



HUMIDITY AND TEMPERATURE CORRECTION FACTORS FOR NO_x EMISSIONS FROM DIESEL ENGINES

FINAL REPORT

SwRI Project No. 03.30.10.06599

Prepared for:

**ENVIRON International Corporation
101 Rowland Way, Suite 220
Novato, CA 94945-5010**

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1.0 BACKGROUND

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 diesel engines are standardized without regard for regional variation in ambient conditions like temperature and humidity. As early as 1970⁽¹⁾, it was recognized that engine NO_x emissions are significantly affected by the thermodynamic conditions of the intake air. Specifically, the intake air temperature and humidity have the dominant effects⁽¹⁻³⁾. Because of these sensitivities, it is reasonable to assume that regional variations in temperature and humidity can significantly impact engine-out emission levels. These temperature and humidity variations are not fully accounted for in ambient air quality models used by states to assess the impact of various strategies for achieving the ambient air quality standards.

Historically, the impact of ambient temperature and humidity on emissions was of interest because it was impossible to make comparisons of the NO_x emissions from engines tested at different locations, or due to variations in the ambient conditions. In an effort to allow these day-to-day and location-to-location comparisons, various correction factors have been developed. The goal for all of these correction factors is to standardize the NO_x emissions back to selected standard reference conditions.

In light of the pressure on states and urban areas for implementing and achieving air quality standards, it seems appropriate to account for regional benefits or penalties imposed by prevailing ambient conditions. Of particular interest is the impact of ambient conditions on oxides of nitrogen (NO_x), a major contributor to ambient air ozone levels.

2.0 OBJECTIVE

The objectives of this project were to review existing data and correction procedures for adjusting diesel engine NO_x levels for ambient temperature and humidity, and to assess the applicability of these procedures for a number of different diesel engine categories that are used in the Houston Area.

3.0 APPROACH

The existing procedures for correcting NO_x emission levels for ambient temperature and humidity effects were reviewed. The Houston area population of diesel engines was reviewed and divided into subcategories for application of the various existing correction procedures. The correction procedures were compared to each other and to accepted engine performance and emission models for quantitative effects. Recommendations were then made on the application of the correction factors to the engine subcategories.

3.1 Existing NO_x Correction Procedures

A survey of the literature found four applicable procedures for adjusting NO_x emission levels for ambient temperature and humidity. Two procedures were for the heavy-duty diesel engine class⁽³⁻⁵⁾, one for locomotives^(6,7), and one for light-duty diesel engines⁽⁸⁾.

The SAE correction factor for heavy-duty diesel engines was based on work performed by Krause, et al., in 1973⁽³⁾. The relationship, presented as Equation 1, includes the effects of both temperature and humidity, and is referenced to standard conditions of 85°F (29.4°C) and 75 grains/lb (10.71 g/kg) humidity,

$$\begin{aligned}KNO_x &= 1 + A(H - 75) + B(T - 85) \\ \text{Where:} & \\ A &= 0.044(F/A) - 0.0038 \\ B &= -0.116(F/A) + 0.0053\end{aligned}\tag{1}$$

where F/A is the fuel-to-air ratio by mass. The SAE standards J177 and J1003 that reference this correction procedure were recently cancelled on October 1, 2002 with the comment that these procedures were no longer required. This correction factor was also, and continues to be, used as part of the EPA standards CFR title 40 part 89⁽⁴⁾.

Note that the above methods require knowledge of the operational fuel-air ratio, a value that is not easily obtainable for a fleet of vehicles. Also, since these engines/vehicles operate over a wide range of conditions, selection of an average fuel-air ratio for general use would be difficult. Krause, et al., also presented a more generalized equation without the fuel-air ratio term. This equation is,

$$KNO_x = 1 - 0.00216(H - 75) + 0.00076(T - 85)\tag{2}$$

Fritz (5) developed a correction for temperature and humidity based on measurements made in a number of modern (1998-1999) on-road truck engines. A characteristic of this class of engine is the use of air-to-air charge-air coolers. For this study, each manufacturer set up the air-to-air intercooler, which determines the relationship between ambient and charge air temperature. During testing, both the intake and manifold temperatures were controlled per the supplied relationships. This correction factor is shown in Equation 3.

$$KNOx = 1 + [0.00446(T - 25) - 0.018708(H - 10.71)]$$

where :

$$T = \text{ambient temperature, } ^\circ\text{C}$$

$$H = \text{ambient humidity, g / kg}$$
(3)

Fritz and Dodge⁽⁶⁾ developed correction factors for use with locomotive engines. The correction factors include both temperature and humidity parameters. This method was incorporated into the EPA regulations related to locomotive emission standards⁽⁷⁾ and is presented in Equation 4. It is important to note the temperature term is actually the intake manifold temperature, not the ambient temperature, and thus the ambient effects are obscured by the generally unknown relationship between the intake manifold and ambient temperatures. The proposed rule incorporated an additional term in the final correction factor related to the uncertainty regarding the overall procedure.

$$K_H = \frac{C_1 + C_2 e^{(-0.0143)(10.714)}}{C_1 + C_2 e^{(-0.0143)(1000H)}}$$

$$K_T = \frac{1}{1 - 0.017(T_{30} - T_A)}$$

Where:

$$C_1 = -8.7 + 164.5e^{-0.0218(A/F)}$$

$$C_2 = 130.7 + 3941e^{-0.0248(A/F)}$$

H = The specific humidity on a dry basis of the intake air (grams of water per kilogram of dry air).

(A/F) = Mass of moist air intake divided by mass of fuel intake.

T₃₀ = The measured intake manifold air temperature in the locomotive when operated at 30°C.

T_A = The measured intake manifold air temperature in the locomotive as tested.

$$KNOx = \frac{1}{K_H K_T} \quad (4)$$

The effects of temperature and humidity on light-duty diesel engines were investigated by Hare and Bradow⁽⁸⁾. This study included four naturally aspirated diesel engines with prechamber-style combustion chambers. The resulting correction for ambient conditions included only humidity effects, as the range of temperature variation was small; thus, no clear trend for ambient temperature effects was observed. The correction factor is shown in Equation 5.

$$KNO_x = 1 - 0.0152(H - 10.71) \quad (5)$$

where :

H = ambient humidity, g / kg

The NO_x emissions are kinetically controlled during combustion and are fundamentally related to the composition of the fuel, and the time-temperature history during combustion through the adiabatic flame temperature. It is clear that the intake air temperature and humidity affect the adiabatic flame temperature through their impact on the chemical equilibrium conditions during combustion. The initial air temperature affects the compression temperature, which, in turn, affects the flame temperature. The humidity affects both the dilution of the mixture and the specific heat. In fact, these interactions are well understood and can be predicted reliably in a number of engine cycle simulation models.

Thus, in addition to the correction procedures found in the literature, ambient temperature and humidity effects can also be predicted using cycle simulation software. ALAMO_ENGINE⁽⁹⁾ is a cycle simulation code that was developed at Southwest Research Institute that has been demonstrated to provide good predictions of the effects of fuel composition and intake mixture conditions and composition on changes in the NO_x emissions. These effects are accounted for in the model through the use of an adiabatic flame temperature calculation that is performed on a crankangle-resolved basis. The NO_x predictions made using ALAMO_ENGINE have been compared to engine test data, and the results have been good for a wide range of diesel engine designs (e.g., ref. 9).

3.2 Houston Area Diesel Engine Population

The diesel engines used in the Houston can be conveniently considered in terms of four different categories of application, and from two to three different technology levels in each category. They are:

3.2.1 Category 1 - On-Road

- a. Pre-1994
- b. 1994-2002
- c. 2002-

3.2.2 Category 2 – Off-Road

- a. Naturally Aspirated Construction/Farm (<50 HP)
- b. Turbo Charged and Charge Cooled Construction/Farm (>50 HP)

3.2.3 Category 3 – Railroad

- a. Two-Stroke Cycle Engines
- b. Four-Stroke Cycle Engines

3.2.4 *Category 4 – Marine*

- a. Generators
- b. Main Propulsion

All of the correction factors presented above are based on the use of the ambient temperature and humidity, except for the railroad application, where the correction factor is based on the intake manifold conditions. The thermodynamic conditions of the intake air are affected by passage through the intake system.

The intake system can be conveniently considered in terms of two sections. The first section is from the ambient to the intake manifold, the second is from the manifold to the cylinder. The first section can be relatively simple, consisting of simply a filter and a pipe or plenum, typical of a naturally aspirated engine, such as categories 1a, 2a, and 4a listed above. Alternatively, the first section can also be very complex, including the use of an exhaust driven turbocharger compressor and heat exchanger. These configurations are exemplified by categories 1b, 2b, 3b, and 4b. The first section could also include the use of an engine-driven compressor, in addition to the turbocharger, exemplified by 3a.

In all of these cases, the first section affects the temperature of the intake air as it passes through the various devices. Additional changes are likely as the air passes through the second section, where it is affected by heat transfer from the hotter surfaces of the intake port and intake valve.

Every different engine design incorporates features that can, and probably do have different effects on the thermodynamic conditions of the intake air as it enters the engine. In this sense, every engine could theoretically have its own correction factors. The categories and sub-categories, listed above, were identified for this study because they represent, on average, the various combinations of engine technologies that may be affected differently by variation in the ambient temperature and humidity.

ALAMO_ENGINE was used to demonstrate the relative effects of intake manifold humidity, temperature, and EGR level. The results of these predictions are presented in Figures 1 and 2, where the NO_x predictions are plotted versus humidity and EGR level, at constant temperature, and versus humidity and intake temperature at zero EGR. Although there are very few EGR-equipped engines in the field today, it is important to predict the effect of ambient temperature and humidity on these engines to see if their response is dramatically different from non-EGR engines. The calculations were performed assuming that the engine was a 1998 12.7-liter DDC Series 60 engine, equipped with a turbocharger and charge-air cooler, but with the addition of EGR to bring the engine to 2002 standards. The conditions were assumed to be full load at 1800 rpm, with EGR levels that span a reasonable range for this load condition. Over a heavy-duty cycle, most of the NO_x is produced at the higher load conditions, so full load was chosen for these simulations. The intake manifold temperature and humidity ranges were selected to be representative of conditions at various times throughout the year in Houston.

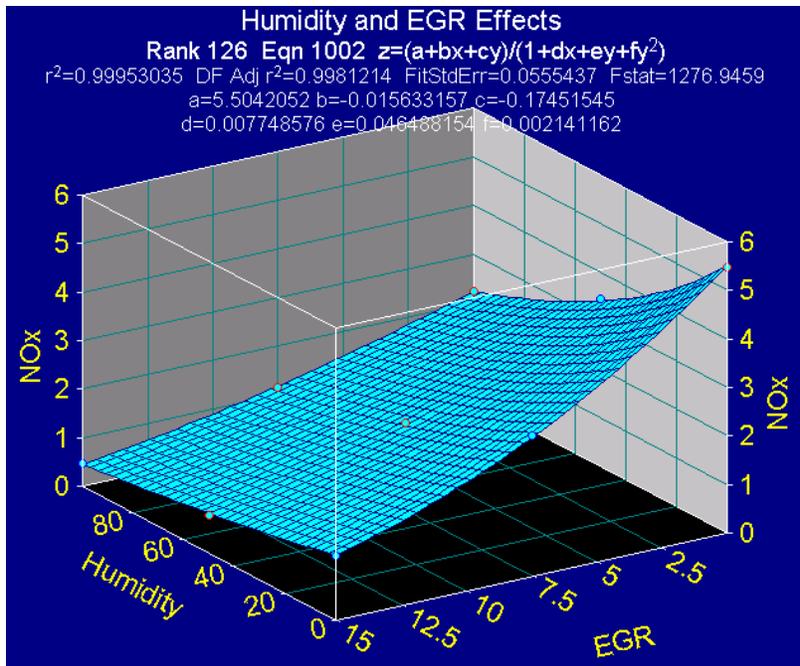


Figure 1 . Humidity and EGR Effects on NO_x - Model Results

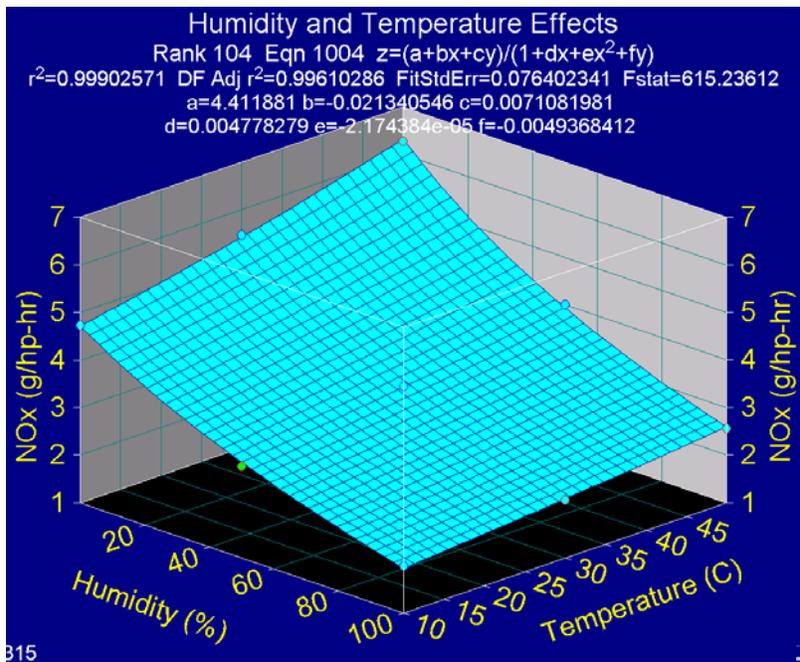


Figure 2. Humidity and Intake Manifold Temperature Effects on NO_x – Model Results

The results of the calculations indicate that the NO_x is affected by all of the parameters, with EGR and humidity having the largest effects. These predictions justify the need for the correction factors and also demonstrate the relative importance of the various parameters that are incorporated in the correction factor calculations.

3.3 Correction Factor Comparisons

As discussed briefly above, there are several problems with the existing correction procedures for ambient effects. First, it should be noted that only limited data for diesel engines were found in the literature. Two of the four studies, the light-duty⁽⁸⁾ and EPA/SAE⁽³⁾ heavy-duty procedures, were conducted in the 1970's and represent effects with engine technology of that time period. Second, two of the published procedures, the EPA/SAE⁽³⁾ and the locomotive⁽⁶⁾ procedures, require the use of fuel-air ratio as a predictor variable. While this is convenient for steady-state testing, application of this procedure for fleet emissions is problematic due to the uncertainty of the operational fuel-air ratio. Third, the light-duty and the locomotive procedures are not functions of ambient temperature. The locomotive correction factor requires the use of the manifold air temperature that may be difficult to estimate due to the wide variation in locomotive cooling system configurations. Fundamentally, the manifold air temperature should be a better predictor of NO_x formation; however, the relationship between manifold air temperature and ambient temperature is not always straightforward, particularly with turbocharged, aftercooled engines. The light-duty procedure, which may be useful for naturally aspirated engines, does not incorporate a temperature variable due to the limited temperature range over which the data were collected. In spite of these limitations, the correction factors by the various methods are remarkably similar.

The four different correction factor calculations were incorporated into an EXCEL spreadsheet. The four equations were then used to calculate the correction factors as functions of ambient temperature and humidity. The results of these calculations are presented in Figure 3, where the correction factors are plotted versus the humidity, at constant temperature (25°C). For these comparisons, Equation 2 was used to represent the EPA correction procedure that is based on the work by Krause et al⁽³⁾, since it does not require an air/fuel ratio. The results indicate that the four different methods are very similar. Also plotted in Figure 3 are the ALAMO_ENGINE predictions of the relative effects of humidity on the NO_x for a Series 60 12.7-liter engine at 25.5:1 AFR. As can be seen, the ALAMO_ENGINE predictions are similar to the published results but indicate a larger humidity effect than observed. The humidity effect is predicted to be slightly less at lighter loads. Although EGR dramatically lowers NO_x, the humidity effect on NO_x is predicted to be similar for EGR and non-EGR engines.

The effects of ambient temperature on the NO_x correction factors are presented in Figure 4. In this case, the calculated temperature effects are assuming that the ambient temperature change results in the same temperature change in the intake manifold, where the actual temperature change is less than the ambient temperature change. However, the magnitude of the change in the intake manifold temperature depends on whether the engine is turbocharged/intercooled, turbocharged but not intercooled, or naturally aspirated. There is a larger variation in the correction factors for ambient temperature than observed for humidity. It should be noted that, as discussed above, the light-duty and the locomotive correction factors are not a function of ambient temperature, and hence, show no effect. This could be misinterpreted to imply incorrectly, that for these classes of engine, ambient temperature has no effect. For the locomotive correction factor, a relationship between ambient and manifold temperature is required to account for ambient temperature variation. For the light-duty engine class, insufficient temperature range obscured the temperature effects when the correction factor

method was developed. In the case of a naturally aspirated engine, the relative NO_x can be predicted using ALAMO_ENGINE by assuming that the manifold air temperature is equal to the ambient temperature. This estimated correction factor is illustrated in Figure 4. As shown, the modeled results are similar to the results obtained by Fritz (5) for the heavy-duty engine class. This approach would be considered a worst case approach, as the manifold temperature would not be expected to vary as widely as the ambient air temperature. Limited testing at SwRI has compared the change in ambient air temperature to the change in temperature at the intake port area (which should be the best predictor for changes in NO_x emissions) of a turbocharged intercooled engine, and a 50°C change in inlet air temperature resulted in a 25°C change in the temperature in the intake port.

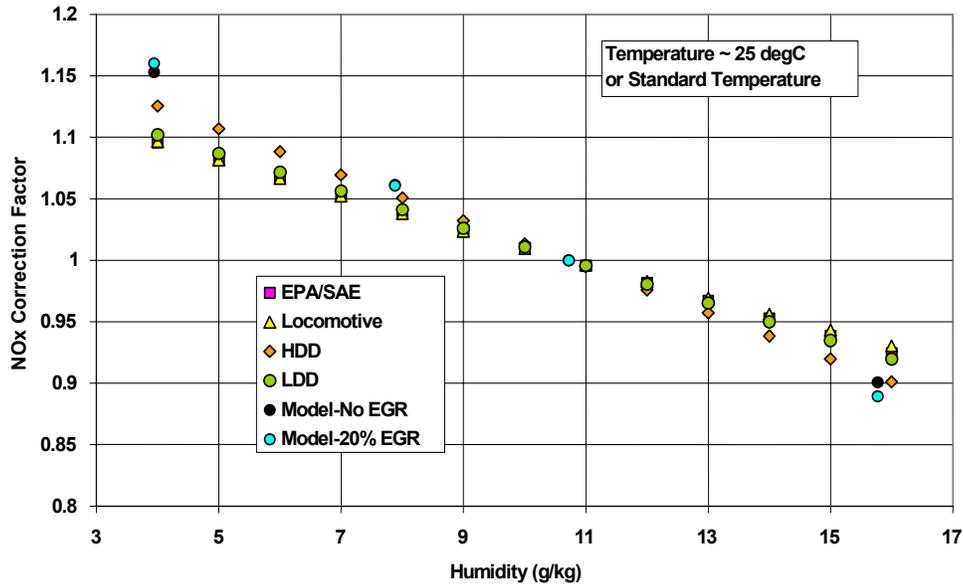


Figure 3. Humidity Effect on NO_x Correction Factors at Constant Temperature

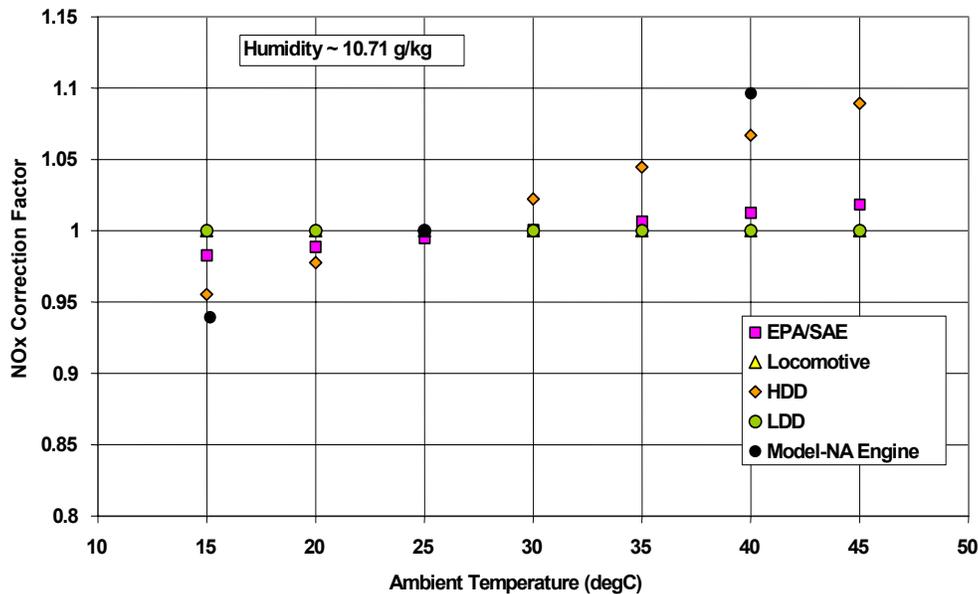


Figure 4. Temperature Effect on NO_x Correction Factors at Constant Humidity

3.4 Recommended Practice

The variations in the correction factors are not large. The recommended approach is to apply the appropriate correction to each of the engine categories. This approach requires the existence of an inventory that includes the numbers and types of engines. It further requires that the engines in the inventory be categorized according to the scheme presented above. If this is done, then the correction factors should be applied as follows:

3.4.1 *Category 1 - On-Road*

- a. Pre-1994 Equation 2, essentially the EPA correction factor without the F/A ratio dependence. This eliminates the requirement for determining the F/A ratio of the fleet.
- b. 1994-2002 Equation 3, heavy-duty correction procedures published by Fritz for late model diesel engines.
- c. 2002- Equation 3, heavy-duty correction procedures published by Fritz for late model diesel engines.

3.4.2 *Category 2 – Off-Road*

- a. Naturally Aspirated Construction/Farm: The light-duty correction procedure, Equation 5, is not recommended for this class of engine due to the lack of temperature correction. Therefore Equation 2, essentially the EPA correction factor without the F/A ratio dependence, is recommended. This eliminates the requirement for determining the F/A ratio of the fleet.
- b. Turbocharged and Charge-Cooled Construction/Farm: Equation 3, heavy-duty correction procedures published by Fritz for late model diesel engines.

3.4.3 *Category 3 – Railroad*

- a. Two-Stroke Cycle Engines: Equation 4, the locomotive factors developed by Fritz. In order to use this equation, estimates of the F/A ratio and intake manifold temperature are required. If these values are not known, SwRI recommends an A/F ratio of 38, and no temperature correction (a value of 1.0 for this term of the equation).
- b. Four-Stroke Cycle Engines Equation 4, the locomotive factors developed by Fritz. In order to use this equation, estimates of the F/A ratio and intake manifold temperature are required. If these values are not known, SwRI recommends an A/F ratio of 25.6, and no temperature correction (a value of 1.0 for this term of the equation).

3.4.4 *Category 4 – Marine*

- a. **Generators** Equation 4, the locomotive factors developed by Fritz. In order to use this equation, estimates of the F/A ratio and intake manifold temperature are required. If these values are not known, SwRI recommends an A/F ratio of 38 for two-stroke engines, or 25.6 for four-stroke engines, and no temperature correction (a value of 1.0 for this term of the equation).
- b. **Main Propulsion** Equation 4, the locomotive factors developed by Fritz. In order to use this equation, estimates of the F/A ratio and intake manifold temperature are required. If these values are not known, SwRI recommends an A/F ratio of 38, and no temperature correction (a value of 1.0 for this term of the equation).

4.0 SUMMARY

Existing correction procedures for ambient effects on NO_x emissions from diesel engine were reviewed. These procedures were developed for heavy-duty, light-duty, and locomotive diesel engines. In general, these procedures were similar in the effect of humidity, although the ambient temperature effects were not as clearly determined by the existing procedures. The defining temperature for NO_x emissions is the intake manifold air temperature, which is dependent on the ambient temperature but is also influenced by the engine configuration, turbocharged-aftercooled, naturally aspirated, or scavenged. Recommendations were made for application of existing correction procedures for the identified class of engines.

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