MINI-PEMS: A TECHNICAL REVIEW ON WHAT IS NEEDED FOR USING IT AS A SCREENING AND COMPLIANCE TOOL

Carl Fulper[1], Cheryl Caffrey[1], Eric Meloche[2], Gregoire Berube[2], Leeson Guay[2], Stephanie Davis[2], Scott Bacon[3], Anthony Grandov[3], and Jason McPhee[3]

[1]U.S. Environmental Protection Agency (EPA), 2000 Traverwood Dr, Ann Arbor, MI 48105
[2]Environment and Climate Change Canada (ECCC), 351 Boulevard Saint-Joseph, Gatineau, QC J8Y 3Z5, Canada
[3]California Air Resources Board (CARB), 4001 Iowa Avenue, Riverside, CA 92507

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Outline

- Background
- Why do we need a new tool?
- Market Research
- Tests and findings conducted by the three groups (CARB, ECCC and EPA)
- Mini-PEMS Tool Capabilities Needed
  - Functionality Specifications
    - Phase 1: Screening Tool
    - Phase 2: Compliance Tool
- Potential Regulatory Use with Mini-PEMS
  - Currently used in Large SI EPA Regulation (field test and standard) and Heavy Duty In-Use
  - Potential for Development of Test Programs for Other Sectors

How do you test smaller vehicles/engines in the real-world?

Plus:
Mini-PEMS units could also be used for larger on-highway LDVs, HDVs and Nonroad equipment just like larger PEMS (CFR 1065 certified) are presently used for real-world testing

3DATX parSYNC Unit

ECM miniPEMS2 Unit

Global MRV Axion Unit

MTU Unit

Examples of Mini-PEMS

Background

Three regulatory groups: U.S. Environmental Protection Agency (EPA), the California Air Resources Board (CARB) and Environment and Climate Change Canada (ECCC) have been working together to find solutions to be able to test smaller engines

- **Regulatory test cycles for nonroad applications used in North America were developed when engine controls were much simpler.**
  - 1990's for specific nonroad vehicles/engines (~30 years ago)
  - Motorcycles are tested with FTP (developed for light duty vehicles in 1970's)
  - Modern NR engines are ECM controlled with fuel injection with much higher HP to weight ratios that allows for higher accelerations rates.

- **Regulatory cycles do not capture all facets of a vehicle/engine operation**
  - Some test cycles are steady state and do not capture transient portions of operation
  - Some test cycles are weighted on average operation of a variety of applications and do not represent a specific application

- **Field testing and standards do exist for several vehicle types – precedent is set**
  - EPA: large spark ignition engines (field test standard is 1.5 times the dyno standard)
  - Europe: LDV and HDV field testing requirements.
  - Expanding field testing to better understand use patterns (vehicle speed, engine load, engine RPM, etc) in the real-world.

Why do we Need a New Tool: Mini-PEMS

- **Better Understand Emissions from In-Use Nonroad Engines and On-Highway Motorcycles**
  - Motorcycles (on/off road), ATVs, marine, snowmobiles, riding lawn movers, etc.
  - Understanding how driving and usage patterns impact emissions (speed, accel/decel, start/stop, RPM, load, etc.)
- **Lightweight and compact system needed for certain applications (ex: motorcycles)**
  - Existing emission measurement systems impact typical use of certain applications due to weight and size
- **Regulatory cycles capture only part of the real-world use activity and emissions.**
  - Real world activity varies dramatically based on vehicle type, application, traffic conditions, and operator
  - ECU programming to cycles/certain operating conditions
  - Advancements in engine technologies (fuel injectors, turbocharging, etc.)
- **Improve emission modeling:**
  - Very little activity and emission data gathered to properly understand the real-world activity and emissions on nonroad engines and on-highway motorcycles.
- **Compliance Activity Screening of Vehicles/Engines**
  - Screen a larger number of vehicles/engines to focus compliance activities on vehicles/engines of concern.

Market Research

- **The three agencies held discussions with the current PEMS manufacturers in 2020**.
  - No current lightweight option was readily available that had all the features we were looking for.

- **Conducted a market review of known mini-PEMS manufactures**
  - Found over 12 different manufacturers
  - Conducted a technical specification review of existing products
  - Selected the most promising mini-PEMS products to have additional discussions with

- **Further discussions held with one University and two MiniPEMS developers**
  - Michigan Technological University completed a MiniPEMS study for ECCC on snowmobiles
  - 3DATX – system reads in ppm
  - ECM – MiniPEMS2

MiniPEMS Systems

Note: Research conducted in Early 2021

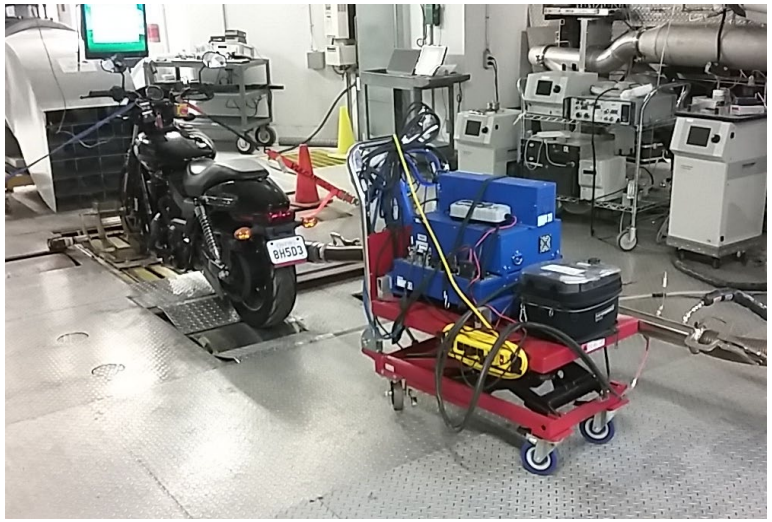
Preliminary Comparison of Available Mini-PEMS, 2/24/21

System	Manufacturer	Does NOx	Does CO/CO2	Does HC	Does PM	Size (inxinxin)	V (in^3)	Weight	Flow Measurement	Integrated Battery
Axion R/S+	Global MRV	Yes	Yes	Yes	Yes	21.7x16.9x8.5	3117.21	39lb	Engine Sensor Parametry	No
Axion R/S	Global MRV	Yes	Yes	Yes	No	21.7x16.9x8.5	3117.21	38lb	Engine Sensor Parametry	No
AxionGo	Global MRV	Yes	Yes	Yes	No	16.7x21.7x8.7in	3152.79	20lb…. plus external laptop	Engine Sensor Parametry	No
PEMS-GAS	AIP MAHA	Yes	Yes	No	No	24.8x15.7x7.9in	3075.94	"<20kg" (44lb)	Add-on flowmeter (2.5in tube = 17.6lb)	Yes, Lithium Ion
PEMS-GAS/PM	AIP MAHA	Yes	Yes	No	Yes	24.8x15.7x7.9in	3075.94	"<20kg" (44lb)	Add-on flowmeter (2.5in tube = 17.6lb)	Yes, Lithium Ion
M.O.V.E. GAS PEMS iS	AVL	Yes	Yes	No	No	21.7x16.5x16.9in	6051.05	66lb	Not Published	Optional
M.O.V.E. PM PEMS iX	AVL	No	No	No	Yes	19x16.6x20.9in	6591.86	99lb	Not Published	Not Published
OBS-ONE GS LDV	Horiba	Yes	Yes	No	No	13.8x18.5x13in	3318.9	70.4lb	Additional Flowmeter or OBD	Yes, Lead-Acid
OBS-ONE GS HDV	Horiba	Yes	Yes	Yes	No	13.8x18.5x18.5in	4723.05	99lb	Additional Flowmeter or OBD	Yes, Lead-Acid
OBS-ONE PM	Horiba	No	No	No	Yes	13.8x18.5x18.1in	4620.93	99lb	Signal from GS unit	Not Published
OBM 5.0	TU Wien/Dr. Ernst Pucher	Yes	Yes	Yes	PN	Not Published	???	"<15kg" (33lb)	Needs Signal from Another Instrument	Not Published
MiniPEMS	ECM	Yes	Optional	No	No	Backpack-sized	???	"<15lb"	OBD Only?	Yes
parSYNC RDE	3DATX	Yes	Yes	No	Yes	Not Published	???	8.14lb (!)	Needs Signal from Another Instrument	Yes
MicroFID	PhotoVAC	No	No	Yes	No	17.1x3.85x7.4in	487.179	8.1lb	No	Yes
Testo, DaqPro, and SQUID	CARB Internal R&D Project	Yes	Yes	Yes	No*	TBD	TBD	TBD	RPM; IAT+MAP using CARB SQUID device	Yes
EPA Mini-PEMS	EPA	Yes	Partial CO2	No	No	12 x 18 x 8	1500	20 lbs	Mass Flow Sensor	Yes

ECCC Experience with Mini-PEMS on ON-HMC

- An ECM product was utilized on motorcycles in 2017-2018 EPA/ECCC test program.

- The tests conducted included:
  - Comparison of per-phase emissions for three test cycles (FTP, WMTC, RWDC) on on-highway motorcycles
    - Bags (dyno cell)
    - Standard PEMS (Sensors® LDV),
    - and mini-PEMS (ECM MiniPEMS1™)
  - Comparison of instantaneous emissions measured from
    - Mini-PEMS™,
    - LDV (Sensors PEMS)
    - and test cell analyzers



- *"ECM's miniPEMS™ is an inexpensive, but versatile, **M**odular **I**nternal-combustion engine **N**etworked **I**nstrumentation (mini) package for the auditing of combustion engine emissions. A key feature of miniPEMS™ is the use of ceramic exhaust emissions sensors, a technology pioneered by ECM. Ceramic exhaust sensors are smaller, more rugged, and faster responding than classical gas analyzers.*
  - NOxCAN – NOx, O2, Lambda
  - CO/CO2CAN – CO, CO2, O2, Lambda
  - LambdaCAN – O2, Lambda

- Exhaust flow rates were measured using Sensors® Exhaust Flow Meter (EFM) – essentially a pitot meter
  - Alternative flow derivation methods: ultrasonic, vortex sensors, or calculated from OBD data

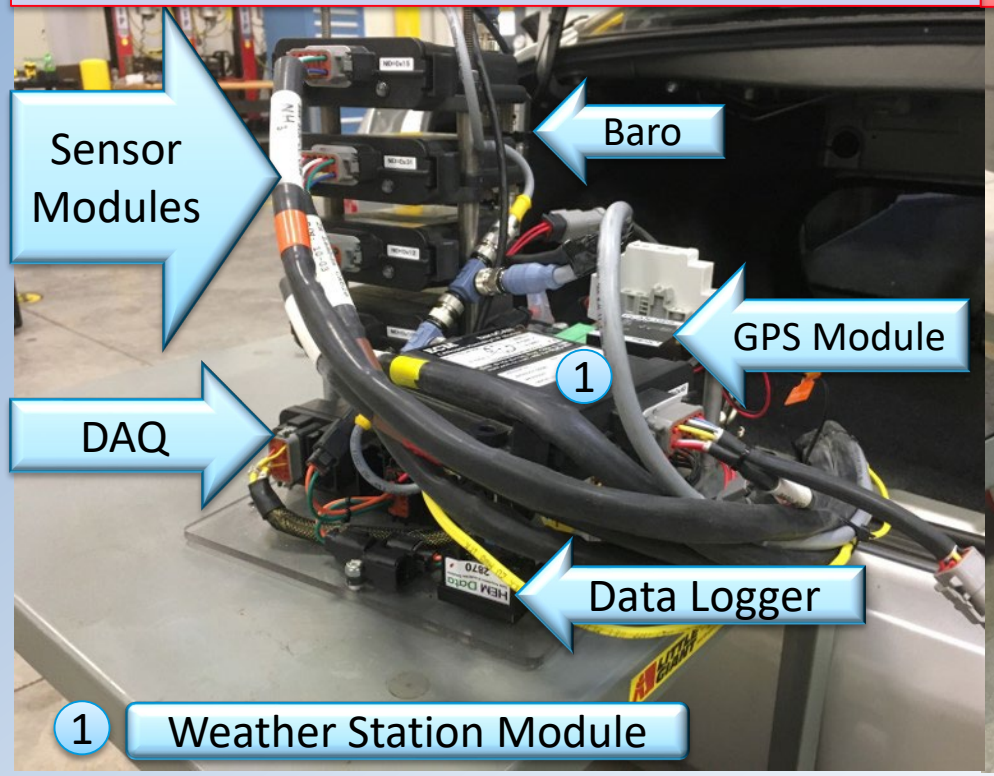
EPA's Review of PEMS and Mini-PEMS

- **ASD has looked at multiple PEMS and mini-PEMS designs:**
  - Axiom (Firefly)
  - ECM
  - Sensors Inc
  - AVL
  - Horiba
  - EPA Own Versions

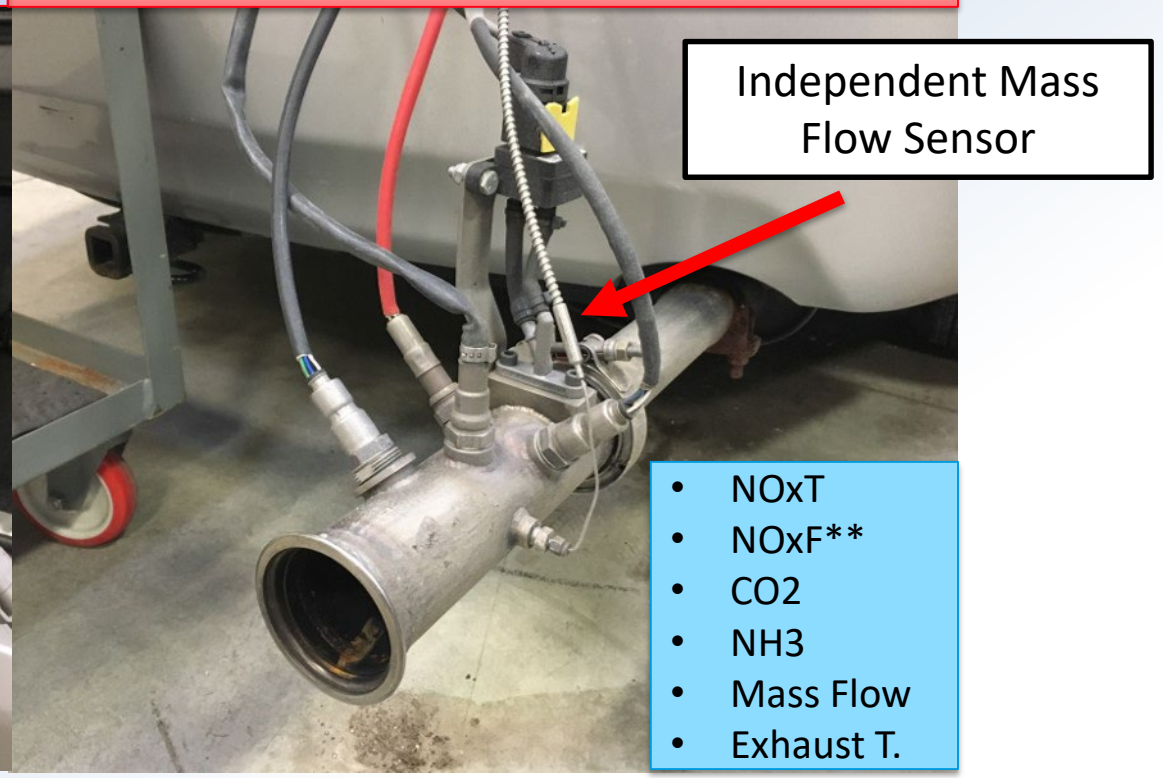
- **EPA's MiniPEMS Version**
  - Based-off of ECM (Engine Control and Monitoring Company) ceramic sensors
    - 02, CO2, NOx, NH3, wide lambda
  - Added flowmeter capability with exhaust temperature
    - Flowmeter size version for 1.5, 2, 2.5, 3, 4, and 5 inch to handle all exhaust sizes
  - Added environmental probe (barometric pressure, relative humidity & air temperature)
  - GPS
  - Vehicle ECM OBD capable (J1939/J1979/OEM databases)
  - Future added abilities:
    - Add fuel flow capability for smaller engines
    - Add PM sensor from ECM
    - Upgrade to ECM's MiniPEMS2

Measurement Setup – Sensors, Modules and DAQ*

Sensor Modules and DAQ



2.5” LDV Tailpipe Adapter



Future Development – Robust Packaging

Development Design

Prototype Design

Design Includes: Control Modules, DAQ, Data Logger, Battery (8 hours) and Barometric Pressure
Dimensions: W21”xH8.5”xD16”
Weight: approx. 25 lbs (Usage for 8 hours)

Next generation prototype expected to be smaller with less batteries plus add PM sensor and optional fuel flowmeter

CARB's Experience with On-Road Motorcycle PEMS

- **Evaluated capabilities of Global MRV Axion miniPEMS when applied to on-road motorcycles**
- **Size and weight of miniPEMS is at upper limits of feasibility for motorcycles**
- **External Li-ion batteries, 2+ hours run time**
- **Mounting requires vehicle-specific engineering and fabrication**
  - Motorcycle subframe structural failure on one bike
  - Not possible to mount on certain bikes
- **System was generally reliable, but some failures occurred**
  - Intermittent loss of connection to power supply
  - Data gaps in GPS signal

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CARB's Experience with On-Road Motorcycle PEMS

- **Acceptable performance from analytical bench**
- **Accuracy of calculated exhaust flow varies significantly by vehicle**
  - Correction factor can be established using a PEMS flowmeter as a reference system
- **Data quality not suitable for regulatory compliance, but valuable as a screening and research tool**

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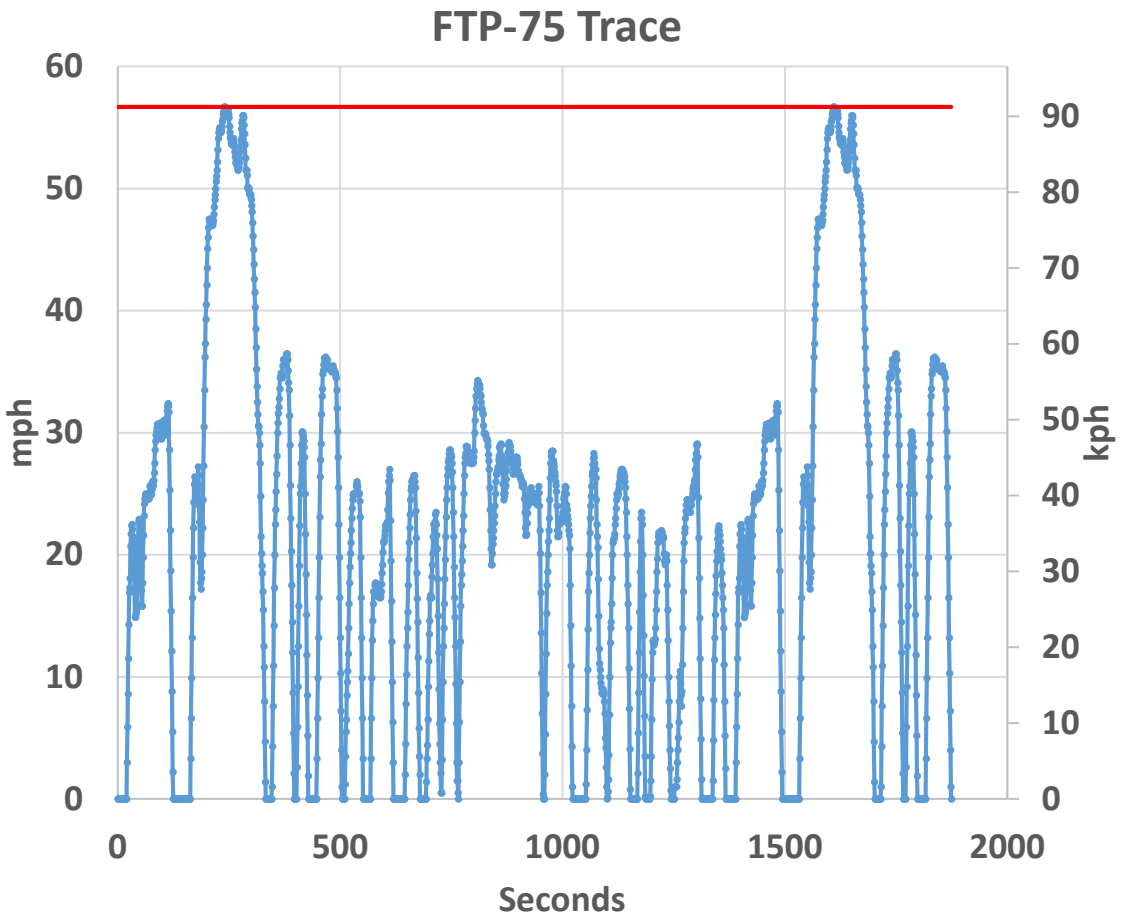
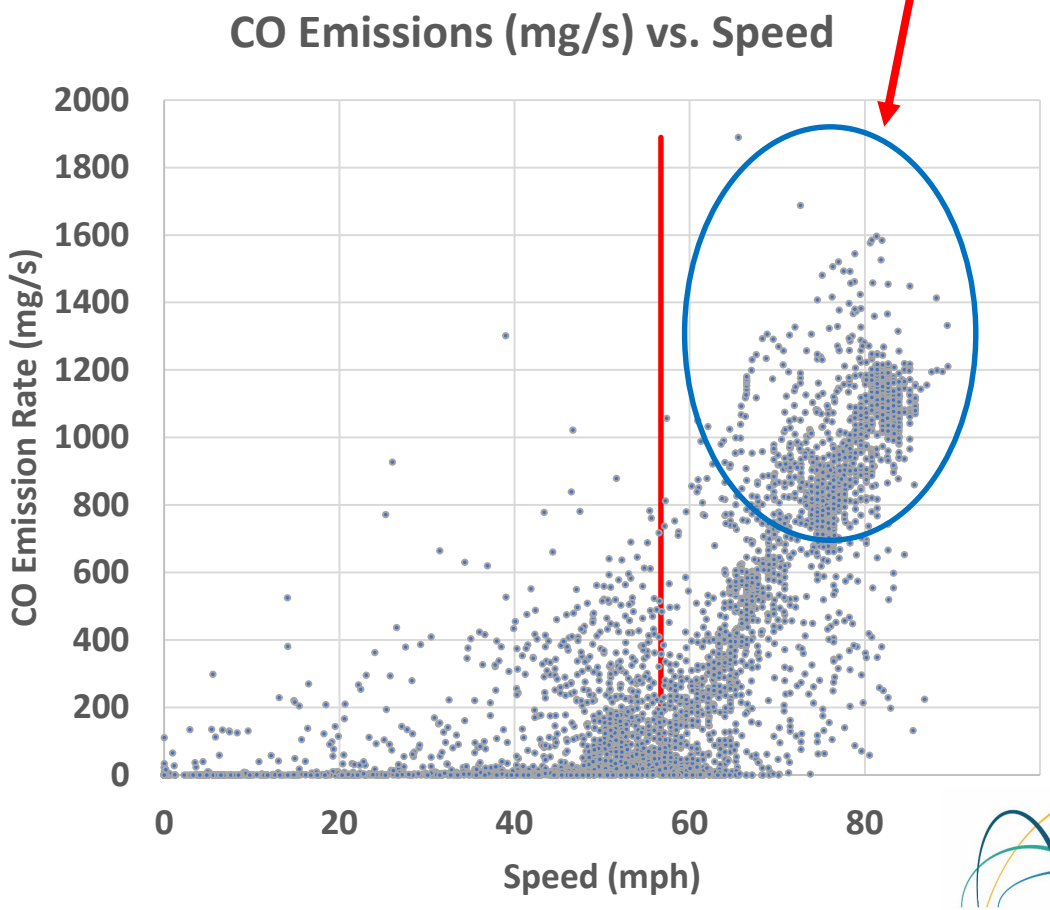
CARB's Experience with On-Road Motorcycle PEMS

An example of PEMS as a screening tool: Unexpected spike in CO emissions above the FTP max speed





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Mini-PEMS Specifications

PEMS/Mini-PEMS/PAMS Data Logger: Data Fields

Allows for Modeling, Screening and Compliance Analysis on:

Date/Time Clock: Engine On/Off Date/Time
ECU: Vehicle Speed (if not, use GPS)

→

- Soak times, starts, idle times, VMT, speed distributions, drive cycle development, usage patterns, etc.
- Able to calculate VSP if hp and vehicle mass are known

+

Size and Weight:
Weight: < 30 lbs (including batteries)
Size: 24 inches x 18 inches x 36 inches

→

- Needs to be able to fit on a small rack on the back of the vehicle
- Needs to be environmental proof, resistant to dust and rain
- Needs to be able to handle shock & vibration of real-world testing
- Unit can be single or modular to allow for greater flexibility for installation

+

Batteries:
Testing for at least 2 to 3 hours

→

- Allows testing in a wide variety of conditions
- Needs to be operable on shore power before and after vehicle testing, during warm-up and calibration

+

ECM/CAN data recording:
Engine parameters, diagnostic messages

→

- ECM OBD capabilities (allow for recording of engine parameters: vehicle speed, engine load, engine rpm at a minimum)
- Able to gather Diagnostic Messages, DTCs and Monitor Readiness

Note: All Data Gathered at 1Hz – second-by-second

PEMS/Mini-PEMS/PAMS Data Logger: Data Fields

Allows for Modeling .Screening and Compliance Analysis on:

Emission Measurements:
CO, CO2, O2 wide lambda, THC/NMHC, NOx, NH3 channels

- Screening Tool: At least CO2, O2 wide lambda, PM & NOx
- Compliance Tool: add HC/NMHC, & CO
- Able to get measurements in ppm or %, 1Hz minimum

+

GPS Fields: (lat./long./altitude/vehicle speed)
(Note: Signal blocked by underpasses/tall buildings

- Able to cross check ECU vehicle speed/acceleration w/ GPS
- GPS Fencing (ports, hoteling, county, city boundaries), road types, etc.
- Road Grade load by altitude or enhanced with GIS maps

+

External Flowmeter OR Fuel flowmeter:

- Able to cross check ECU's MAF/MAP equations w/ independent exhaust or fuel flow measurement
- Need to convert emission concentrations (ppm) to mass units (g/s, g/mile, g/kW-hr).

+

Environmental Probe: (relative humidity, ambient temperature, and barometric pressure)

- Used to correct the NOx measurement and air density calculations.

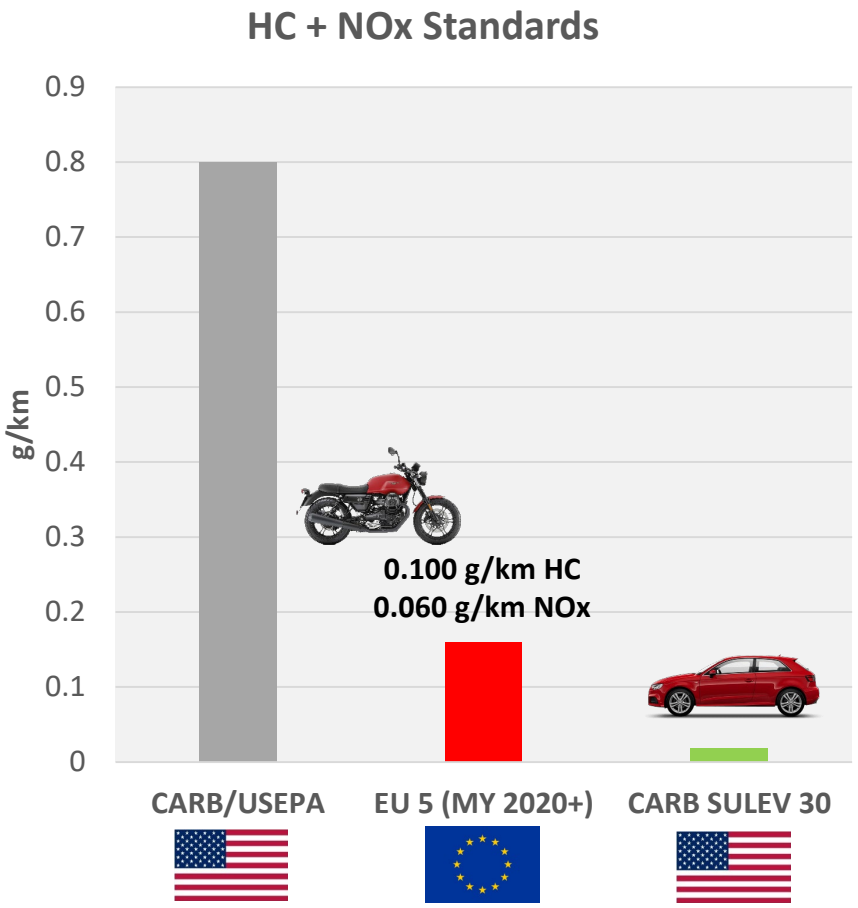
+

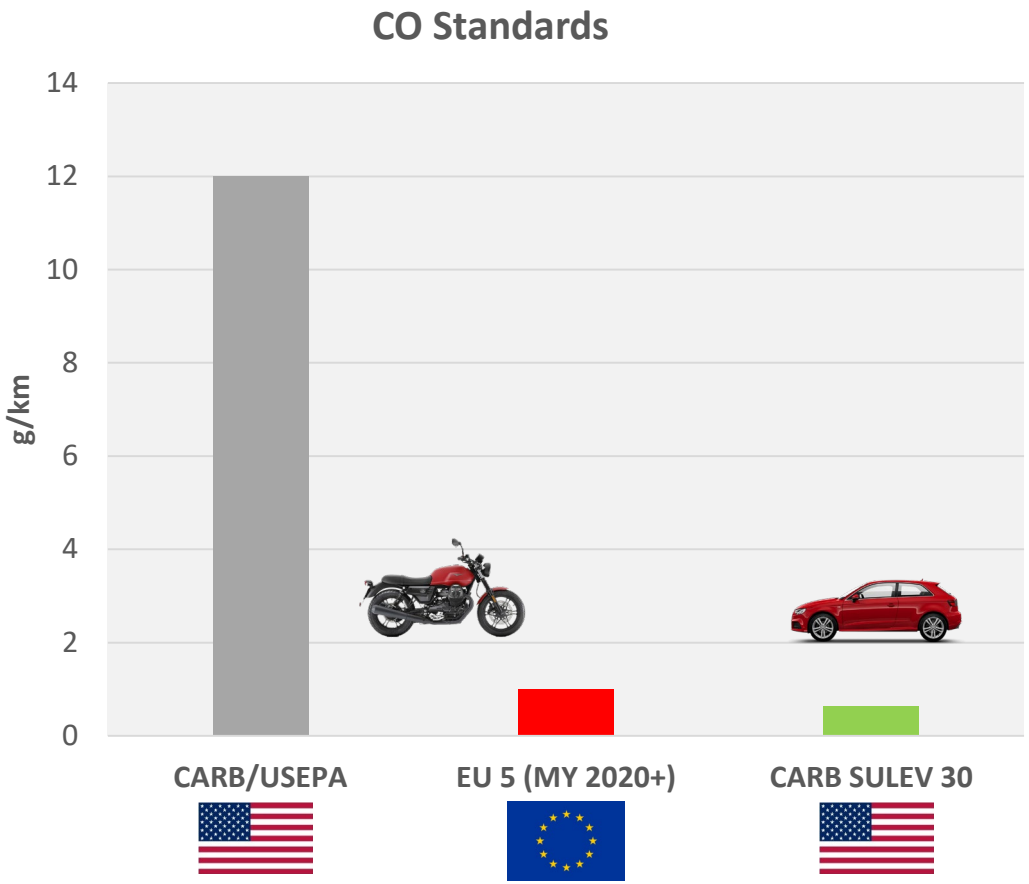
Data Logger: 4 channel minimum

- Analog, digital and CAN signals including thermocouples for exhaust.

Note: All Data Gathered at 1Hz – second-by-second

Comparison of Motorcycle and LDV Standards





Accuracy and range of measurement devices must reflect decreasing emissions limits.

Accuracy of Mini-PEMS

Screening Tool

- Accuracy: +/-15% max
- Emission measurement (PPM) with emission ratios (PPM comparison)
- Minimum emissions measurements: NOx, CO2, PM and O2 (wide lambda)
- Easy application on/off

Certification Tool (same as above but add or improve)

- Accuracy: +/-10% max
- g/power unit, g/s or g/mile output
- Full emissions capabilities to add: CO, THC/NMHC

Suite of Tools to Measure Activity and Emissions

		Equipment Only Costs:
Laboratory Testing: Chassis and/or Engine Dynamometer		~$3,000,000+
Portable Emissions Measurement Systems (PEMS) CFR 1065 Real World		~$200,000-$300,000
Mini-PEMS (Screening/Compliance) Real World		~$30,000-$100,000
Portable Activity Measurement Systems (PAMS) Real World		~$600 -$1,000

Note: The next tool needed to support data gathering for understanding activity and emissions in the real-world

Conclusions

- The team found many mini-PEMs manufacturers have some of the capabilities needed for a “screening” or “compliance” tool.
  - Improvements to “key” components are needed to be able to use them in the real-world environment.
    - Adopting existing and/or improved sensors, or analyzers into their instruments
    - Adopting existing tools: GPS, probes, ECM OBD needs to be incorporated
    - Improvements that reduce size, weight and power usage
    - Improvements in functionality (quick to calibrate, install and use)

- This new tool is needed now to support and expand our understanding of activity and emission patterns vehicles and nonroad equipment in the real-world for modeling.

Contact Information

- EPA Staff:
  - Carl Fulper, fulper.carlr@epa.gov, 734-214-4400
  - Cheryl Caffrey, caffrey.cheryl@epa.gov, 734-214-4849

- CARB Staff:
  - Scott Bacon, scott.bacon@arb.ca.gov, 279-842-9122
  - Tony Grandov, anthony.grandov@arb.ca.gov, 916-322-2411

- ECCC Staff:
  - Eric Meloche, eric.meloche@ec.gc.ca, 613-295-7142
  - Gregoire Berube, gregoire.berube@ec.gc.ca, 343-809-4374

Questions