Applying Humidity and Temperature Corrections to On and Off-Road Mobile Source Emissions

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ABSTRACT

The effect of humidity on internal combustion (gasoline, LPG, CNG, and diesel) engines has been known for many years: higher humidity results in lower NOx emissions. Likewise, higher temperatures have historically been associated with higher emissions except during the cold start of light-duty vehicles when emission control devices and other engine controls may not function properly. Once the engine has warmed up though, higher temperatures result in higher NOx emissions. The effect of humidity and temperature has been included in light-duty on-road vehicle emissions estimates in MOBILE6, which includes the effect of air conditioning loads on the engine and the exhaust emission effects described. However, the effect of temperature and humidity has not been included in the MOBILE6 for heavy-duty vehicles and NONROAD emission models even though the emission data used in the development of emission factors has been adjusted for temperature and humidity. This work presents a review of humidity and temperature corrections and applies them to the Houston-Galveston area (HGA) emission inventory demonstrating the effect of humidity and temperature on emissions. Overall the effect of applying the humidity and temperature adjustments on emissions inventory was relatively small for the HGA ranging from a less than 1% to 9% NOx reduction by episode day, however the effect varied temporally and spatially. The emissions rates decreased most significantly in the evening and early morning where humidity levels were high and temperature was low. The emission rates also vary spatially where counties closer to the coast had higher humidity levels and lower temperatures and so had lower NOx emission rates.

INTRODUCTION

The effect of humidity on internal combustion engines, including spark-ignition (SI) engines (gasoline, LPG and natural gas engines) and compression ignition (CI) or diesel engines, has been known for many years, with trends indicating that higher humidity results in lower NOx emissions. Likewise, higher temperatures have historically been associated with higher emissions except during the cold start for light-duty vehicles when emission control devices and other engine controls may not function properly. Once the engine has warmed up though, higher temperatures result in higher NOx emissions. The effect of humidity and temperature has been included in light-duty on-road vehicle emissions estimates in MOBILE6 and includes the effect of air conditioning loads on the engine and the exhaust emission effects described. However, the effect of temperature and humidity has not been included in the emission models, MOBILE6 for heavy-duty vehicles and NONROAD for off-road equipment, even though the emission data used in the development of emission factors has been adjusted for temperature and humidity.

The technical approach of this work was to define the effect of ambient conditions on NOx emissions for on-road vehicles and off-road engines or equipment. This effect was then used to adjust the emission estimates for the Houston-Galveston nonattainment area (HGA) on the portion of the emissions consistent with the engine technology by the hourly and spatial ambient temperature and humidity conditions.

DEVELOPMENT OF HUMIDITY AND TEMPERATURE CORRECTION FACTORS

Emission regulations continue to place additional restrictions on urban areas trying to achieve ambient air quality standards. Although ambient air quality standards are national, achieving the standards is a regional problem delegated to the states. However, the certification procedures for on-road and off-road spark-ignited engines are standardized without regard for regional variation in ambient conditions like temperature and humidity. As early as 1970[1], it was recognized that the concentration of oxides of nitrogen (NO_x) in engine exhaust is significantly affected by the thermodynamic conditions of the intake air. Specifically, the intake air temperature and humidity are the ambient conditions having the dominant effect on NOx emissions from internal combustion engines without aftertreatment devices.[1,2,3] Because of these sensitivities, it is reasonable to assume regional variations in temperature and humidity can significantly impact engine-out emission levels. Emissions inventory models such as the EPA's MOBILE and NONROAD[4,5,6] have been developed to account for pollutants attributed to both on-road and off-road mobile sources. These models often use local information including fuels, regional temperature and humidity for some, but not all, categories of engines types to adjust the emissions inventory.

Historically, the impact of ambient temperature and humidity on emissions was of interest because it was difficult to make comparisons of the NO_x emissions from engines tested at different locations and/or with variations in the ambient conditions. In an effort to allow day-to-day and location-to-location comparisons, various correction factors have been developed. The goal for all of these correction factors has been to standardize the NO_x emissions to reference conditions, but could be used to adjust emissions inventory models to more accurately predict ambient air quality. To improve the air quality modeling, it is appropriate to account for regional differences by including the effect of ambient conditions on emissions rates particularly oxides of nitrogen (NO_x) emissions, a major contributor to ambient air ozone levels.

This section provides an overview of the literature search results of studies for humidity and temperature effects on NOx emissions for CI and SI engines. Recommendations are provided for a set of NOx correction factor equations for CI and SI engines by application, technology, and fuel types.

The NOx correction factor to account for humidity and temperature is defined as the KNOx variable in equation (1). The NOx emission at the reference condition multiplied by the correction factor yields the best estimate of the in-use emissions. The reference conditions are not consistent across all the correction factor equations.

$$\text{NOx-actual} = \text{KNOx} * \text{NOx-reference} \qquad (1)$$

The correction factor equations vary by engine type and technology, and the best estimates are described for each type. Southwest Research Institute (SwRI)[7] reviewed the literature and used engine thermodynamic models to suggest different equations by the technology and fuel types described here.

CI (Diesel) Engines

The review work performed by SwRI[7] provided further evidence that the humidity levels do affect the emission levels in late model diesel engines. In general, the results indicated that emission levels could be corrected by applying a NOx correction factor, KNOx (see Equation 2), to a reference NOx emissions value as shown in Equation 2. This NOx correction algorithm is comparable but more straightforward than those correction equations found in the Code of Federal Regulations (CFR) used to correct laboratory emissions estimates. As shown in Equation 1, the NOx correction factor is a function of humidity and temperature. The constant coefficients in Equation 1 vary by application and technology types for the engine.

$$KNOx = 1.0 + [0.004460 \times (TEMP - 25)] - [0.018708 \times (HUMID - 10.71)] \quad (2)$$

where TEMP is temperature in ^{o}C and HUMID is humidity in grams of water per kilogram of dry air

As part of this work, a set of equations to estimate emission adjustments, KNOx, were used to correct emission rates for each engine type.

On-Road Diesel Vehicles

Pre-1994: Naturally Aspirated Diesel Engines

English Units:

$$KNOx = 1 + 0.00076\ (T - 85) - 0.00216\ (H - 75) \quad (3)$$

(Units of T in ^{o}F, and H in grains per pound of dry air)

SI Units:

$$KNOx = 1 + 0.001368\ (T - 29.444) - 0.01512\ (H - 10.71) \quad (3a)$$

(Adjusted to consistent units of ^{o}C and grams per kg of dry air)

The correction algorithm is essentially similar to the EPA correction factor in the Code of Federal Regulations (Š 86.345-79) without the Fuel/Air ratio dependence. This eliminates the requirement for determining the Fuel/Air ratio of the fleet.

Post 1994: Turbocharged Diesel Engines

$$KNOx = 1 + 0.00446\ (T - 25) - 0.018708\ (H - 10.71) \quad (4)$$

Where T = ambient temperature, ^{o}C
H = ambient humidity, g $H2O$/kg of dry air

Off-Road Diesel Engines

Naturally Aspirated Diesel Engines for Construction/Farm Equipment

Similar to Pre 1994 on-road vehicles, Equation 3 or 3a was recommended.

Turbocharged and Charge-Cooled Diesel Engines for Construction/Farm Equipment

Similar to Post 1994 on-road vehicles, Equation 4 was recommended.

Railroad and Marine Diesel Engines

$$KNOx = 1 / (K_H\ K_T) \quad (5)$$

Where $K_H = 1989.6/(85.444 + 2219.426 \exp(-0.0143H))$
$K_T = 1 / (1 – 0.017 (30 – T))$

SI (Gasoline, LPG and NG) Engines

All of the current humidity correction factors for NO_X for SI engines were based on historical data taken in 1971 and 1972. Some of the engines today are more technically advanced, incorporating port or throttle-body fuel injection, air-fuel ratio feedback, exhaust aftertreatment, and knock detection. While many off-road vehicles do not have all of these features, this technology is becoming more prevalent with the implementation of Federal rulemakings beginning with model years 2004. SwRI's[7] analysis conducted indicated that the historical correction factors do not adequately account for operating cycles with higher load factors, or advanced technologies such as A/F control and knock detection. No engine test data were found documenting humidity effects for these additional variables.

SwRI's[7] engine model results showed these effects to be significant and the results were used to modify the historical correction procedures. While SwRI recommended some NOx correction factor algorithms for SI engines as follows, SwRI recommends engine testing to quantify the effects for different engine/vehicle classes, if a more rigorous approach is desired:

The recommended equation to adjust standardized emissions for a **carbureted heavy-duty on-road or off-road (above 19kW) engine** under non-standard inlet air conditions takes the following form:

$$C_{SwRI}(H,T) = 1 + 0.0022\cdot(T - 25) - 0.0280\cdot(H - 10.71) \qquad (6)$$

Where:
T = Temperature of the inlet air [°C]
H =Absolute humidity of the inlet air [g of H_2O/kg of dry air]

For **heavy-duty on-road or off-road (above 19kW) spark-ignition engines** that use a 3-way catalyst (A/F control, typically with port fuel injectors), the recommended NO_x correction equation is as follows:

$$C_{SwRI}(H) = 1 - 0.0232\cdot(H - 10.71) \qquad (7)$$

with no correction for ambient temperature.

For **light-duty, spark-ignition engines**, the recommended practice is whatever procedure is used in MOBILE6, which can be approximated by Equation 4, except for load adjustments due to increased use of air conditioning compressors during hot and humid weather.

$$C = NOx_{corr\_MOBILE}(H_a) = \begin{cases} 1.2 & \text{if } H_a \le 20 \\ (-0.004\cdot H_a + 1.28) & \text{if } 20 < H_a < 120 \\ 0.8 & \text{if } H_a \ge 120 \end{cases} \qquad (8)$$

Where:
H_a = Absolute humidity of the inlet air [grains/lb]

For **small off-road, spark-ignition engines (< 19kW)**, the recommended practice is,

$$C = 1 - \frac{546}{AFR}\cdot(\omega - 0.01071) \qquad (9)$$

Where:
AFR = Air-fuel ratio of the engine
ω = Absolute humidity of the inlet air [kg/kg]

APPLICATION OF CORRECTION FACTORS

In order to determine the proper emissions adjustment for the Houston-Galveston area, the fraction of emissions for each engine technology type was estimated for each on-road heavy-duty vehicle category and off-road source category code (SCC, used to identify off-road equipment types). The engine types used in equipment varied by engine size and model year grouping; both of which could affect the technology used in such engines. For on-road heavy-duty diesel the model year of 1994 was used to divide the technology types as shown below.

On-road Heavy-Duty Diesel Adjustment
<1994 Model Years; 100% Equation 3
1994 and later Model Years; 100% Equation 4

For off-road diesel engines other than locomotive and marine engines, the primary deciding factor was whether the engine was turbocharged or not. According to EPA[8], the fraction of turbocharged engines has been and will be associated with the size of the engine. For the power category of 50 to 100 horsepower, EPA[8] estimated none were turbocharged, but the latest information from EPA[9] indicated that approximately 10% of these engines in the 1998 –2002 model year certification data were turbocharged. These assumptions were used when applying the NOx correction factors.

Off-road (Latest NONROAD model)
<50 hp; 100% Equation-3
50-100 hp; 10% Equation-4 & 90% Equation 3
100-175 hp; 58% Equation-4 & 42% Equation 3
>175 hp; 100% Equation-4

The SI engine definitions are straightforward in that the emission standard forces the technology definition of equation (7) for large (>19kW) off-road engines in model years 2004 and later, and model years 2005 and later for on-road SI heavy-duty vehicles. Earlier heavy-duty on and off-road engine emissions were given the equation (6) adjustment. Smaller off-road 4-stroke SI engine emissions were given the equation (9) adjustment, with no adjustment to 2-stroke SI engine emissions.

The Houston-Galveston area emission inventory was then divided into groups associated with each adjustment equation described above. As demonstrated in the results section, the adjustment magnitude does not vary much between each equation, so the uncertainty in defining the fraction of the emission inventory associated with each technology type adds much less uncertainty to the overall estimates than it appears.

For on-road vehicles, the model year is the defining characteristic. While the actual emissions inventory was developed using a detailed link level (small sections of the road network) analysis with specific emissions for each link, it was not possible to use this inventory analysis to delineate by model year. So a single MOBILE6 run with a distribution of speeds and roadway facility reflecting average conditions was developed that estimated emissions well within 10% of the link level estimates. This run was then used to determine the fraction of the emission inventory by model year to apply the correction of each equation.

For off-road equipment both power level and model year were defining characteristics. The NONROAD2002 model was used to estimate the emission inventory fractions by SCC (individual equipment types grouped to general off-road categories) according to the description above.

PRELIMINARY EMISSION INVENTORY RESULTS

ENVIRON and the Texas Commission on Environmental Quality (TCEQ) jointly modified the 8-county Houston-Galveston nonattainment area (HGA) emission inventory to reflect the best estimate of humidity and temperature corrections to the in-use emissions inventory. A new computer tool CNTRLHR, a modified version of CNTRLEM, was developed by ENVIRON to apply emission control factors by hour, by county, by emission source, using the Emissions Processing System (EPS). TCEQ then modified their emission inventory to reflect the conditions experienced during their ozone-modeling episode. The HGA ozone episode used to demonstrate future year attainment is based on the dates August 18 through September 6, 2000. The data presented here reflect the emission inventory likely to exist in 2007, though the 2000 baseline emission inventory was also adjusted accounting for differences in the age distribution of the in-use fleets.

Average hourly county-level conditions for the modeling episode were used to estimate the adjustment to the emissions. The hourly ambient conditions were derived from data recorded at monitors operated by the National Weather Service, TCEQ air quality stations, and the Conrad Blucher Institute coastal stations for each county within the HGA. The county and hourly ambient conditions estimates used in the NOx adjustment were identical to those used in MOBILE6 when developing the link level on-road emissions inventory.

An example of the adjustment for hourly conditions for one modeling day is provided here for diesel engines in Figures 1-3. The NOx emissions are reduced for late night and early morning when the temperature is low and relatively unchanged for mid-day. The data reflect the most important county for emissions (Harris), a wet county (Galveston), and a dry county (Montgomery). So emissions vary spatially where the coastal counties experience higher humidity and therefore lower NOx emission rates.

Figure 1. Diesel engine emissions adjustments for Harris County on August 30.

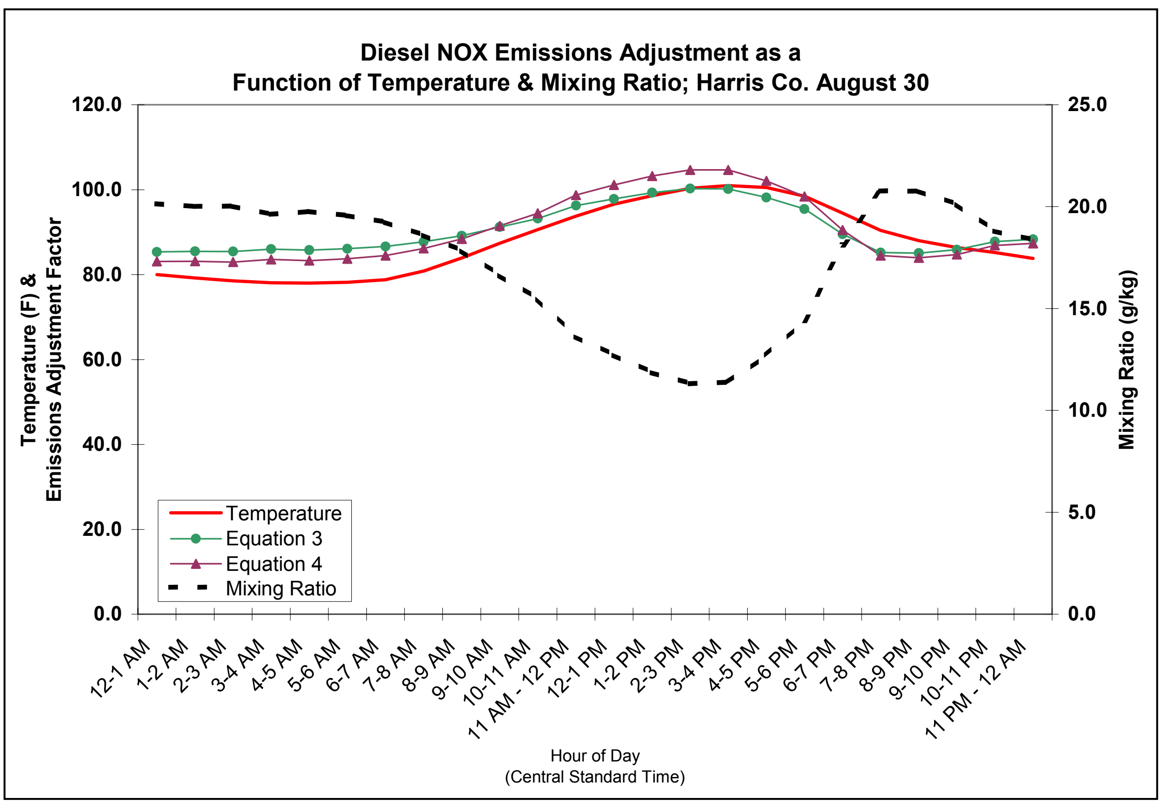


Figure 2. Diesel engine emissions adjustments for Galveston County on August 30.

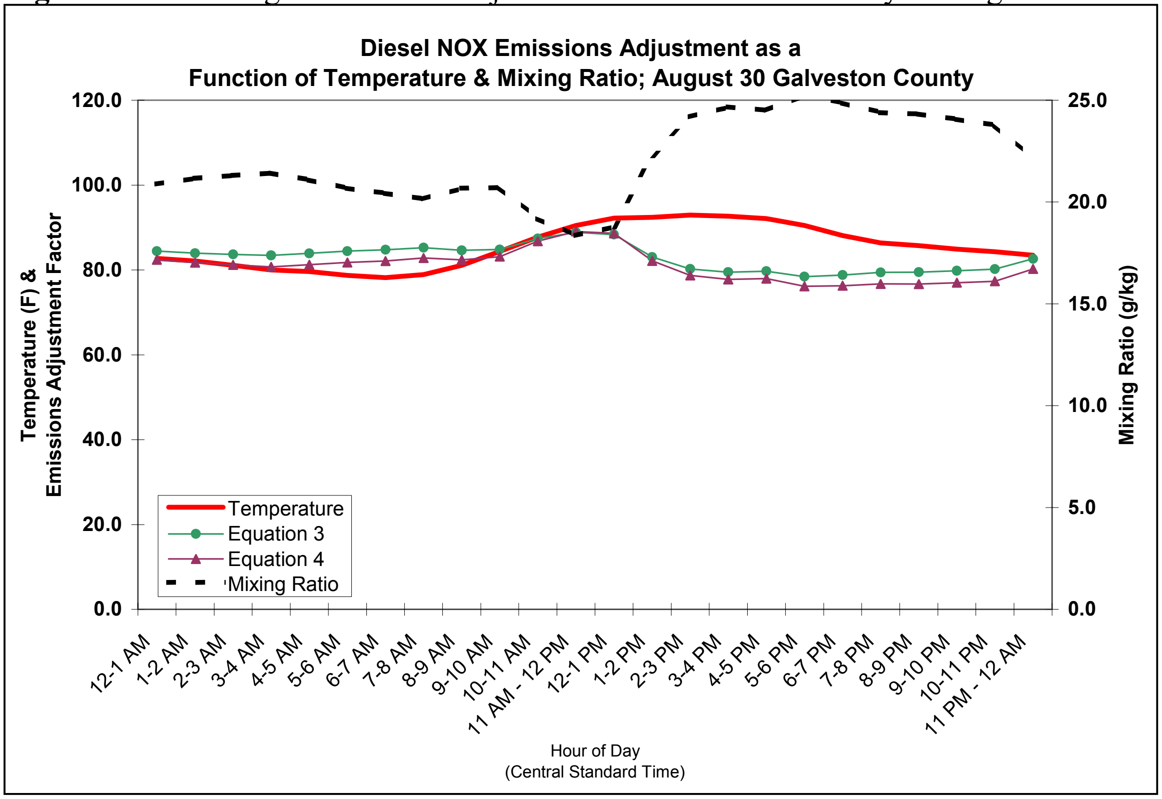
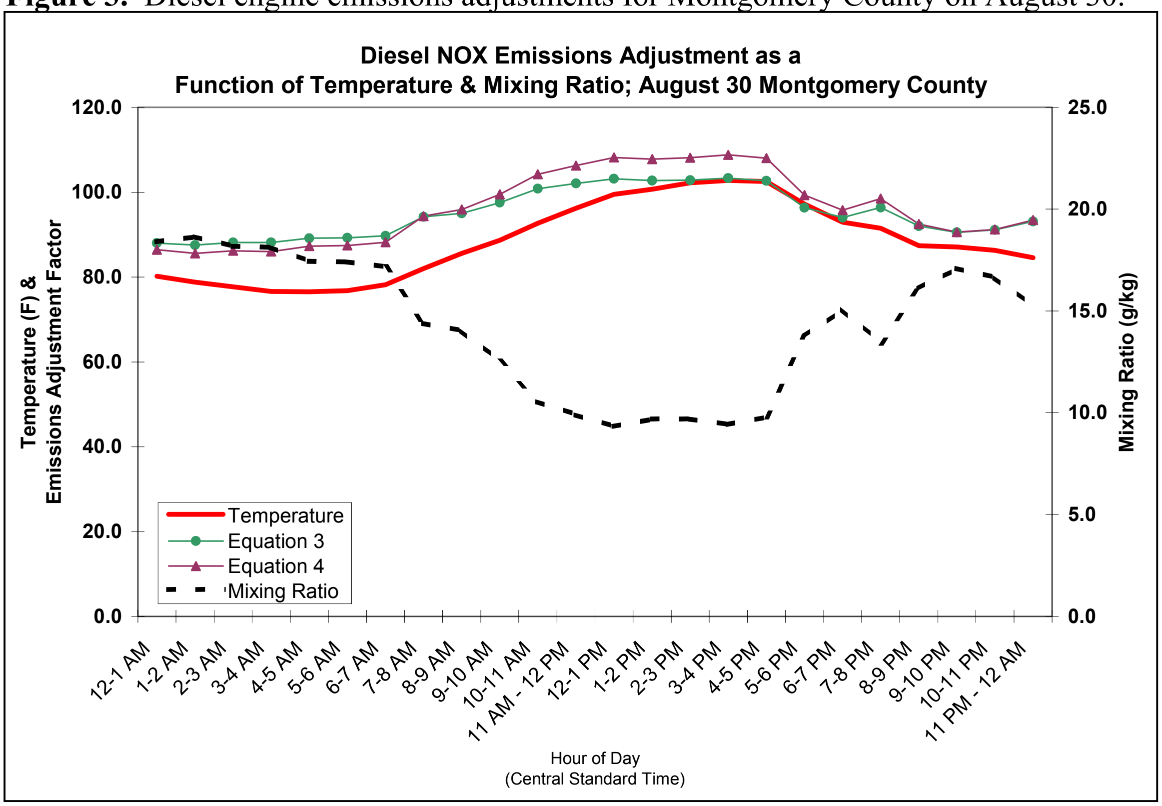
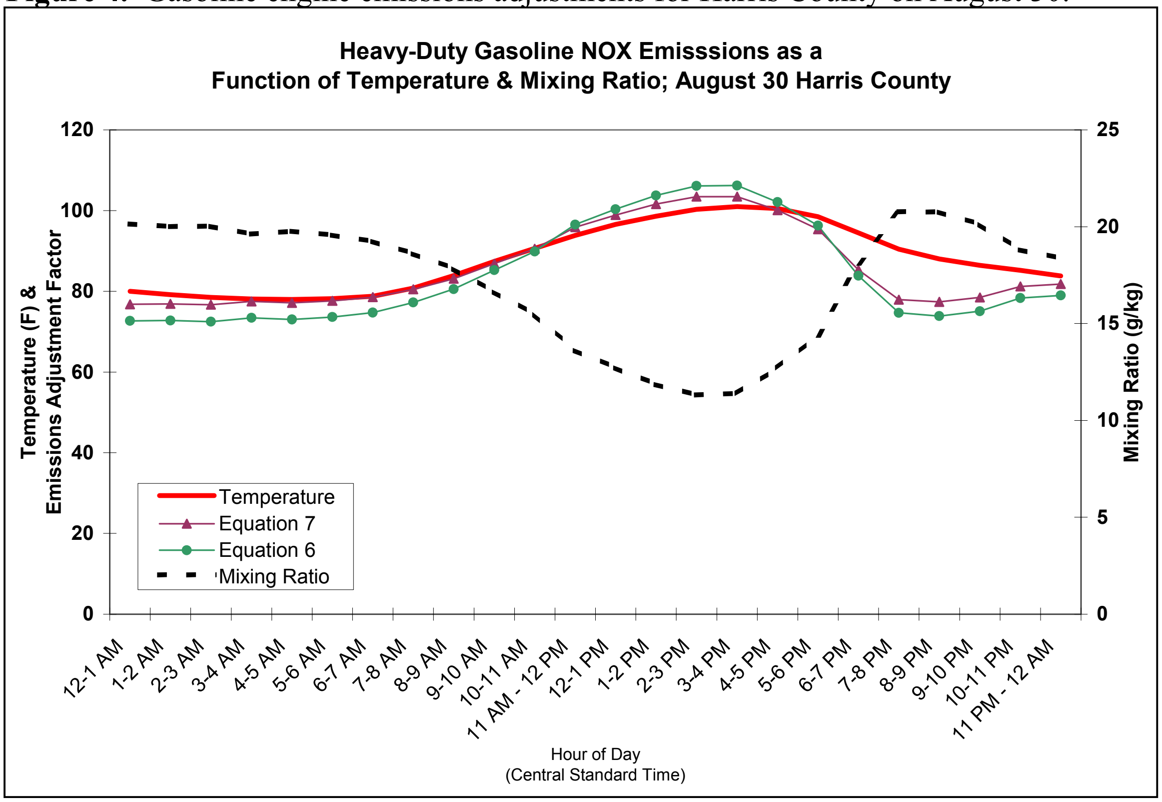


Figure 3. Diesel engine emissions adjustments for Montgomery County on August 30.



The NOx corrections for heavy-duty gasoline vehicles and equipment are typically much less important than the diesel correction because the NOx emission inventory for heavy-duty gasoline vehicles is usually about 10% of the diesel NOx emission inventory. Still the correction equation is different than that for diesel vehicles showing a greater reduction during low temperature evenings and early mornings and equivalent or higher adjustment factors during the higher temperature mid-day period.

Figure 4. Gasoline engine emissions adjustments for Harris County on August 30.

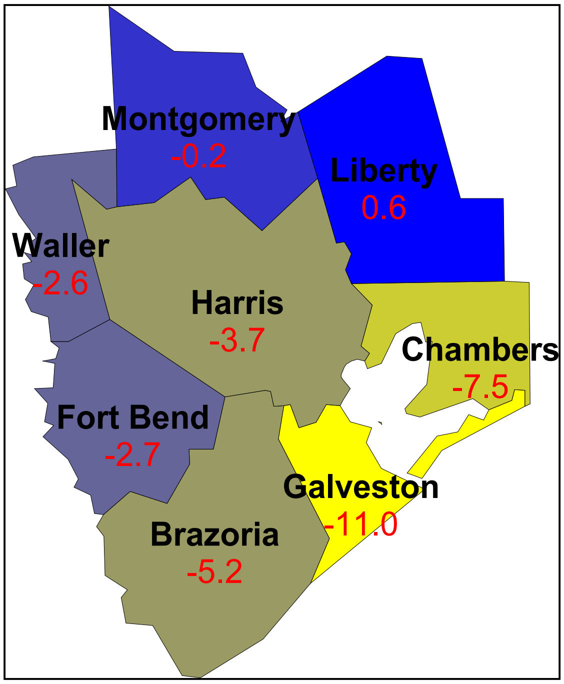


Overall 24-hour county emission adjustments for August 30 by county are shown in Table 1 and in Figure 5. The drier counties, such as Montgomery and Liberty, have much less adjustment compared with the coastal counties of Brazoria, Chambers, and Galveston reflecting the higher humidity near the Gulf.

Table 1. NOx emission adjustment for August 30 for on-road vehicles by county.

County	NOx Adjustment (tpd)	NOx Adjustment (%)
Brazoria	-0.5	-5.2 %
Chambers	-0.3	-7.5 %
Fort Bend	-0.4	-2.7 %
Galveston	-0.9	-11.0 %
Harris	-5.3	-3.7 %
Liberty	0.02	0.6 %
Montgomery	-0.03	-0.2 %
Waller	-0.1	-2.6 %
8-County HGA Totals	**-7.4**	**-3.7 %**

Figure 5. The NOx adjustment by county for August 30 for on-road vehicles.



The daily adjustments will vary with the weather, so for the HGA episode the NOx adjustment ranged from a 0 to 10% reduction in the NOx emission inventory as shown in Table 2. The 8-county totals mostly reflect the adjustment of Harris County, which represents the overwhelming majority of 8-county emission totals. The relative adjustment (% effect) was calculated for the entire on-road inventory though the adjustment was applied to only the heavy-duty portion.

Table 2. NOx emission adjustment for the on-road emission inventory in the 8-county area by episode day.

Day	NOx Adjustment (tpd)	NOx Adjustment (%)
August 18	-6.0	-3.4 %
August 19	-5.5	-3.7
August 20	-2.6	-3.0
August 21	-10.3	-5.2
August 22	-15.4	-8.1
August 23	-15.3	-8.1
August 24	-16.3	-8.6
August 25	-9.3	-5.3
August 26	-7.5	-5.1
August 27	-3.0	-3.6
August 28	-11.0	-5.6
August 29	-11.1	-5.7
August 30 Wednesday On-road Off-road (except Marine and Locomotive	-7.4 -5.7	-3.7 -7.0
August 31	-1.9	-0.9
September 1	-5.6	-3.1
September 2	-6.0	-4.0
September 3	-1.0	-1.1
September 4	-0.4	-0.4
September 5	-3.2	-1.6
September 6	-5.8	-2.9

The locomotive and marine adjustments are shown in Figures 6 and 7 where for these preliminary results, 8-county average conditions were used. The primary difference between locomotive and marine adjustments was that the coastal stations were used for the commercial marine adjustments, which had high and constant humidity levels typical of the marine environment. The higher humidity for marine conditions results in lower NOx emissions than the inland adjustments for locomotives.

Figure 6. The NOx adjustment for locomotives for August 30.

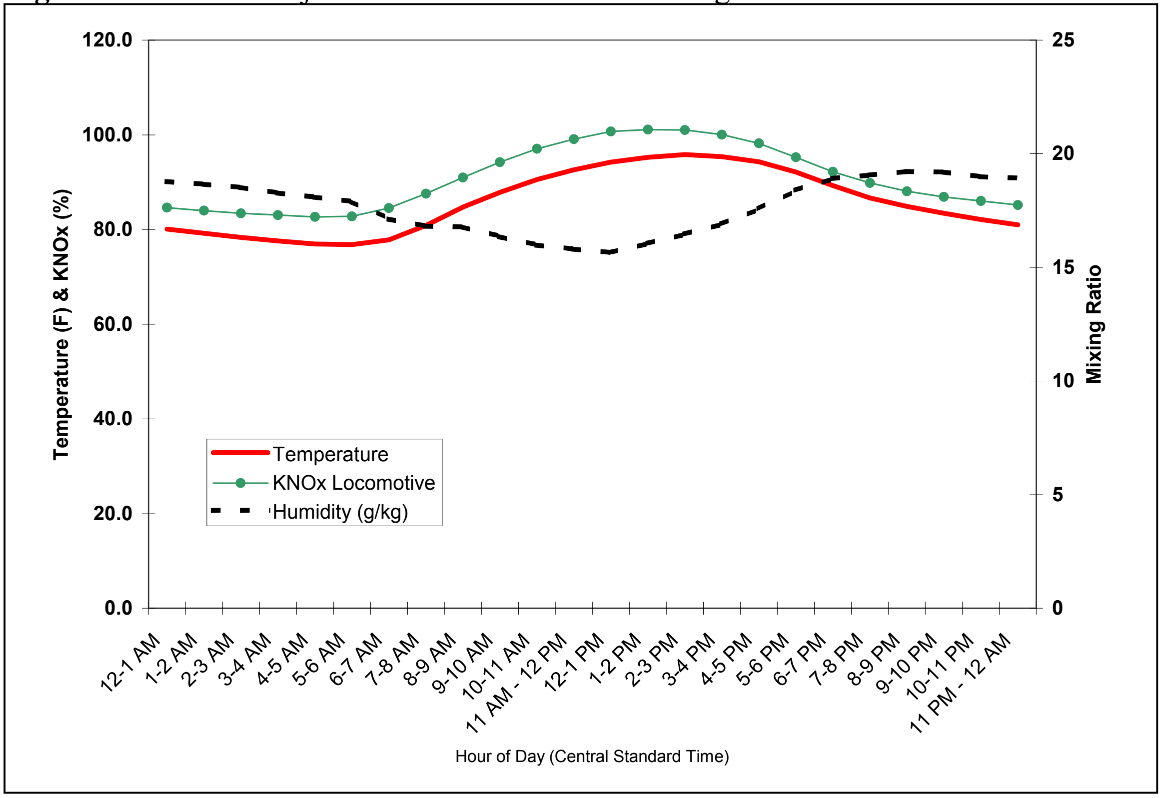
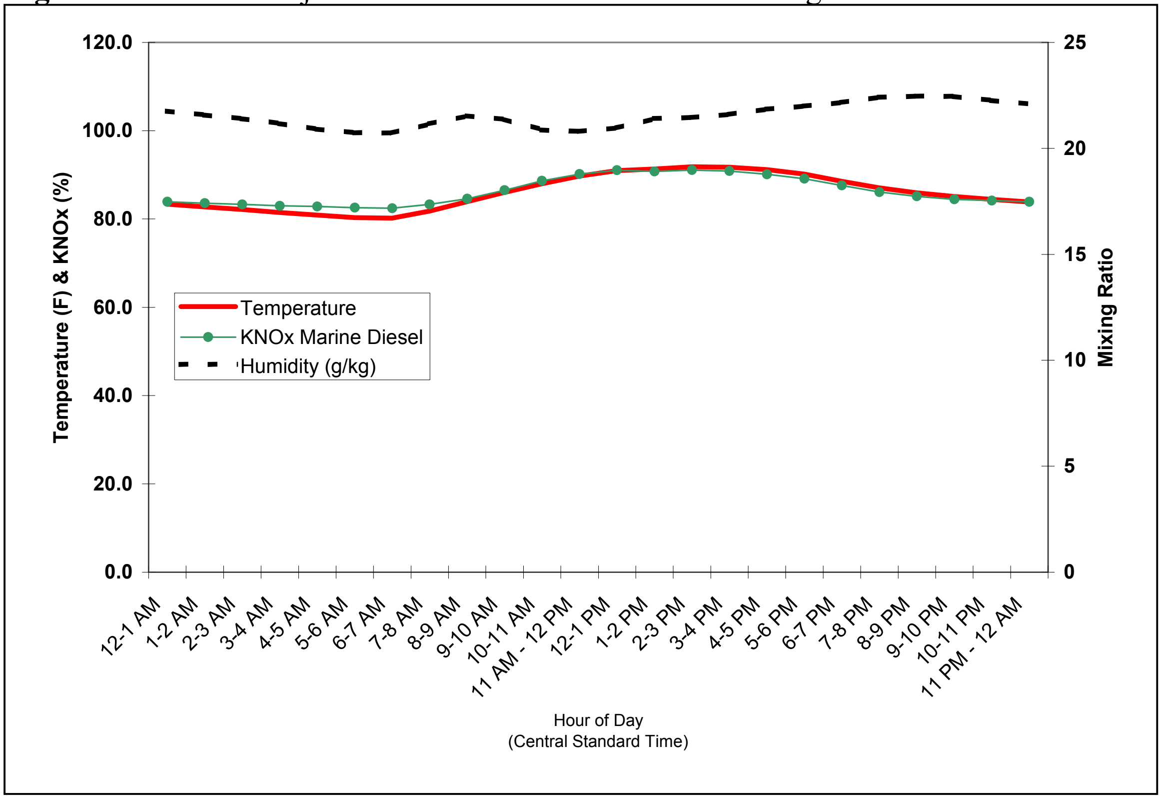


Figure 7. The NOx adjustment for commercial marine for August 30.



Overall the NOx adjustment for the humid HGA was relatively small resulting in less than a 10% reduction in the 24-hour mobile source emissions inventory, but more significant NOx emission reduction occurred (~20%) during the early morning and late night conditions with either no reduction or slight increases in NOx emissions in the mid-day period. The effect of these adjustments on the ozone production and modeling performance has yet to be evaluated, but an evaluation is planned for this project. This work investigated the effect of humidity on NOx emissions for a humid area resulting in an overall reduction of NOx emission, but a drier area will likely show a NOx increase when the adjustment equations are applied.

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