# Assessment of a Candidate Metric for a New Paradigm of In-Use NOx Emissions Compliance for Heavy-duty On-Highway Engines

Matthew Spears, EMA

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# Key Points

- Goals
  - Cost-effectively achieve additional NOx reductions
  - Focus on what is happening in-use
- This presentation is a status update on work in progress
  - Exploratory work; more work needs to be done
  - EMA has drawn no conclusions at this time
  - EMA is interested in feedback and any new ideas



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# Background on HDOH Low-NOx

- In 2016 SCAQMD petitioned EPA to set new standards
- CARB initiated technical research and a series of workshops to develop an Omnibus Rulemaking
- In 2018 EPA announced a Cleaner Trucks Initiative
- EMA is engaged with the agencies, NGOs and has funded a multi-million dollar, multi-year program to sponsor technical research
  - WVU, Ramboll, SwRI

# EMA’s Goals

- Cost-effectively deliver additional in-use NOx reductions from heavy-duty engines
- Maintain or improve product reliability and durability
- Move from prescriptive lab and PEMS procedures and other compliance requirements to performance-based on-board compliance assessments
- Goals for a new paradigm of in-use compliance
  - Leverage on-board sensing, telematics and big data analytics
  - Cover all engine operation in some way—some operation might be unique



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# Focus on In-Use

- Peak SCR NOx reduction efficiency currently is ~98%
  - Exhaust gas and SCR catalyst temperatures are duty cycle dependent
  - SCR hardware and controls must function as designed
- Due to PEMS capabilities and the costs and effort required to install PEMS to comply with the current HDIUT program, today's compliance approach is only able to sample a very small fraction of engines; might not fully reflect in-use
- Cost-effectively aggregating NOx from a large number of in-use vehicles should better relate compliance to inventory

# Preliminary Concepts for a New Paradigm

- Compliance
  - Manufacturer compliance assessed annually, based on aggregate emissions
  - Include an in-use averaging, banking and trading program
- Data flow
  - Each engine's electronics would continuously update its in-use metric data for periodic wireless broadcast to the emissions certificate holder
  - Certificate holder would aggregate data and submit annual compliance reports
  - More frequent reporting could be triggered, based on data
- Oversight
  - Periodic audit processes could be defined
- Remedial action
  - Annual in-use credit balance adjustments
  - Prolonged credit deficits could trigger additional testing and remedial action
  - Complementary in-use I/M could enhance timely maintenance and repair

# A New In-Use Paradigm Requires a New Metric

- Some disadvantages of NTE and WBW metrics
  - Brake-specific metrics approach infinite values at low load
  - NTE and WBW metrics fall apart when applied to all operation
    - There always will be some corner-case duty cycle, where insufficient exhaust heat precludes DEF dosing without forming deposits that decrease SCR efficiency
    - Analysis shows that this leads to a de facto engine-out NOx standard
    - That is why the Euro VI WBW approach mandates prescribed driving

- Goals of a new metric
  - Keep it simple
  - Prevent asymptotic metric behavior at low load
  - Cover all operation in some way—some operation might be unique
  - Facilitate data aggregation across a large sample size
  - Collect additional data to separate emissions by duty cycle

# High-level Concepts for a New Metric

- Sum-over-Sum
  - See EMA's 2018 CRC presentation for details
  - Numerator is the mass emitted—inventory
  - Denominator normalizes; likely fuel- or CO2-based
  - Simple to aggregate across an engine family
- If a Sum-over-Sum metric indicates higher emissions, utilize secondary analyses to examine why
- Separating emissions by in-use duty cycle is challenging
  - Should reflect expected engine and aftertreatment response to duty cycles
  - SCR efficiency depends upon the time-history of thermal energy inputs and outputs of the exhaust and aftertreatment system

# How to Introduce a Thermal Time-History into a Secondary Analysis?

- Preliminary concepts
  - Introduce a time-history within the normalizing denominator
  - Start simple and add complexity only as necessary
  - Heat transfer: from exhaust gas to DEF and catalyst, then to ambient
  - Discretization of the differential heat equation leads to an equation similar to an exponentially-weighted moving average ("EWMA")
  - Fuel ($CO_2$) rate can represent the potential for thermal energy input
  - Time constant, $\tau$, seems to be on the order of 60 s (See Appendix)

Heat: $T_{new} = T_{old} + (T_{oldadjacent} - T_{old}) * \Delta t/\tau$

EWMA: $CO_{2ewmanew} = CO_{2ewmaold} + (CO_{2inew} - CO_{2ewmaold}) * \alpha$

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# Observations and Next Steps

- EWMA secondary analysis seems to separate duty cycles
  - Low load, moderate load, high load after low load…
- Next steps
  - Incorporate ambient temperature into secondary analyses
  - Investigate distributional assumptions to strengthen statistics
    - NOx data appears log-normal, might be log-skew-normal
  - Analyze larger datasets and aggregate data across many engines
  - Consider a unique emissions rate-based metric for idle
    - Like CARB's clean idle standard
- EMA invites feedback and additional ideas



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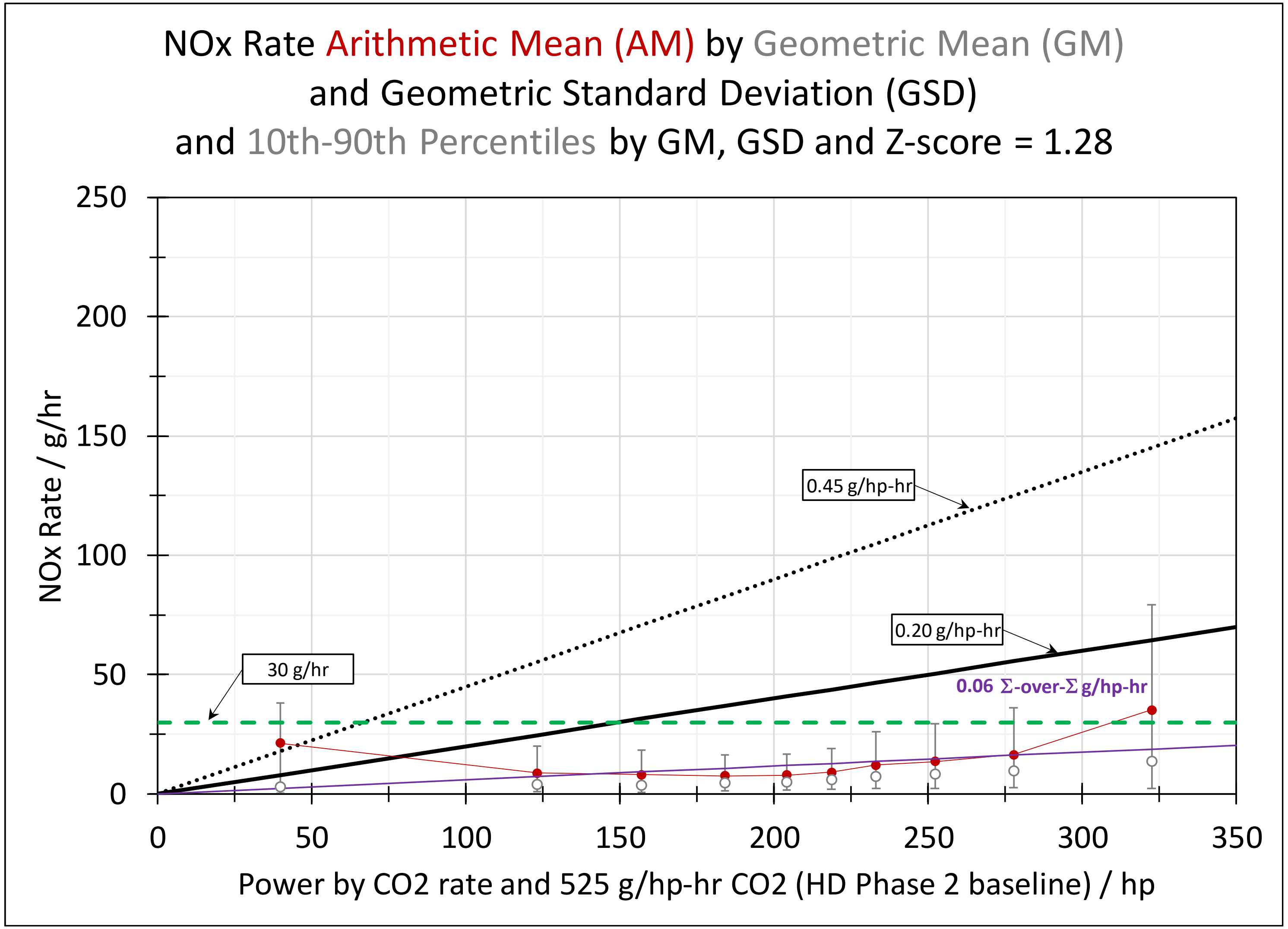
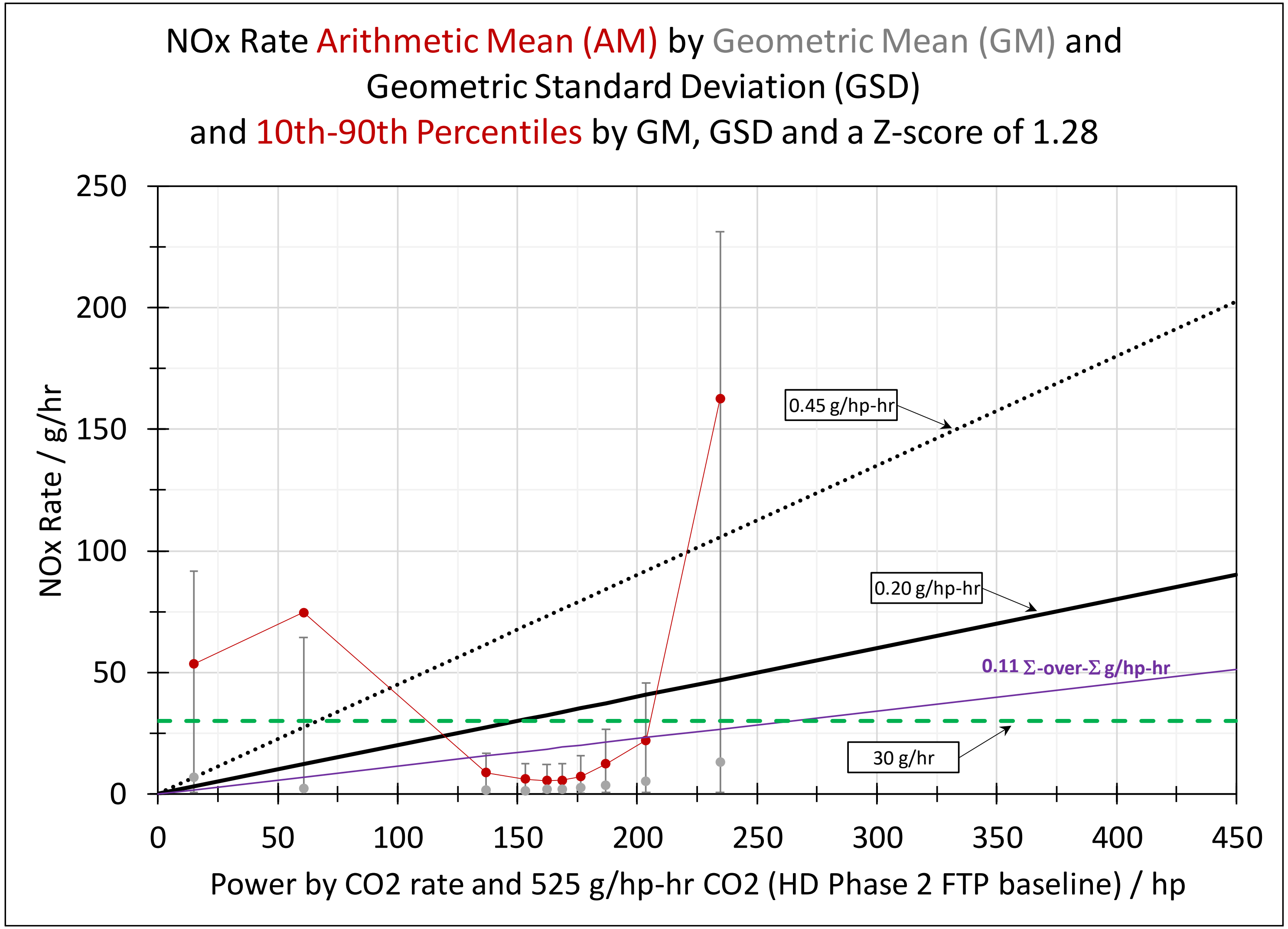
# Examples of In-Use Tractor Data

- Description of the following three charts
  - These are **NOT** metric charts; they're secondary analyses
  - Data are from single HDIUT shift-days; not aggregated across engines
  - 1Hz NOx mass rate versus $CO_{2ewma}$ mass rate, $\tau = 60s$
  - $CO_{2ewma}$ rate converted to "Power" using constant 525 gCO2/hp-hr
    - This value is only used as a placeholder for a characteristic engine family-specific value
  - Brake-specific NOx lines are plotted only for reference to a familiar historical metric
  - Same for CARB clean idle standard (30 g/hr)
  - Data was binned into 10% data increments; same amount of time per bin
  - NOx rate data appears log-normal within bins and overall
    - Log-normal statistics used to present arithmetic means
    - 10th and 90th percentile values based on log-normal statistics
  - To aggregate this analysis across different engine ratings, axes ultimately would be replaced by flow-weighted average concentration and % of maximum power
    - These only differ by dividing the axes presented by a constant
    - Horizontal axis scaling factor would be engine sub-family maximum mapped power (per 40 CFR Part 1065); vertical would be exhaust flow rate at maximum mapped power.

# HDIUT Example 1
# Tractor (50 mph ave, 4% idle time, 9% off, 32-53F)



# HDIUT Example 2
# Tractor (48 mph ave, 12% idle time, 0% off, 52-66F)

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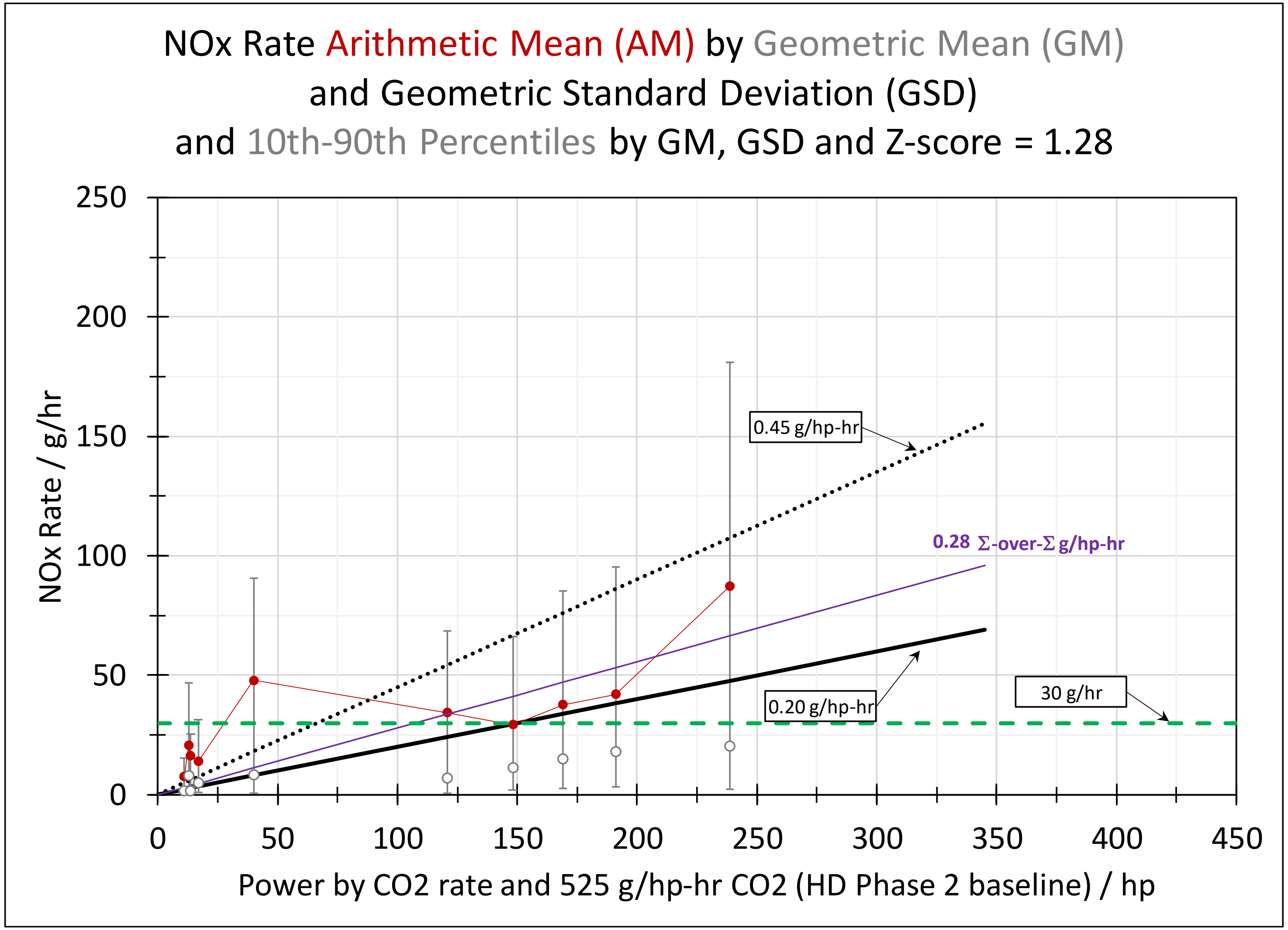
# HDIUT Example 3
# Tractor (27 mph ave, 23% idle time, 19% off, 62-97F)



# Appendix: $\tau$

Heat: $T_{new} = T_{old} + (T_{oldadjacent} - T_{old})*\Delta t/\tau$

EWMA: $CO_{2ewmanew} = CO_{2ewmaold} + (CO_{2inew} - CO_{2ewmaold})*\alpha$

$\alpha$ is equal to $\Delta t/\tau$, for $\alpha$ not "too close" to 1

$\tau = C_m*m*l/(k*A)$

$C_m$ = specific heat of material; steel, ceramics = ~600 J/kg*K

$m$ = mass; "1-box" aftertreatment = ~ 65 kg (~ 143 lb)

$l$ = length; average of mass as a single wall = 0.015 m (9/16")

$k$ = thermal conductivity, very rough average = 13 W/m*K

$A$ = surface area; average of mass as a single wall = 0.63 $m^2$

$\tau$ = ~ 71 s; probably within an order of magnitude

$\tau$ (1/$\alpha$) that looked best "by eye" for separating duty cycles = 60 s

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