Real-World Heavy Duty Diesel Vehicle Emissions in Utah During the Summer

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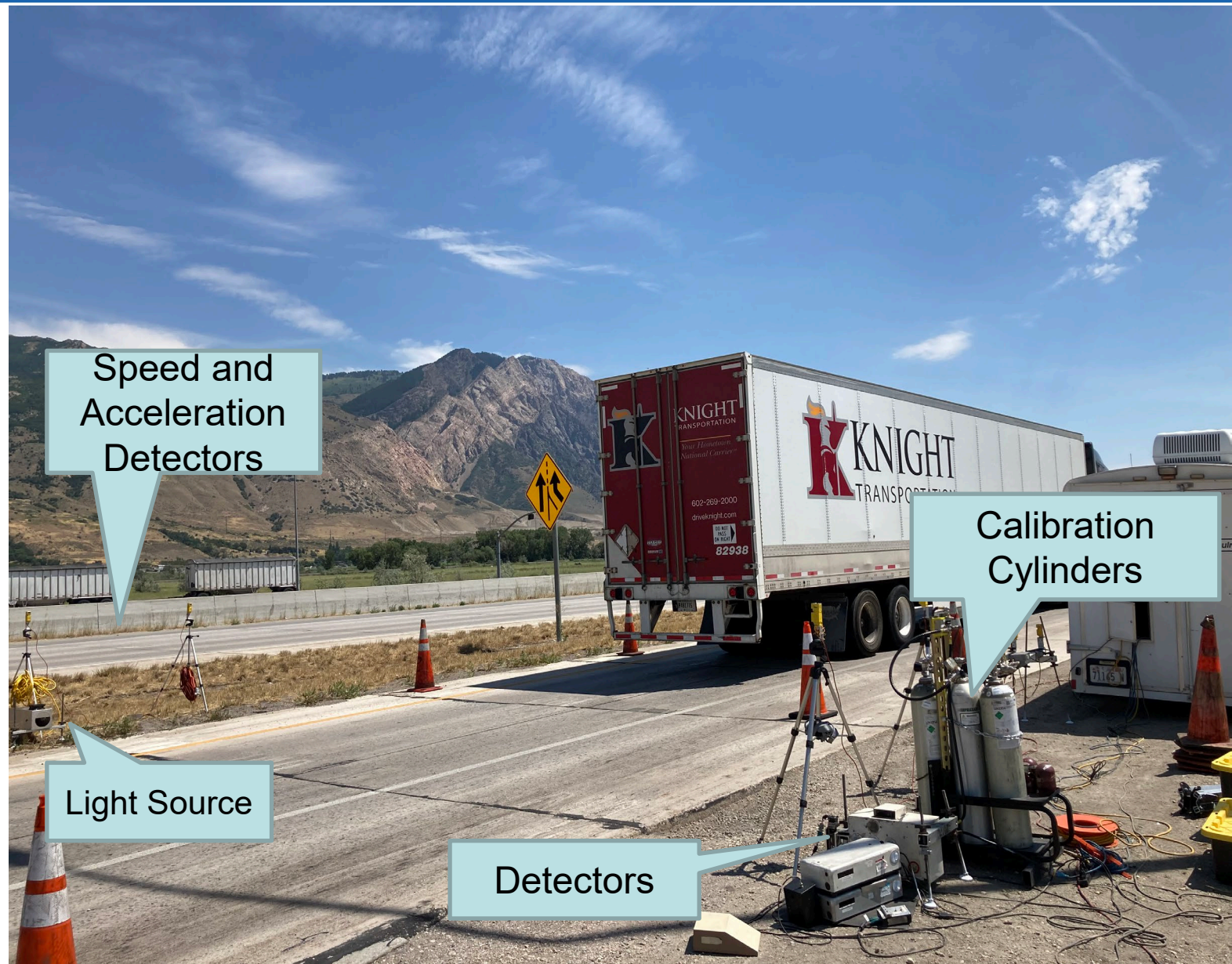
FEAT Overview

- Fuel
- Efficiency
- Automobile
- Test

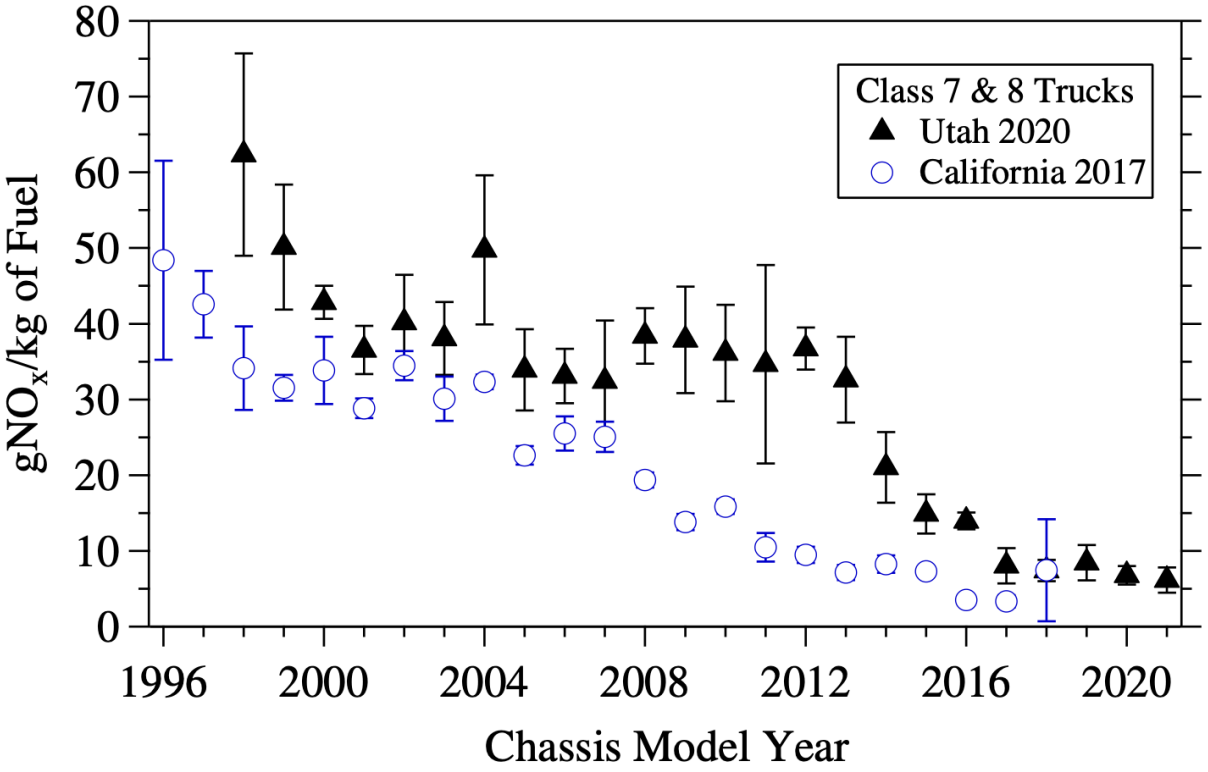
- Developed by Donald Stedman and Gary A. Bishop, University of Denver

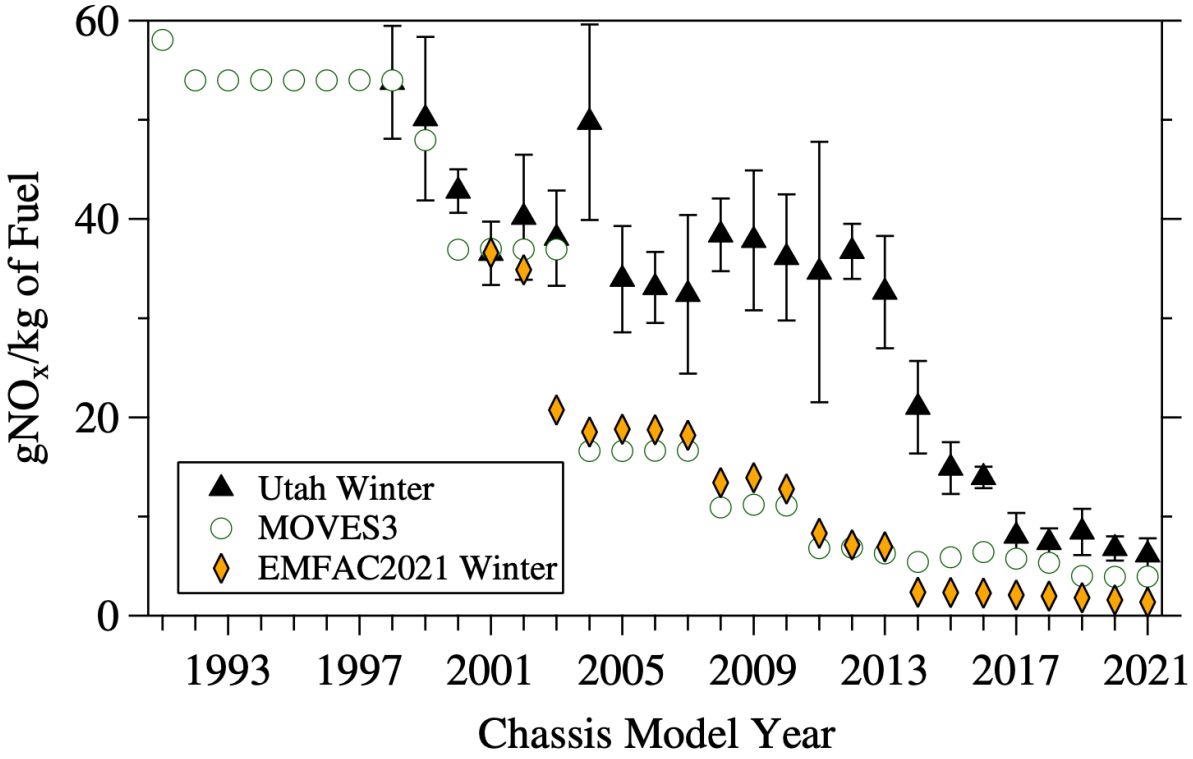
- Pollutants
  - Carbon dioxide (CO_2)
  - Carbon monoxide (CO)
  - Gaseous hydrocarbons (HC)
  - **Nitrogen oxides ($NO+NO_2$)**
  - Ammonia (NH_3)
  - Opacity (IR absorption)

- Vehicle emission rates estimated relative to fuel consumption
  - **$grams_{pollutant}/kilograms_{fuel}$**



FEAT Overview

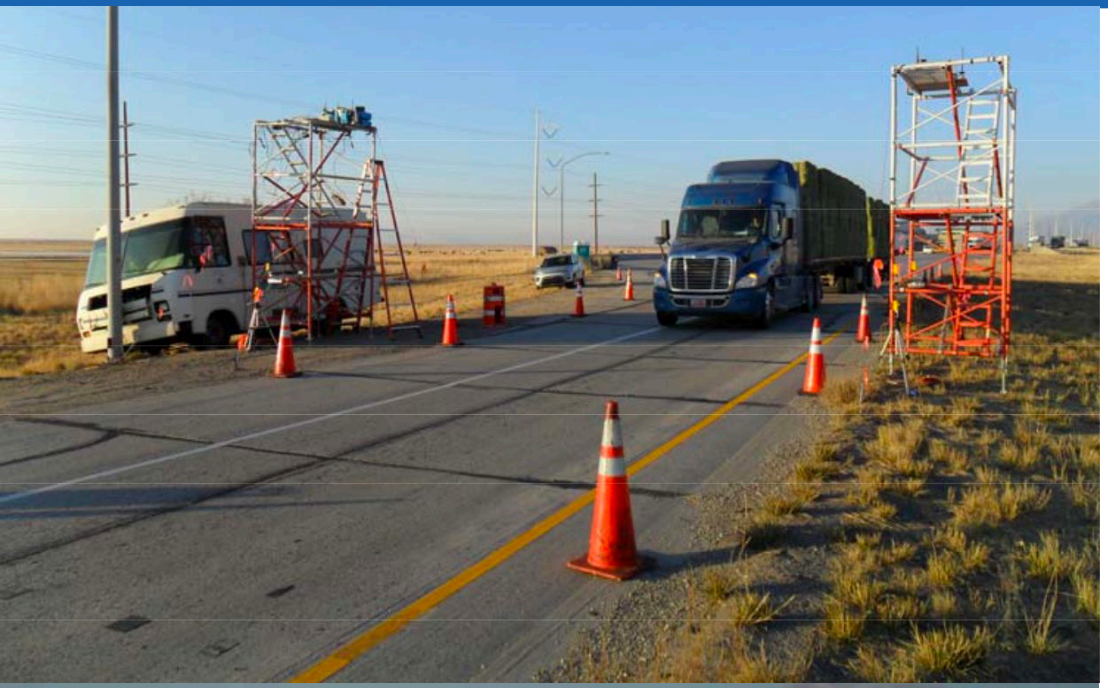




Gary Bishop et al. (2021) observations:

- Heavy Duty (HD) NOx measurements in winter in UT were higher than similar model years measured California.
- HD NOx measurements were higher in UT than MOVES3 and EMFAC 2021 estimates.

High v Low FEAT



	CAMPAIGN		
	Winter 2020		Summer 2023
Dates	12/6/2020- 12/11/2020		7/31/2023-8/1/2023
Temperature	3.6-3.9ºC (38 – 39ºF) (Daily Average)		24.4-32.8ºC (76 – 91ºF) (Hourly Range)
# of Valid Observations	High FEAT	Low FEAT	Low FEAT
	1053	538	1073

Heavy-duty NOx emissions control

- Selective catalytic reduction (SCR) used to meet the US EPA 2010 NOx emissions standards
- Known issues :

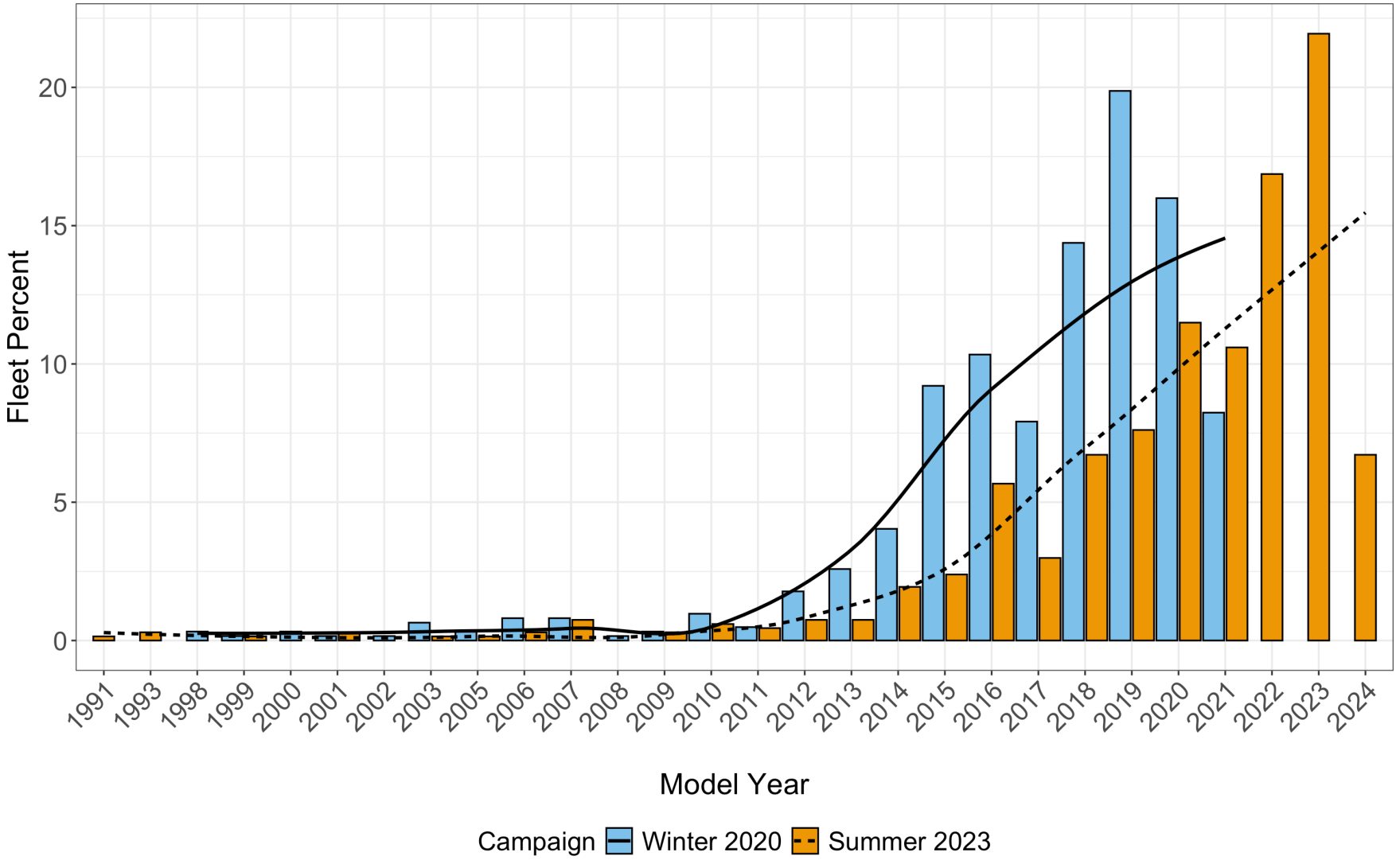
1. **Temperature Sensitivity**
   - Low-load driving cycles have higher NOx emissions due to lower catalyst temperatures (Quiros et al. 2016)
   - Higher NOx emissions observed from heavy-duty trucks at cold ambient temperatures (Wang et al. 2019, Hall et al. 2020, US EPA, 2023)
2. **Catalyst Deterioration**
   - 10-30% increase in NOx emissions in HD diesel trucks with odometer increase of 200,000 kilometers (Lyu et al. 2023)
   - Recall of ~ 500,000 Cummins engines due to deterioration (EPA, 2018)
3. **Tampering**
   - Tampering the SCR can lead to large increase in NOx (24 times, Tian et al. 2024)
   - Limited information on tampering prevalence (Sabisch 2020, Braun et al. 2022)

Questions

- Do HD truck NO_X emissions in Utah differ in Winter and Summer?
- Are Utah HD trucks different than California trucks?
  - Do they have higher NOx in the Summer?
  - Do they have higher deterioration or tampering?
- How to Utah HD truck NO_X compare to MOVES in the summer?

Utah Campaign fleet vehicle age distribution

About ~45% of the both campaign's vehicles were three years old or newer.



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Winter vs Summer NOx emissions in Utah

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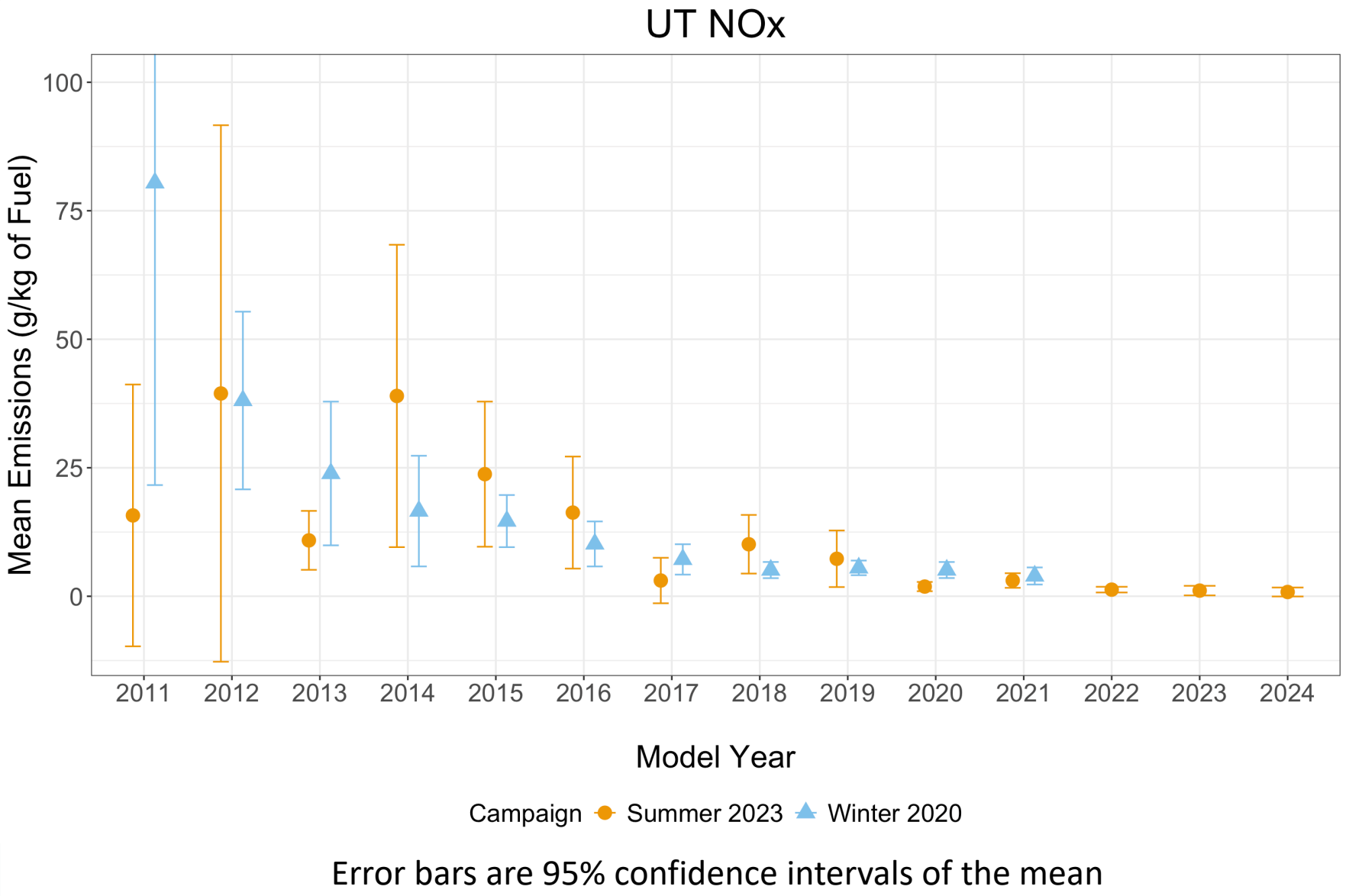
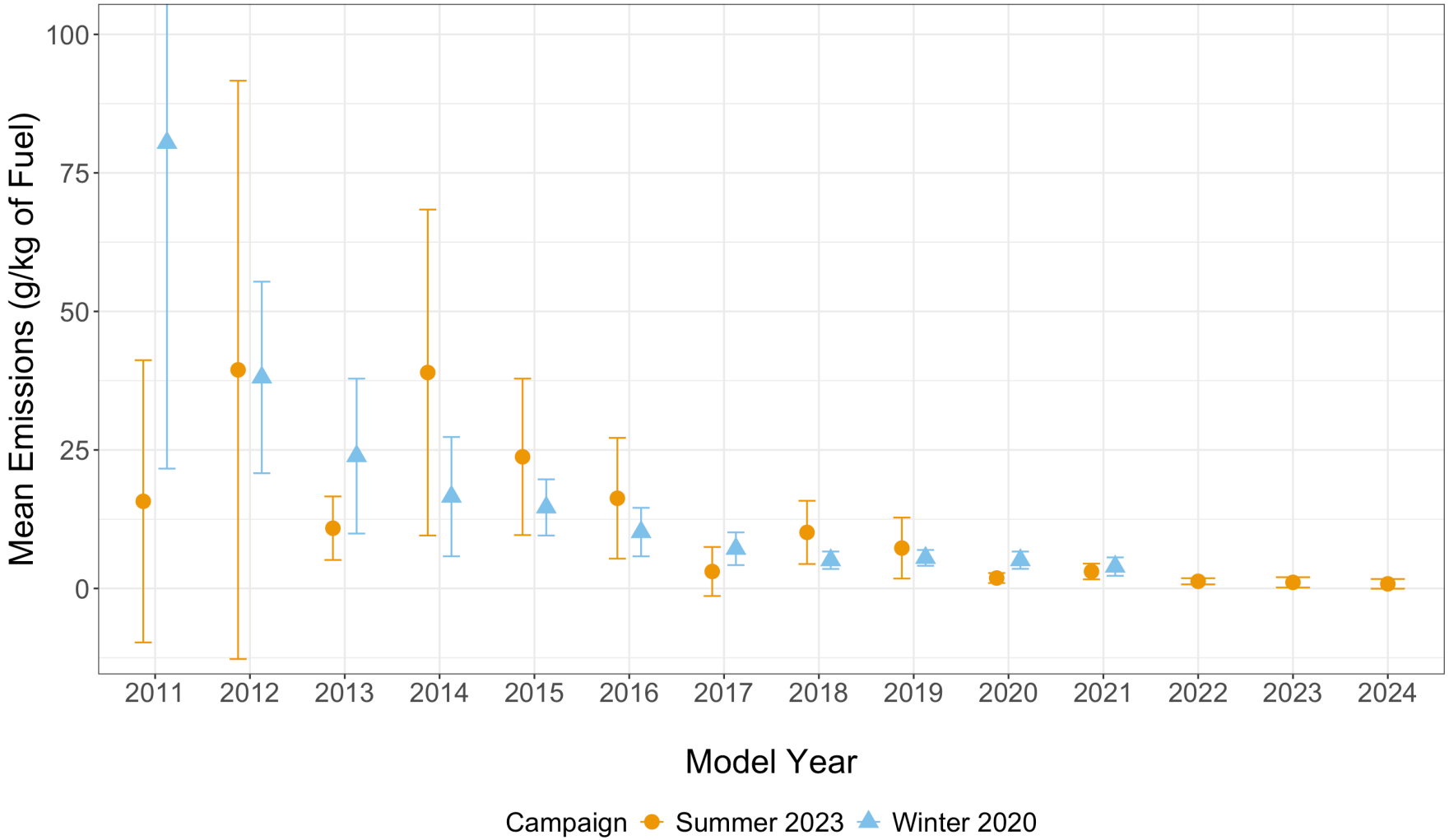


Error bars are 95% confidence intervals of the mean

Winter vs Summer NOx emissions

No consistent differences in NOx by model year
2020 - ↑ temperature ↓ deterioration
2023 - ↓ temperature ↑ deterioration



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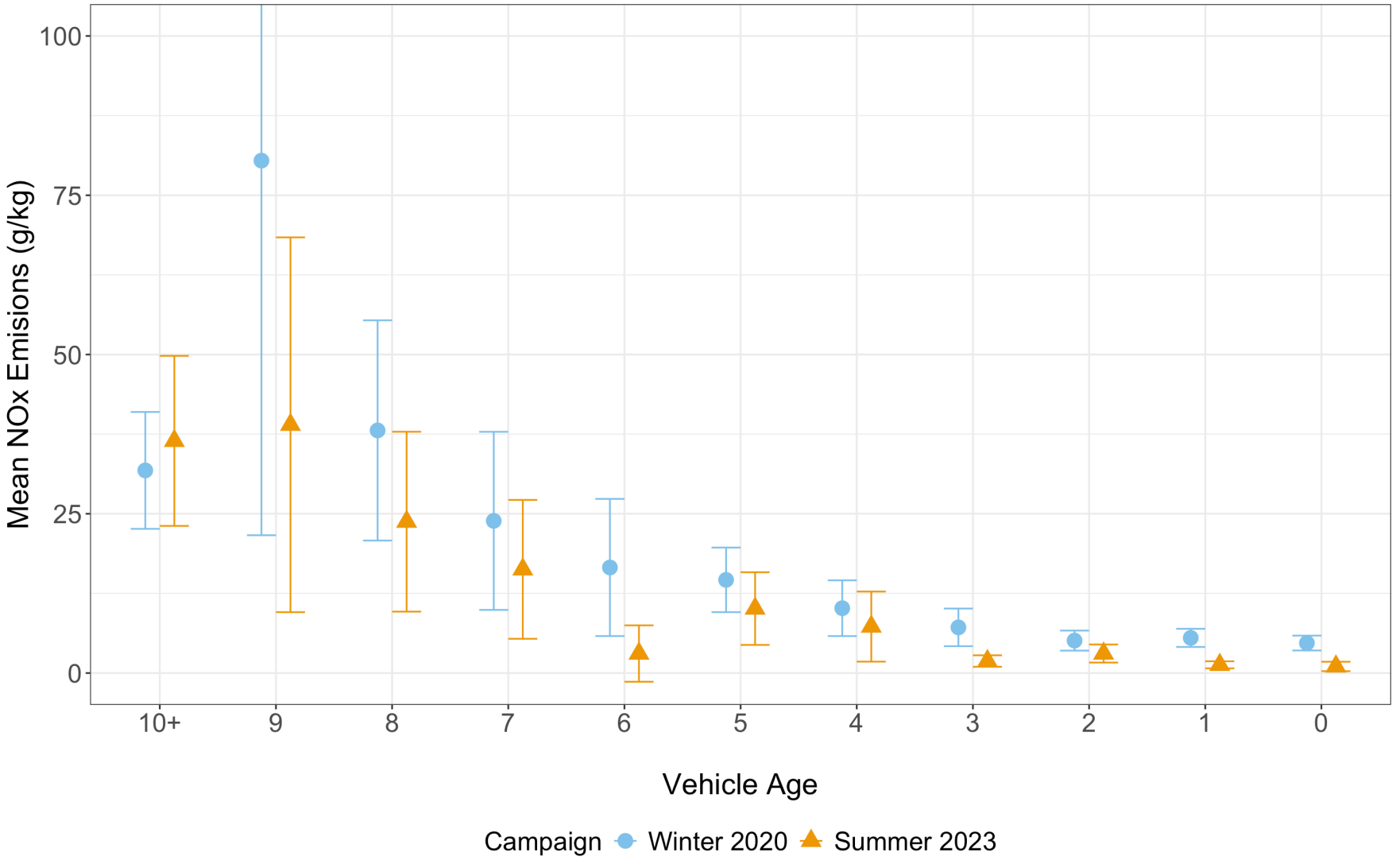
Mean NOx emissions by vehicle age



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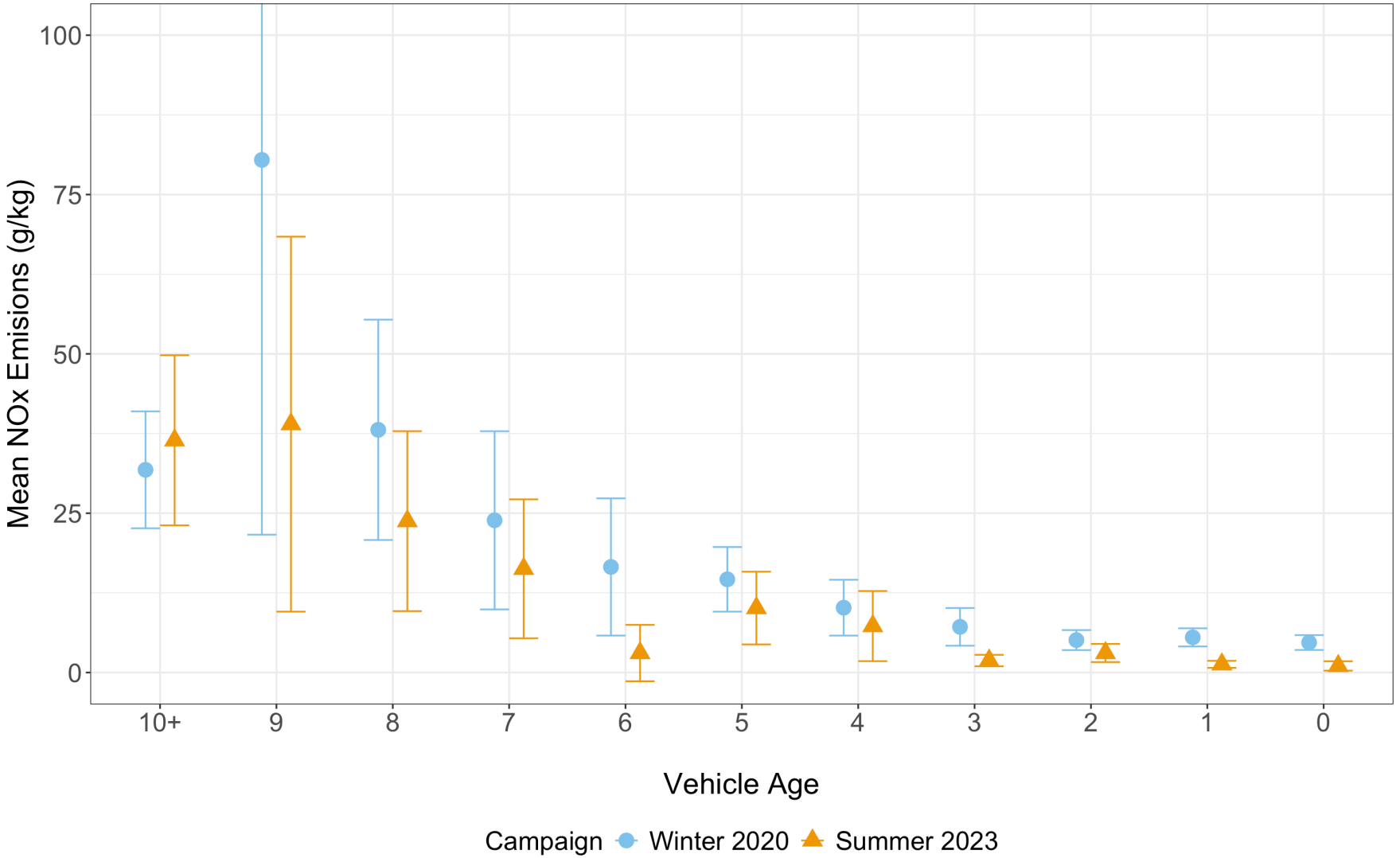
Mean NOx emissions by vehicle age

Consistent differences observed in NOx by age
2020 - ↑ temperature for ages 0-9



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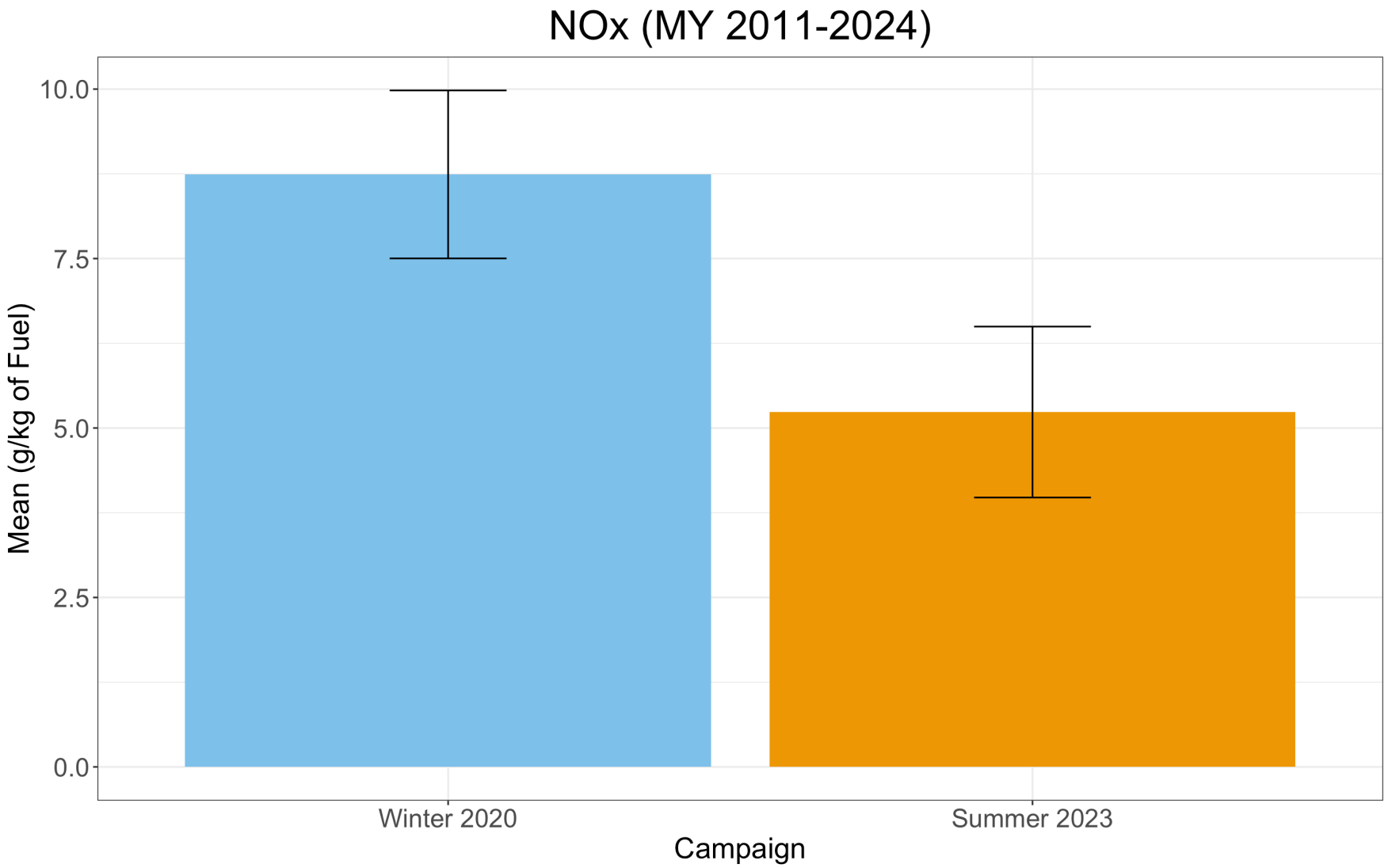
Mean NOx emissions including newest MY (2011-2024)



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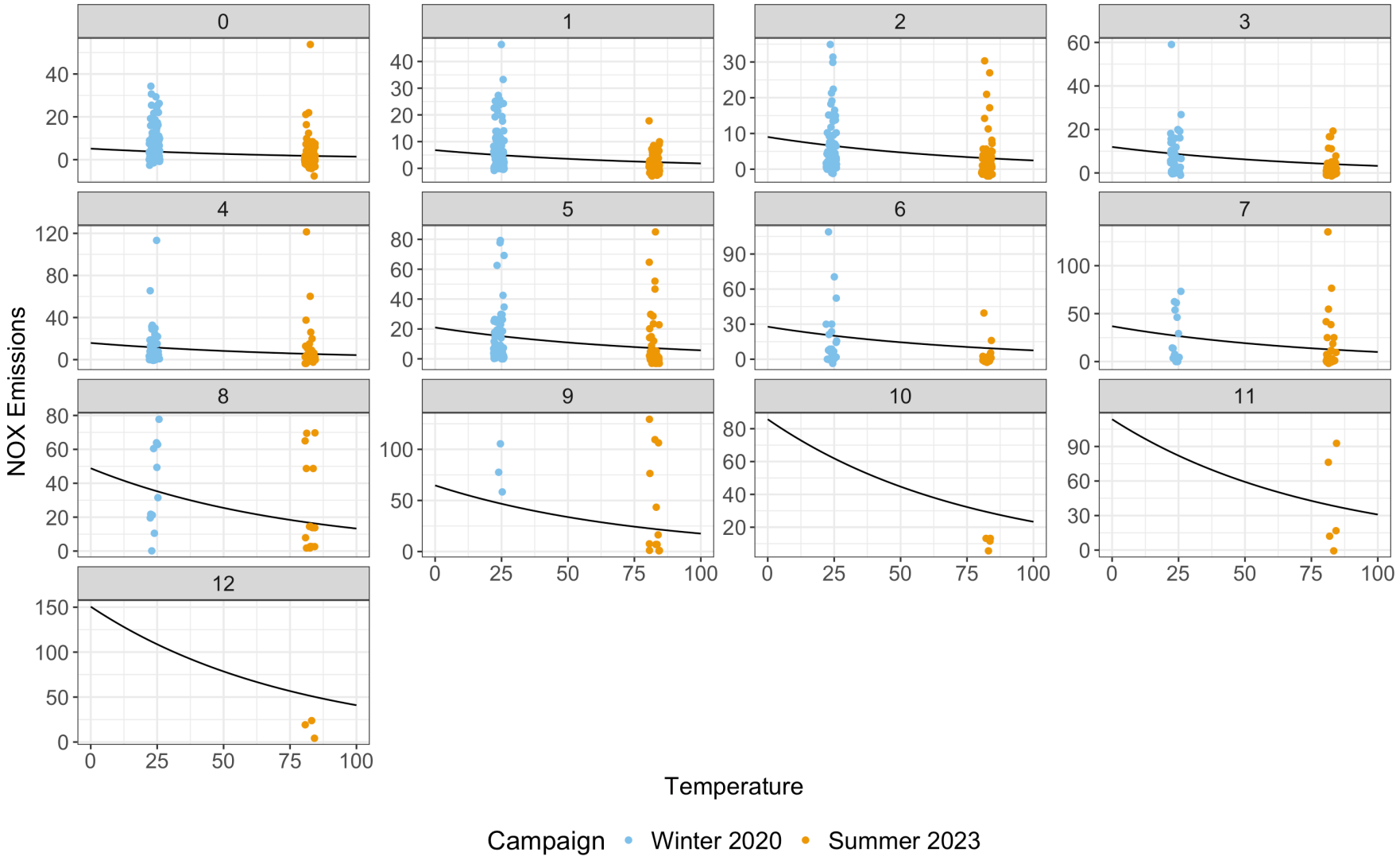
Model fit: NOx emissions for temperature range and vehicle age

$$NOx = a \cdot e^{(b \cdot temperature)} \cdot e^{(c \cdot age)}$$



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Temperature Effects

- Utah HD running exhaust
  - **2.14 times higher NOx in winter (24°F) than in summer (83°F)**
- MOVES4 NOx temperature effects
  - No effect for MY 2026 and earlier vehicles for tailpipe (start and hot-running emissions)
  - MY 2027 heavy-duty trucks have same temperature effect for start and running exhaust:
  - **1.44 times higher at 24°F than baseline temperature (77°F)**

NOx emissions by vehicle age and temperature (F):

2011 -2024 model years

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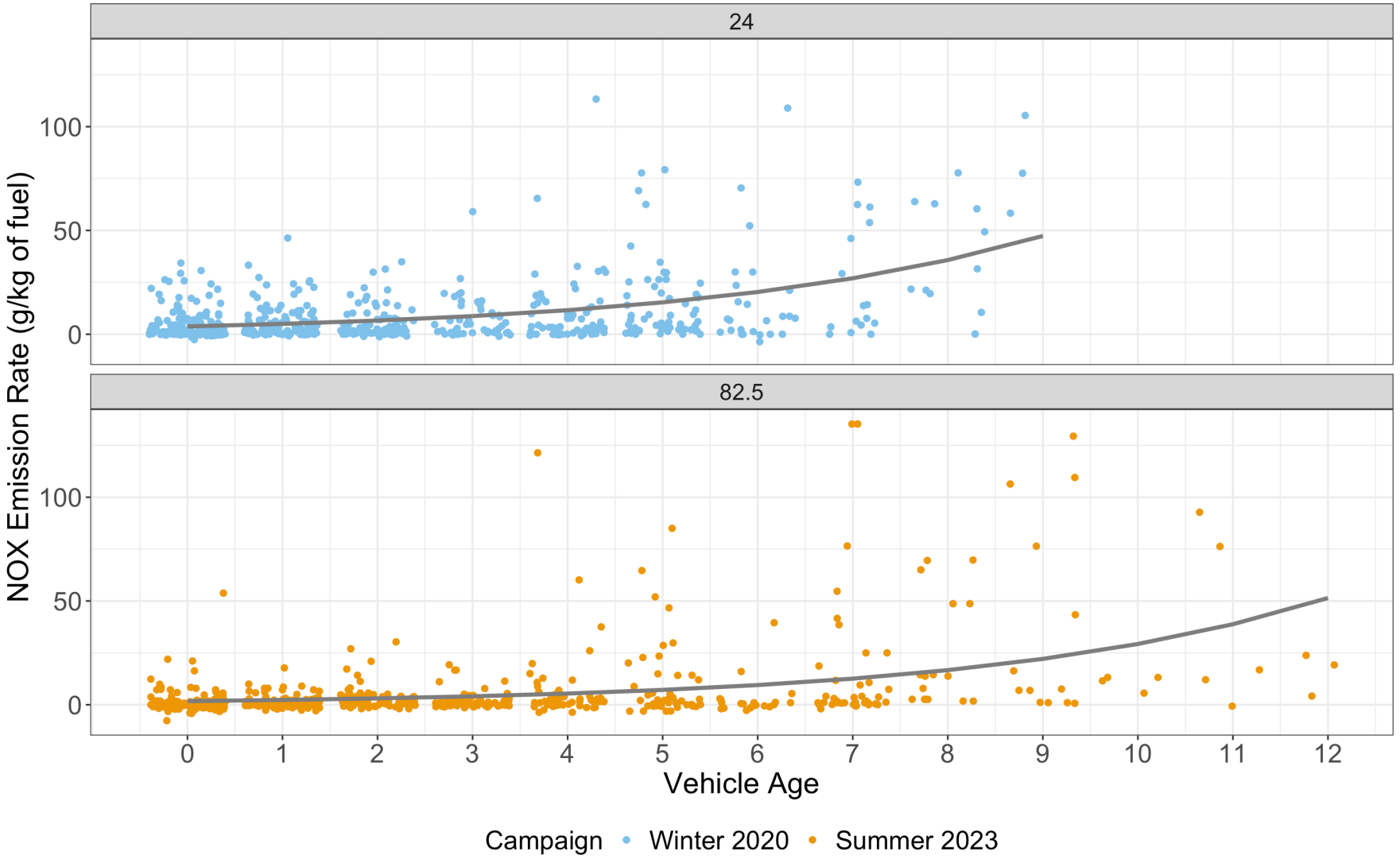
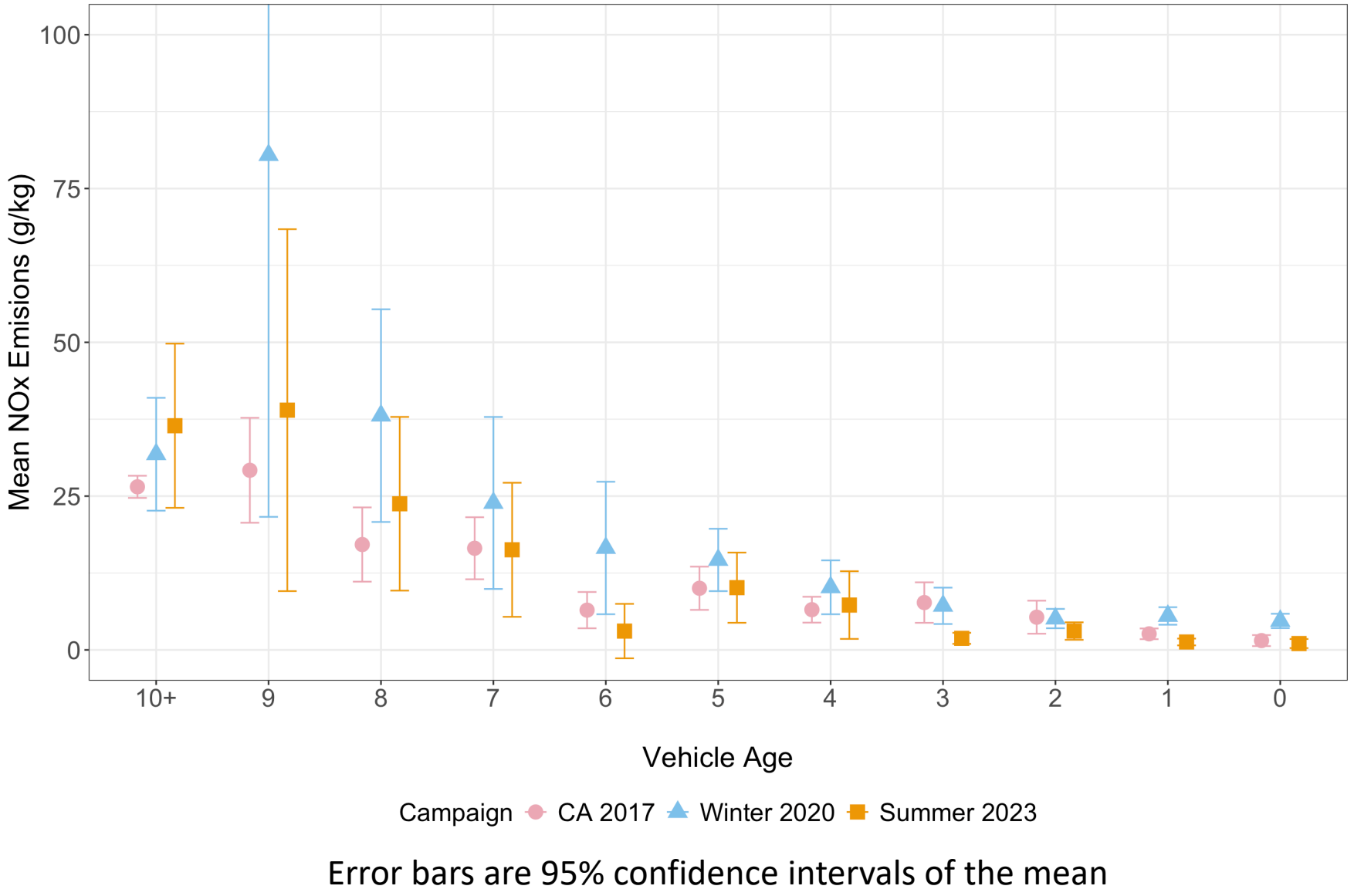
$$NOx = a \cdot e^{(b \cdot temperature)} \cdot e^{(c \cdot age)}$$



Deterioration Effects

- Utah HD measurements
  - **~29 times** higher NOx emissions after 12 years of aging
- MOVES4 deterioration effects
  - **~1.6 times** higher after 12 years
- EMFAC2021 deterioration effects
  - **~1.7 times** higher after 12 years
- Aging effects
  - **~1.1 to 1.3 times** higher after 200,000 km (124,000 miles)
    - Three 2021/2023 heavy-duty diesel trucks SCR + DPF (China VI standards)
  - **~2.2-2.6 times** higher after ~645,000 miles
    - 12 years assuming MOVES4 accumulation rates
    - Assuming linear increase (Lyu et al. 2023)
- Tampering effects
  - ~ **24 times** higher NOx from with tampered SCR
    - One truck compliant with (China VI standards) EGR + SCR+ DOC + DPF

How do HD Utah NOx emissions compare to California?



Error bars are 95% confidence intervals of the mean

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How do HD Utah NOx emissions compare to California?

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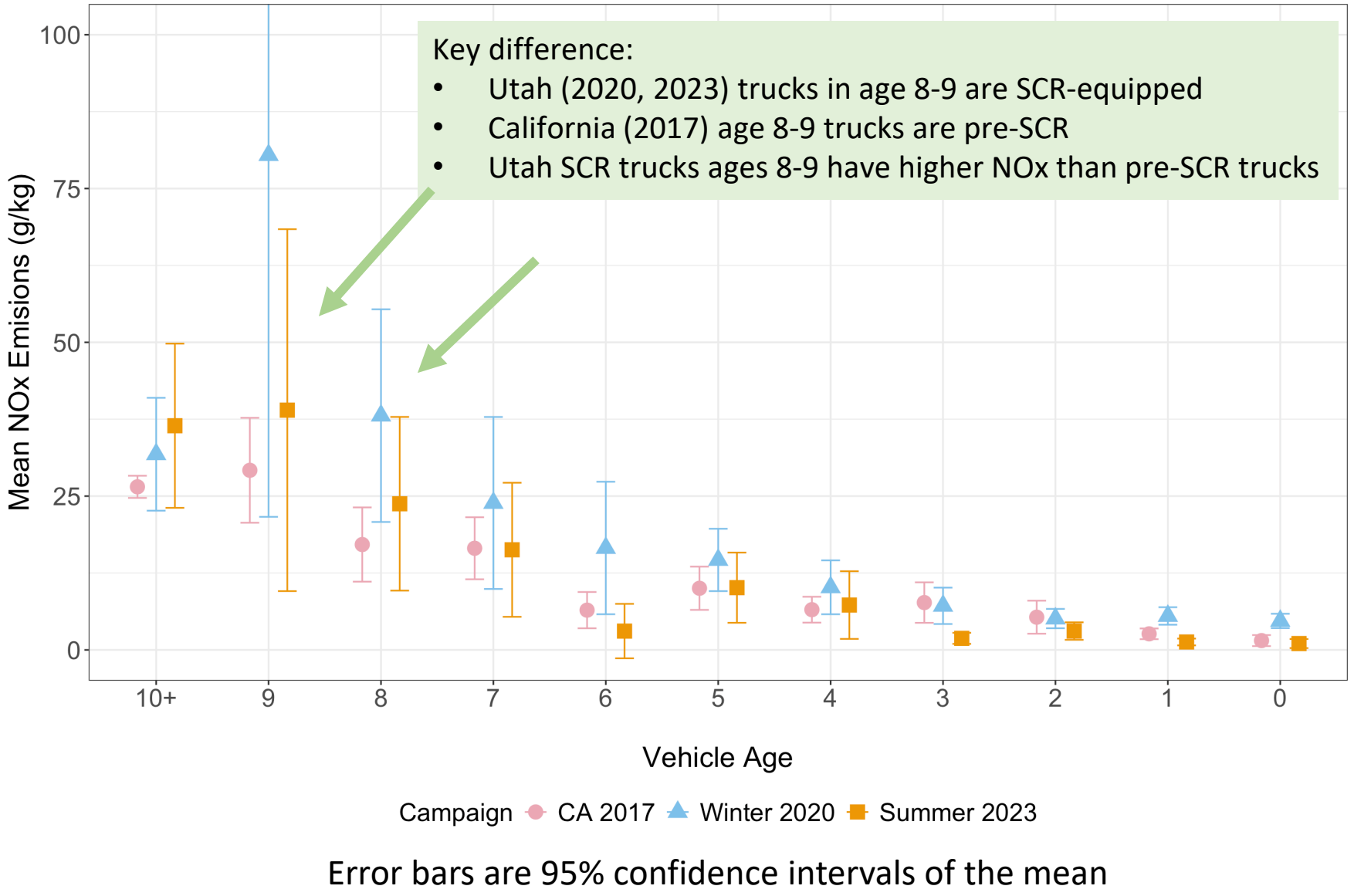
NOx emissions appear to be similar between Utah Summer and California 2017 trucks.



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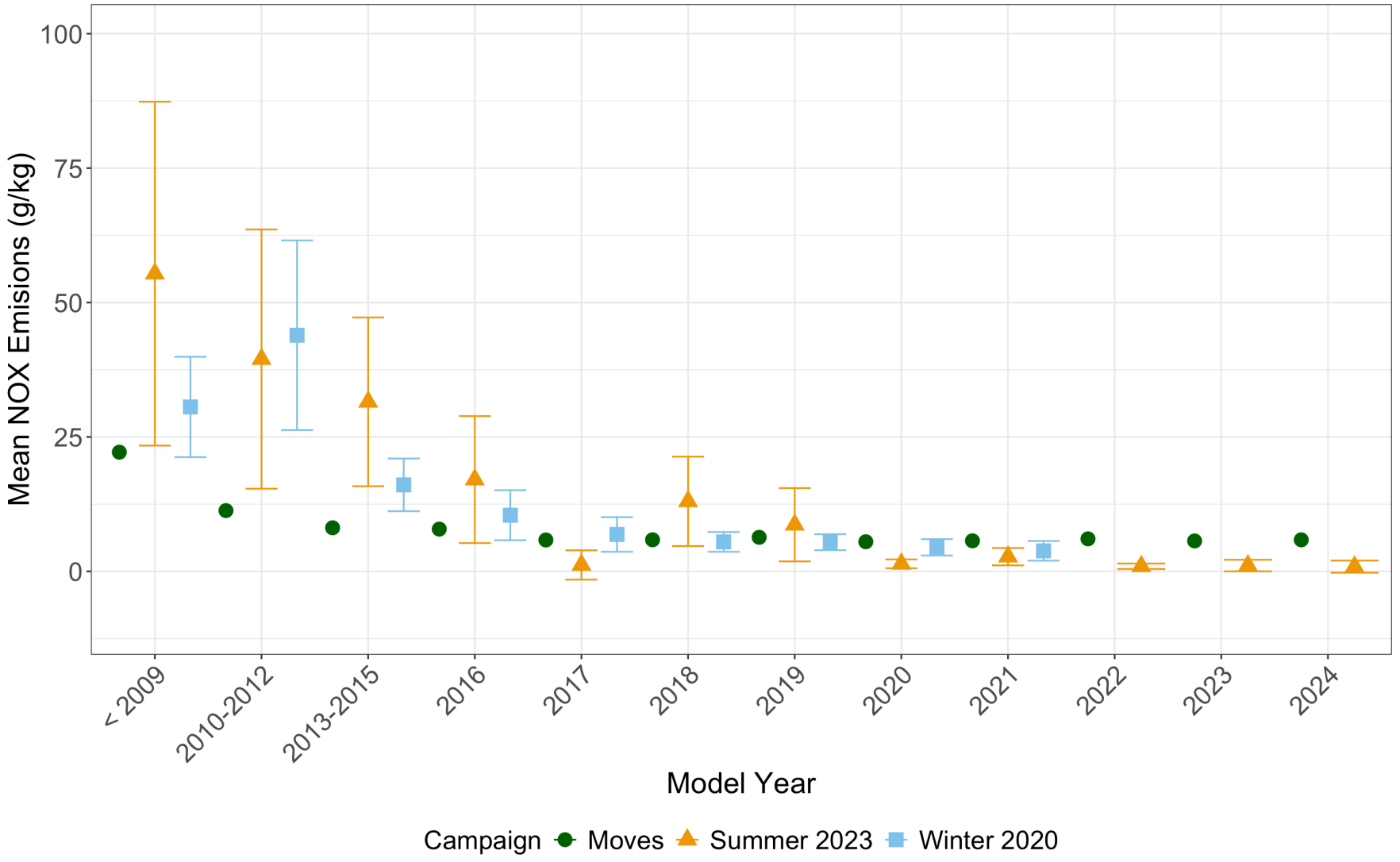
How do MOVES4 estimates compare to real-world measurements?



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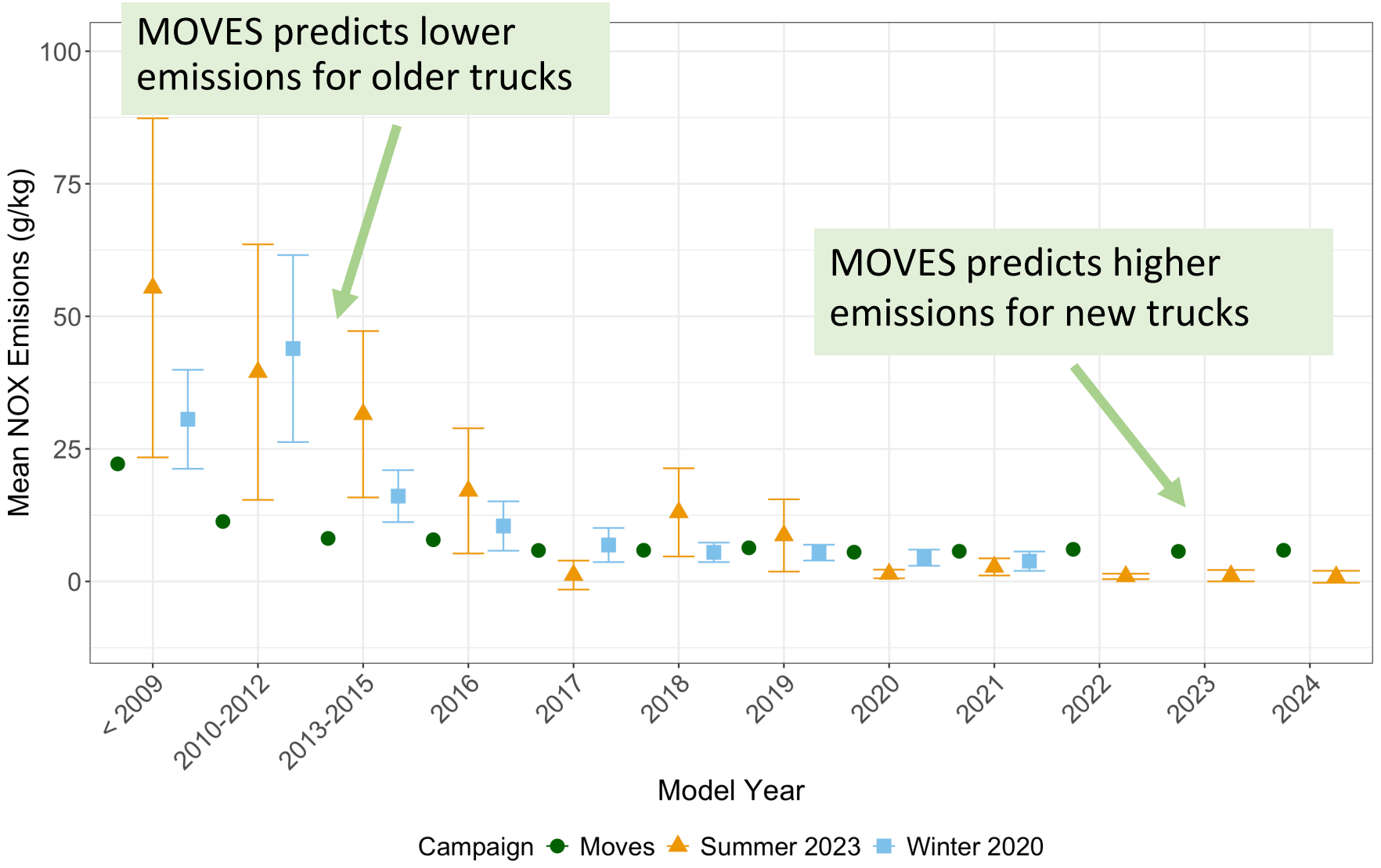

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MOVES4 Fleet Averages

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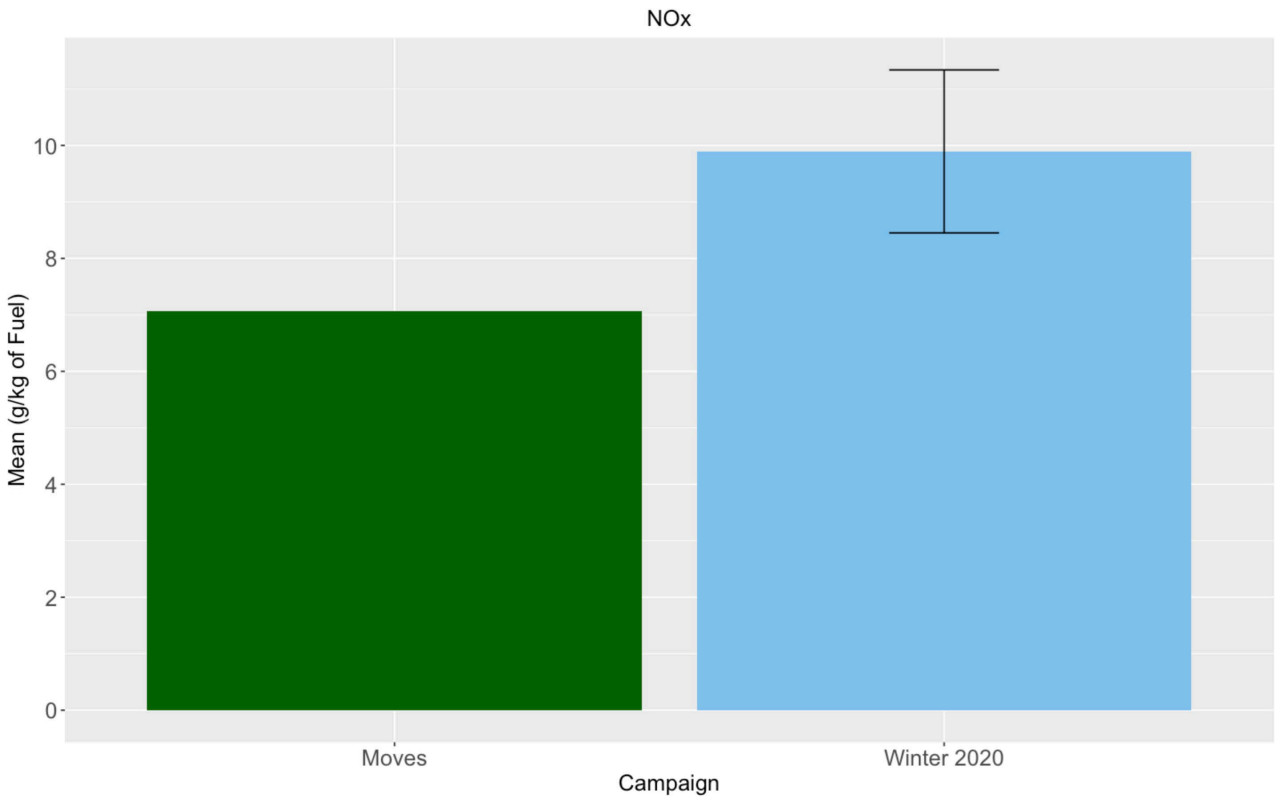
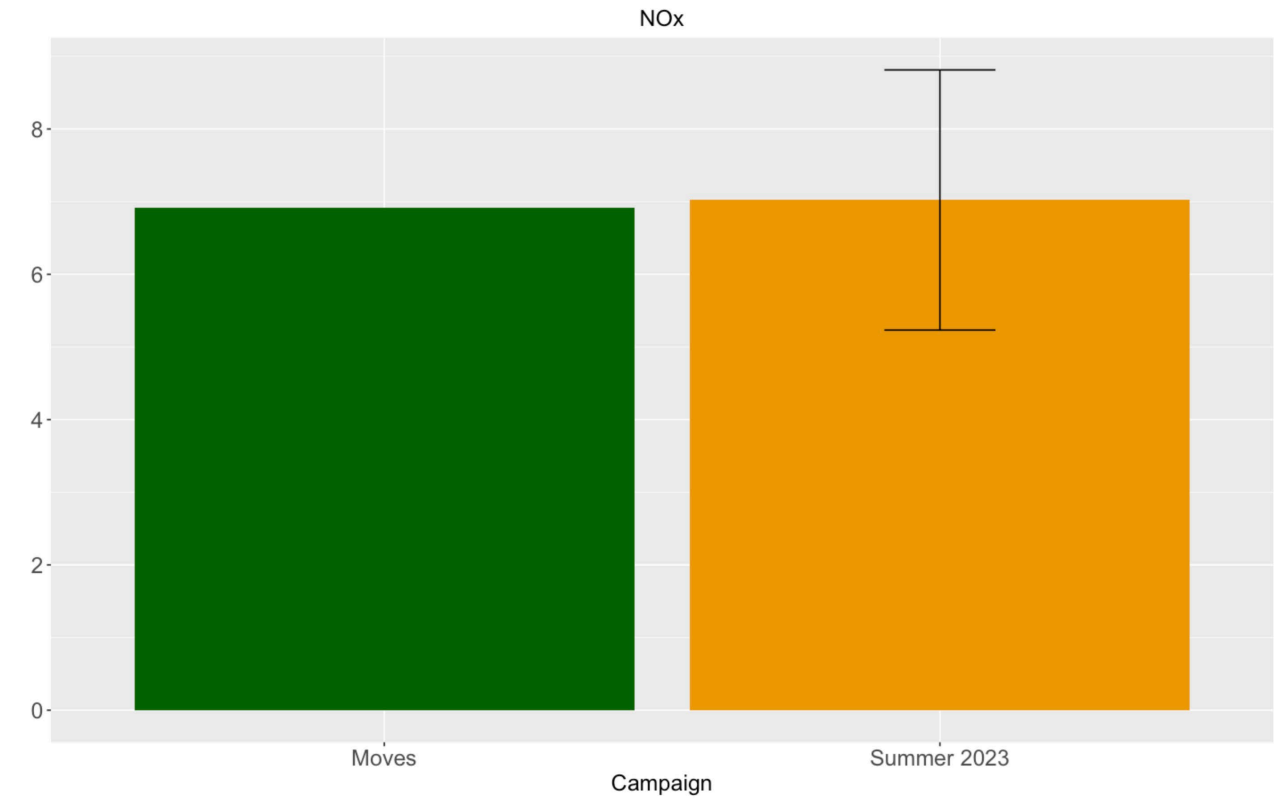


MOVES4 underpredicts emissions in winter in Utah



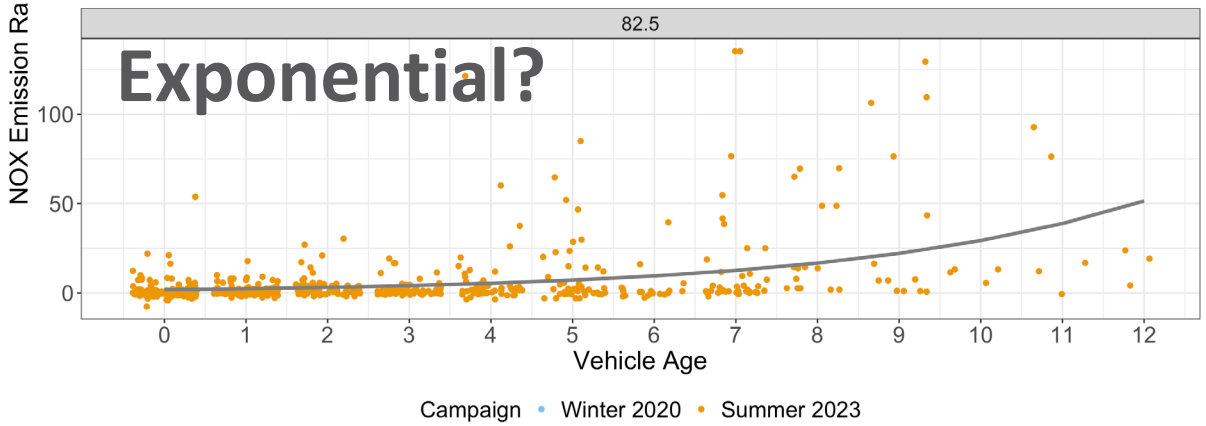
Fleet-average MOVES4 emission rates compare well to Summer 2023 data (despite significant differences in deterioration)

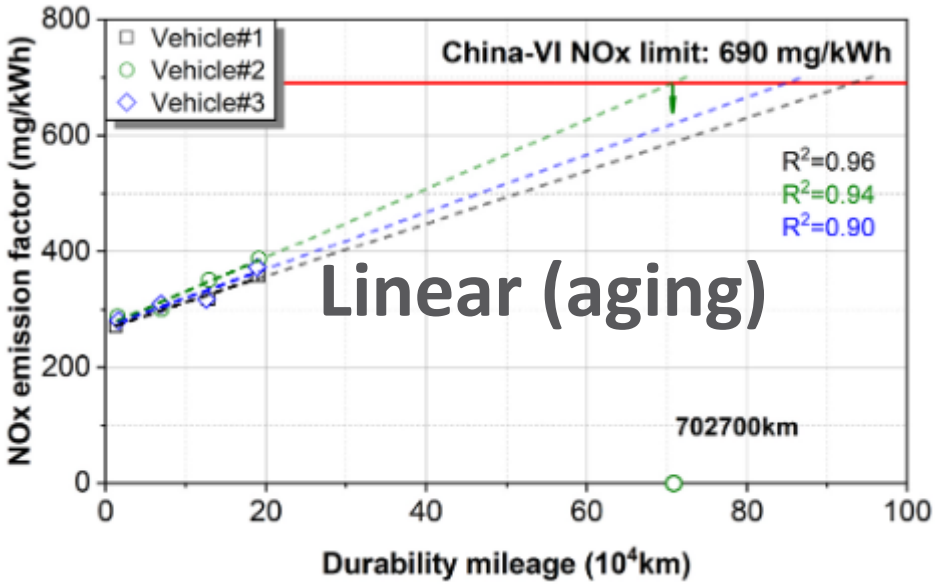
Take-aways

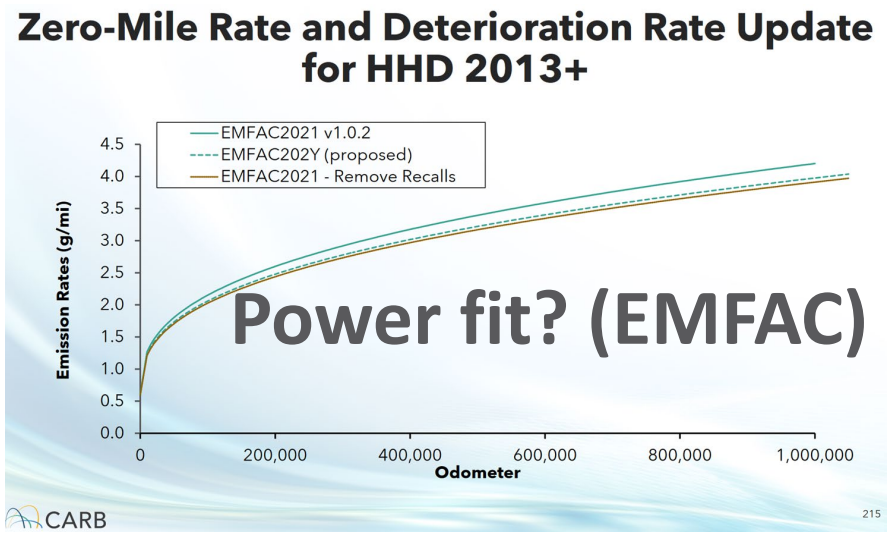
- **Temperature**
  - ~ 2 X higher NOx emissions for SCR-equipped trucks in winter
  - Temperature effect is not included in MOVES4 for current and historic model years
- **Deterioration**
  - Real-world effects of deterioration (~29 times higher) on HD NOx emissions appear steeper than MOVES4 and CARB estimates (1.6 to 1.7 times higher)
  - SCR-equipped trucks in (ages 8-9) have higher NOx than pre-SCR trucks (ages 8-9) measured in California in 2010
  - Real-world deterioration seems higher than literature values based on catalyst aging alone
  - Evidence for HD tampering of SCR trucks?

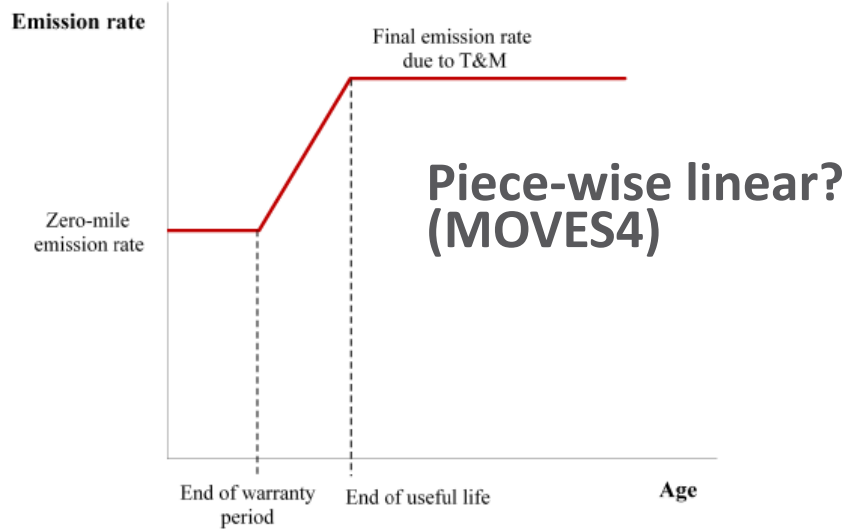
Take-aways

Mathematical form for Deterioration?









Limitations

- Our deterioration and temperature model assumes the baseline (age 0) NOx emissions are the same between 2011 and 2024 trucks
  - Need to incorporate additional studies
- Not all trucks are required to stop at the Perry Port of Entry.
  - ~50% of trucks bypass the station
  - Large fleets are more likely to bypass if their company pays for it?
- Our data is only from ground-level exhaust trucks.
- MOVES4 comparison limitations
  - We do not include glider trucks emission rates in our MOVES4 comparisons
  - Our MOVES4 calculations are not location specific and do not consider local weather conditions (e.g. temperature, humidity, altitude)

Acknowledgements

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- Gary Bishop from the University of Denver for donating the FEAT to our research lab
  - Bishop, G. A.; Haugen, M. J.; McDonald, B. C.; Boies, A. M., Utah Wintertime Measurements of Heavy-Duty Vehicle Nitrogen Oxide Emission Factors. Environ. Sci. Technol. 2022, 56, (3), 1885-1893, DOI: 10.1021/ acs.est.1c06428.
- Suzanne Covert from the Utah Department of Motor Vehicles for providing vehicle data

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Questions?

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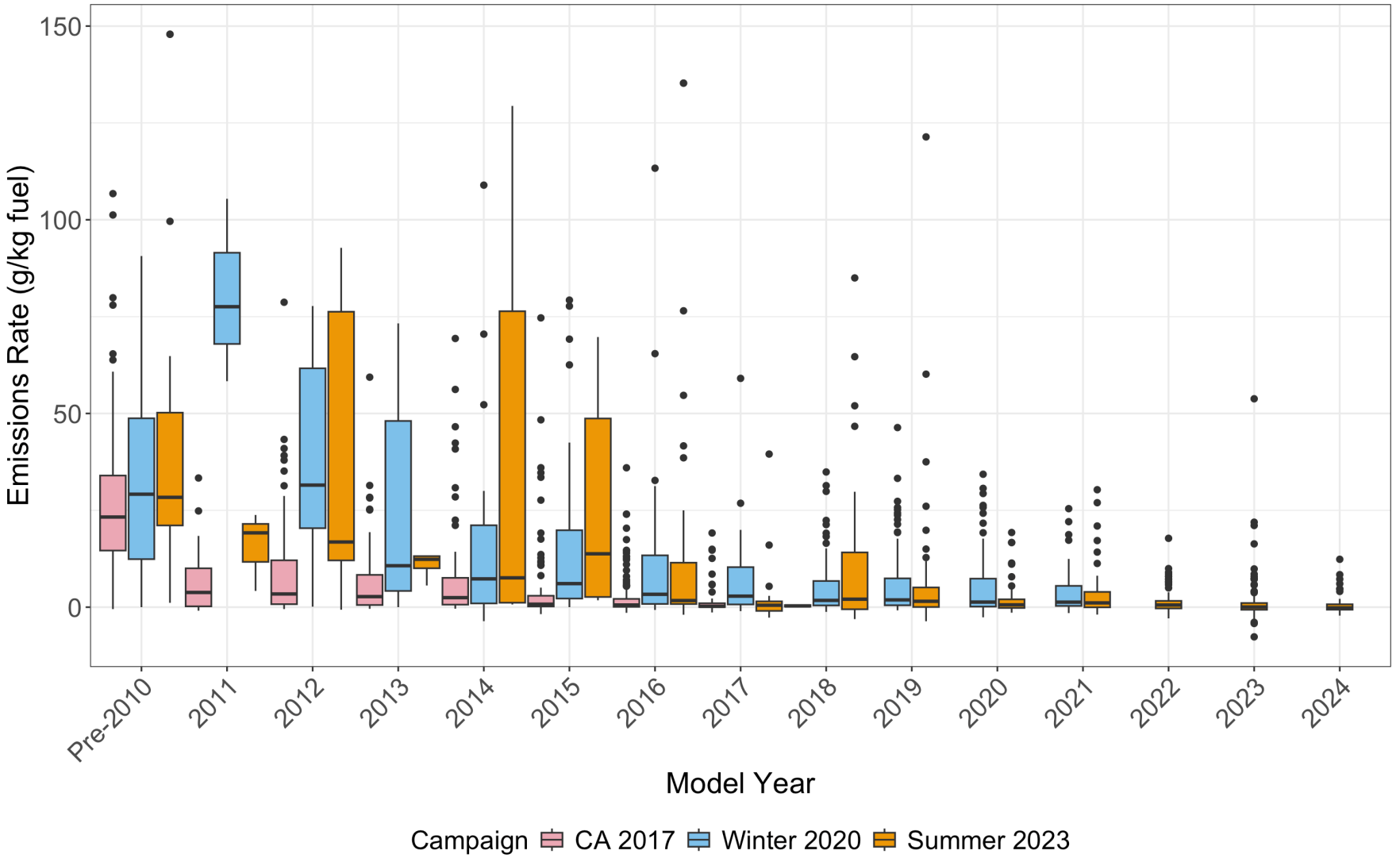
Extra Slides

HD NOx emissions from Low FEAT

1) Peralta CA (2017)
2) Perry UT (Winter 2020)
3) Perry UT (Summer 2023)



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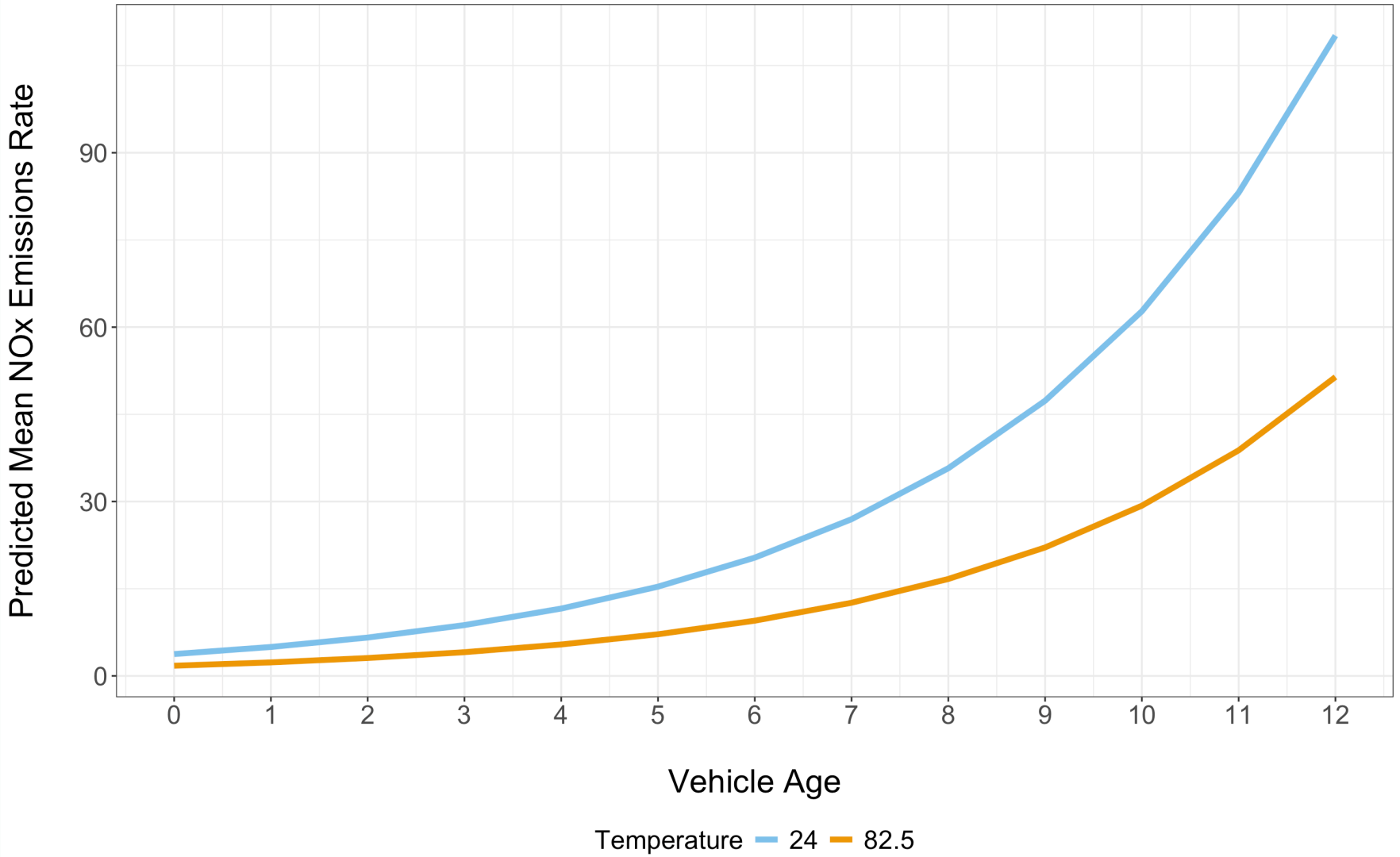
Model fit: NOx emissions by vehicle age and temperature (F)

2011 -2024 model years

$$NOx = a \cdot e^{(b \cdot temperature)} \cdot e^{(c \cdot age)}$$



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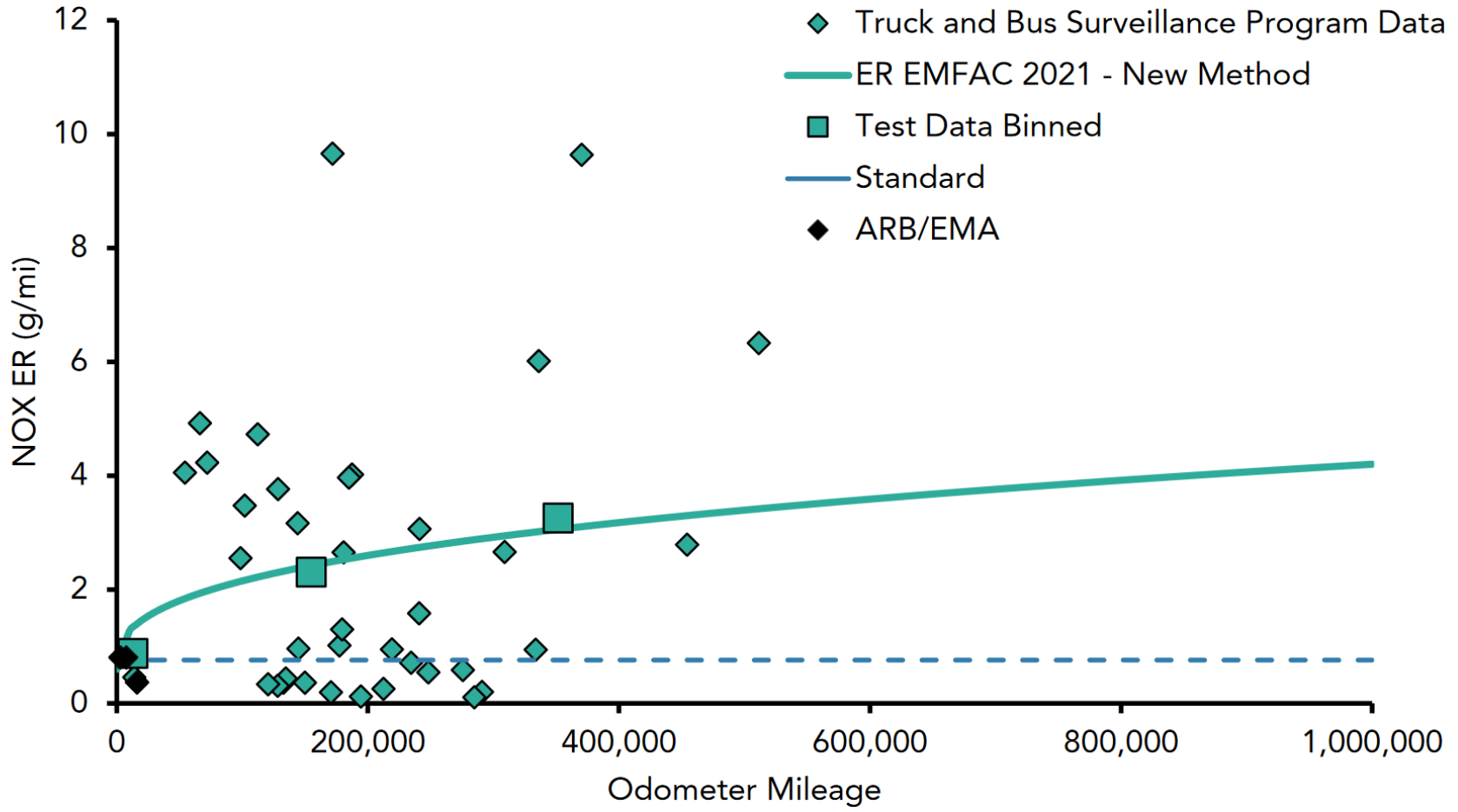
CARB deterioration trends

Non-linear power fit had similar shape as frequency of malfunction indicator lamp (MIL) rates for telematics data

Figure 4.3.6-3. Modelled and Observed NOx Emission Rates



CARB, "EMFAC2021 Volume III Technical Document Version 1.0.1 April, 2021," Apr. 2021. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2021-08/emfac2021_technical_documentation_april2021.pdf

Modeled Temperature Effects

MOVES4 estimates that the temperature effect for HD NOx emissions at low temperatures is **1.44 times higher** than at high temperatures (US EPA, 2023).

MOVES temperature adjustment formula (starting MY '27)

NOx = (77-24)*0.008397+1 =

1.44

Our model estimates that the temperature effect of HD NOx emissions at low temperatures **2.14 times higher** than at high temperatures.

Our model formula for NOx temperature effect:

NOx = exp(-0.13021*24)/ exp(-0.13021*82.5) =

2.14