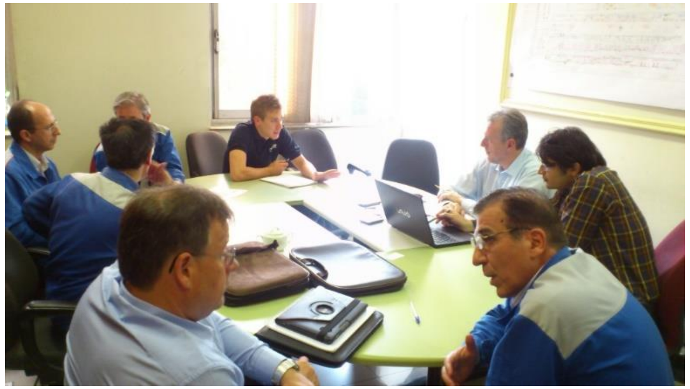
- The engine lab in IDEM Co., Tabriz, Iran is a hot test engine lab at the end of production line of Mercedes engine.
- The lab was equipped and instrumented by AQCC
- The data acquisition and control software was set to be able to run the soot loading, balance point, and filter efficiency tests.
- Low, medium, and high sulfur diesel was prepared and re-analyzed.
- Enough FBC was supplied for engine tests

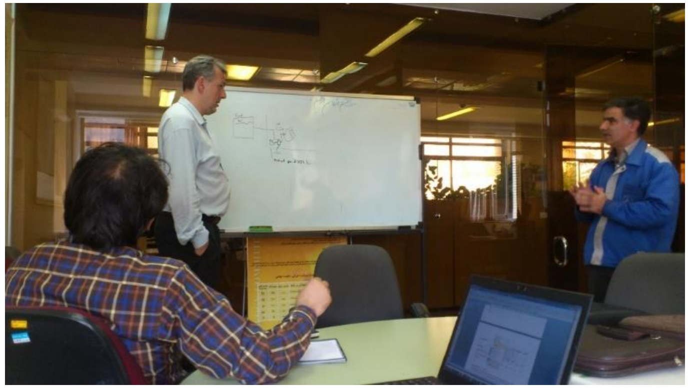
Stage 2: engine test cell preparation



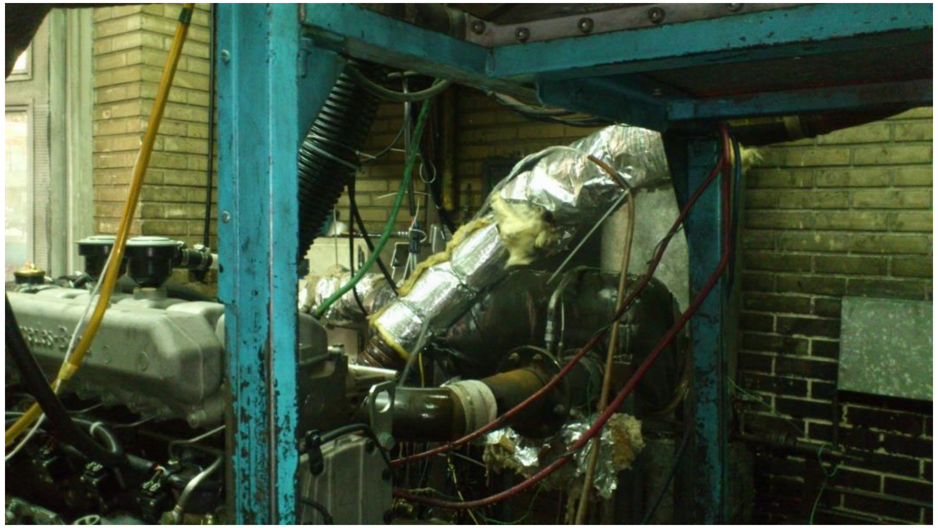


Stage 2: engine test cell preparation

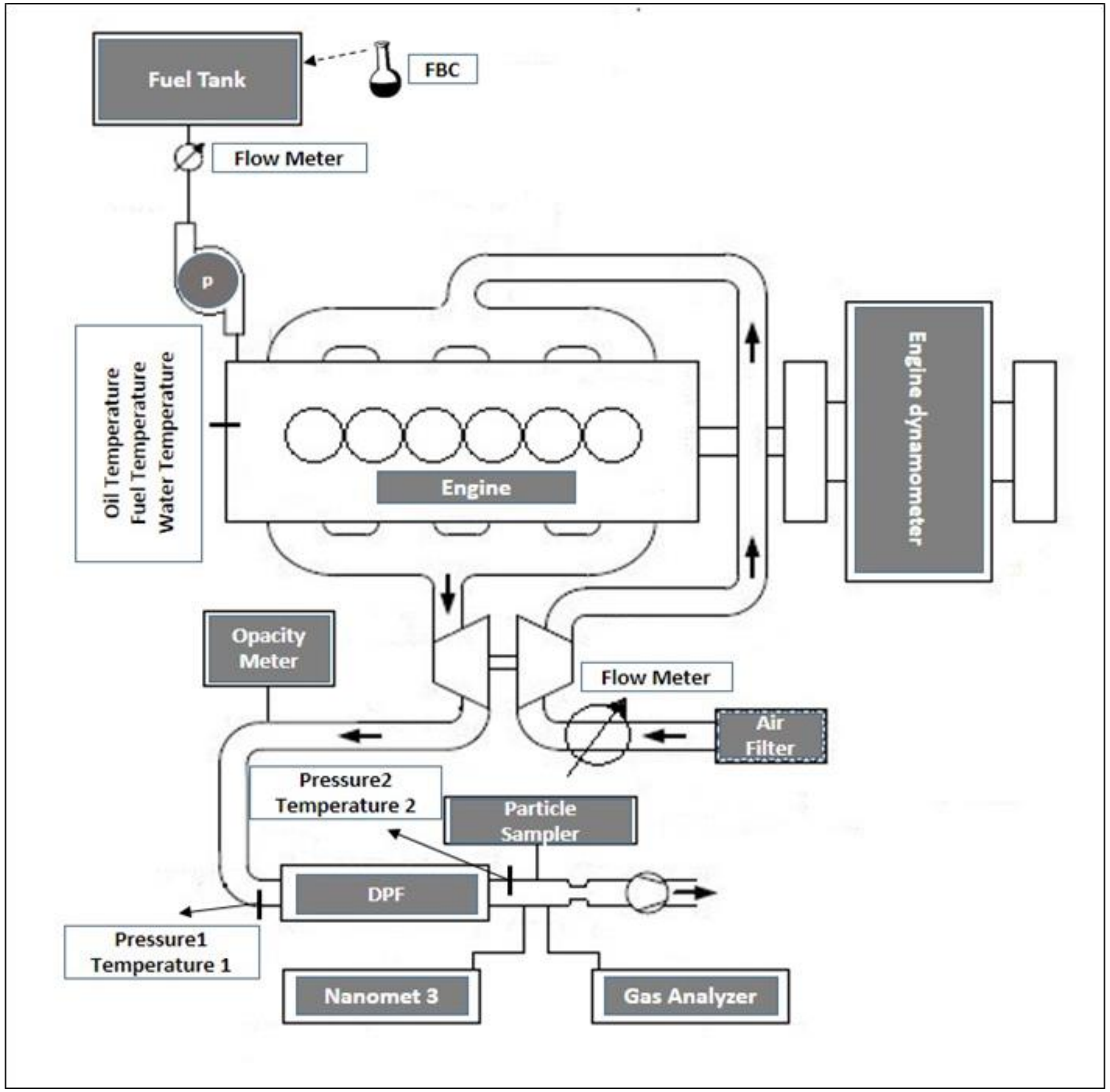




Stage 2: engine test cell preparation



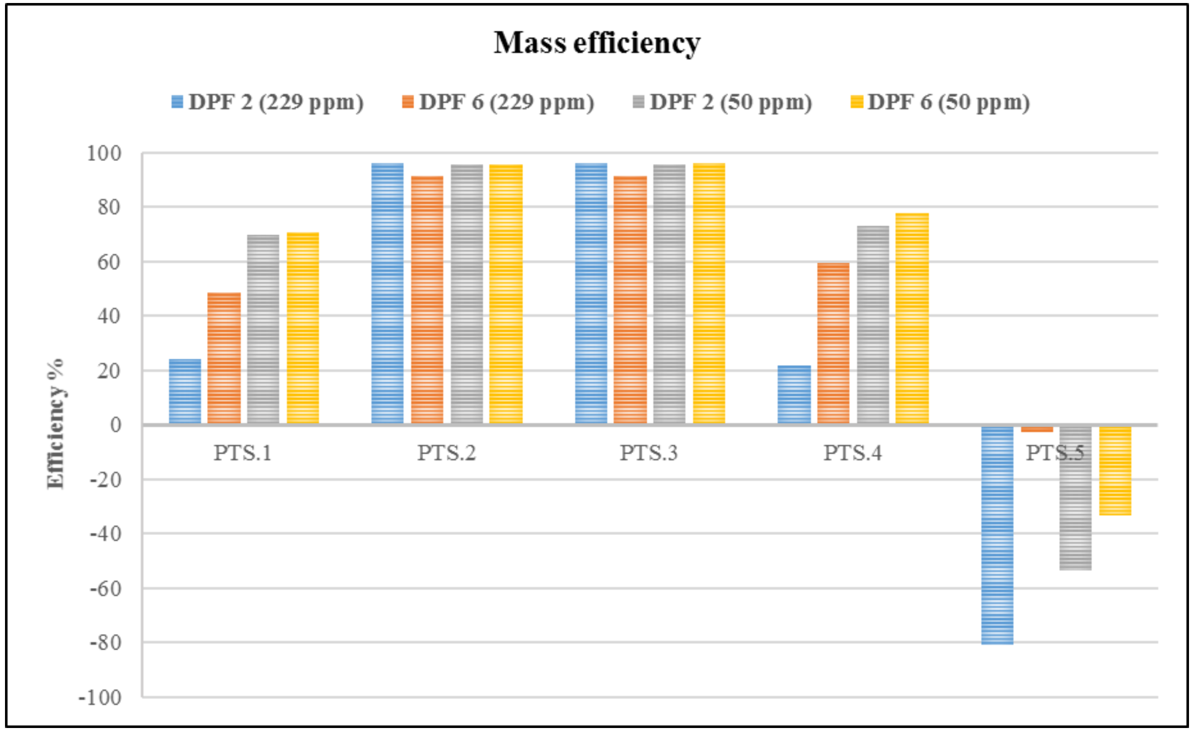
Stage 2: engine test cell layout

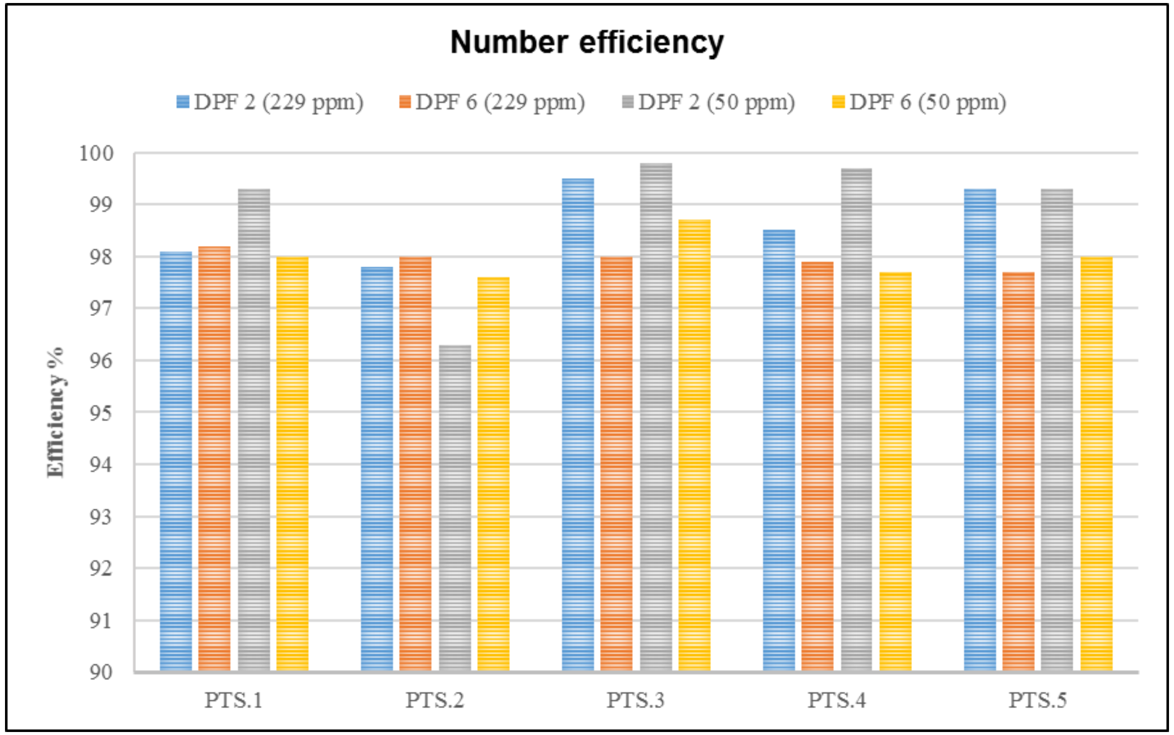


Stage 2: Engine test results

DPF type and technology				Tested fuel sulfur content			Cause of failure
DPF No.	**Active/Passive**	**Regeneration method**	**Core type**	**50 ppm**	**229 ppm**	**7000 ppm**	
1	Active	Electrical heater+ FBC	Sintered metal	-	✓	✓	-
2	Passive	DOC upstream of filter **(CRT)**	Sintered metal	✗	✗	-	Fuel sulfur content Low PM efficiency
3	Passive	FBC	Silicon carbide	-	✓	✓	-
4	Passive	FBC + Catalyst upstream of DPF	Silicon carbide	-	✓	✓	-
5	Passive	Catalyzed DPF **(CDPF)**	Cordierite	-	✓	-	-
6	Passive	DOC upstream of filter **(CRT)**	Silicon carbide	-	✗	-	Fuel sulfur content Low PM efficiency
7	Passive	DOC upstream of filter **(CRT)**	Silicon carbide	-	✗	-	Fuel sulfur content Low PM efficiency
8	Passive	FBC	Silicon carbide	-	✗	-	Damaged
9	Active	diesel burner technology	Silicon carbide		✗	✗	Low soot loading capacity
10	Passive	FBC	Silicon carbide	-	✓	-	-

Stage 2: Mass and number filtration efficiencies of CRT filters for 50 ppm and 229 ppm sulfur diesel

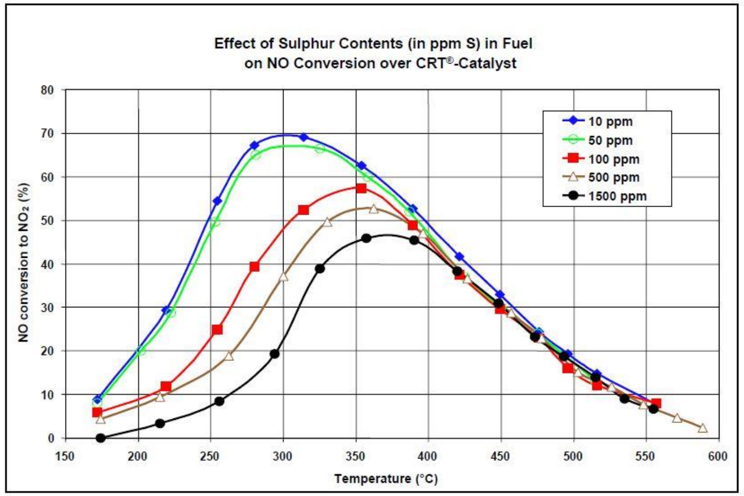




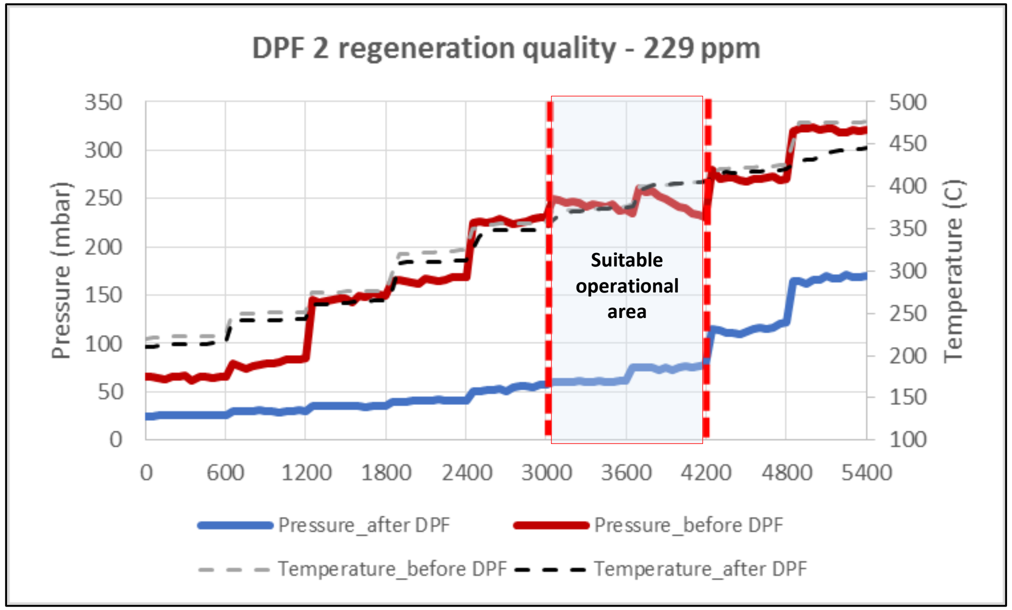
Point No.	Engine rotational speed (rpm)	Load (%)	Average temperature (°C)
PTS.1	1000	100	470
PTS.2	1000	50	327
PTS.3	2000	50	330
PTS.4	2000	100	415
PTS.5	1000	100	480

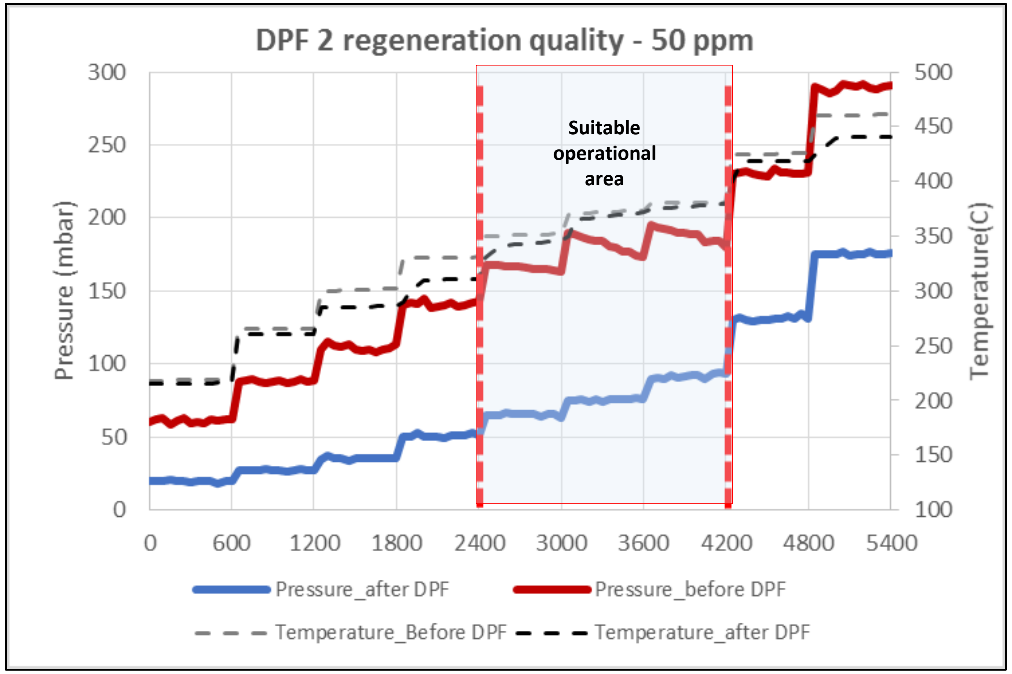
DPF No.	DPF 2 (229ppm)	DPF 6 (229ppm)	DPF 2 (50 ppm)	DPF 6 (50 ppm)
Average	98.6	97.9	98.8	98

Stage 2: Regeneration quality of CRT filters

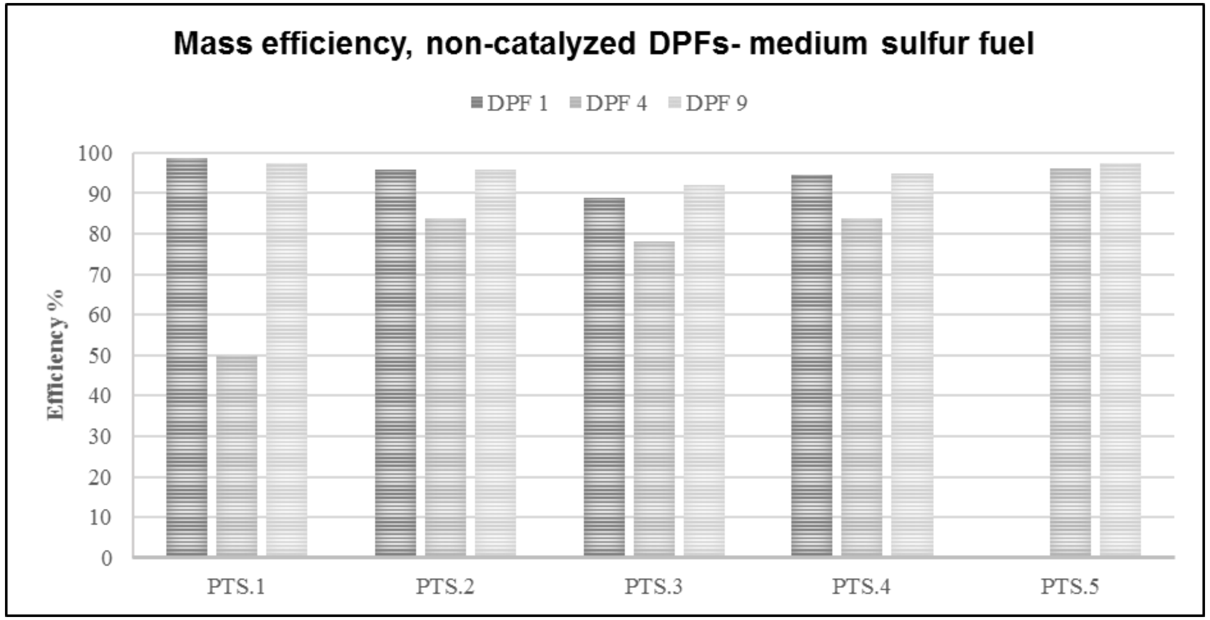


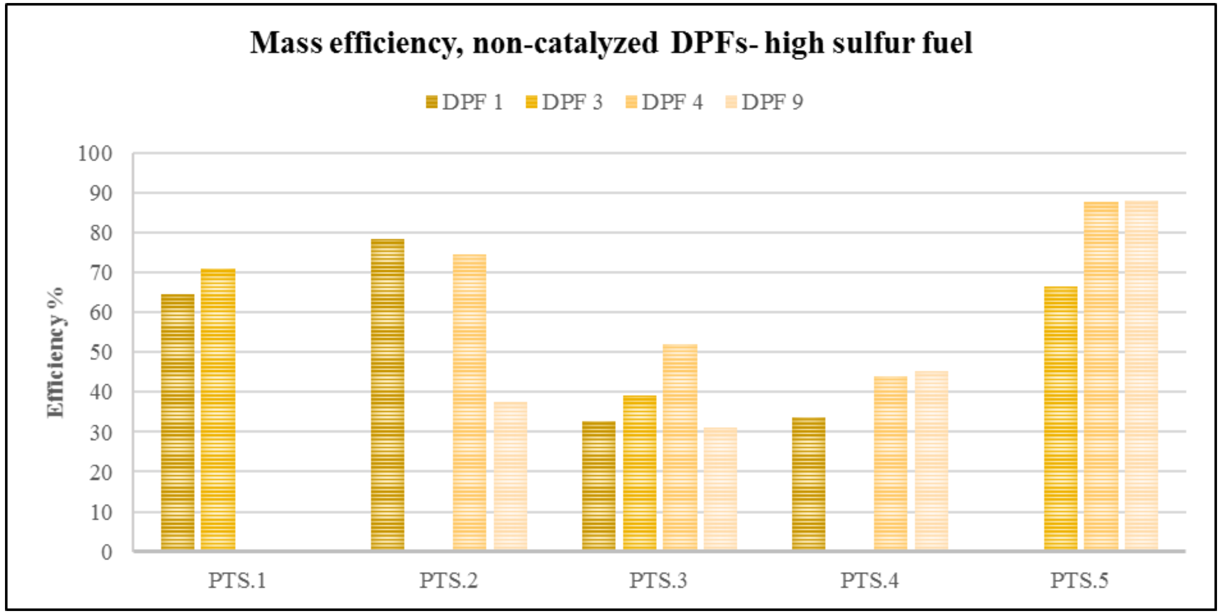
Warren 1998





Stage 2: Mass filtration efficiencies of non-catalyzed filters for 229 ppm and 7000 ppm sulfur diesel

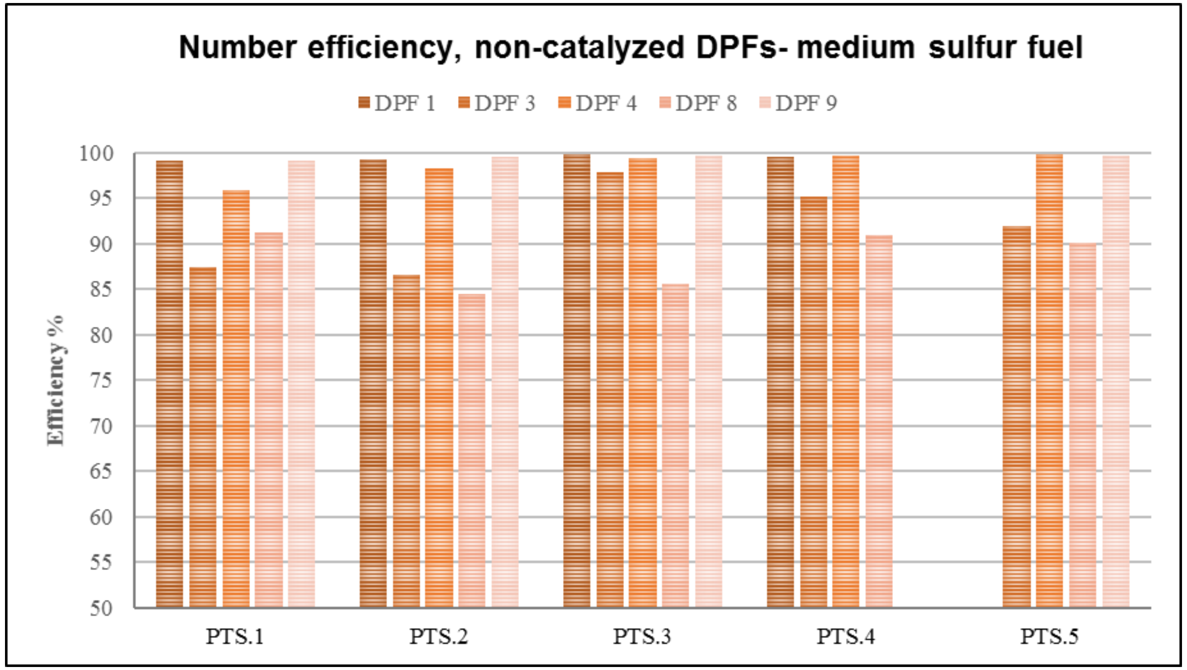


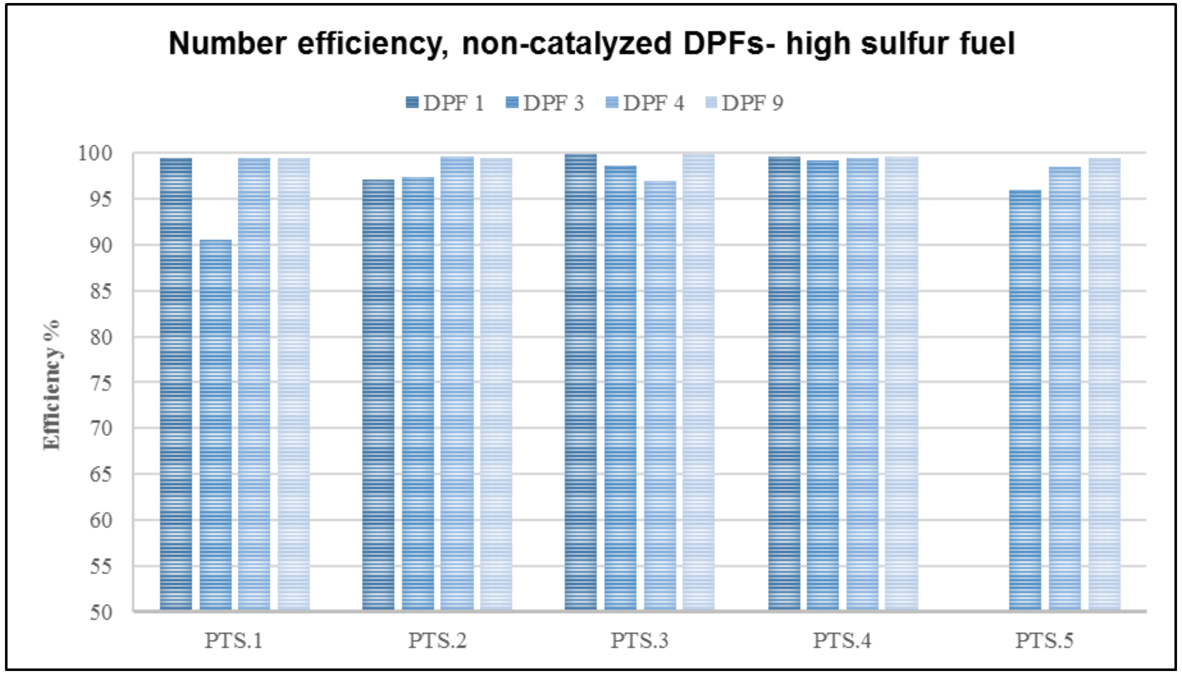


DPF No.	DPF 1	DPF 4	DPF 9
Average	94.5	78.3	95.5

DPF No.	DPF 1	DPF 3	DPF 4	DPF 9
Average	52.3	58.7	62.4	50.4

Stage 2: number filtration efficiencies of non-catalyzed filters for 229 ppm and 7000 ppm sulfur diesel

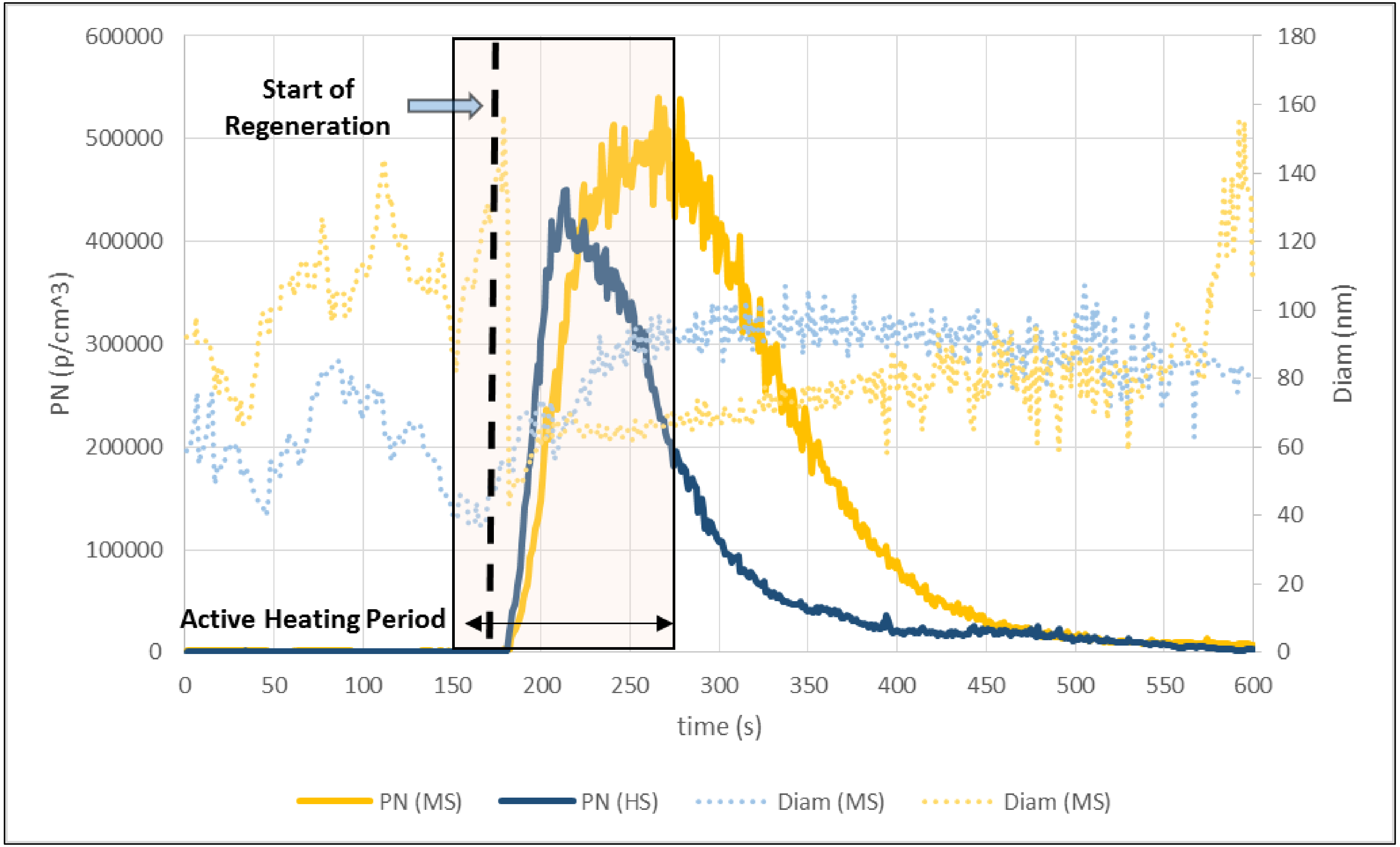




DPF No.	DPF 1	DPF 3	DPF 4	DPF 8	DPF 9
Average	99.5	91.8	98.6	88.46	99.7

DPF No.	DPF 1	DPF 3	DPF 4	DPF 9
Average	99	96.3	98.7	99.5

Stage 2: Particle count and diameter during regeneration of non-catalyzed quasi-active filter with 229 ppm and 7000 ppm sulfur diesel fuel



Stage 3: durability tests on the buses – data loggers

CPK Automotive
Member of the Heinzmann Group

Welcome Project Iran -

Filter

Project	Vehicle ID	System	Install. Date	Vehicle Description	Fleet	Date, Time	Status	last known position	Action
	78-524	LN: 001443 DN: 1930	17.02.2014	Line 4	Iran	02.11.2014 23:41	In Motion	35.63275 : 51.4052	
	78-515	LN: 001490 DN: 1954		Line 4 - Dinex Installed (22/10/2014)	Iran	04.11.2014 12:16	In Motion	35.63256 : 51.40575	
	85-156	LN: 001491 DN: 1930		Line 10	Iran	04.11.2014 23:08	In Motion	35.677 : 51.30753	
	33-637	LN: 001492 DN: 1933		Line 2	Iran	02.11.2014 14:50	In Motion	35.63296 : 51.48338	
	32-938	LN: 001493 DN: 1927		Line 3 - (CPK Temp Sensor Error)	Iran	04.11.2014 21:53	In Motion	35.73371 : 51.50686	
	85-182	LN: 001494 DN: 1952		Line 10	Iran	04.11.2014 23:47	In Motion	35.67775 : 51.30685	
	33-457	LN: 001495 DN: 1927		Line 1 - Engin problem / Out of Service	Iran	27.10.2014 13:42	In Motion	35.74661 : 51.49253	
	78-514	LN: 001496 DN: 1914		Line 4 - HJS installed (10/09/2014)	Iran	03.11.2014 11:53	In Motion	35.63188 : 51.40455	
	33-592	LN: 001497 DN: 1953		Line 2 - BUS STOP for wheel problem	Iran	06.10.2014 14:34	In Motion	35.62961 : 51.48126	
	33-469	LN: 001499 DN: 1948		Line 1 - (CPK Pressure Sensor Error)	Iran	03.11.2014 22:04	Alarm	35.72303 : 51.52048	

Legend

Stage 3: durability tests on the buses – 9 buses out of 17 have filters






Stage 3: durability tests on the buses – latest conditions

DPF Producer Company	Operation Report		
	Installation date	Working days	Bus mileage
Passive system with FBC/V. ID: 78514 (line 4) (DPF No.1 without electrical heater)	10/Sep/2014	613 days	92406 km
Passive system with FBC/V. ID: 78515 (line 4) (DPF No.3)	22/Oct/2014	436 days	49616 km
Passive system with FBC/V. ID: 78524 (line 4) (DPF No.4)	28/Jan/2015	473 days	77062 km
Active system with FBC/V.ID: 85423 (line 4) (DPF No.1)	19/Feb/2015	455 days	78093 km
Active system with FBC/V.ID: 33572 (line 2) (DPF No.1)	19/Feb/2015	445 days	73049 km
Passive system with FBC/V.ID:85476 (line 10) (DPF No.1 without electrical heater)	23/Feb/2015	478 days	85692 km
Passive system with FBC/V.ID: 33637 (line 2) (DPF No.3)	02/Jun/2015	This system works with DPF only for 21 days.	-
Passive - Catalyzed DPF/V.ID: 85182 (line 10) (DPF No.5)	24/Sep/2015	185 days	10557 km
Passive- Catalyzed DPF/V.ID: 33592 (line 2) (DPF No.5)	25/Jan/2016	112 days	5000 km

Special thanks to

Dr. Andreas Mayer of TTM
Mr. Volker Hensel of VERT

Thanks for listening

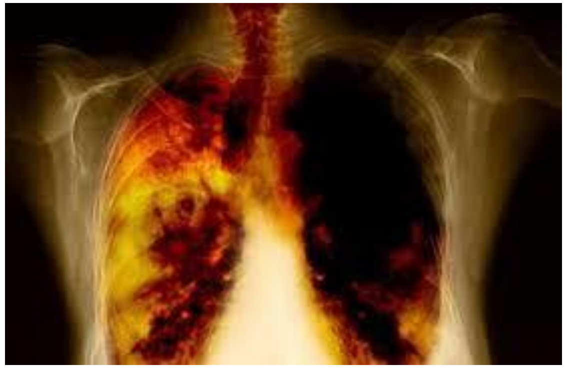
Questions?

vhosseini@sharif.edu

Study on particle deposition in the lung during successive respiratory cycles

Why it matters?

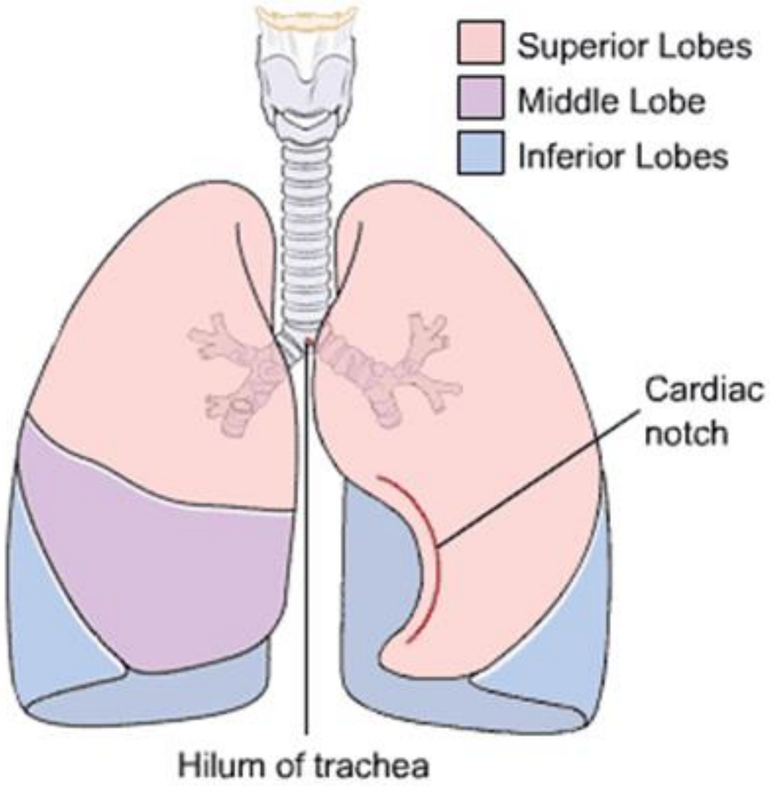
- Particulate matter air pollution → pulmonological and oncological studies of diseases caused by air pollution
- Aerosolized drug delivery systems

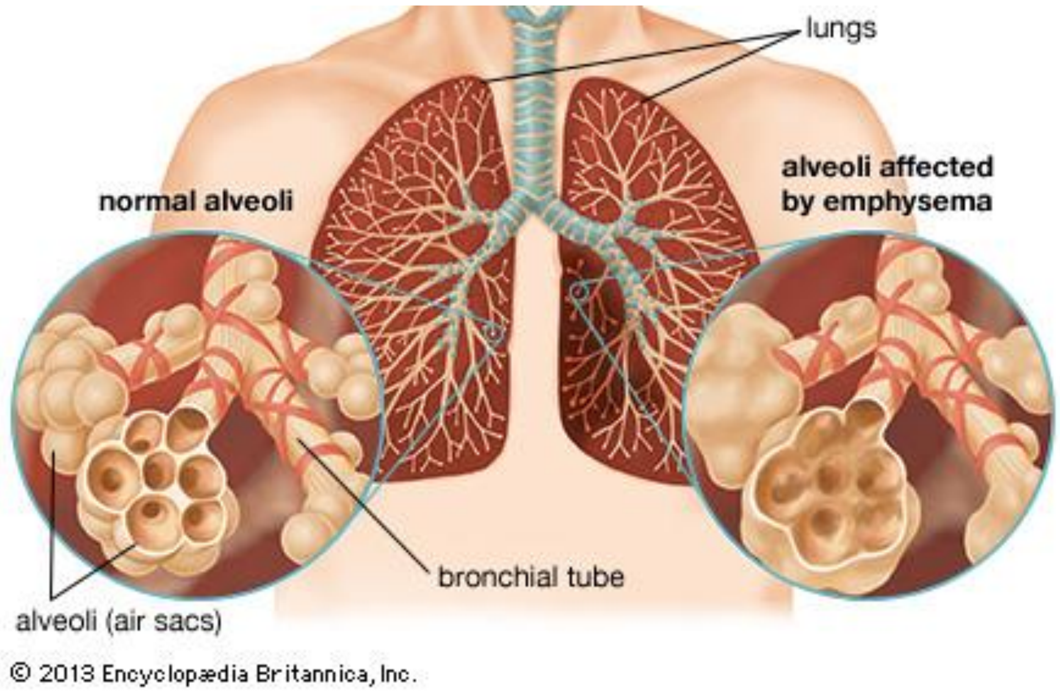


Methodology

Building up the geometry → Calculation of air flow → Calculation of deposition

Geometry


Superior Lobes
Middle Lobe
Inferior Lobes
Cardiac notch
Hilum of trachea


lungs
normal alveoli
alveoli affected by emphysema
bronchial tube
alveoli (air sacs)
© 2013 Encyclopædia Britannica, Inc.

Geometry

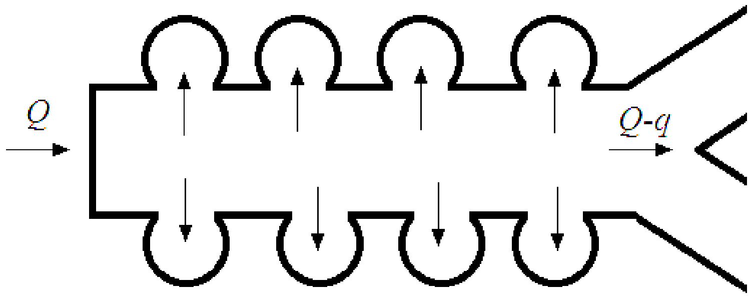
✓ **Modified 5-lobe Yeh and Schum geometric model**

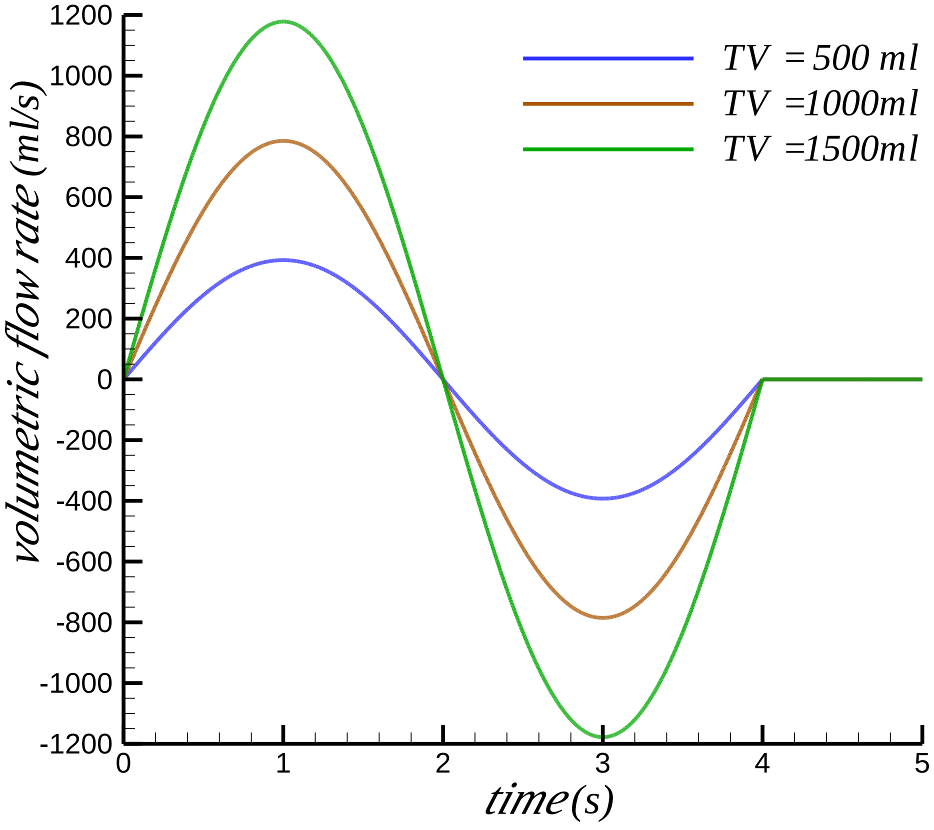
Modification: considering the lateral alveoli based on Weibel et al. (2005)

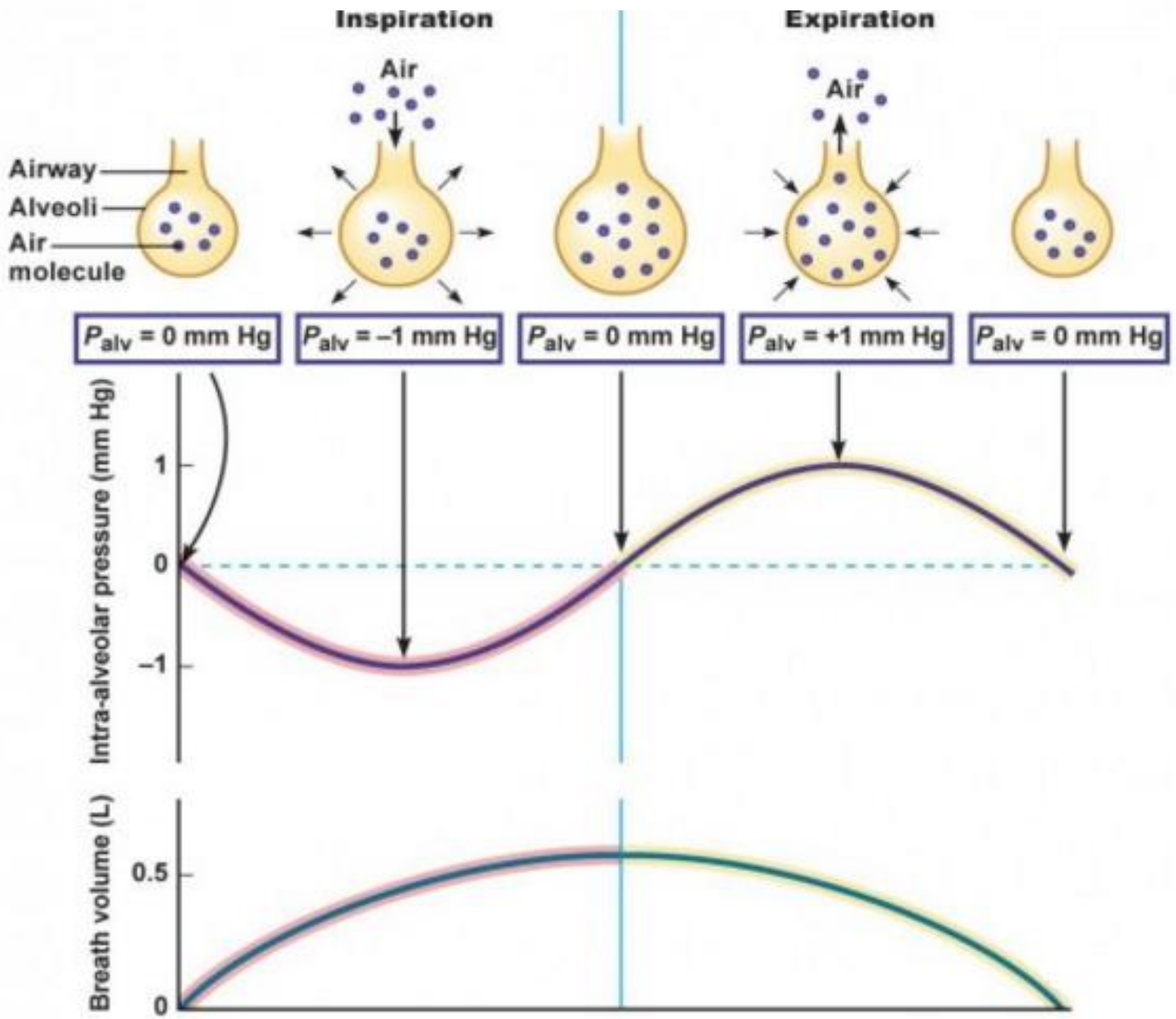
Alveoli number in the original model: 3e8
Alveoli number in the modified model: 4.55e8
Average alveoli number in a male adult: 4.8e8 (Ochs et al. (2004))

Air flow

- Based on the alveoli number distal to an airway







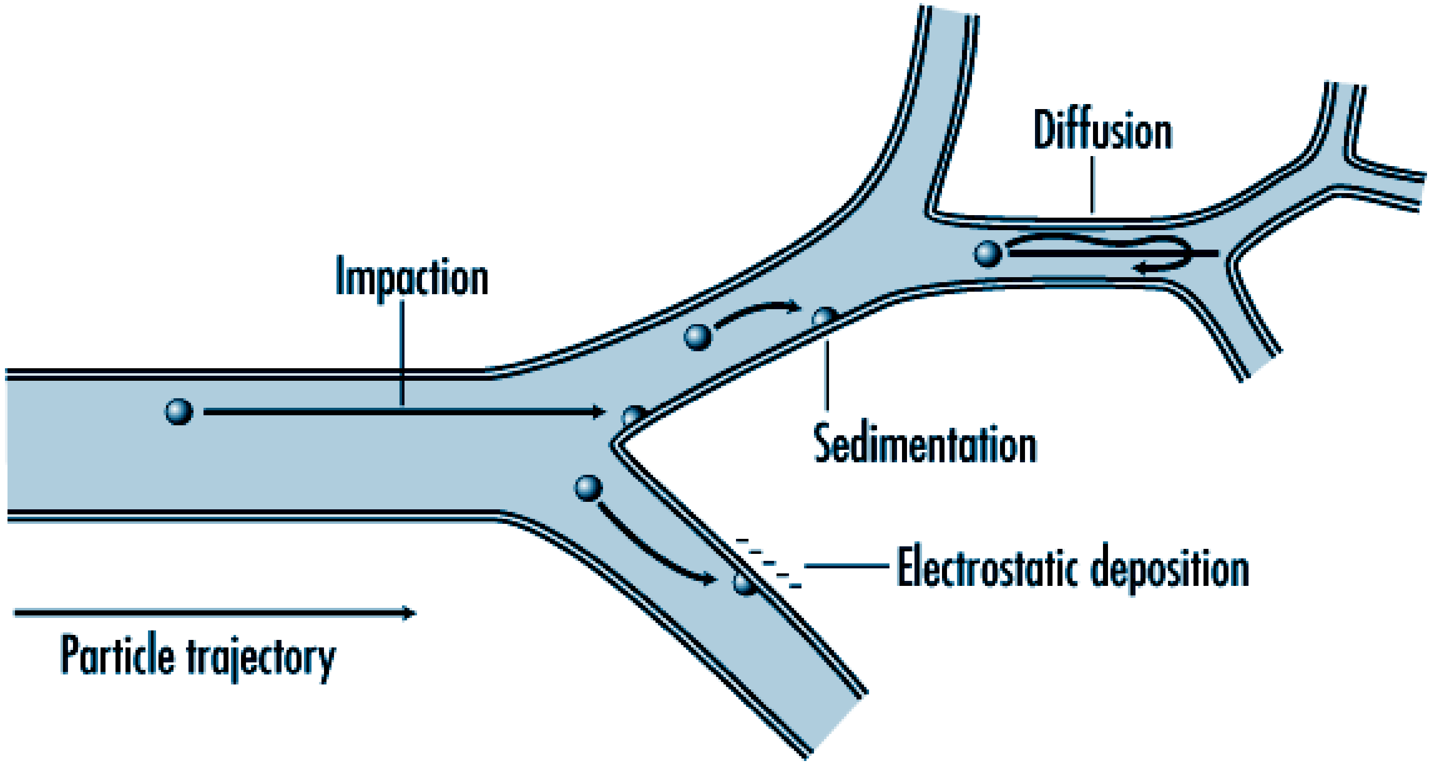
Deposition calculation

Assumptions:

- At the inlet (inhalation): constant concentration of particles
- At the outlet (exhalation): escape boundary condition
- Mass division based on the flow division
- Particles between 1nm and 10 microns
- 3 respiration routes are considered (nasal, oral and tracheal)
- Initial condition: lungs are completely empty of particles
- Modeling successive respiratory cycles is done until reaching to the quasi steady state

Main deposition mechanisms

- Impaction
- Sedimentation
- Diffusion



$$p = p_d + p_i + p_s - p_d p_i - p_d p_s - p_i p_s + p_d p_i p_s$$

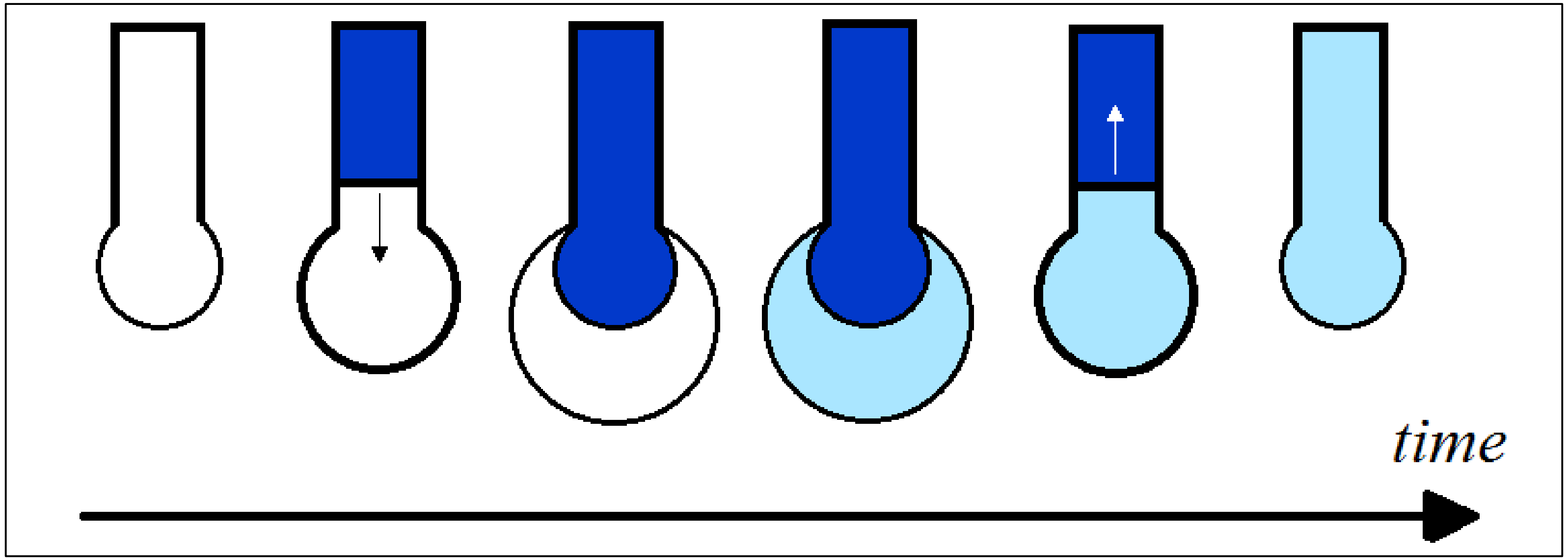
Deposition calculation formulas

Deposition probability of particles: the deposition formulas (according to the following researchers)

- NCRP (National Council on Radiation Protection and Measurements) report (1997)
- Shang et al. (2015)
- Shi et al. (2007)
- Golshahi et al. (2013)
- Xi & Longest (2008)
- Zhang et al. (2008)
- Koblinger & Hofmann (1990)

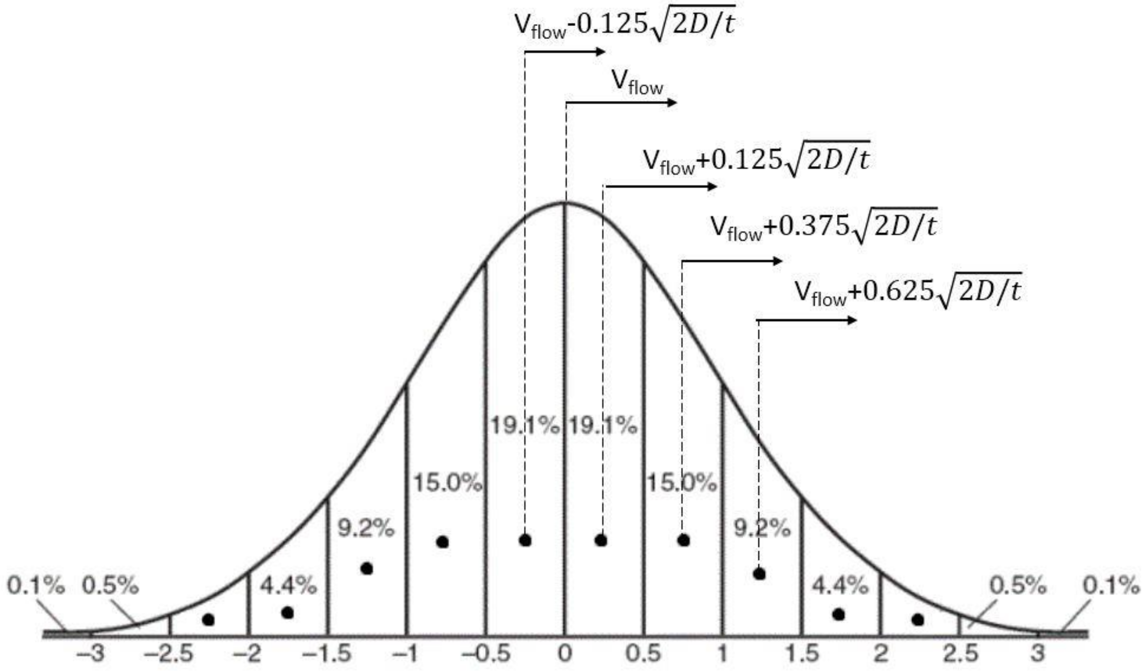
The alveolar mixing

Modeling the alveolar mixing during one cycle:
mixing factor = 0.25 (based on Koblinger & Hofmann (1990))

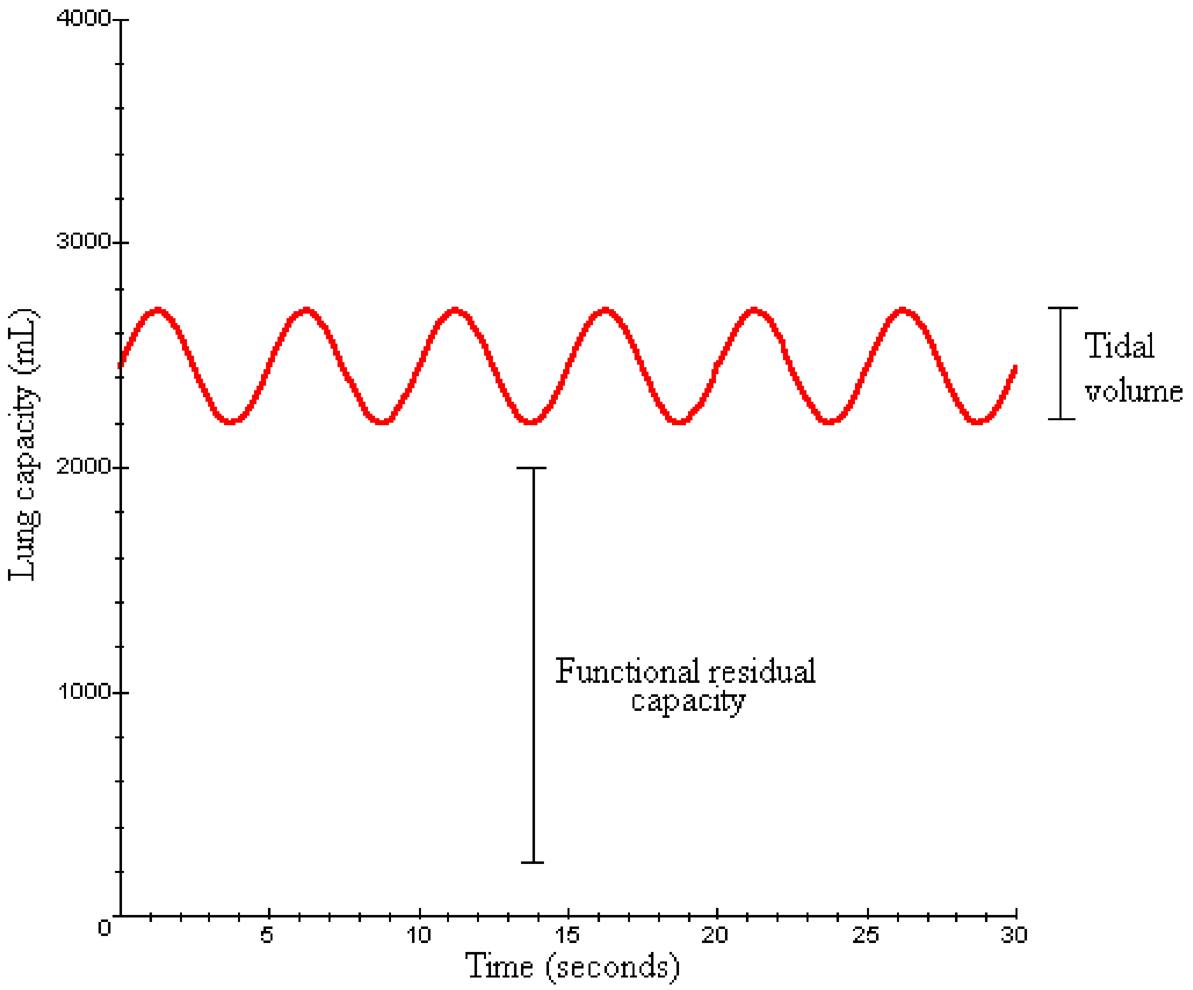


Axial diffusion modeling

Modeling the axial diffusion:
consideration of every group of moving particles as a "spreading" moving normal distribution



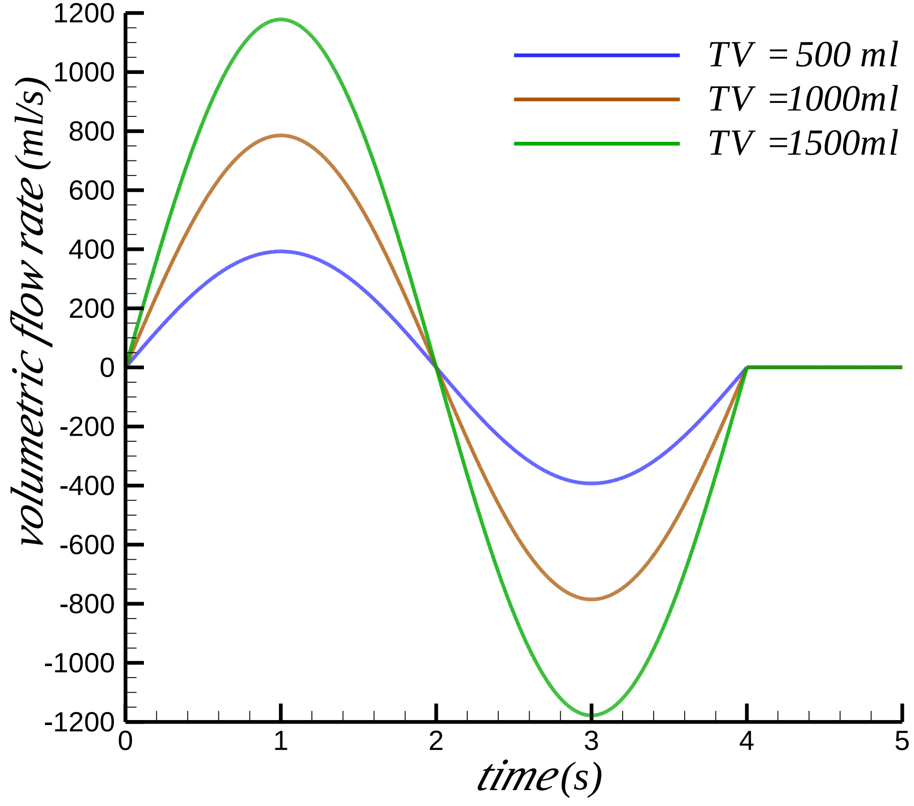
Modeling reference parameters

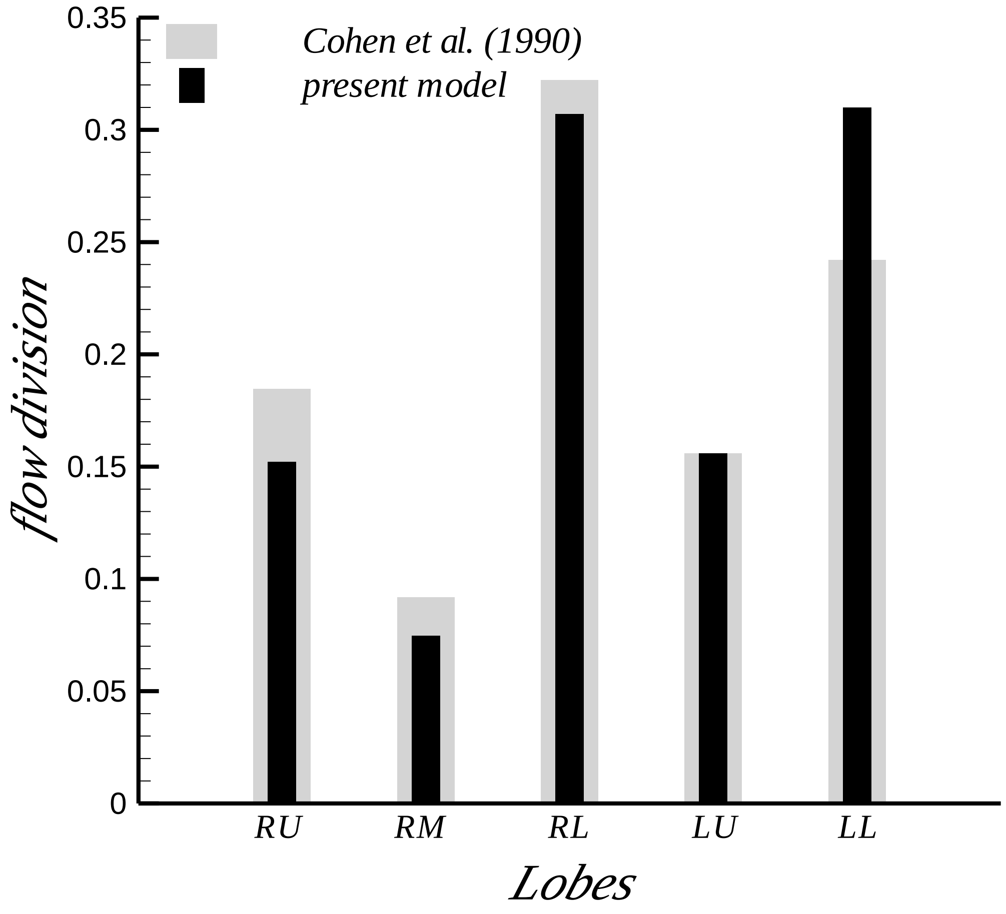


Parameter	Value
Tidal vol. (ml)	**500, 1000, 1500**
Functional residual capacity (ml)	**2300**
Inhalation length	**2 s**
Respiratory pause length	**1 s**
Air viscosity	**1.8e-5 Pa.s**
Particles density	**1 g/ccm**

Results

Air flow results: Right lower and Left lower lobes have more share of the air flow due to their great number of alveoli





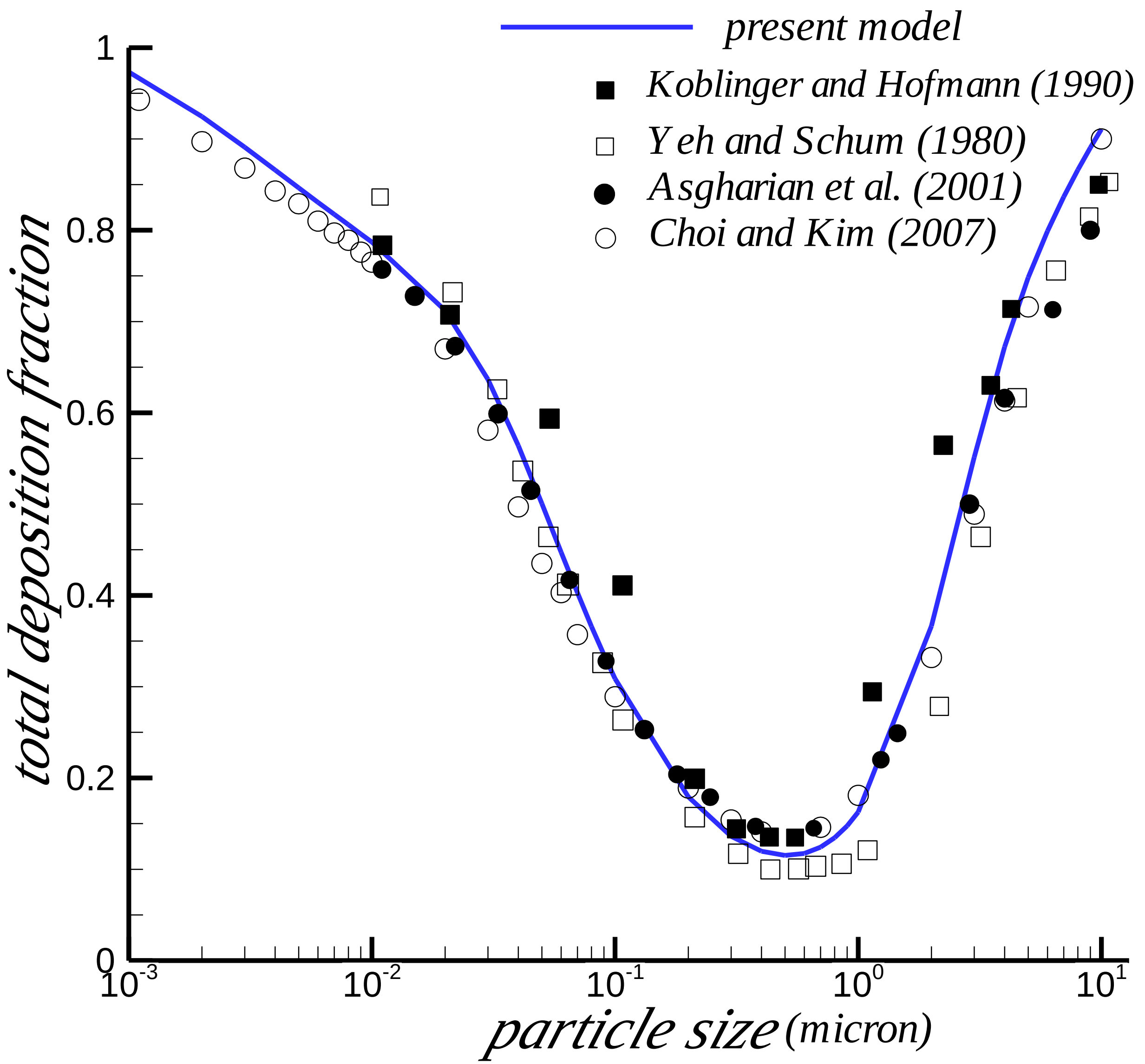
Verification

- Verification for
  a single respiratory cycle

- Large particles(d>5 micron)
  due to intensive impaction
  and sedimentation

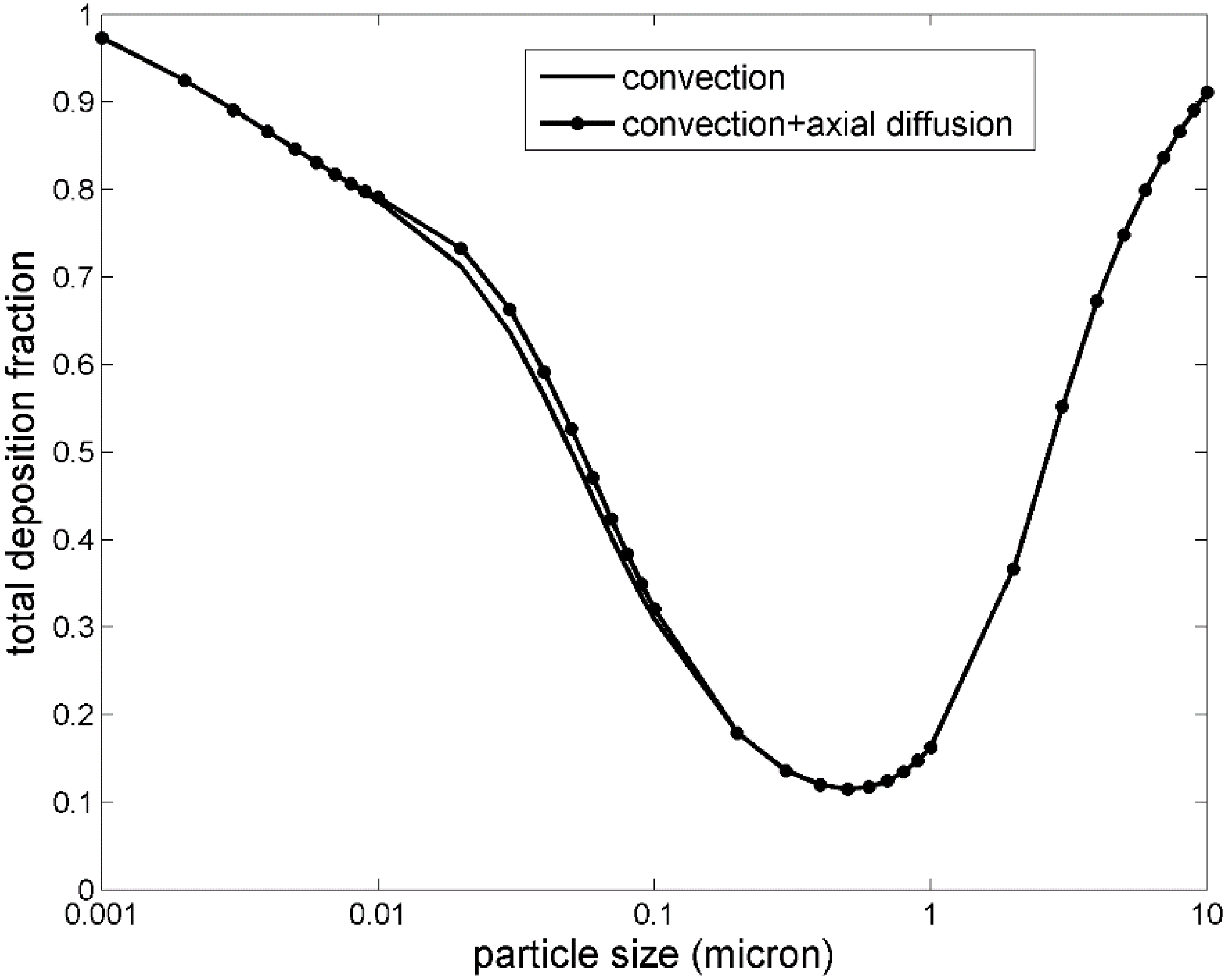
- small particles(d<10 nm):
  due to intensive diffusion

- median particles:
  no mechanism is intensive



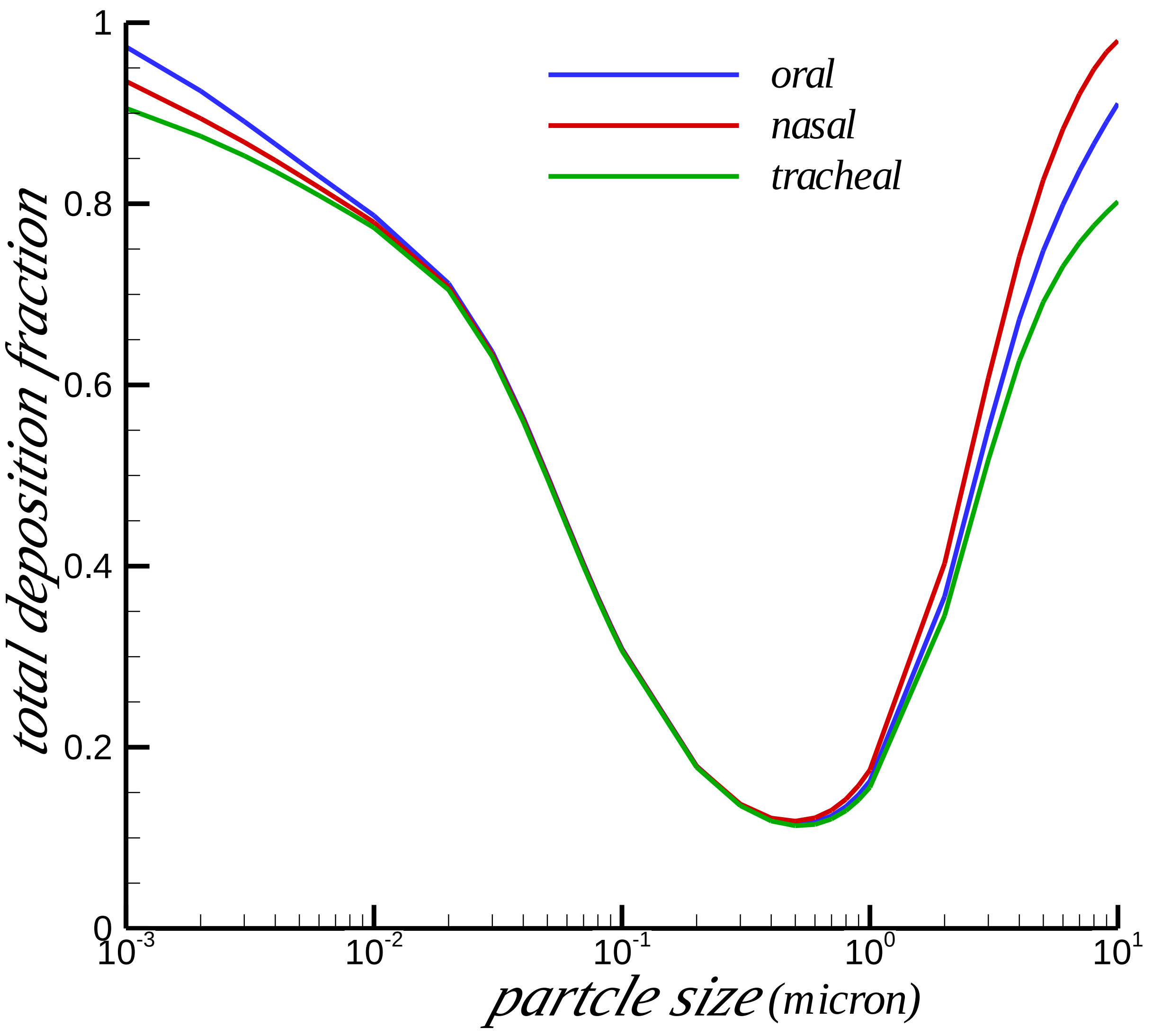
Axial diffusion effect

- The effect of considering axial diffusion
- Observable for particles between 8 and 200 nm
- For all particle sizes less than 6 %, so the rest of calculations are done without considering this effect



Different respiration routes

- Total deposition per cycle
- Different respiration routes
- TV=500 ml

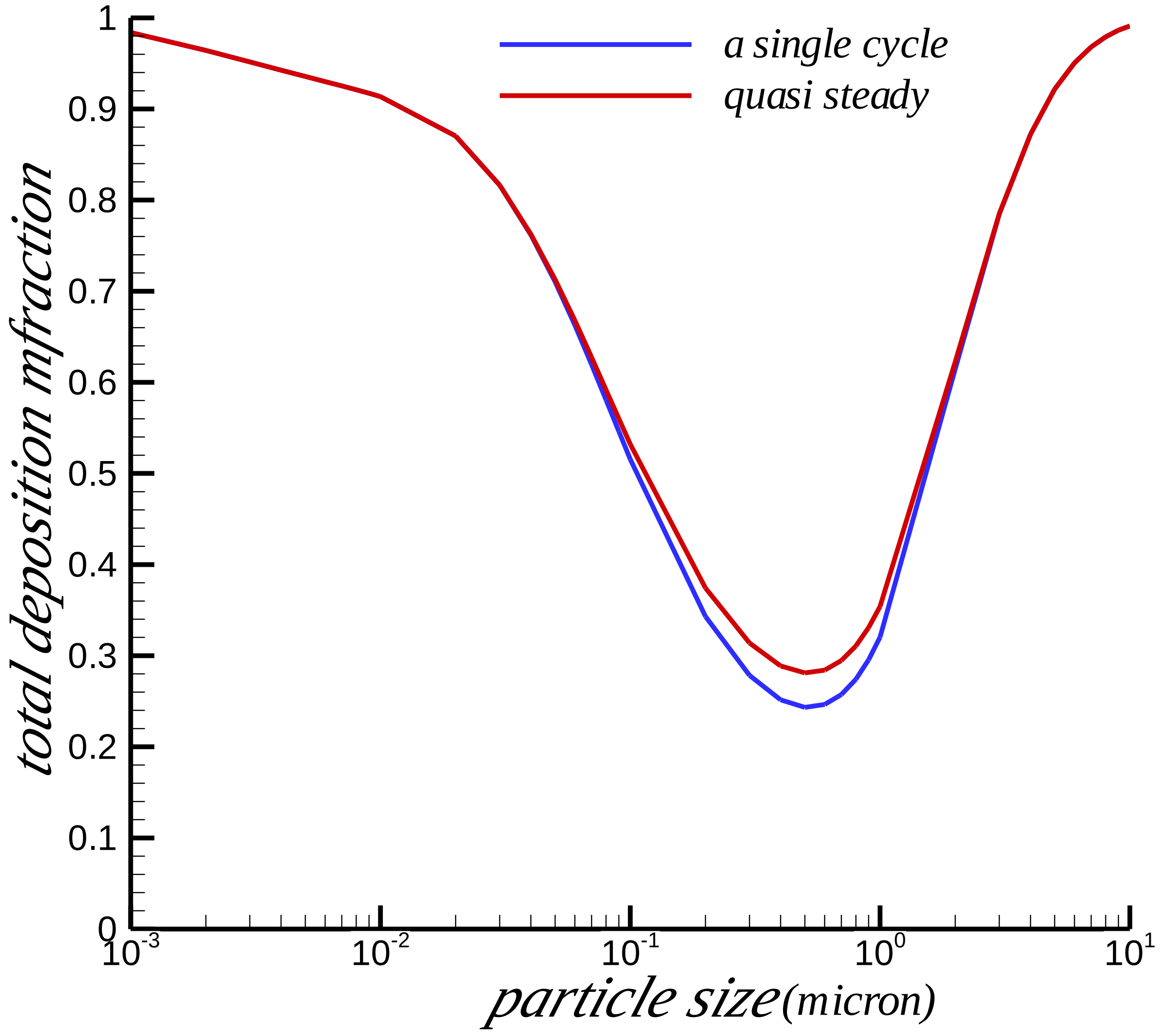


Total deposition per cycle

- TV = 1500 ml

- For TV=500 ml the results was almost the same and for TV=1000 ml, the difference was less than TV=1500 ml.

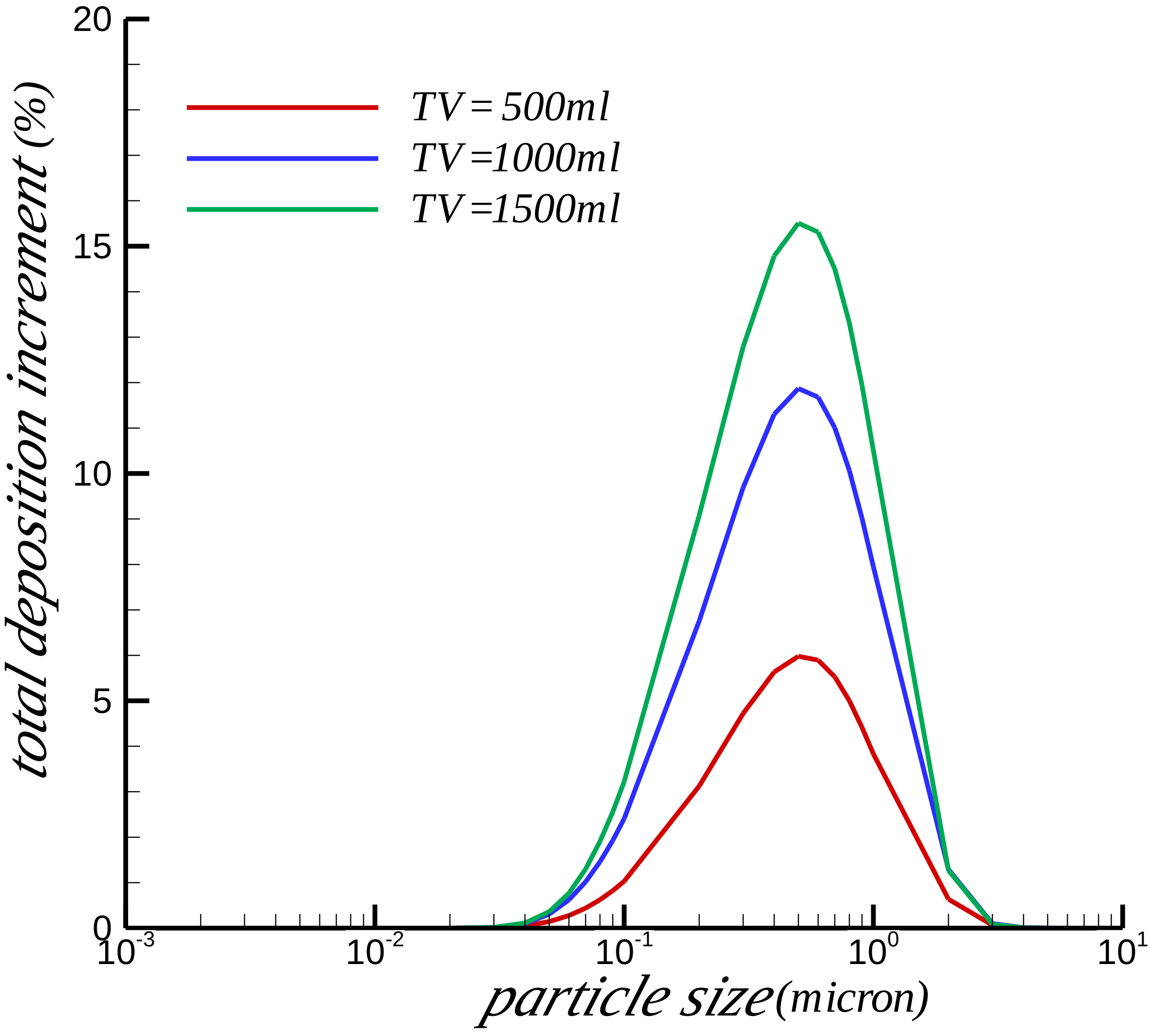
- Heavy computational cost of multiple cycles models
- The small difference between the results of a single cycle and multiple cycles ➡ single cycle results can be used with reasonable accuracy.



Total deposition per cycle increment (%)

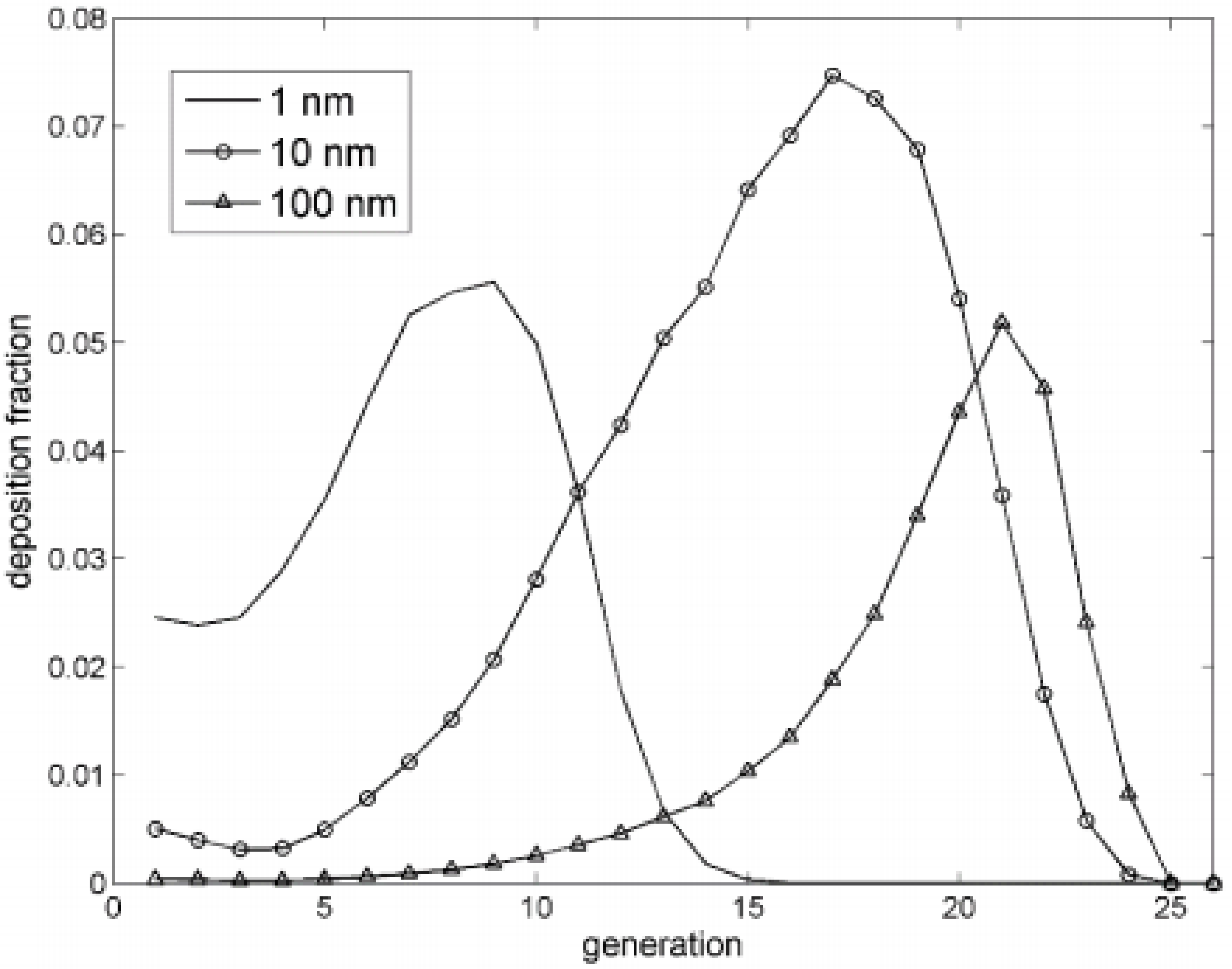
- Comparison between a single cycle and the quasi steady state

- Maximum increment:
  TV = 500ml: ~5%
  TV = 1000ml: ~12%
  TV = 1500 ml: ~16%



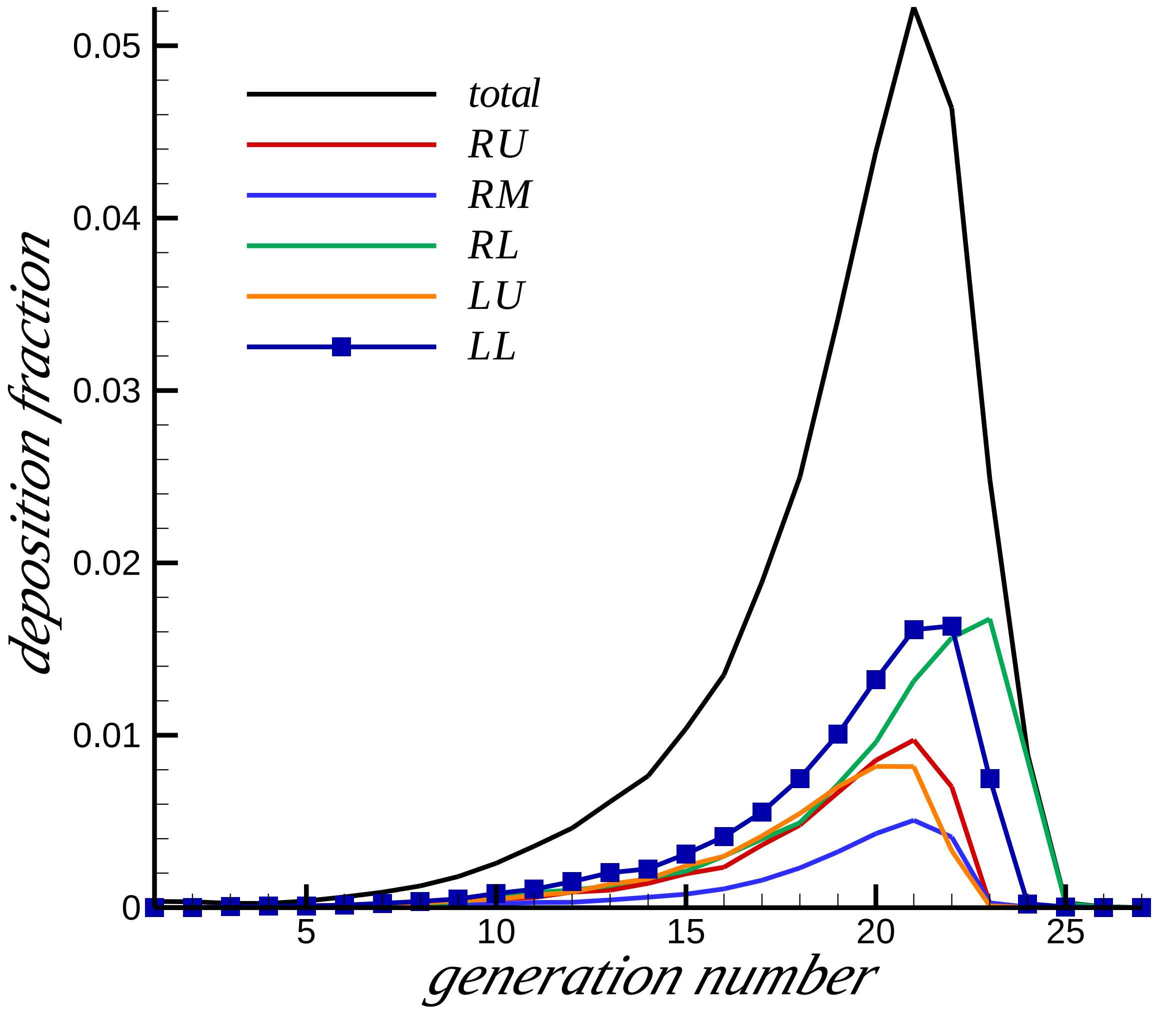
Generational deposition fraction

- for 3 particle sizes
- TV=500 ml
- In the domain of nanoparticles (d<100 nm), smaller particles due to great diffusivity, have deposition fraction peak in the earlier generations



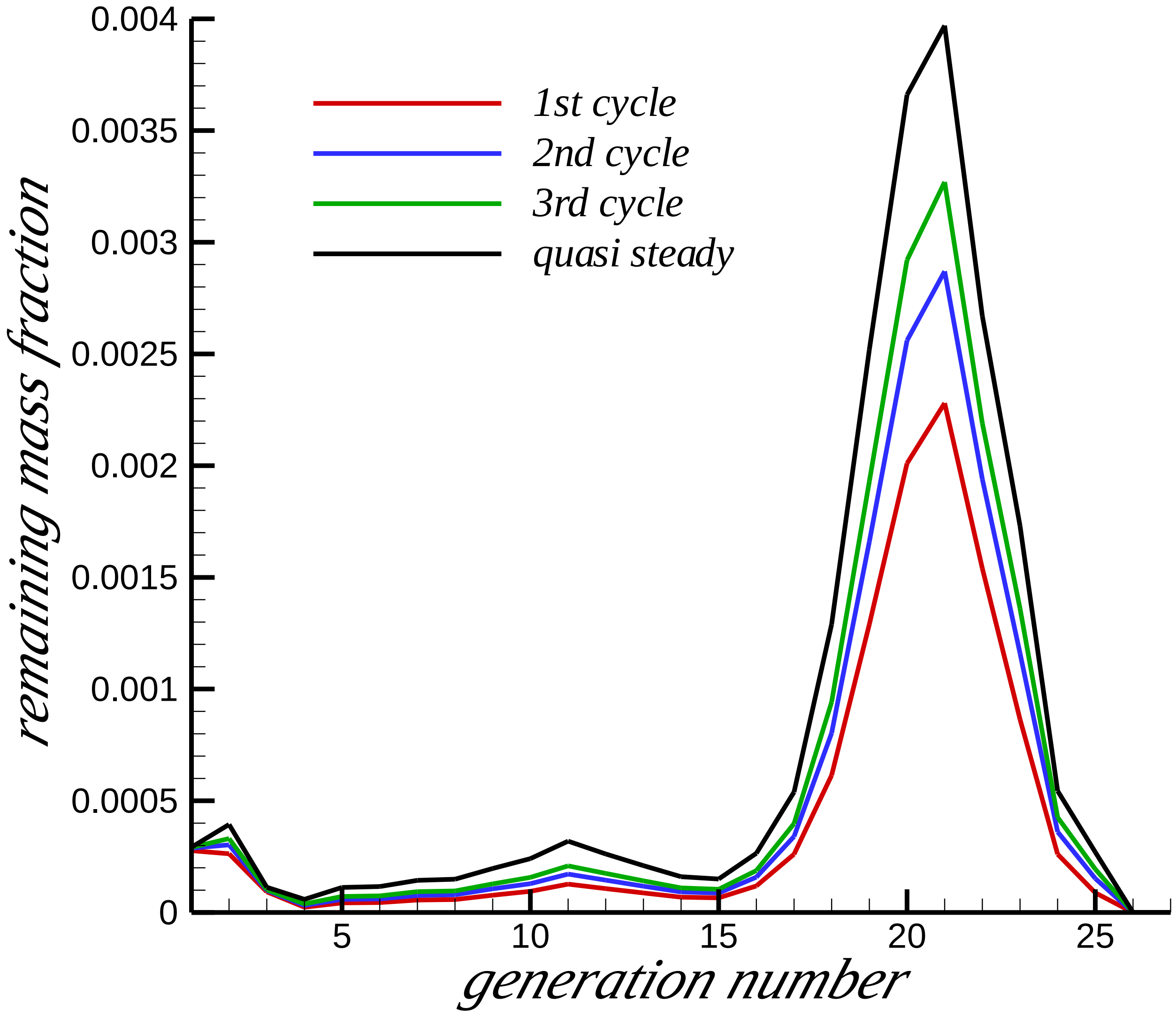
Lobar generational deposition fraction

- particle size= 100 nm
- TV=500 ml
- Left lower and Right lower lobes have more deposition than others, due to their great share of air flow.



Generational remaining mass fraction

- Just when the cycle totally ends
- particle size= 500 nm
- TV=500 ml
- It grows until reaching an invariant distribution at the quasi steady state



conclusion

- Using a modified 5-lobe model, particle deposition in the respiratory system is calculated during successive respiratory cycles.
- when the respiration begins, after a few cycles the deposition per cycle reaches a quasi steady state.
- For tidal volume smaller than 500 ml, there was almost no difference between single cycle calculations and successive cycles.
- More tidal volume, more difference between single and successive calculations can be observed.
- For the particles greater than 2 micron and smaller than 100 nm, in the all values of tidal volume, there was no difference between single and successive calculations.
- Considering the small difference between the single and multiple cycle models, we can avoid the high computational cost of multiple cycle models and use the single cycle model results with reasonable accuracy.