MOVES

Motor Vehicle Emission Simulator

Incorporation of Air Toxics and Improved Speciation for Nonroad Emissions in MOVES

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Presentation for the International Emissions Inventory Conference

San Diego, CA

April 16, 2015

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Background

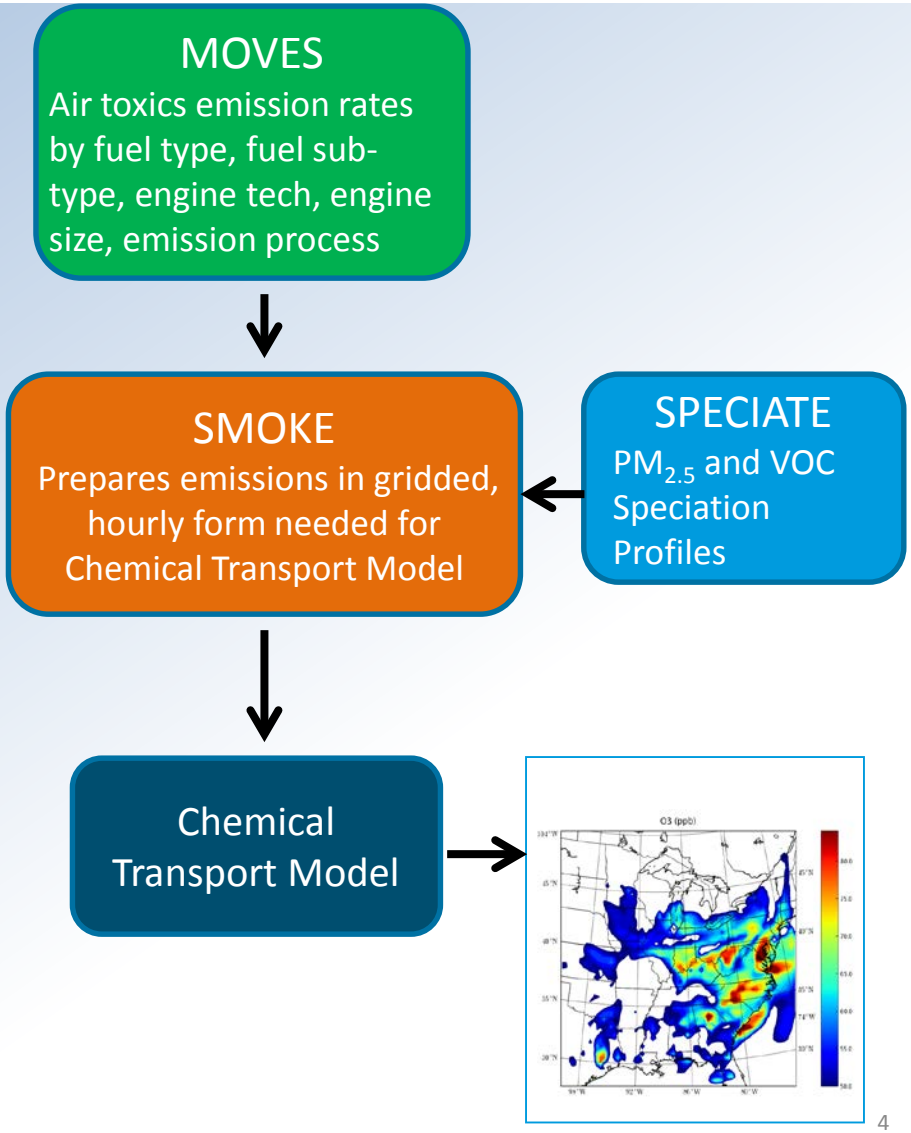
- Motor Vehicle Emission Simulator
- Current release - MOVES2014, July 2014 (updated October 2014)
  - NONROAD added to the model
- Nonroad air toxics previously estimated from volatile organic compounds (VOCs) and PM in NONROAD2008 and post-processing with the National Mobile Inventory Model (NMIM)
- Nonroad toxics will be added to MOVES2014a
  - VOCs including benzene, formaldehyde, acrolein, etc.
  - Polycyclic aromatic hydrocarbons (PAHs) (gaseous and particle, including naphthalene)
  - Metals (e.g. mercury, chromium IV)
  - Dioxin/Furans (17 congeners)
- New speciation profiles of nonroad exhaust emissions

Motivation for Updating Nonroad Air Toxics

- Current nonroad toxics modeling is outdated and data is not well characterized
  - Do 2-stroke or 4-stroke engines have different exhaust composition?
  - Does ethanol in fuel matter?
  - Do diesel emission standards (i.e. control Tiers) change the composition of engine exhaust emissions?
  - Do nonroad engines have an exhaust composition similar to onroad engines?
- Nonroad inventory is expected to become a larger part of the picture with onroad control programs and high rates of growth

Nonroad Speciation using MOVES2014

- Allows differentiation in VOC speciation profiles by:
  - Engine Technology
    - (e.g. stroke, engine Tier)
  - Engine size
    - (e.g. small and large horsepower)
  - Fuel Type
    - (gasoline, diesel, CNG, LPG)
  - Fuel Sub-Type
    - (E0, E10)
  - Emission process
    - Exhaust (composite)
    - Evaporative - vapor venting, refueling, permeation
    - Crankcase
- Speciation profiles from SPECIATE 4.4
  - http://www.epa.gov/ttn/chief/software/speciate/index.html



Modeling Air Toxics

- Two applications of the profiles
  - Toxics estimated within MOVES2014a
  - Speciation for air quality modeling occurs in SMOKE
- Gaseous VOCs
  - Toxic/VOC fractions
    - Based on VOC speciation profiles
- PAHs
  - PAH/VOC ratios for gas-phase PAHs
  - PAH/PM2.5 ratios for particle-phase PAHs
- Dioxins, furans, metals
  - Emission rates applied to fuel consumption

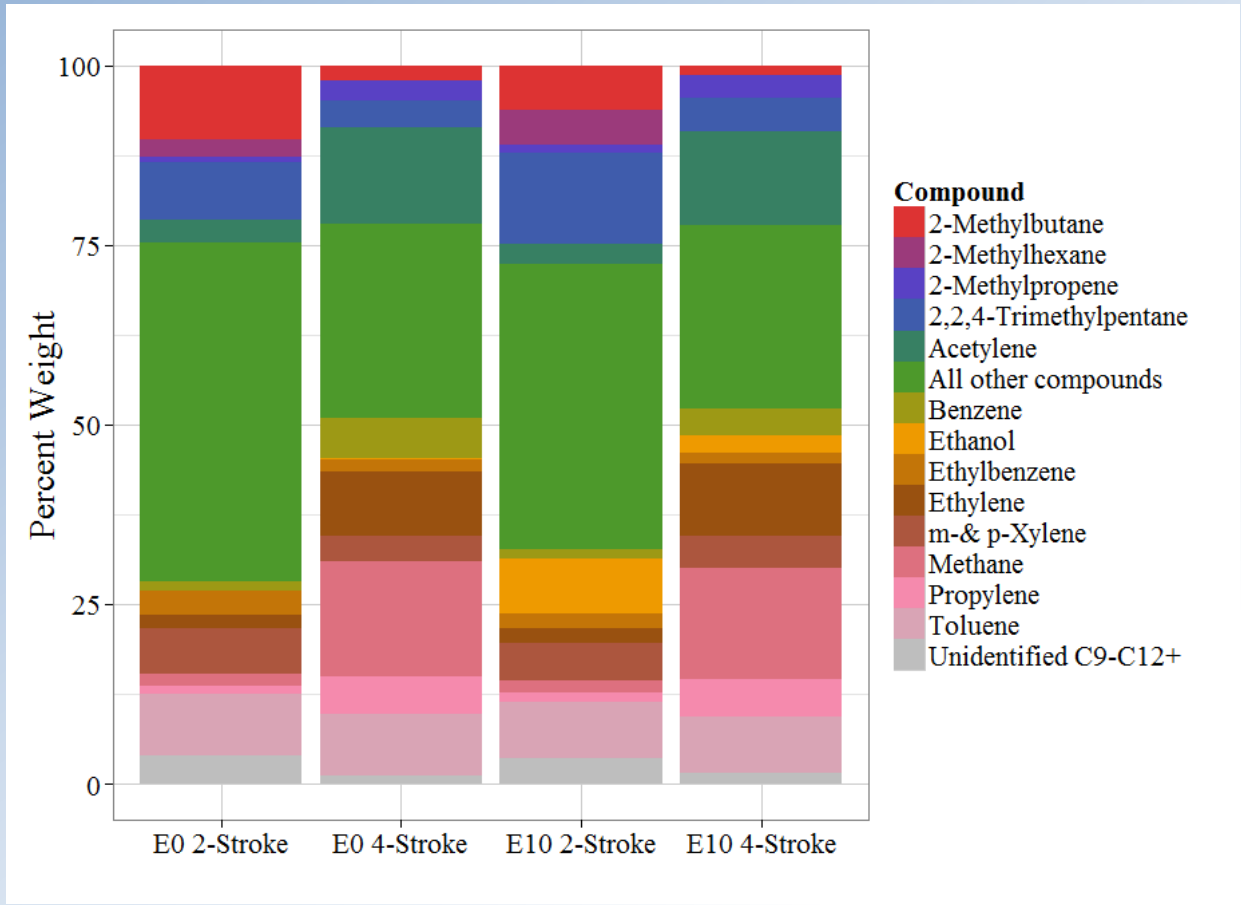
Developing TOG Speciation Profiles

- Two EPA test programs, contracted to SwRI
  - Spark-Ignition (SI) engines and equipment [1]
    - 4-stroke engines - mowers, riding mowers, generators, and a blower
    - 2-stroke engines - all-terrain vehicles and nonroad motor cycles
    - E0 and E10 like fuels
    - Paraffins, olefins, aromatics, alcohols, and methane speciation (GC-FID)
    - Aldehyde and ketone speciation (HPLC)
  - Compression-Ignition (CI) engines [2,3]
    - Construction engines and equipment, forklift truck, and an agricultural tractor
    - Similar compounds and analysis

Speciation Profiles for SPECIATE4.5

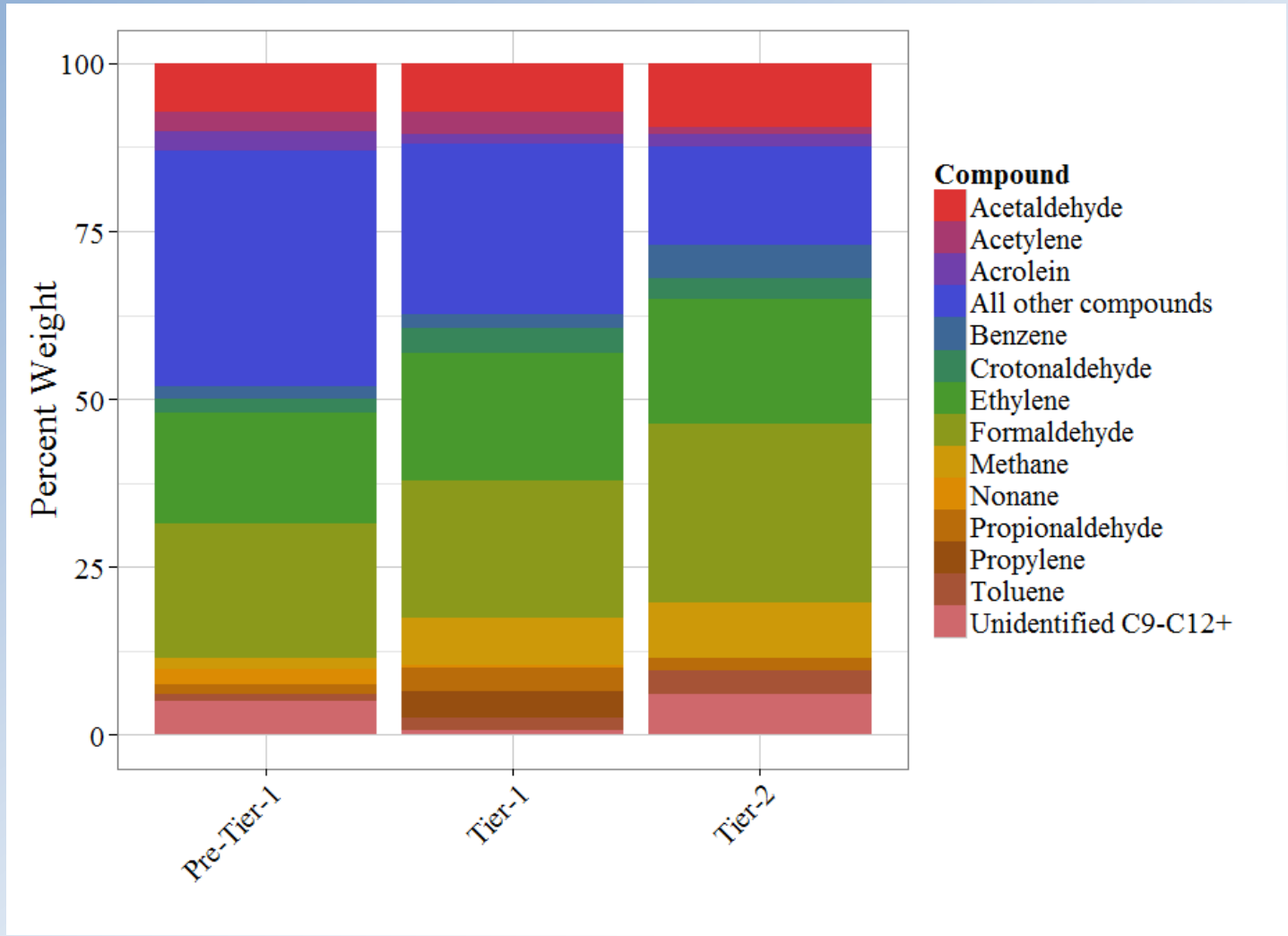
- 2-stroke E0 (Spark-Ignition Exhaust Emissions from 2-stroke off-road engines - Non-oxygenated gasoline)
- 2-stroke E10 (Spark-Ignition Exhaust Emissions from 2-stroke off-road engines - E10 ethanol gasoline)
- 4-stroke E0 (Spark-Ignition Exhaust Emissions from 4-stroke off-road engines - Non-oxygenated gasoline)
- 4-stoke E10 (Spark-Ignition Exhaust Emissions from 4-stroke off-road engines - E10 ethanol gasoline)
- Pre-Tier 1 Diesels (Diesel Exhaust Emissions from Pre-Tier 1 Off-road Engines)
- Tier 1 Diesels (Diesel Exhaust Emissions from Tier 1 Off-road Engines)
- Tier 2 Diesels (Diesel Exhaust Emissions from Tier 2 Off-road Engines)

Compounds which are the largest contributors to spark-ignition profiles



Reichle, L. et al. 2015 [4]

Compounds which are the largest contributors to compression-ignition profiles



Reichle, L. et al. 2015 [4]

Comparing VOC Reactivity and Ozone Formation Between Speciation Profiles

- Maximum Incremental Reactivity of VOC used to determine ozone formation potential
- Engine and fuel type changes VOC reactivity
- Ozone formation may be different between onroad and nonroad engines

Engine	Fuel	ΔReactivity w/ [EtOH] (%diff)	ΔReactivity Nonroad vs. Onroad Profiles (%diff)
4-stroke	E0	7.6	1.2
	E10	8.2	11.6
2-stroke	E0	2.3	0.6
	E10	2.3	0.4

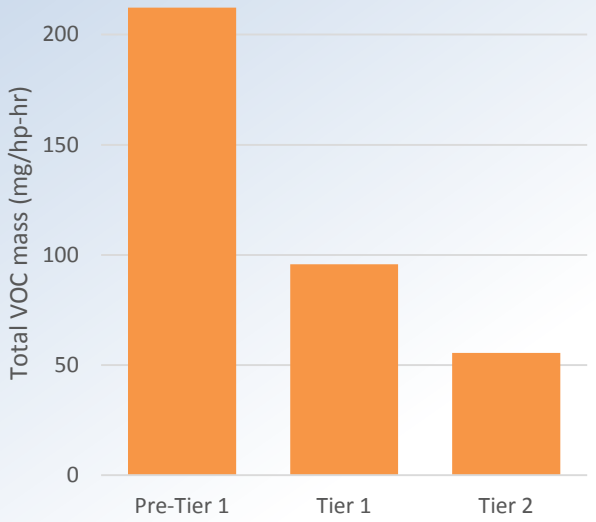
Reichle, L. et al. 2015 [4]

Comparing VOC Reactivity and Ozone Formation Between Speciation Profiles

- While ozone forming potential goes up with Tier, overall HC goes down between Tiers (lowering overall ozone)

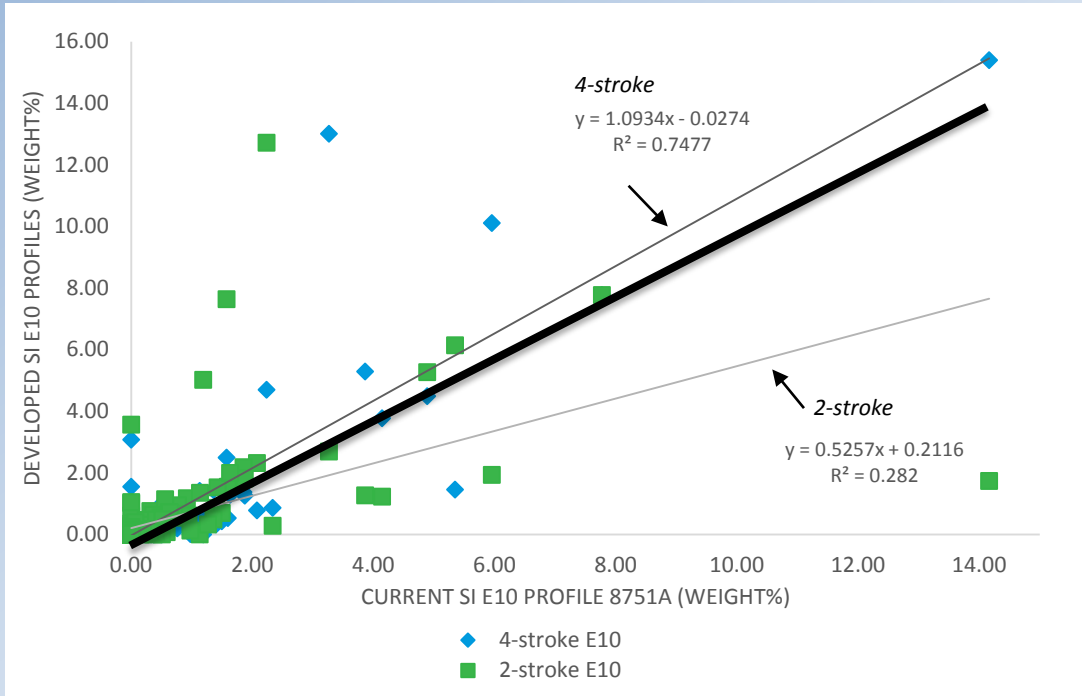
Engine	Fuel	ΔReactivity with Tier* (%diff)	ΔReactivity Onroad:Nonroad Profiles (%diff)
Tier 1	Diesel	2.8	8.2
Tier 2	Diesel	3.3	11.3

**Compared to a pre-Tier 1 baseline*



Reichle, L. et al. 2015 [4]

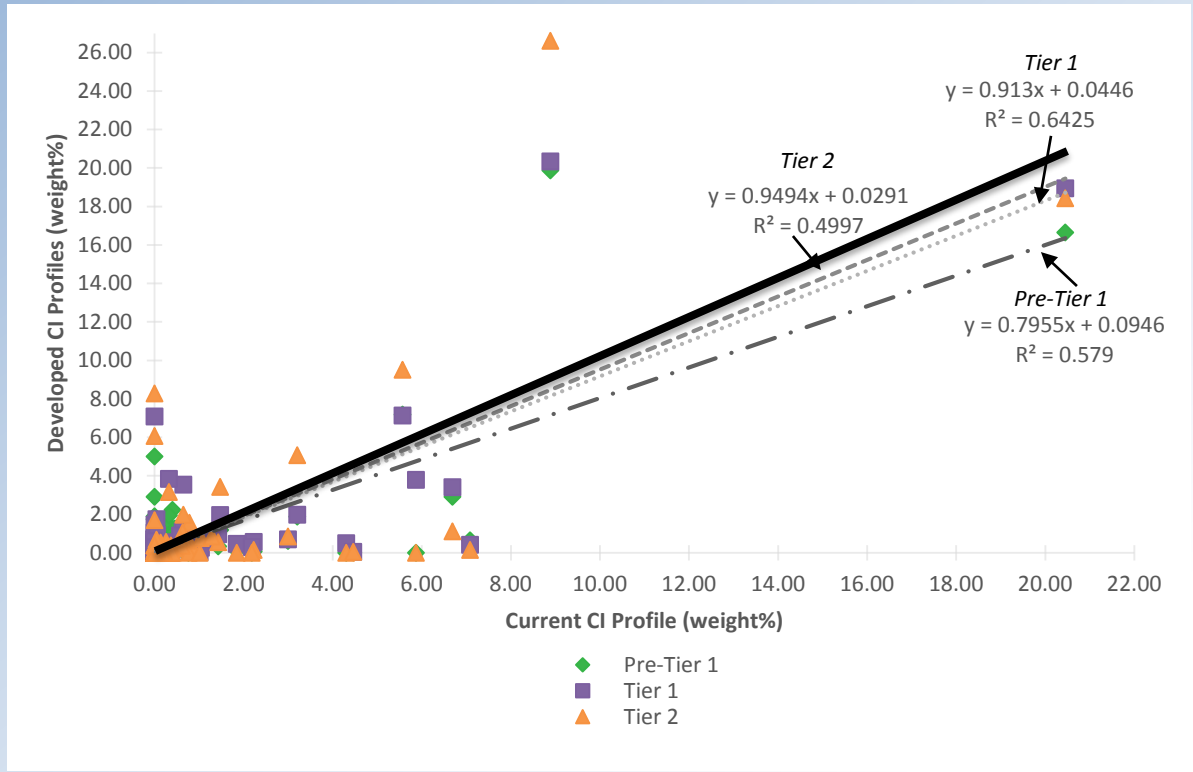
Comparison of onroad pre-Tier 2 gasoline vehicle E10 profile to nonroad SI E10 profiles



Weight percents represent the contribution of an individual species to the total of organic gases

Reichle, L. et al. 2015 [4]

Comparison of onroad pre-2007 diesel profile 8774 to nonroad CI profiles



Reichle, L. et al. 2015 [4]

VOC Toxics

- Gasoline engines
  - EPA SI test program
- Diesel engine
  - Tiers 0 – 3, Tier 4 < 56 kW
    - EPA CI test program
  - Tier 4 ≥ 56 kW
    - Advanced Collaborative Emissions Study (ACES) [5] of onroad diesel vehicles
- CNG engines
  - Uncontrolled MY2000 CNG Transit bus (CARB) [6]
- LPG engines
  - 3 LDV fueled with LPG [7]

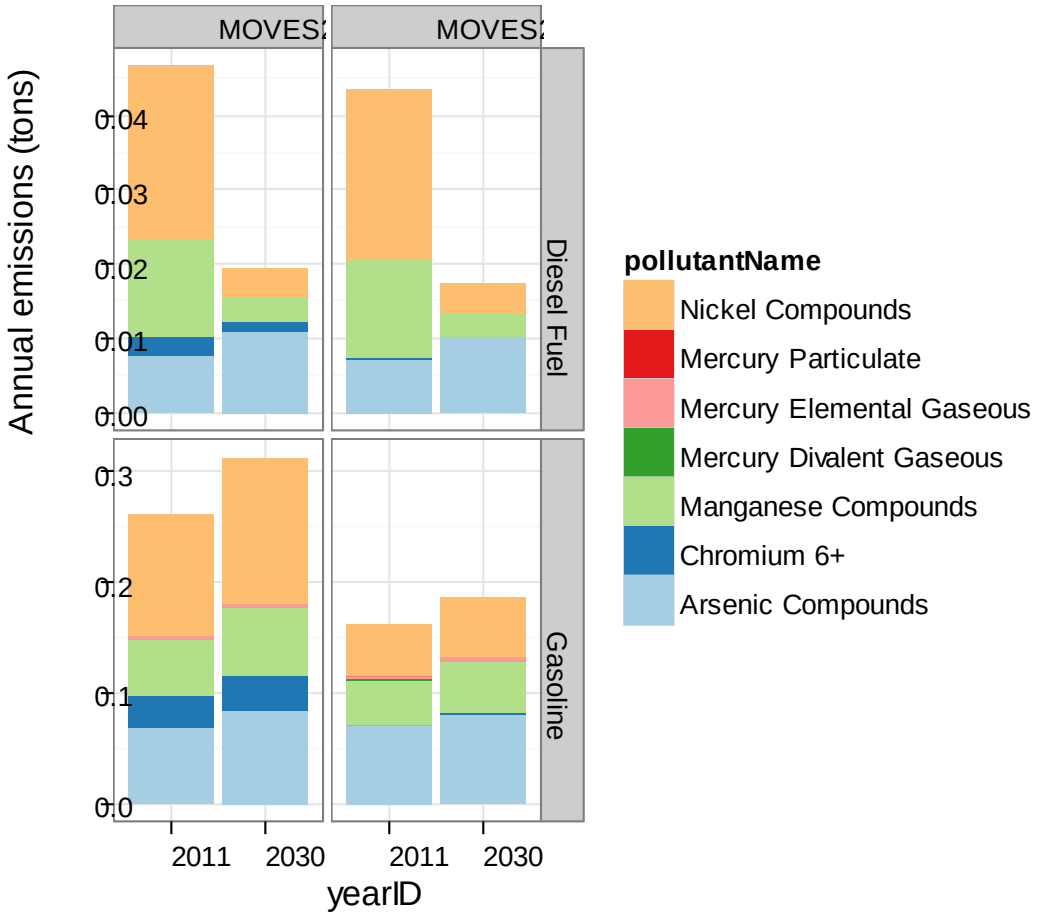
Pollutants	
Benzene	Hexane
Formaldehyde	Propionaldehyde
Acetaldehyde	Styrene
Acrolein	Toluene
1,3-butadiene	Xylene
Ethanol	Naphthalene
2,24-Trimethylpentane	MTBE
Ethyl Benzene	

Polycyclic Aromatic Hydrocarbons

- 16 PAH compounds in model
  - Gasoline vehicles
    - Emission fractions from Kansas City Light-Duty Vehicle Emissions Study [8] (cars and light trucks, model years 1968-2004)
    - 99 vehicles
  - Diesel
    - Tiers 0 – 3, Tier 4 < 56 kW – EPA CI test program
    - Tier 4 ≥ 56 kW – ACES
  - CNG and LPG
    - Based on MY2000 CNG transit bus data (CARB) [9]

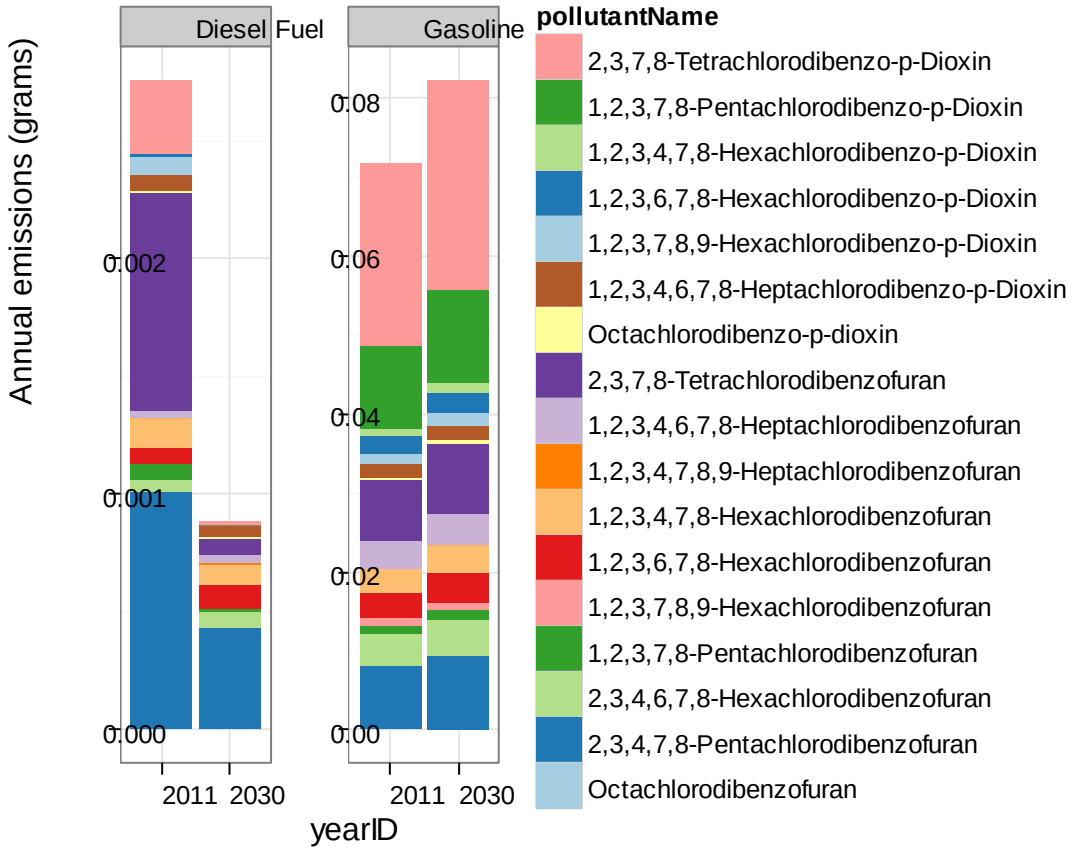
Metals

- Fuel-based emission factors estimated from onroad studies
- Manganese and nickel
  - Gasoline from Kansas City Vehicle Emissions Study
  - Earlier diesels from CRC E-75
  - Advanced diesels from ACES
- Hexavalent chromium
  - Analysis of EPA Ann Arbor test samples at University of Wisconsin
- Arsenic
  - 2000/2001 tunnel study data
- Mercury
  - Data from EPA/ORD National Exposure Research Laboratory



Dioxins

- Fuel-based emission factors estimated from onroad studies
- MOVES2014 estimates emissions for 17 dioxin and furan congeners.
  - Emissions estimated as toxic equivalents (TEQs)
    - MOVES2010b reported mass emissions
  - Gasoline vehicle EFs from 1998 API-sponsored tunnel study
  - Diesel EFs from EPA Ann Arbor testing



Limitations and Data Needs

- Limited number of test programs on full nonroad engine exhaust speciation
- Limited sample size and low number of tests
- Lack of data on diesel engines with varying power ratings within a control tier
- Limited types of nonroad engines with speciated air toxics data
  - Need outboard and stern-drive marine engines,
  - SI engines with catalytic converters,
  - CI engines meeting Tier 3 and 4 U.S. EPA standards,
  - Engines running on liquefied petroleum gas, and
  - Engines running on compressed natural gas.

Summary

- MOVES2014a will include nonroad air toxics for the first time
- MOVES2014a will be used for the 2014 National Emissions Inventory
- Nonroad speciation data incorporated into MOVES2014
  - 2-stroke and 4-stroke SI engine and E0 and E10 fuel differences have an effect on inventories and air quality modeling
    - Using separate profiles for these engines is critical
  - New profiles for nonroad diesel engines are different from onroad profiles
  - Will improve AQ modeling of nonroad diesel engines
  - PAHs updated from CI test program
  - Onroad surrogates used for the remainder of PAHs, dioxins, and metals using data from recent test programs
- More speciated VOC and PM data from nonroad engines is needed

References

- 1- U.S. Environmental Protection Agency. 2014. Broad Emissions Testing Support for In-Use Vehicles and Engines. EPA-420-R-14-029.
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- 4- Lawrence J. Reichle, Rich Cook, Catherine A. Yanca & Darrell B. Sonntag (2015): Development of Organic Gas Exhaust Speciation Profiles for Nonroad Spark Ignition and Compression Ignition Engines and Equipment, Journal of the Air & Waste Management Association, DOI: 10.1080/10962247.2015.1020118
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Extra Slides

Four-stroke nonroad spark-ignition test equipment and engines without exhaust catalysts

Type	Year[a]	Equipment Make/Model	Engine Make/Model	E0 Tests[b]	E10 Tests[c]
22" Mower	2006	MTD 11A-084F229	Briggs & Stratton 10T502158	1	1
Mower	2007	Honda HRC 2163HXA	Honda GXV160	1	1
Riding Mower	2007	MTD 638RL Yard Machine 13A1762F229	Techumseh OV 358 EA	1	1
Riding Mower	2007	Snapper S150X	Kawasaki FH641V-ES25-R	1	1
Generator	2004	Briggs & Stratton Elite Series 6200 30386	Briggs & Stratton 1015499427	1	1
Generator	2006	Honda EB11000	Honda GX620KI	1	1
Blower	2007	Makita BHX2500	Makita EHO25	2	2

[a] California certification year

[b] E0-like fuels include ARB E0, CERT2

[c] E10 fuels include ARB E10-7, ARB E10-10, EPA-E10

Two-stroke nonroad spark-ignition recreational equipment engines without exhaust catalysts

Type	Model Year	Engine Make/Model	Oil Lubrication	E0 Tests[a]	E10 Tests[b]
NRMC	2007	Honda CR125	Pre-mixed	1	2
NRMC	2002	Kawasaki KX250	Pre-mixed	1	2
ATV	2006	Yamaha Blaster	Injected	1	3
ATV	2005	Polaris Trailblazer	Injected	1	2

[a] E0-like fuel is CERT1

[b] E10 fuels include ARB E10-7, ARB E10-10

Nonroad compression-ignition test engines

Intended Application	Manufacturer	Year/Model	Tier	Horse-power	Transient Tests by Cycle	
					FTP	BHL
motor grader	Deere	1996 6068T	0	160	4	2
forklift truck	Kubota	1999 V2203E	1	50	4	4
telescoping boom excavator	Cummins	2001 ISB190	1	194	4	2
excavator	Cummins	1997 M11C	1	270	4	2
construction equipment	Cummins	1999 QSL9	1	330	4	4
rubber-tired loader	Caterpillar	1999 3408	1	480	4	4
agricultural tractor	Caterpillar	2001 3196	2	420	4	2

Spark-ignition test fuel properties

Test fuel	Fuel description	Ethanol (Wt%)	RVP (psi)	T50 (deg F)	T90 (deg F)	Aromatics (Vol%)	Olefins (Vol%)	Saturates (Vol%)	Benzene (Wt%)	Sulfur (ppm)
ARB E0	Non-oxygenated gasoline	<0.2	7.2	228	304	31.8	1.2	67.0	0.3	<10
CERT1	Federal Certification, non-oxygenated	<0.1	9.0	224	309	31.5	4.3	64.2	0.7[a]	2.3
CERT2	Federal Certification, non-oxygenated	NP	9.2	223	318	27.9	0.4	71.7	NR	3.2
ARB E10-7a	10% ethanol, RVP 7 psi	9.7	7.0	214	315	22.1	5.2	63.6	1	<10
ARB E10-7b	10% ethanol, RVP 7 psi	9.9	6.8	213	314	24.9	5.4	60.3	0.7[a]	2.8
ARB E10-10	10% ethanol, RVP 10 psi by adding butane to ARB E10-7	9.7	9.8	207	313	22.7	5.7	62.6	0.7[a]	4.6
EPA-E10	10% ethanol, RVP 9 psi	9.4	9.0	211	319	24.7	8.6	66.7	0.7	21.9

NP = Not performed for this fuel

NR = Not reported

[a] Benzene content reported as volume percentage

Compression-ignition test fuel properties

Test fuel	Type-2D	Nonroad-2D
Sulfur, ppm	390	2570
Cetane Number	48.0	46.1
T50 (deg F)	505	511
T90 (deg F)	618	613
Total Aromatics (Vol%)	32.15	31.9
Saturates (Vol%)	66.05	67.45
Specific Gravity	0.8444	0.8507
API Gravity	36.1	34.8