Air & Waste Management Association, Measurement Methods and Technology, March 15-17, 2016

Disruptive Innovation in Air Measurement Technology: Reality or Hype?

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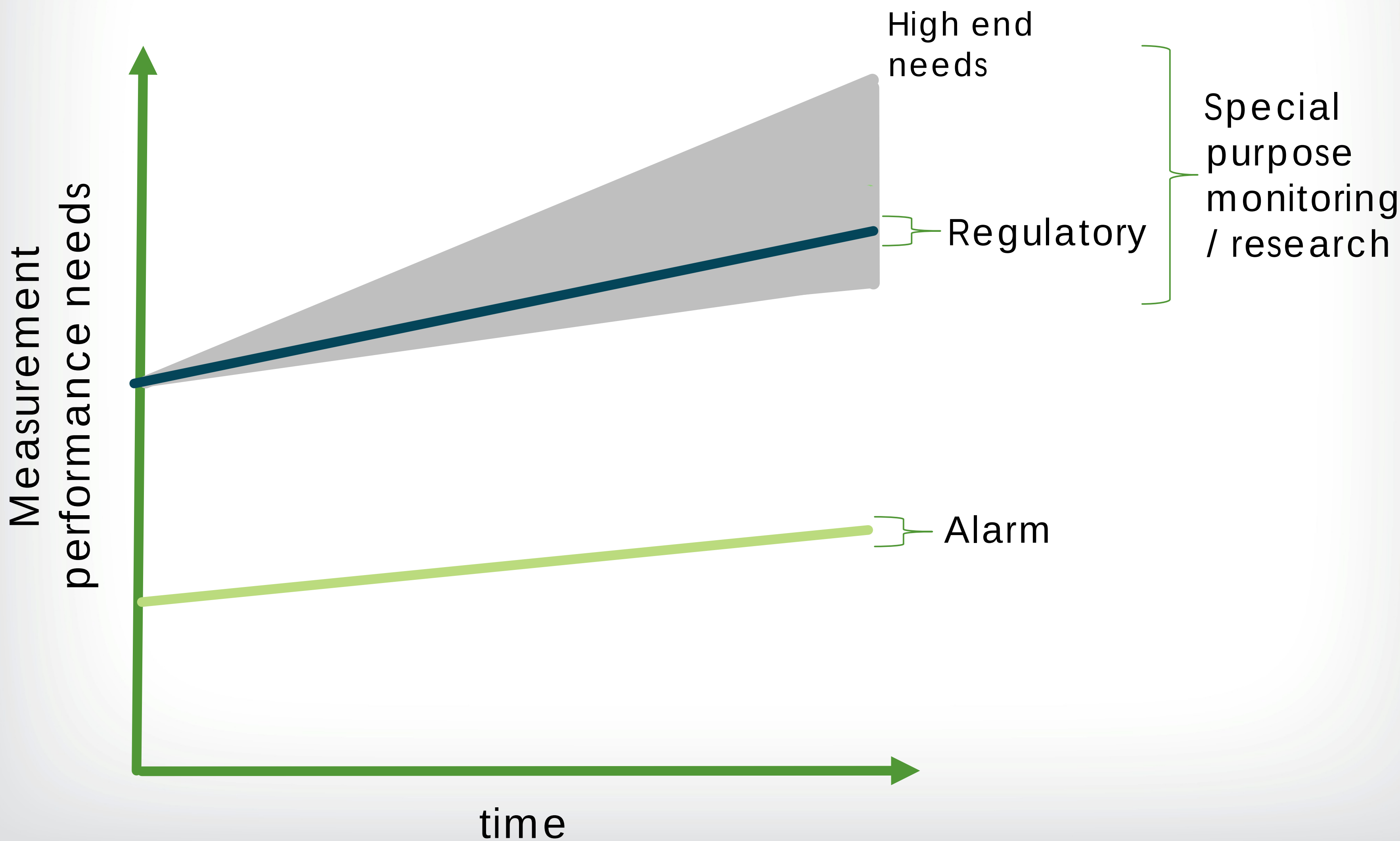
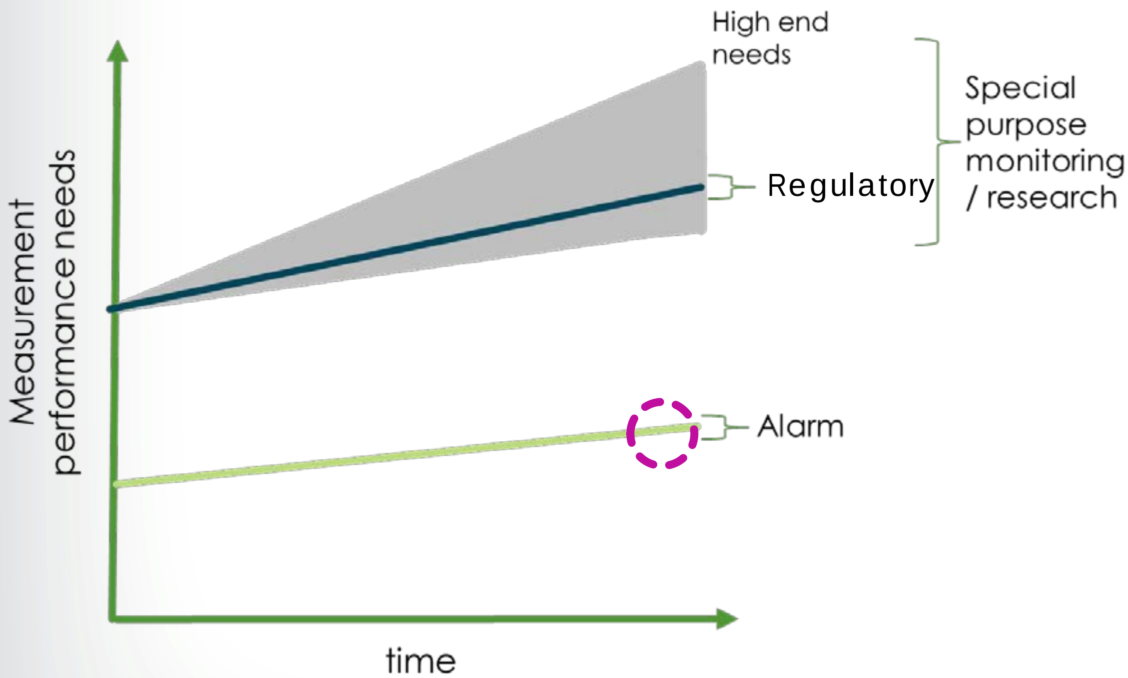
EPA Office of Research and Development
National Risk Management Research Laboratory

The state of air monitoring technology, for a few decades



The state of air monitoring technology, for a few decades

For example, carbon monoxide:



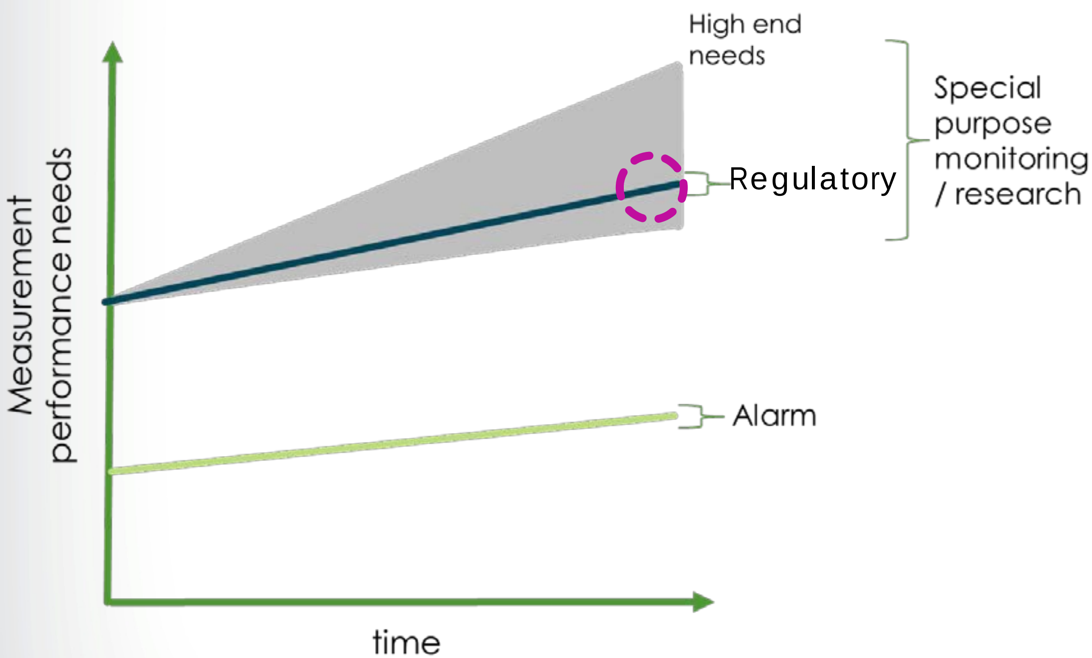
Alarm

- Electrochemical cell
- Begins detection at 11 ppm

User:
Homeowners

The state of air monitoring technology, for a few decades

For example, carbon monoxide:



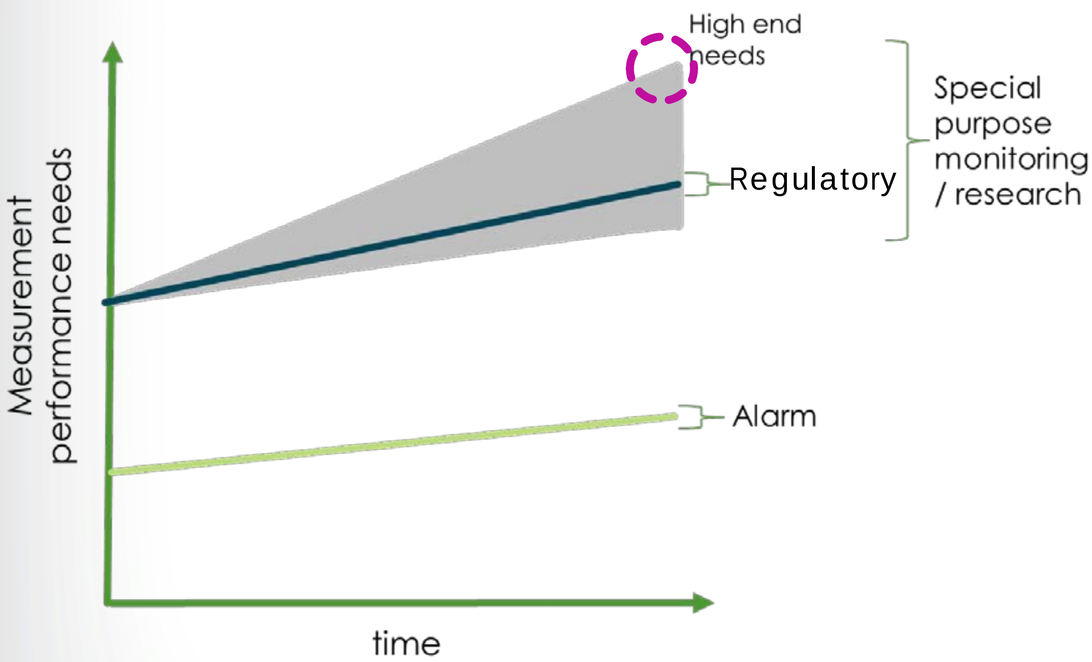
Ambient monitor

- Detects based on non-dispersive infrared radiation
- Detection down to ~40 ppb

User:
Regulatory monitoring agencies, some researchers

The state of air monitoring technology, for a few decades

For example, carbon monoxide:



High time-resolution, low detection limit monitor

- Quantum cascade laser technology
- Detection <1 ppb

User:
A few researchers

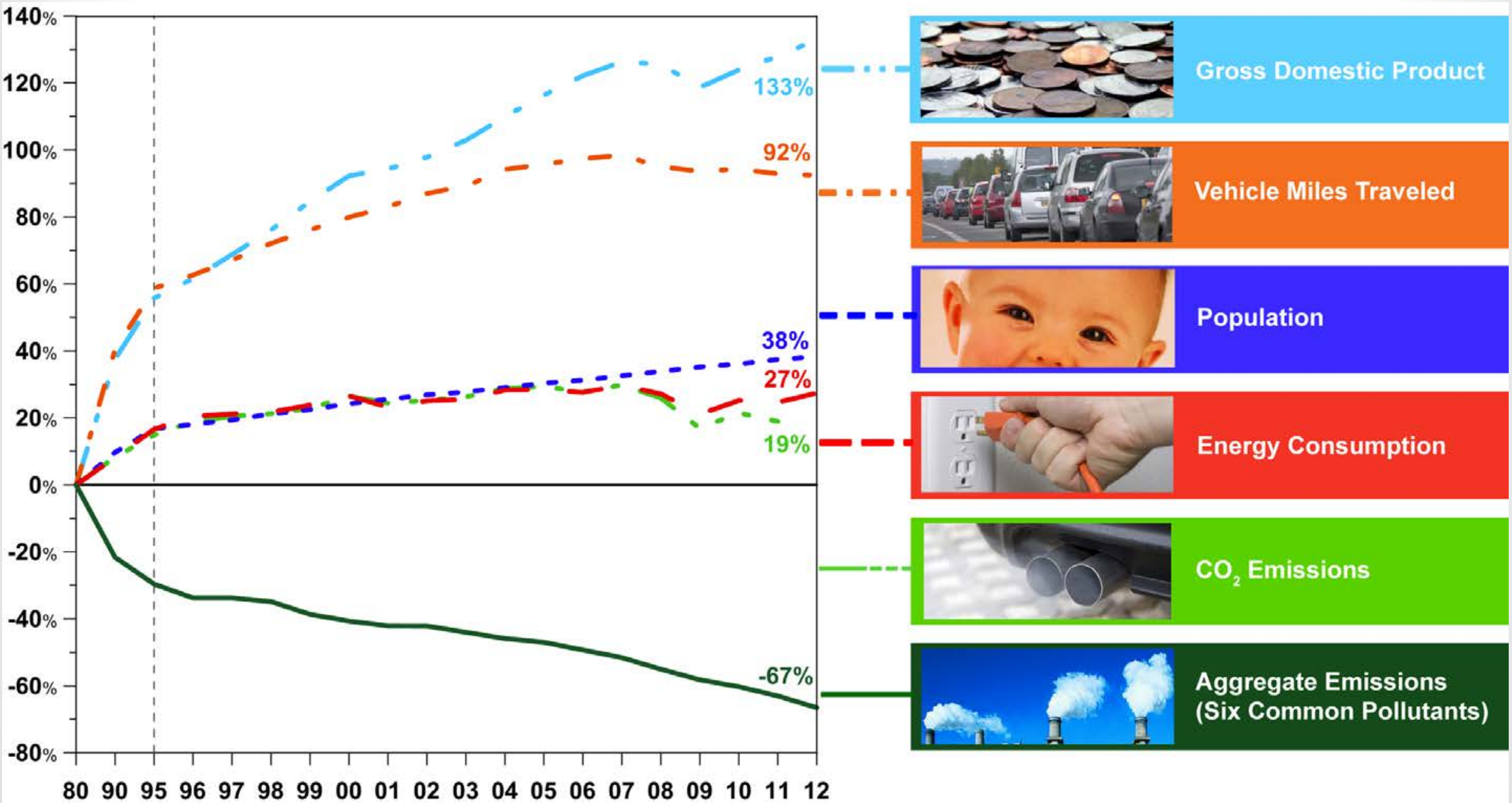
We (the specialists) have a solid set measurement tools supporting existing regulatory and research objectives.

…do we really need innovation?

…what has business-as-usual gained us?

Our current strategy has been successful by multiple measures

In the big picture, the USA story is one of great reductions in pollutant emissions, while GDP continues to increase.



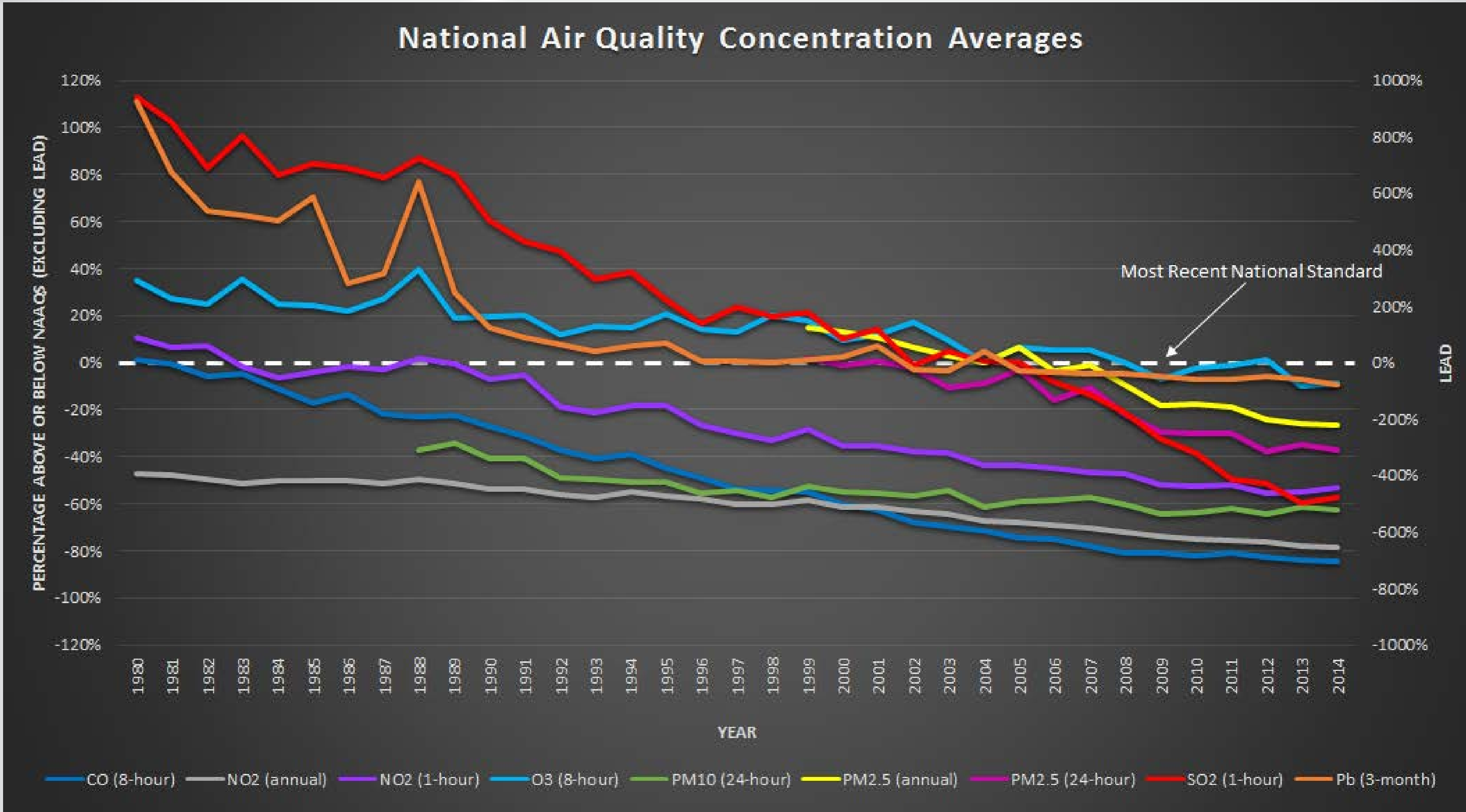
Source: EPA, Comparison of Growth Areas and Emissions, 1980-2012

Official air quality monitoring

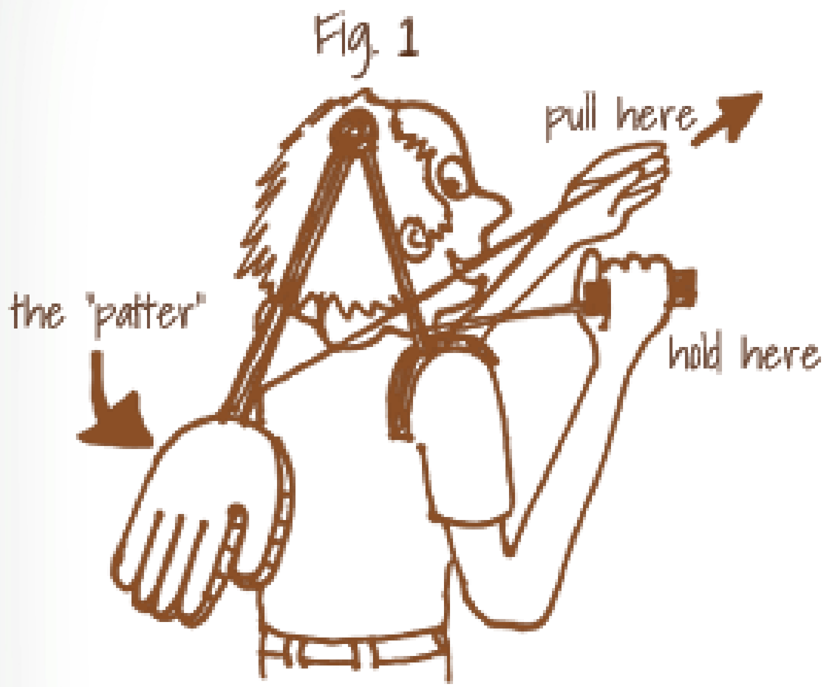
e.g., $PM_{2.5}$ monitoring locations in the USA

http://www3.epa.gov/airdata/ad_maps.html

Our current strategy has been successful by multiple measures



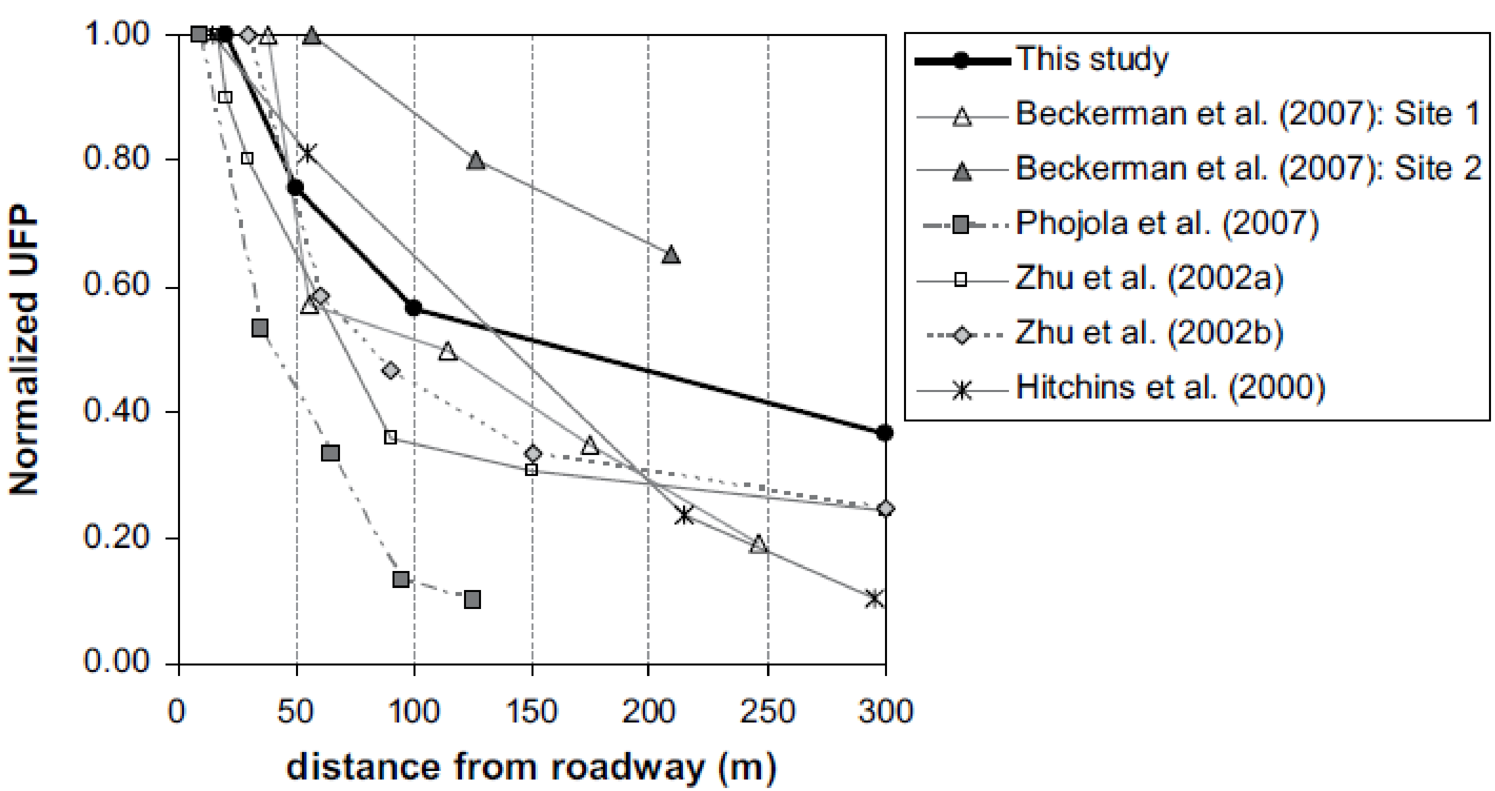
Source: EPA, Comparison of Growth Areas and Emissions, 1980-2012



So, is our job done?

Granular data from research studies reveal variability

Ultrafine particle concentration (UFP) with downwind distance from road



Hagler et al., 2009, Atmospheric Environment

Health effects related to near-source proximity

Infertility Causes: Where you live could put you at risk

According to U.S researchers, women who live in highly polluted cities are more likely to have fertility issues than those who live in areas where the air is cleaner

HEI

SPECIAL REPORT 17

HEALTH EFFECTS INSTITUTE

January 2010

Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects

HEI Panel on the Health Effects of Traffic-Related Air Pollution

UNION STATION FACES AIR POLLUTION ISSUE, EPA SAYS

FEBRUARY 10, 2016

Medill News Service, February 10, 2016

Boston Globe, March 5, 2015

Menu | Metro | **Breaking:** Pope issues strong words on Trump

Study warns of microscopic pollution

Those living near busy roads at risk

ABC Eyewitness News, March 25, 2015

AIR POLLUTION LINKED WITH BEHAVIORAL ISSUES IN CHILDREN, STUDY SAYS

AP Smog covers downtown Los Angeles, on April 28, 2009. (AP Photo/Nick Ut)

Unintended emissions persist

Natural gas: Local leaks impact global climate

EDF and Google Earth Outreach use new approach to pinpoint climate pollution

Natural gas heats our homes and cooks our dinner. But when natural gas—mostly methane—leaks into the air, it's a big problem for the climate. So EDF and Google Earth Outreach teamed up to build a faster, cheaper way to find and assess leaks under our streets and sidewalks. We tested it as part of a pilot mapping program, and here's what we found.

Boston: Older pipes, more leaks

Indianapolis: Newer pipes, fewer leaks

Environmental Defense Fund: https://www.edf.org/climate/methanemaps

Replicating the USA model is not easy

Example: Setting up some of the first $PM_{2.5}$ monitors in the Pearl River Delta Region of China

Logistics: power, space, sample handling
Cost: trained personnel, instrumentation, laboratory support
Access: permission from site owner

EPA

Replicating the USA model is not easy, even in the USA!

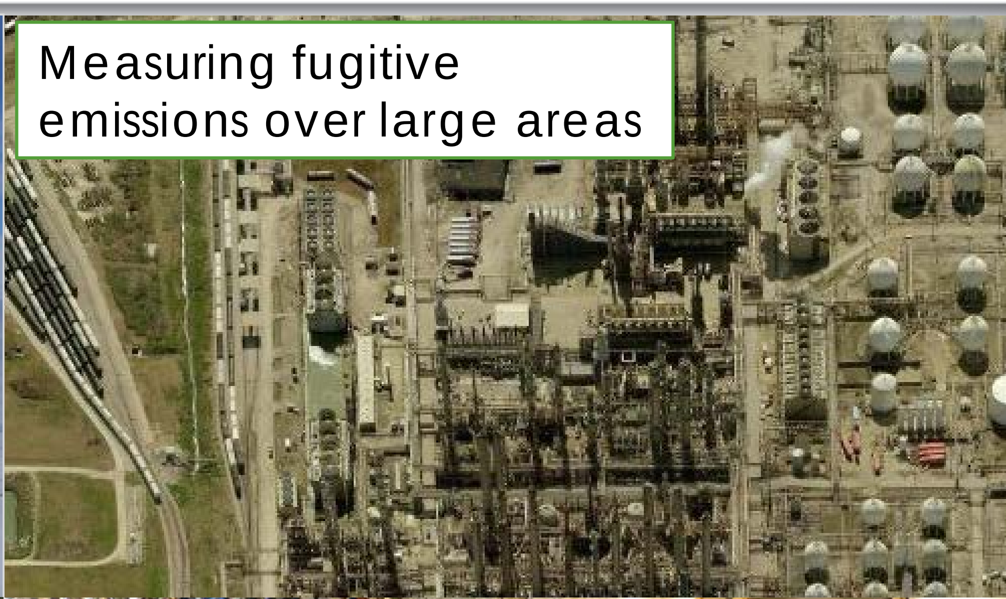
Near-road station in Memphis, Tennesse

Lengthy process to site the small station due to local community college concerns.

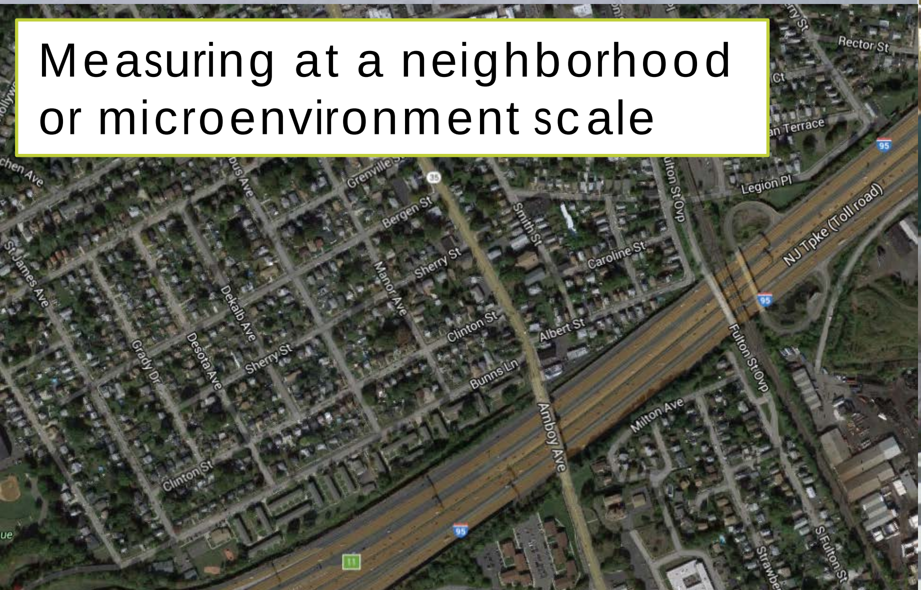
Challenge areas for the specialists

Measuring in areas with limited infrastructure

Measuring fugitive emissions over large areas

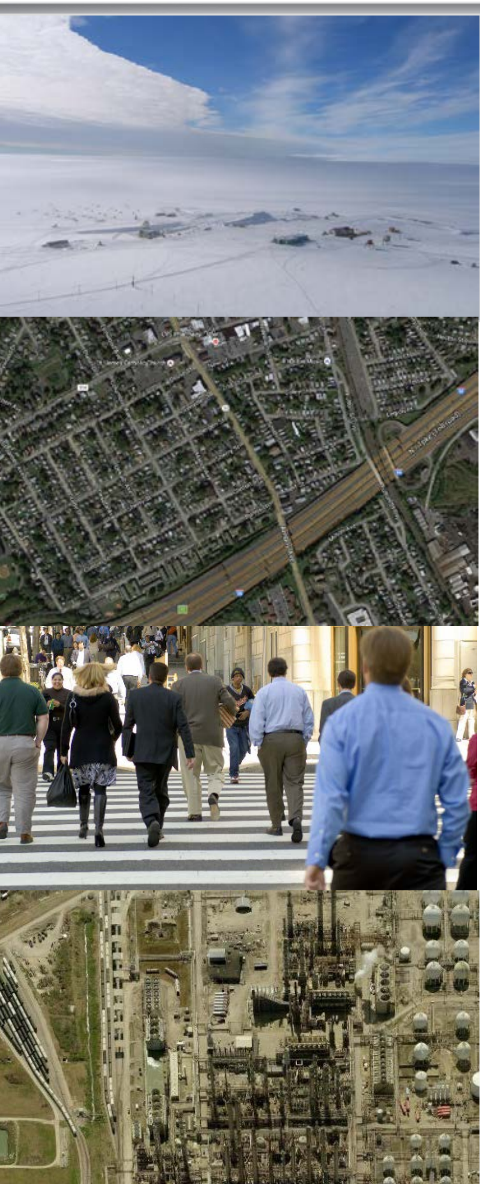


Measuring at a neighborhood or microenvironment scale



Personal exposure & Indoors

Challenge areas for the specialists



Cross-cutting needs:

- Increased time-resolution
- Miniaturized
- Rugged
- Low power requirements
- Low cost

Unique needs:

- Pollutant types
- Detection ranges
- Data management

Plus, needs of the unknown non-specialist population

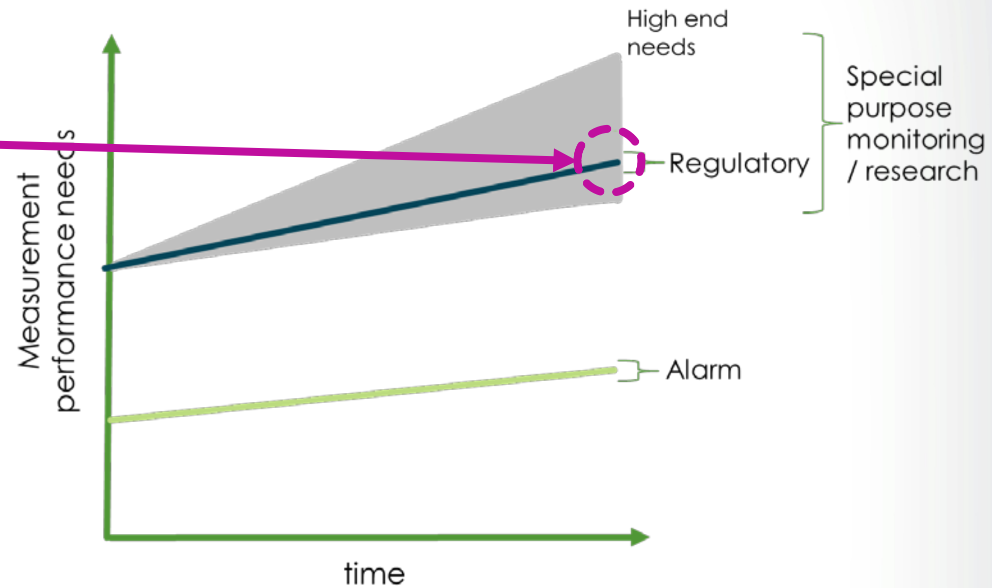
<u>Needs (??)</u>:

- Do we have a good feel for the "voice of the customer"?
- What we *think* people want to know:
  - What is my exposure to air pollution?
  - What is my child's exposure?
  - What is the air quality like in my neighborhood?
  - What actions should I take to reduce my exposure?
  - How can I demand change?

The essential question

What are your minimum requirements?

This is fairly easily stated for regulatory applications.



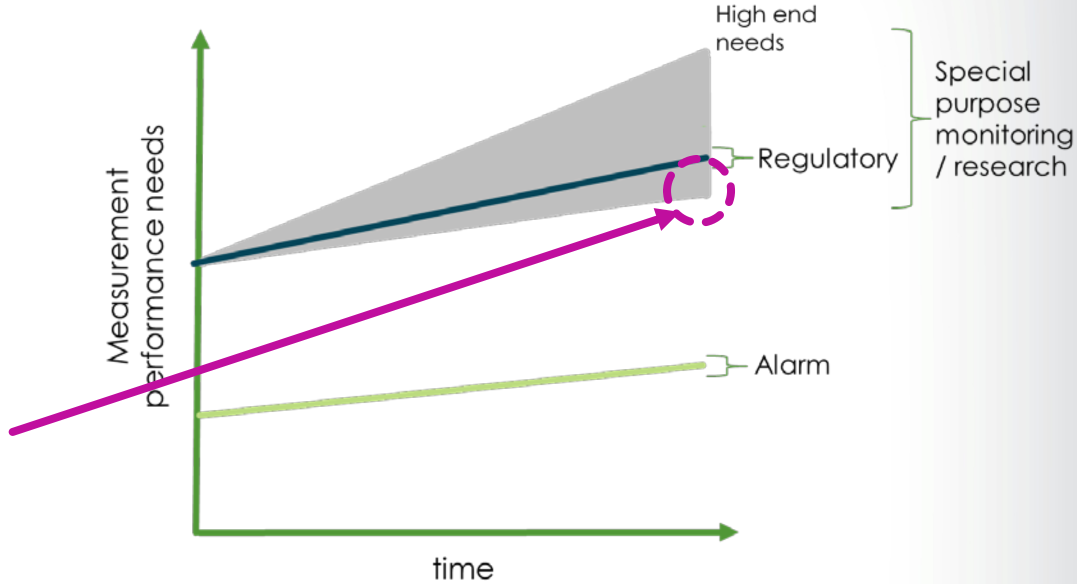
From: 40 CFR Parts 60 and 63 Petroleum Refinery Sector Risk and Technology Review and New Source Performance Standards; Final Rule

" To date, there are no commercially available, real-time open-path monitors capable of detecting benzene at the sub-ppbv levels necessary to demonstrate compliance with the fenceline requirements in this final rule. Only a system that can detect such levels will result in effective action by facilities…"

The essential question

What are your minimum requirements?

This is a fuzzy space for research/special-purpose applications, **but is definable** – conditional on measurement environment, pollutant, and study objective.



To support citizen science, EPA has pulled together expected ranges for a variety of pollutants in the USA.

Air Pollutant of Interest[17]	Type	Source Example	Useful Detection Limits	Range to Expect	Level[18]
Ozone (O_3)	Secondary	Formed via UV (sunlight) and pressure of other key pollutants	10 ppb	0-150 ppb	75 ppb (8 hr)

EPA, 2014. Air Sensor Guidebook, Report: 600/R-14/159

Is air measurement technology experiencing disruptive innovation?

Disruptive innovation

Technology innovation has been defined in two categories

Sustaining innovation

Does not affect existing markets. May slightly or significantly improve an existing product.

EPA's Village Green Project a revolutionary sustaining innovation.

Disruptive innovation

Creates a new market by applying a different set of values

Atmotube: Keychain VOC monitor

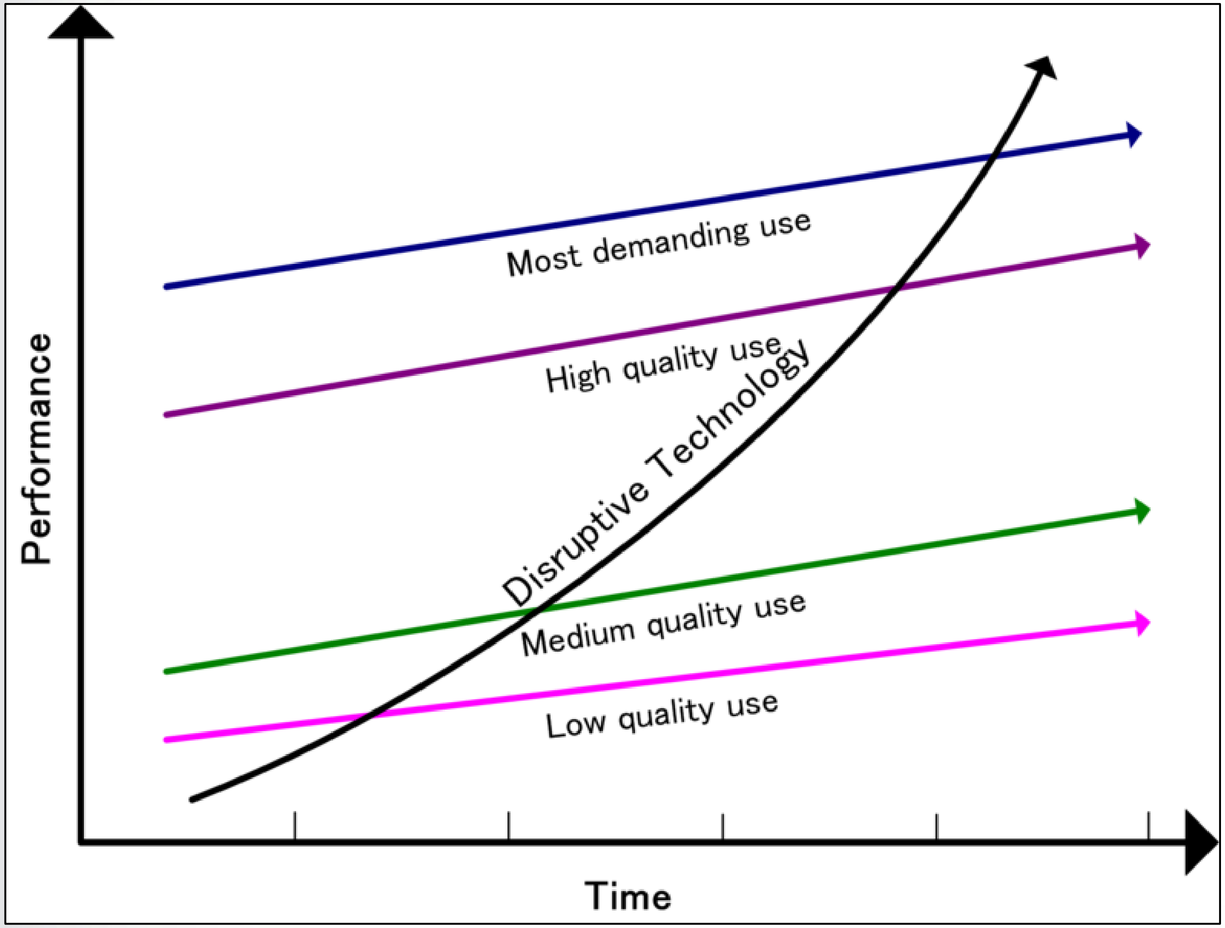
Theory published in 1995 by Clayton Christensen, Harvard Business School

Disruptive innovation

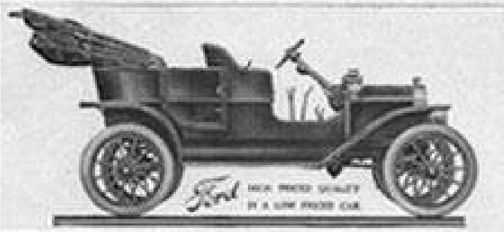
"First, disruptive products **are simpler and cheaper**; they generally promise lower margins, not greater profits. Second, disruptive technologies **typically are first commercialized in emerging or insignificant markets**. And third, leading firms' **most profitable customers generally don't want, and indeed initially can't use**, products based on disruptive technologies."

- Clayton Christensen, the Innovator's Dilemma

Disruptive innovation



Examples of disruptive technologies

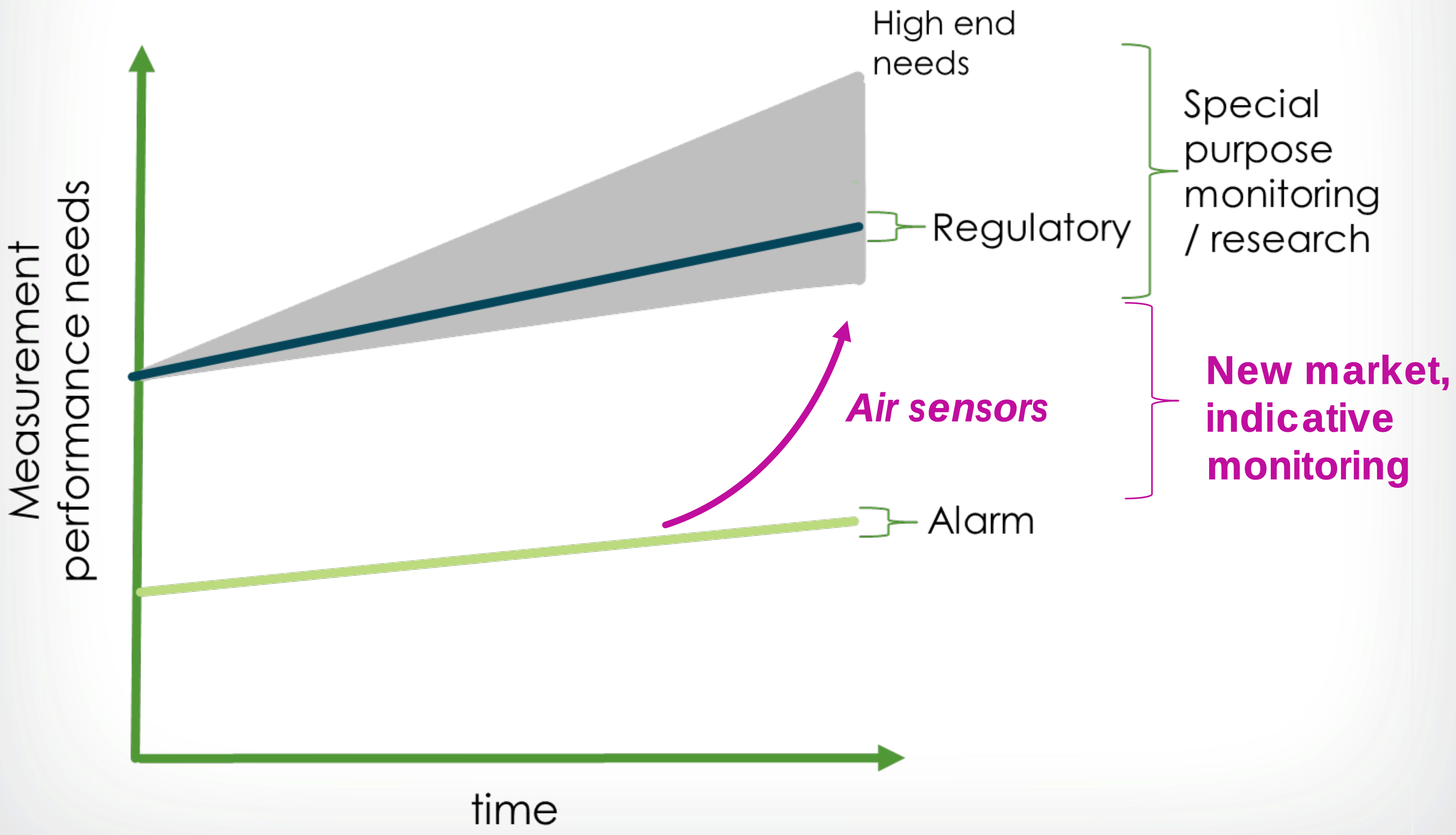


Ford Model T

Personal Computer

Theory published in 1995 by Clayton Christensen, Harvard Business School

Disruptive innovation



Is there a new market?

Wearables – consumer products for individuals

Tzoa

Indiegogo crowd-funded: 543 backers, reached 125% of funding goal

Atmotube

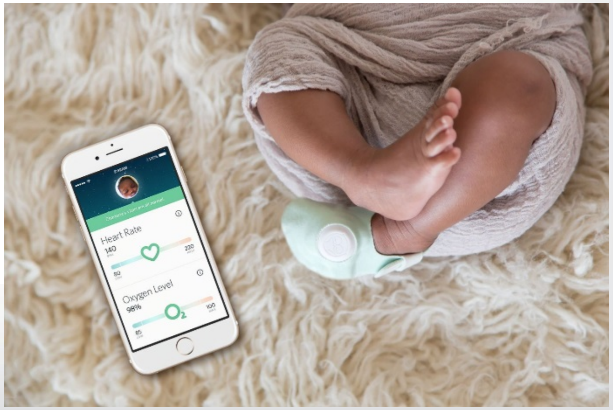
Indiegogo crowd-funded: 1776 backers, reached 338% of funding goal

More to come?

Yahoo! Tech: January 6, 2016

4 Big Trends at CES 2016: Cars, Wearables, Laptops, and Accessories for Everything

Owlet: baby vitals monitoring



EPA

Is there a new market?

Stationary in-home or outside monitors – for individuals

Foobot:

UNI-T

Awair

Laser Egg

Air Mentor Pro

Elgato Eve

AirVisual Node

Speck Sensor

Is there a new market?

Citizen scientists, Makers, Educators

AirBeam – HabitatMap

STI's Kids Making Sense program

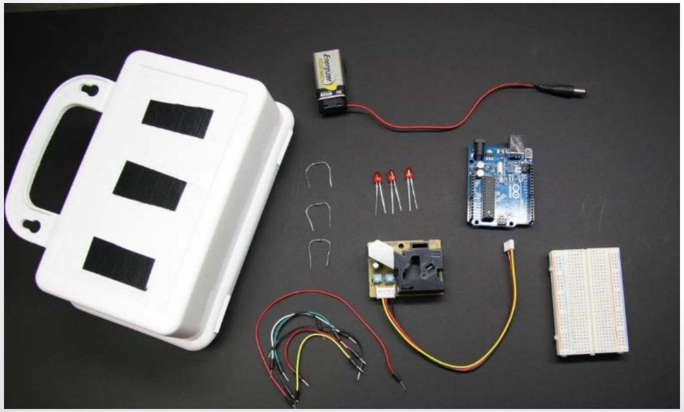
Learn

Measure

Discover

Interpret

Kids Making Sense contact: Tim Dye (STI)



EPA's Particle Sensor Kit activity

Is there a new market?

Citizen scientists, Makers, Educators

EPA has been working to provide guidance and support

- Air Sensor Toolbox: http://www.epa.gov/heasd/airsensortoolbox/
  - Test reports on sensor performance
  - Citizen science guidance

- Community Air Monitoring Training (summer 2015)

Air Sensor Toolbox contact: Ron Williams (EPA)

Is there a new market?

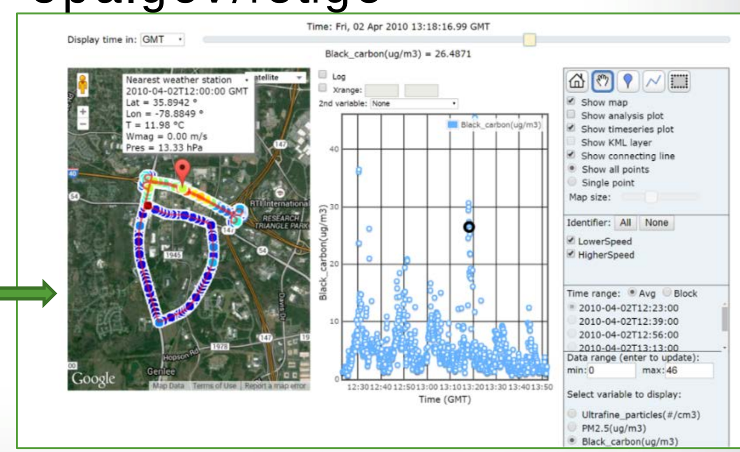
Citizen scientists, Makers, Educators

EPA also delving into citizen science studies

Sensors deployed by citizens in Ironbound community (New Jersey)

AirMapper project: beta-testing in Chicago, IL

epa.gov/retigo

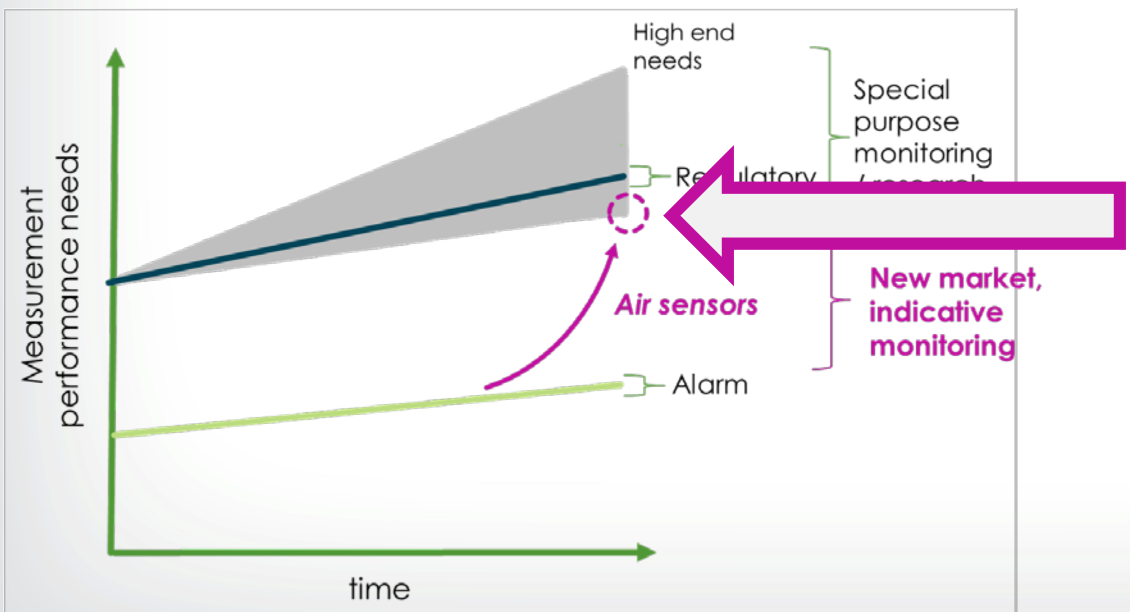


...and many more studies in the works

Ironbound project contact: Ron Williams; AirMapper contact: Gayle Hagler

Disruptive innovation

If that was the end of the story, we may conclude it is “hype” from the specialist point of view – there may be a new market, but it doesn’t affect us.



<u>The disruptive innovation test</u>: Are air sensors being put to use in research or special-purpose monitoring applications?

EPA

Disruptive Innovation

OEM sensors and ancillary equipment for custom devices

Shinyei

Raspberry Pi

Arduino

Alphasense

Turn-key instruments for field / indoor use

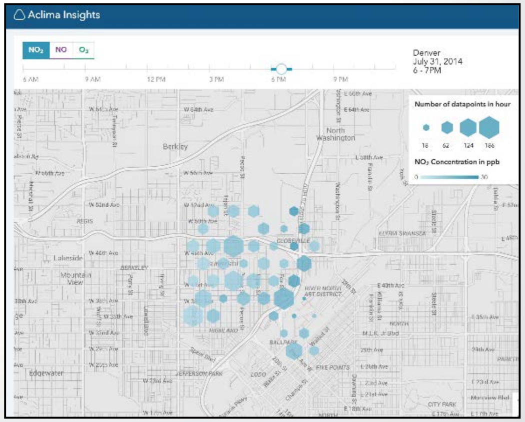
AQMesh

MetOne

Elm is technology for your neighborhood.

Sensor deployment and data services:

Google & Aclima



*OEM: original equipment manufacturer

Will the specialists adopt the technology?

Early-adopter results gave ground for skepticism by the specialists…

ENVIRONMENTAL monitor

Application and technology news for environmental professionals

Mountaintop Removal: Parts Of

Citizen science efforts expand monitoring programs but come with risks

"The devices simply don't provide consistent results."

Environmental Monitor
10/8/2014

…**however**, the rapid design improvement process has led to numerous sensors being applied in exploratory research projects.

Example applications: Hard-to-measure locations

United Nations Environment Programme (UNEP)

UNEP NEWS CENTRE

Home | Press Releases | Speeches | Multimedia

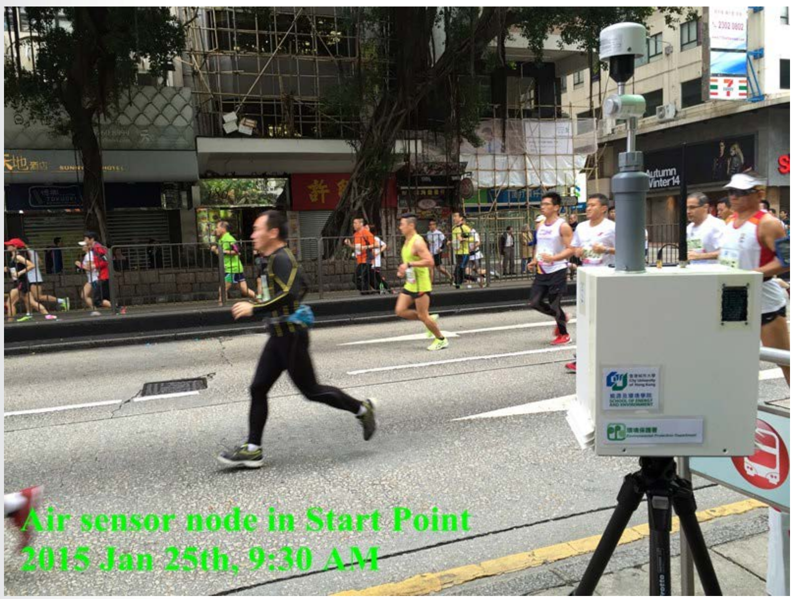
Low-Cost Device Can Revolutionize Air Quality Monitoring and Help Countries Prevent Deaths from Outdoor Pollution

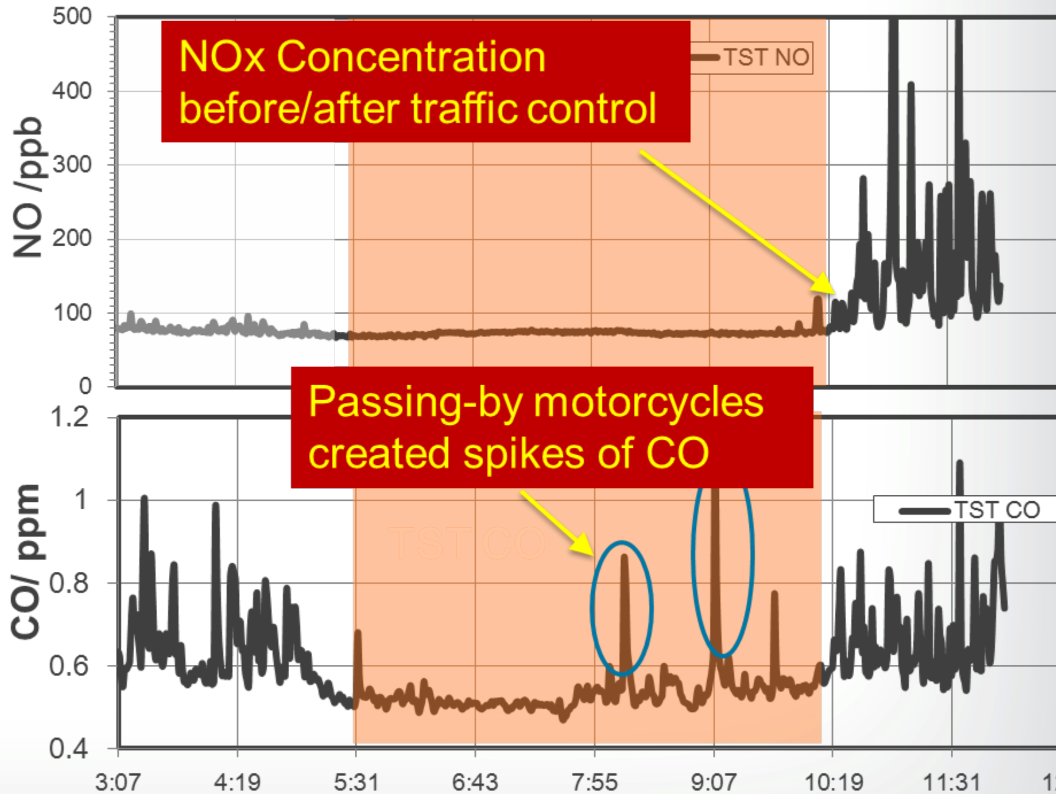
"UNEP plans to make the blueprints of its device publically available. This will allow governments and organizations to assemble or fabricate the units themselves, creating opportunities for innovation, enterprise development and green job creation."

Pictures from: Priyanka DeSouza (UNEP)

Example application: Hard-to-measure locations

City University of Hong Kong: Sensor deployment during 2015 marathon in downtown Hong Kong



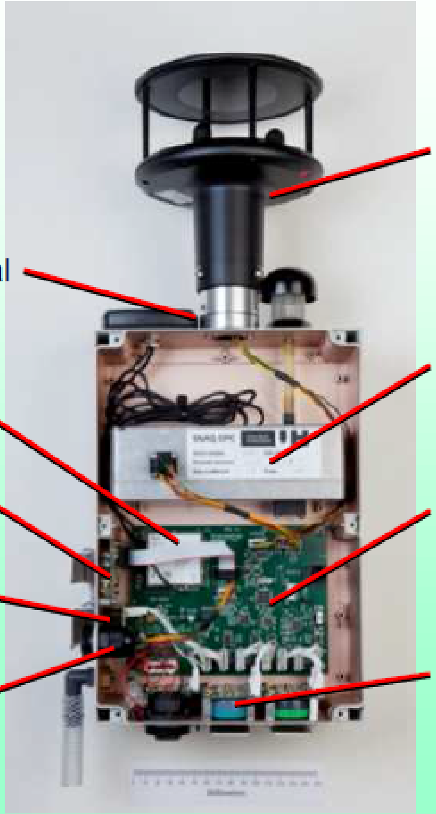


Pictures and figure from: Zhi Ning (City University of Hong Kong)

Example application: Large source areas

50 measurement nodes surrounding London Heathrow airport

- 20cm x 8cm x 30cm (excl. anemometer)
- 2.8 kg
- < 5W
- 20s readings, 12 measurements, 40+ nodes, 22 months
- 2 hourly GPRS transmission
- >9 billion readings



*GPRS: general packet radio service

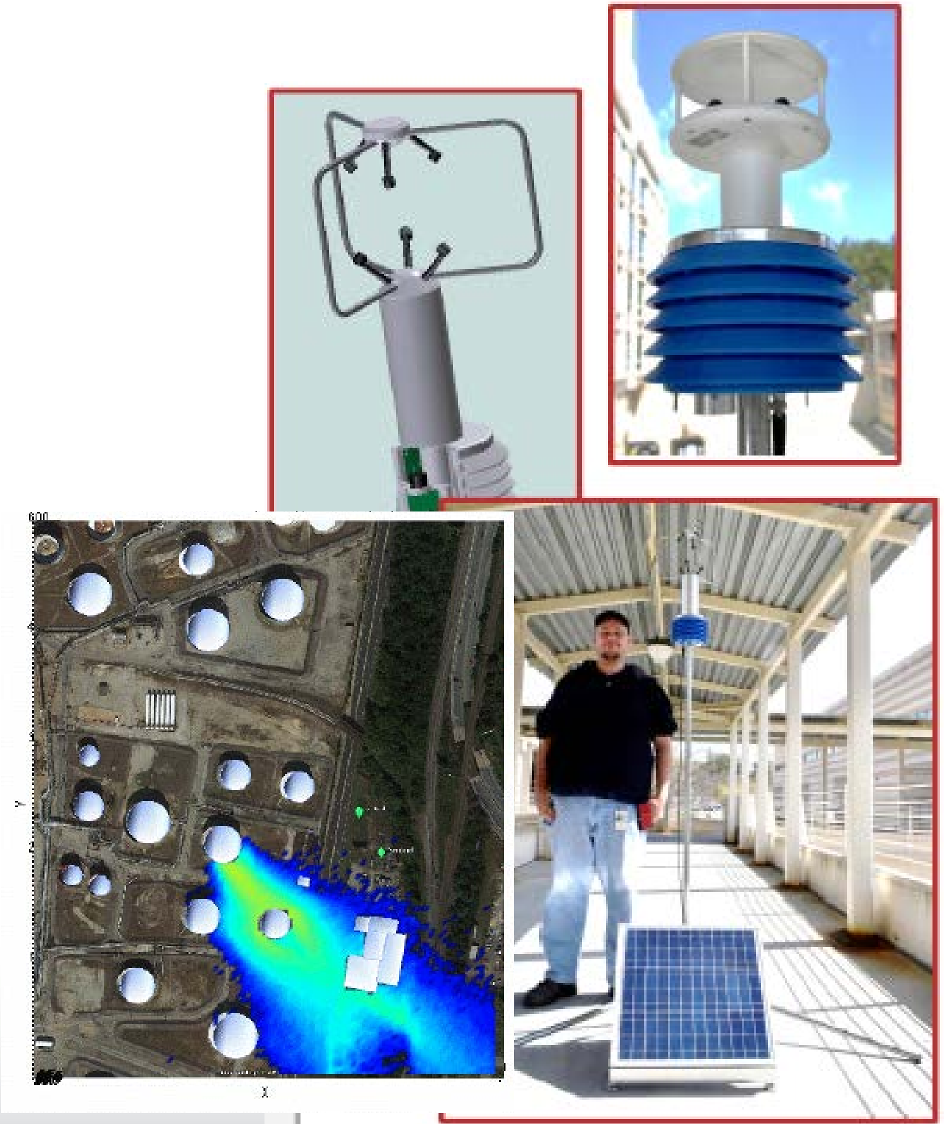
Schematic from: John Saffell (Alphasense), Roderic Jones (University of Cambridge)

Example application: Large source areas

Low cost fenceline VOC photoionization detector (PID) sensor, with integrated wind sensor and microprocessor.

Complements other strategies for fugitive source emission identification:

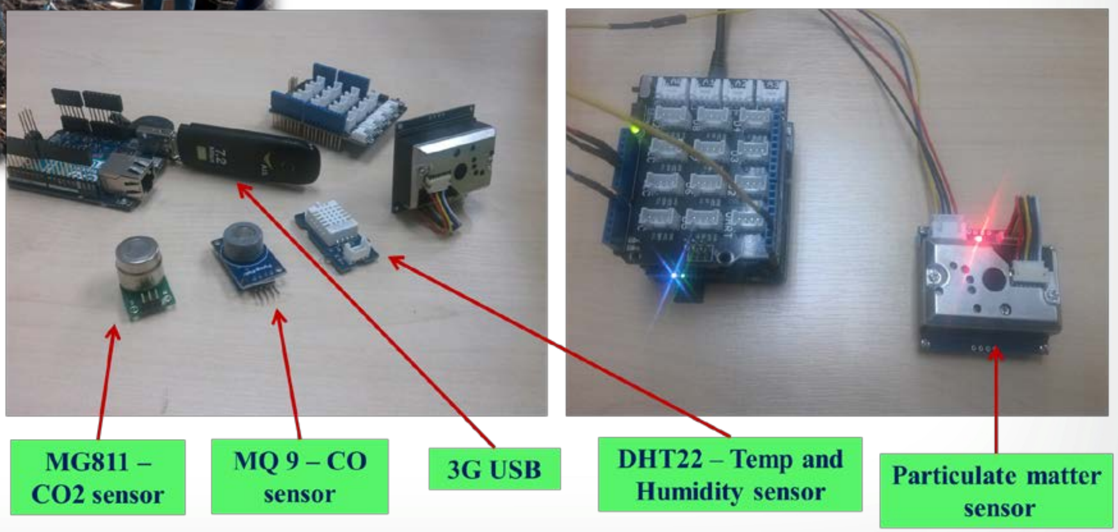
- Combine with modeling
- High-end mobile monitoring
- Passive sampling
- Future: optimization of summa canister sampling?



Images from: Eben Thoma (EPA)

Example application: Large source areas

Measuring rice field burning emissions in Thailand



Images from: Loi Huynh Tan (Asian Institute of Technology)

Example application: Indoors

- Shanghai General Hospital in the suburbs of Shanghai
- Studying the effectiveness of indoor air purifiers

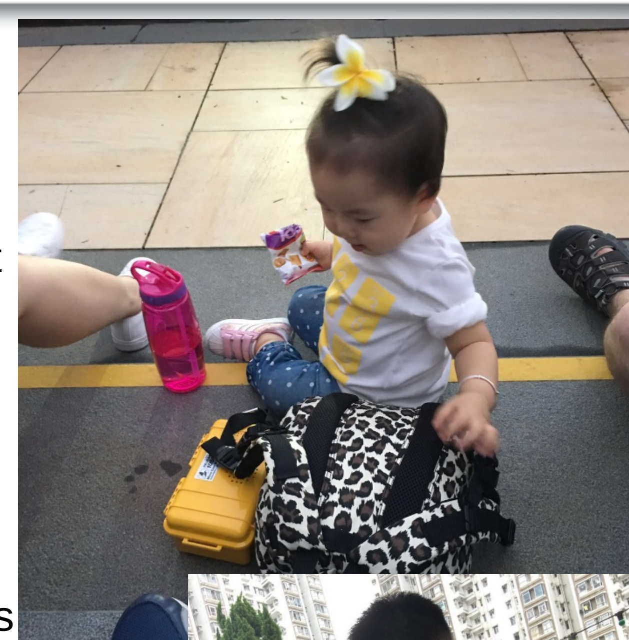
Images from: Karoline Johnson, Mike Bergin (Duke University)

Example application: Personal

Personal exposure research in Hong Kong

1: Central controlling unit
2: PM sensor
3: LED status light
4: Battery package
5: Sound sensor
6: USB Charging port

Plus: another layer of gas sensors, GPS



Images from: Zhi Ning (City University of Hong Kong)

Big networks coming

Internet of Things meets Air Quality

Array of Things received a $3.1 million grant from the National Science Foundation!

"500 nodes by the end of 2017"

Urban Center for Computation & Data – joint initiative of University of Chicago and Argonne National Laboratory

Parallel scale activities in Europe: CITISENSE project

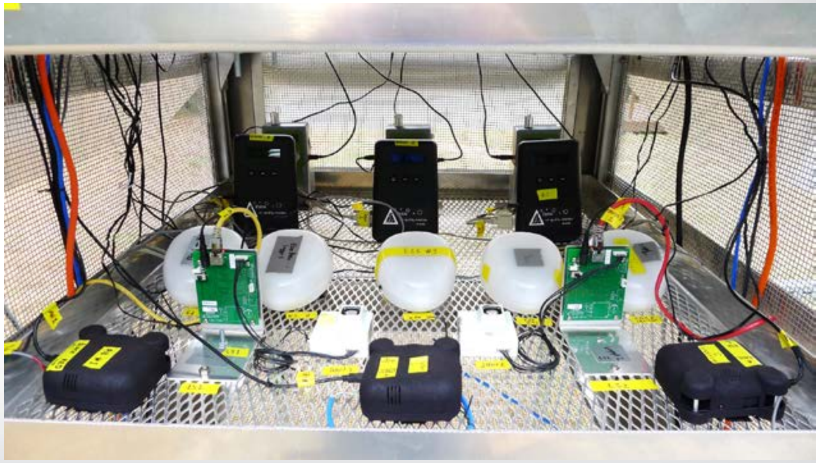
How well are these sensors performing? What are the gaps?

- Ongoing sensor performance evaluation programs (USA)
  - EPA Office of Research and Development – Community Air Sensor Network Program (CAIRSENSE)
  - South Coast Air Quality Management District – Air Quality Sensor Evaluation and Performance Center (AQ-SPEC)

- Field and laboratory evaluations, comparison with reference monitors

- Results range from very good agreement to no correlation.

- No current mobile-mode testing



How well are these sensors performing? What are the gaps?

- Where disruptive innovation is **not occurring (yet)**
  - Speciated VOCs (e.g., benzene)
  - Speciated particulate matter (trace metals, ions, organic and elemental carbon)
  - Ultrafine particles
    - Miniaturized UFP sensor in-development (Daren Chen, Virginia Commonwealth University)
  - Direct particle <u>mass</u> measurement
    - Microelectromechanical systems (MEMs) method in development (Igor Paprotny – University of Chicago)

Getting to "good enough"

A new philosophy on measurement performance

Our established method

<u>My instrument</u>:
Initial calibration
Use
Calibration checks
Analyze data

"…**a separate model was selected for each sensor**….**Fifth order polynomial models** that included relative humidity (RH %) and temperature (C) was found to best convert PUWP signals into $PM_{2.5}$…"

Gao et al., 2015, A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of $PM_{2.5}$ in Xi'an China. Environmental Pollution

An evolving new strategy for sensors with artifacts/drift

<u>My Sensor:</u>
(More complex) Initial calibration
Use
"Virtual calibration"
Analyze data

"….**we presumed that between 01:00 and 04:00 am** the WDSN nodes…and the AQM station (deployed ~600–800 m away…) **report similar concentrations.** A sensor-specific linear regression was developed…."

Moltchanov et al., 2015, On the feasibility of measuring urban air pollution by wireless distributed sensor networks. Science of the Total Environment.

* PUWP: Portable University of Washington Particle monitors; WDSN: Wireless Distributed Sensor Network; AQM: Air Quality Monitoring station

Challenges for the specialists

Expert input needed in this rapidly developing field:

1. Informing individual use of sensors and data sets:

- When should an individual make a behavior change?
- When is there not enough information (or not enough sensors?)
- What is the appropriate averaging time?
- How do we communicate uncertainty?
- How do different generations respond to the mode of data presentation?

Challenges for the specialists

Expert input needed in this rapidly developing field

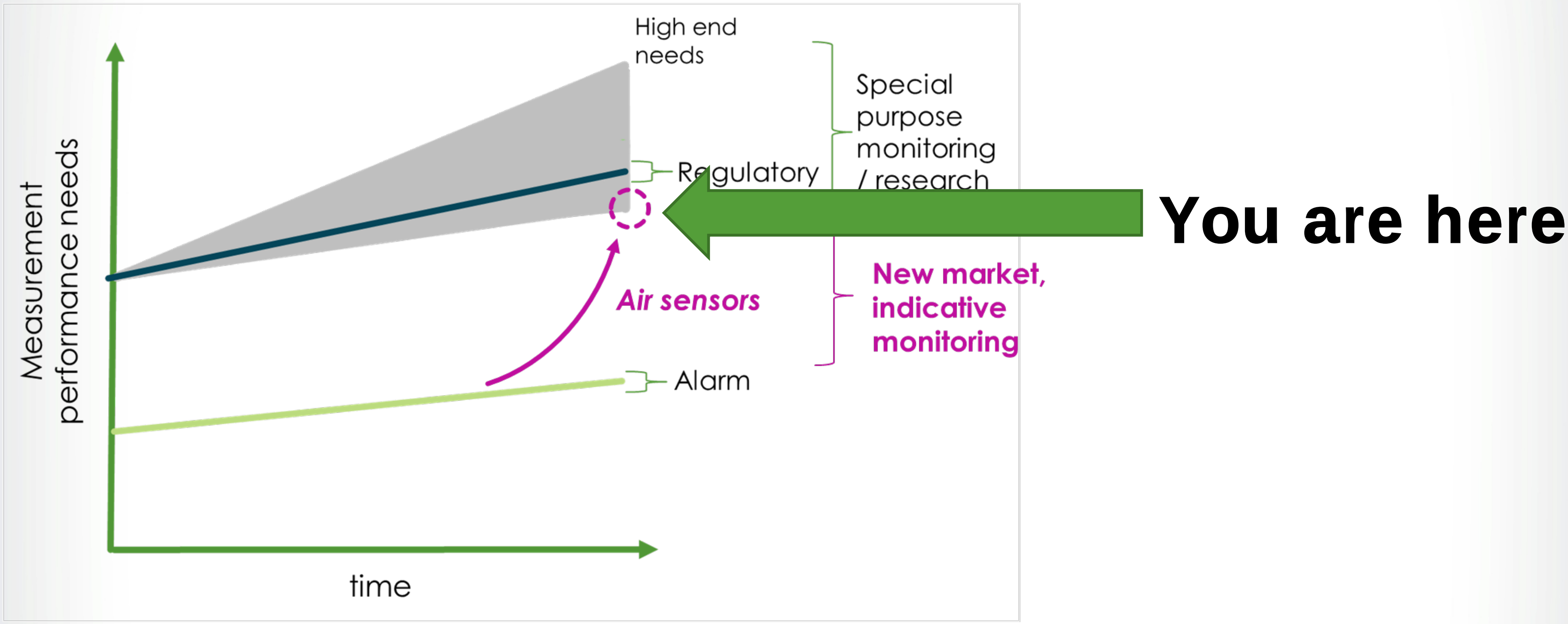
2. Testing and expanding limits of sensor performance

- New strategies to isolate sensor data signals of interest?
- What is a defensible virtual calibration approach and when may it deviate off course?

3. Sensor deployment approaches

- How can data sets of multiple quality and temporal/spatial levels be utilized in combination (e.g., satellite remote sensing, regulatory data?)
- What is the nominal spatial increment for deployment, for pollutant X?
- How can models utilize sensor data?
- How can sensors be used to optimize collection of samples for laboratory analysis?

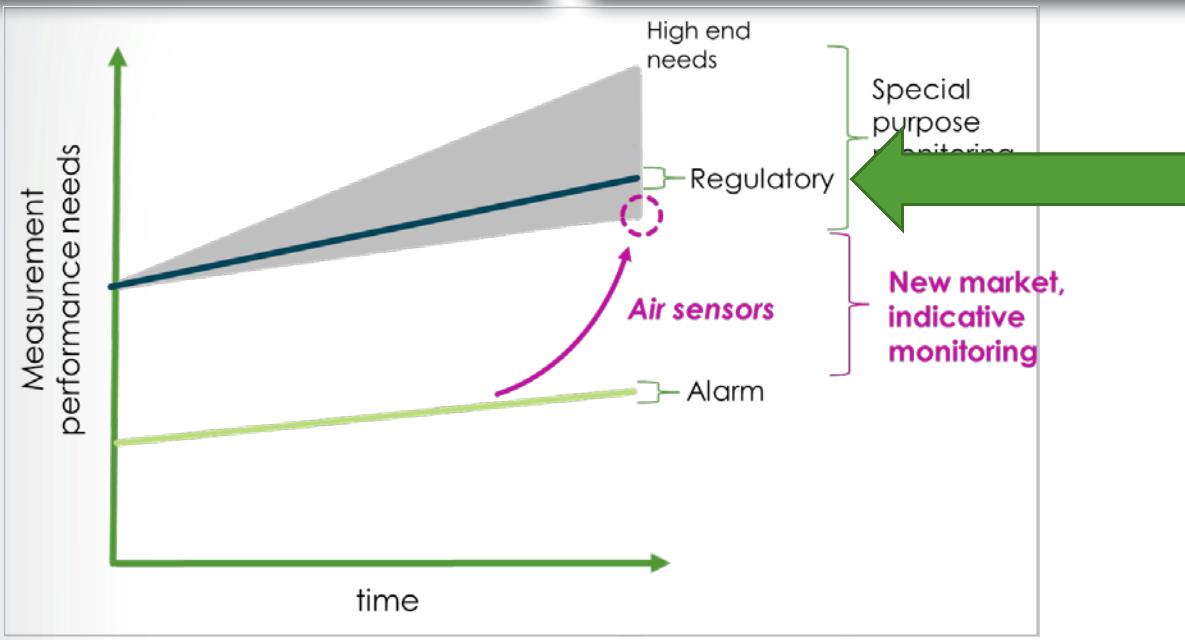
Early-adopter stage for research/special-purpose



For select, but highly desirable pollutants to measure.

Applications: large and distributed sources, near-source communities, exposure science, areas with limited infrastructure

For regulators, a screening but not compliance tool



Limited applicability

From: EPA Near-road NO_2 Monitoring Technical Assistance Document

"A variety of fixed and/or mobile monitoring techniques can be used to accomplish this task, and they can be used in a variety of applications, including **a saturation study**, a more limited and focused monitoring campaign, or through **mobile monitoring**….

"…**care must be taken to ensure that the precision and accuracy of these devices are well characterized**…"

A whole new world unfolding

"An innovation that is disruptive allows a whole new population of consumers at the bottom of a market access to a product or service that was historically only accessible to consumers with a lot of money or a lot of skill."

claytonchristensen.com

Thank you! Enjoy the conference!

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Thank you to contributors and EPA colleagues!
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Alphasense: John Saffell
UNEP: Priyanka DeSouza
Asian Institute of Technology: Loi Huynh Tan
Sonoma Technology: Tim Dye
Duke University: Karoline Johnson, Mike Bergin
Aclima: Melissa Lunden, Davida Herzl

References

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