

# Investigation of Environmental Measures Using Delay

**NCDOT Technical Assistance Request 2025-05**  
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<p>16. Abstract</p> <p>This technical assistance request developed enhanced methods for incorporating environmental considerations into NCDOT's Strategic Prioritization (SPOT) process for P8.0 highway projects. Building on earlier work that established greenhouse gas (GHG), criteria pollutant (CP), and mobile source air toxics (MSAT) measures using EPA's MOVES model and VMT-based estimates, the study addressed several specific improvement types (SITs) for which VMT is not the appropriate input. For these projects, delay serves as the primary driver of emissions impacts. The technical assistance effort evaluated the use of delay as an input for environmental measures, conducted a focused review of how vehicle speeds and air temperature influence emissions, and created formulas that use vehicle hours traveled (VHT) for all remaining mobility SITs to support consistent emissions estimation for both base and build scenarios.</p> <p>The resulting white paper documents recommended approaches for integrating delay-based and VHT-based environmental measures into the SPOT prioritization framework, including guidance on placement within the scoring process and considerations for weighting or costing the measures. It also summarizes the supporting literature review and provides the emissions formulas for all relevant SITs. Key meetings with stakeholders were conducted to ensure that the recommendations align with agency needs and support effective decision-making.</p> <p>The final delay methodologies are included in <i>TA 2025-11: Using EPA MOVES to Build a Repository of Emissions Factors</i>.</p>			
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## Executive Summary

This effort helped advance the integration of environmental considerations into NCDOT's Strategic Prioritization (SPOT) process for P8.0 highway projects by developing improved methods to quantify emissions impacts across a broad range of highway specific improvement types (SITs). Earlier work had introduced greenhouse gas (GHG), criteria pollutant (CP), and mobile source air toxics (MSAT) measures based on EPA's MOVES model and vehicle miles traveled (VMT) estimates. However, several SITs were identified where VMT is not an appropriate input for characterizing emissions. This technical assistance project addressed that gap by evaluating delay-based emissions estimation, reviewing how vehicle speeds and air temperature influence emissions rates, and developing vehicle hours traveled (VHT)-based formulas to support consistent and comparable emissions accounting across all relevant mobility SITs.

The methodologies produced through this work are documented in a white paper that outlines recommended approaches for incorporating delay- and VHT-based environmental measures into the SPOT scoring process. The document provides guidance on where these measures best fit within the prioritization framework, considerations for weighting or costing them, and supporting technical detail from the literature review. These approaches were further refined through engagement with key stakeholders to ensure alignment with program needs and operational practices.

The methods developed here also served as a foundational input to NCDOT Technical Assistance Request TA 2025-11: Using EPA MOVES to Build a Repository of Emissions Factors. That subsequent effort used the delay- and VHT-based methodologies to construct a comprehensive, standardized emissions-factor repository, resulting in the final emissions accounting framework for all highway SITs. Together, these two technical assistance efforts establish a consistent, defensible, and fully integrated approach to emissions quantification within NCDOT's project prioritization process.

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# Literature Review

## Introduction

Vehicle emissions are a major contributor to urban air pollution and greenhouse gas accumulation, with their intensity and composition influenced by a variety of operational and environmental factors. One of the most critical phases for emissions is the initial start-up of the vehicle, cold start, when the engine and emissions control systems have not yet reached optimal operating temperatures. During this phase, emissions of pollutants such as carbon monoxide (CO), total hydrocarbons (THC), and particulate matter (PM) can be significantly elevated, while only slightly elevated for nitric oxides (NO<sub>x</sub>) (EPA, 2024; Nam et al., 2010; Hall-Quinlan et al., 2023).

Emissions literature reveals that acceleration events are particularly emission-intensive, with spikes in CO, CO<sub>2</sub>, and NO<sub>x</sub> emissions often coinciding with rapid changes in speed (Unal et al., 2004; Frey et al., 2003; Kean et al., 2003). Studies using real-world driving data from vehicles such as the Ford Taurus and Oldsmobile Cutlass demonstrate that emission rates during acceleration can be several times higher than during idling or cruising (Frey et al. 2003). Furthermore, increases in posted speed limits have been shown to elevate average driving speeds, which in turn lead to higher fuel consumption, increased emissions, and even adverse safety and health outcomes (Van Benthem, 2015; Chakraborty et al., 2023).

Temperature also plays a complex role. While some pollutants, such as CO and CO<sub>2</sub>, are more sensitive to cold-start conditions (EPA, 2024; Robertson, 2019), others like NO<sub>x</sub> show mixed responses depending on fuel type and catalyst efficiency (EPA, 2024; Knapp et al., 1998). Research also indicates that PM emissions, like black carbon<sup>1</sup> (BC) increase significantly at lower temperatures, particularly during the cold start phase (Nam et al., 2010; Hall-Quinlan et al., 2023).

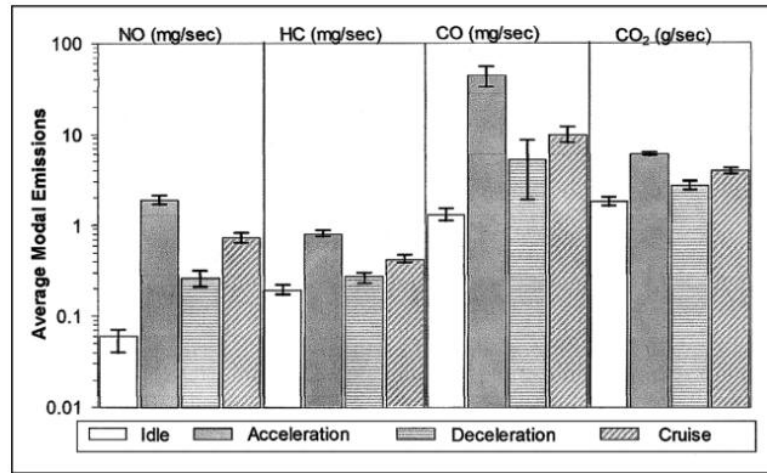
## Speed

The relationship between vehicle speed and emissions is well-documented, with acceleration events consistently identified as major contributors to elevated pollutant levels. Frey et al. (2003) point out that the average emission rate on a mass-per-time basis during acceleration is typically 5 times greater than the idle emission rate for HC and CO<sub>2</sub>, and 10 times or more for NO<sub>x</sub> and CO. They also found that “most peaks in CO emission rates tend to coincide with accelerations” (Frey et al., 2003, p. 996). In contrast to acceleration, they claim that the CO emission rate during idling or crawling, as shown in Figure 1, is low in comparison (Frey et al., 2003, pp. 996-98). Unal et al. (2004) had similar conclusions. They found that the largest peak in CO emission rate, 1.62 g/sec, happened during acceleration from 0 to 50 mph downstream of Dillard Drive,

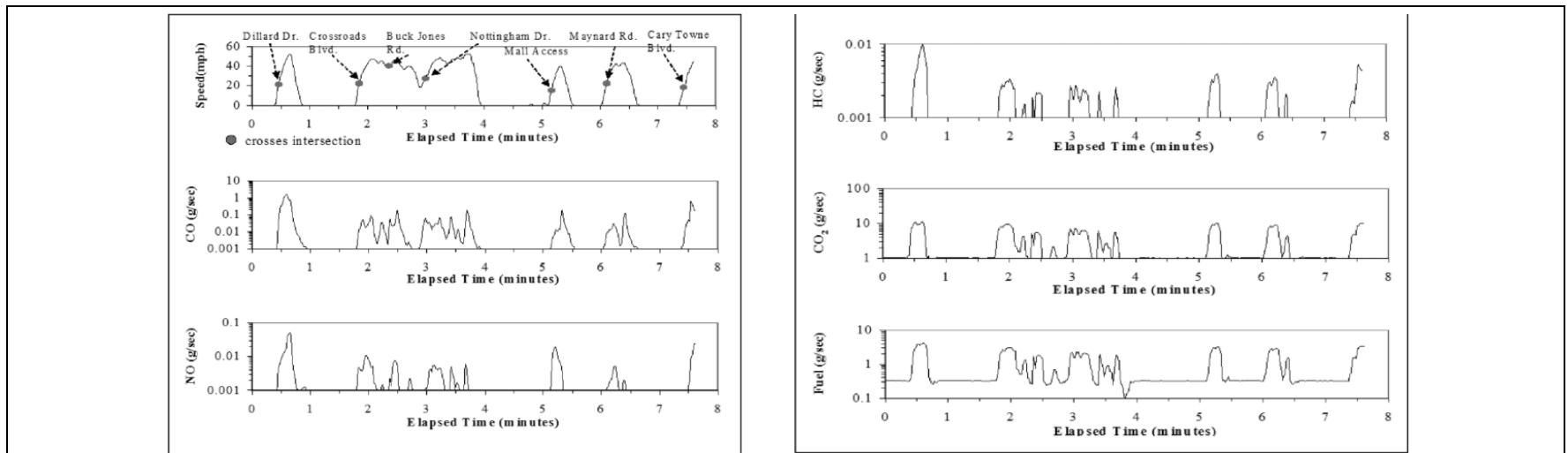
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<sup>1</sup> Black carbon is the sooty black material emitted from gas and diesel engines, coal-fired power plants, and other sources that burn fossil fuel. It comprises a significant portion of particulate matter or PM, which is an air pollutant.

Raleigh. They also noticed the same happening with HC, NO<sub>x</sub>, and CO<sub>2</sub> emission rates peaking during acceleration and high-speed driving at 0.5th and 7.5th minute (see Figure 2) (Unal et al., 2004, p. 133).

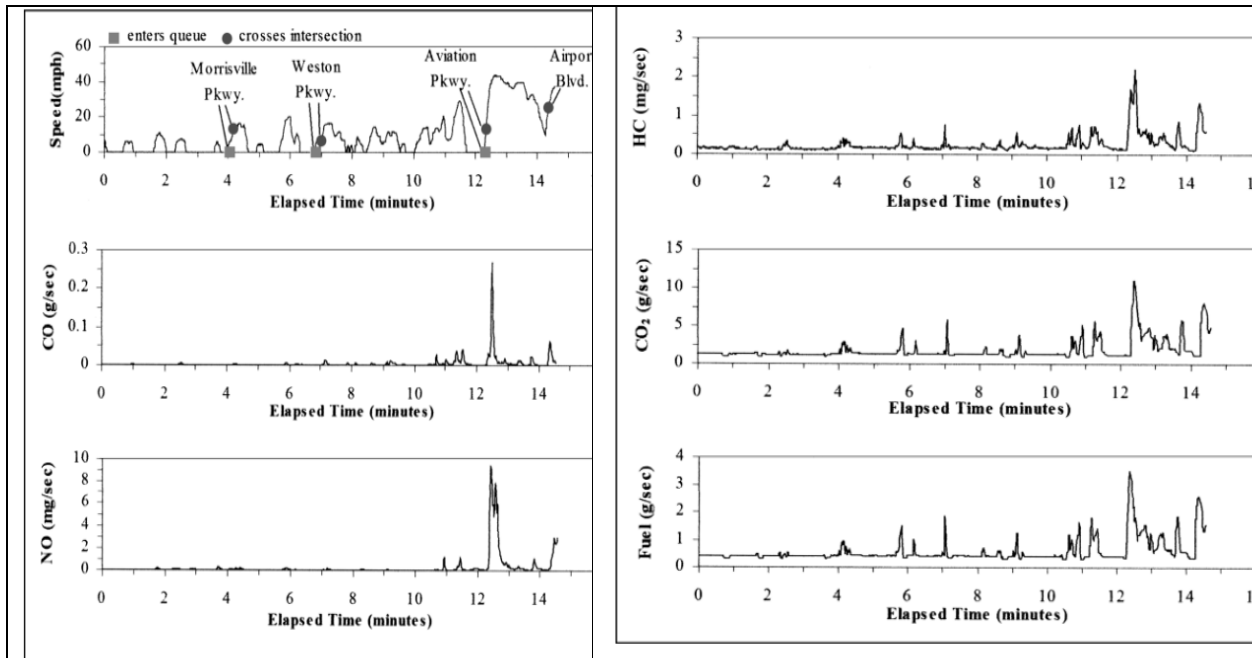


**Figure 1. Average Modal Emission Rates for a 199 Ford Taurus Operated on Chapel Hill Road Based on 141 Trips (Frey et al., 2003, p. 998).**



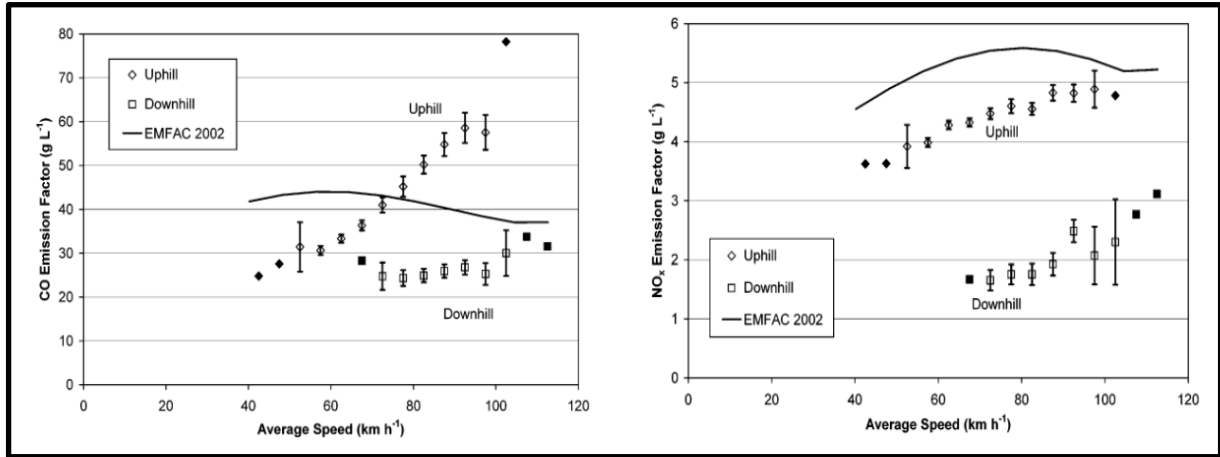
**Figure 2. 1996 Oldsmobile Cutlass Operated on the Walnut Street Study Corridor on October 10, 2000, for Speed, Emission Rates, and Fuel Consumption (Unal et al., 2004, p. 133).**

Regarding NO<sub>x</sub> emissions, Unal et al. (2004) found that the NO<sub>x</sub> emission rate remained below 0.005 g/sec for 90% of the travel time but increased nearly tenfold during acceleration through the Dillard Drive intersection, as shown in Figure 2 (p. 133). Similarly, Frey et al. (2003) observed that the NO<sub>x</sub> emission rate increased by nearly 100 times during acceleration through the intersection with Aviation Parkway, Raleigh (see Figure 3). NO<sub>x</sub> emissions were also sensitive to higher-speed travel toward the end of the trip, with several large peaks in emission rate during the last two minutes—similar to CO, HC, and CO<sub>2</sub> emissions (Frey et al., 2003, p. 996).



**Figure 3.** Time traces of vehicle speed, emission rates, and fuel consumption for a 1999 Ford Taurus driven on Chapel Hill Road on August 29, 2000 (Frey et al., 2003, p. 996).

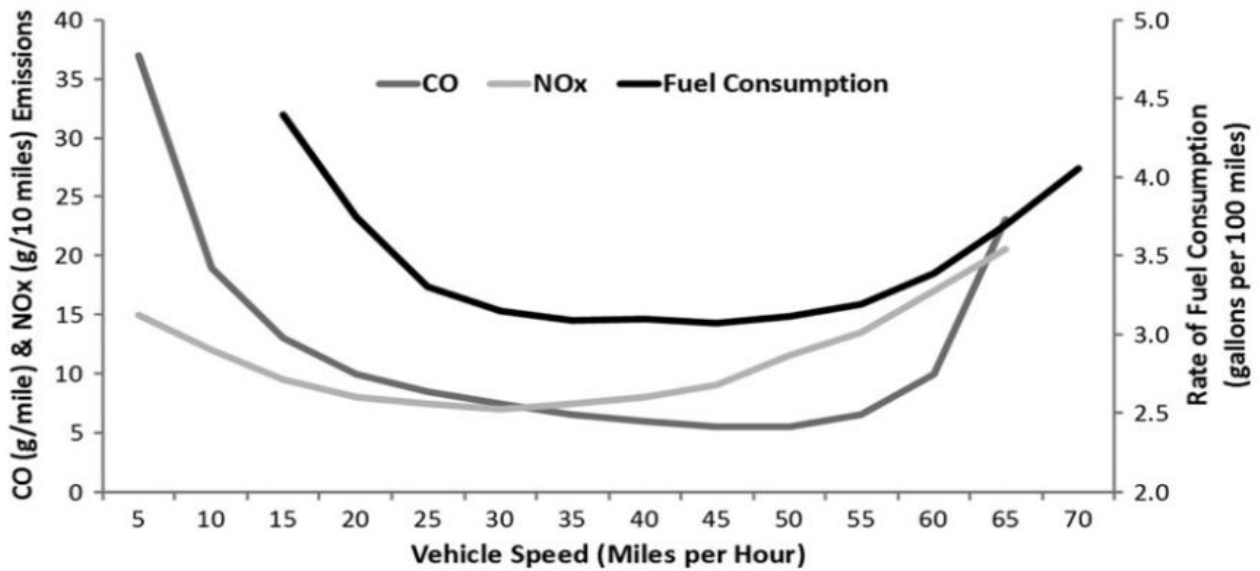
On a similar note, Kean et al. (2003) noted that  $\text{NO}_x$  emissions for light-duty vehicles in a California highway tunnel increased between 3.8 and 5.3 grams per liter of gasoline consumed during uphill driving at 40–80 km/h, although not as strongly as CO emissions which went from 25 grams per liter to 45, as shown in Figure 4. **Error! Reference source not found.** (Kean et al.,



**Figure 4. CO and NO<sub>x</sub> emission factor vs average vehicle speed with comparison to EMFAC2002 (Kean et al., 2003, p. 3742).**

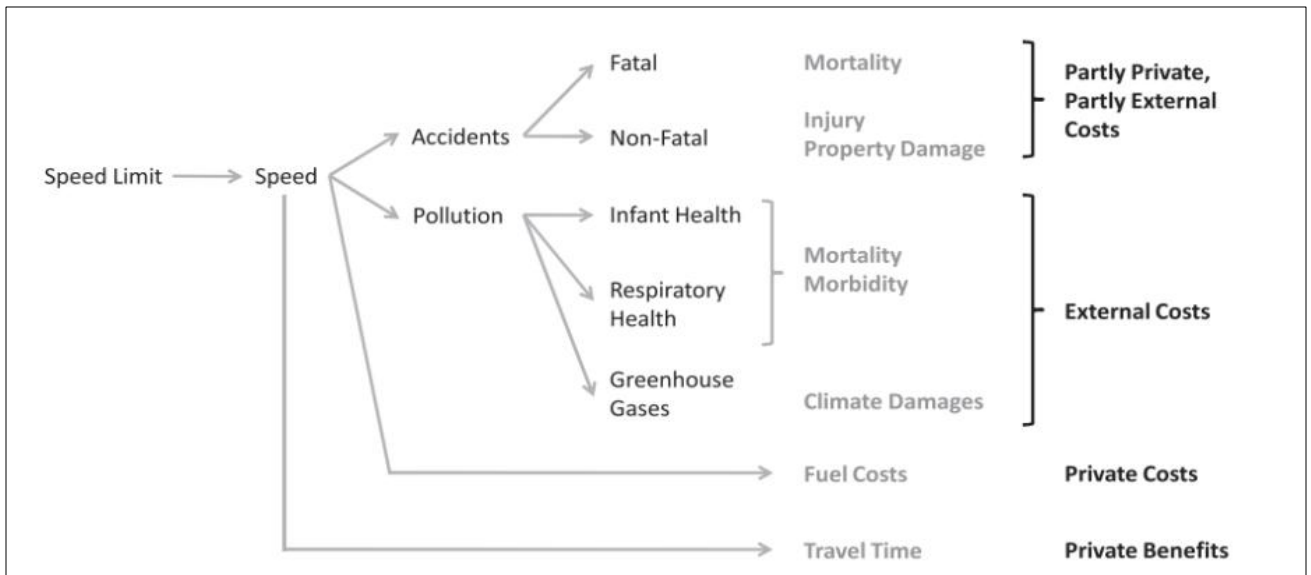
2003, p. 3,739).

The relationship between emissions and varying speed modes is especially affected by speed limit increases. Van Benthem (2015) found that a 10 mph increase (from 55 to 65 mph) on highways in western U.S. led to a 3–4 mph increase in actual speeds, which resulted in elevated pollutant concentrations: 14–24% (CO), 8–15% ( $\text{NO}_x$ ), and 1–11% (ozone) (p. 44). He argues that it also led to a 9–15% increase in accidents, 34–60% more fatal accidents, and a 9% higher fetal death rate near affected freeways. He elaborates on the costs and benefits of increasing speed limits in Figure 6. In Figure 5, Van Benthem visualizes the relationship between speed, per-mile tailpipe emissions, and the rate of fuel consumption for the vehicle fleet in 1990 (Van Benthem, 2015, pp. 44-54).



**Figure 5. Relationship Between Vehicle Speed, Emissions, and Fuel Consumption Using 1990 Fleet-Wide Average for Gasoline Vehicles (Van Benthem, 2015, p. 54).**

Chakraborty et al. (2023) reported that vehicle operating speeds in Michigan increased by 2.3 mph and 2.2 mph for passenger and heavy vehicles on freeways where speed limits were increased from 70 to 75 mph for passenger vehicles and 60 to 65 mph for heavy vehicles. On non-freeways, the speed limit increase was 55 to 65 mph for all vehicles, which led to an operating speed increase of 3.4 mph for passenger vehicles and 3.7 mph for heavy vehicles, as pointed out by Chakraborty et al. They also claim that fuel economy decreased by more than 5%



**Figure 6. Costs and Benefits of Increasing Speed Limit (Van Benthem, 2015, p. 45).**

and 3% for passenger and heavy vehicles on freeways, leading to an annual fuel consumption increase of 11.9% and 11.0%. On non-freeways, the increases were 7.2% and 25.2%, respectively. Among all the pollutants they had analyzed, for passenger vehicles, CO contributed the largest share of the overall increase in emissions, followed by HC, whereas heavy vehicles exhibited the greatest emissions for NO<sub>x</sub>, followed by CO, as shown in Table 1 (Chakraborty et al., 2023, pp. 41-45).

Pollutant	Passenger vehicles			Heavy vehicle					
	Small vehicle EPA emission rate (gms/mi)	Light duty heavy vehicle EPA emission rate (gms/mi)	Annual increase in emission (tons)			EPA Emission rate (gms/mi)	Annual increase in emission (tons)		
			Before	After	% Change		Before	After	% Change
<b>Freeways</b>									
VOC	1.034	1.224	3,973.6	4,445.4		0.447	176.8	196.2	
HC	1.077	1.289	4,168.1	4,663.0		0.453	179.2	198.9	
CO	9.400	11.84	37,603.4	42,068.3		2.311	914.0	1,014.5	
NO <sub>x</sub>	0.693	0.95	2,932.4	3,280.6	<b>+11.9</b>	8.613	3,406.6	3,781.1	<b>+11.0</b>
PM <sub>10</sub>	0.0044	0.0049	16.3	18.2		0.202	79.9	88.7	
PM <sub>2.5</sub>	0.0041	0.0045	15.0	16.8		0.219	86.6	96.1	
<b>Total</b>			<b>48,708.8</b>	<b>54,492.2</b>			<b>4843.1</b>	<b>5375.6</b>	
<b>Non-freeways</b>									
VOC	1.034	1.224	9,405.4	10,086.6		0.447	336.4	421.1	
HC	1.077	1.289	9,865.8	10,580.4		0.453	340.9	426.7	
CO	9.400	11.84	89,007.1	95,453.8		2.311	1,739.2	2,177.0	
NO <sub>x</sub>	0.693	0.95	6,941.0	7,443.7	<b>+7.2</b>	8.613	6,481.8	8,113.6	<b>+25.2</b>
PM <sub>10</sub>	0.0044	0.0049	38.5	41.3		0.202	152.0	190.3	
PM <sub>2.5</sub>	0.0041	0.0045	35.6	38.1		0.219	164.8	206.3	
<b>Total</b>			<b>1,15,293.3</b>	<b>123,644.0</b>			<b>9,215.1</b>	<b>11,535.0</b>	

*Table 1. Emissions Affected by Speed Limit Increase (Chakraborty et al., 2023, p. 45).*

## Temperature

Ambient temperature is a key environmental factor influencing vehicle emissions, particularly during the cold start phase when engine and catalyst systems are not yet fully operational. Researchers at the Environmental Protection Agency (EPA) (2024) argue that cold-start NO<sub>x</sub> emissions are less sensitive to ambient temperature changes than THC and CO emissions. This, as they point out, is because fuel-rich conditions at engine start favor incomplete combustion, forming CO and THC, whereas NO<sub>x</sub> is favored under lean-burn, high-temperature conditions typical of running emissions. However, they admit that NO<sub>x</sub> emissions can still be affected at a greater sensitivity to cold start, dependent on the condition of the three-way catalyst in vehicles. With running exhaust for all gasoline vehicles on MOVES, they state that they do not model temperature effects for THC, CO, and NO<sub>x</sub> because they “did not find a significant temperature effect” (EPA, 2024, pp. 20-32).

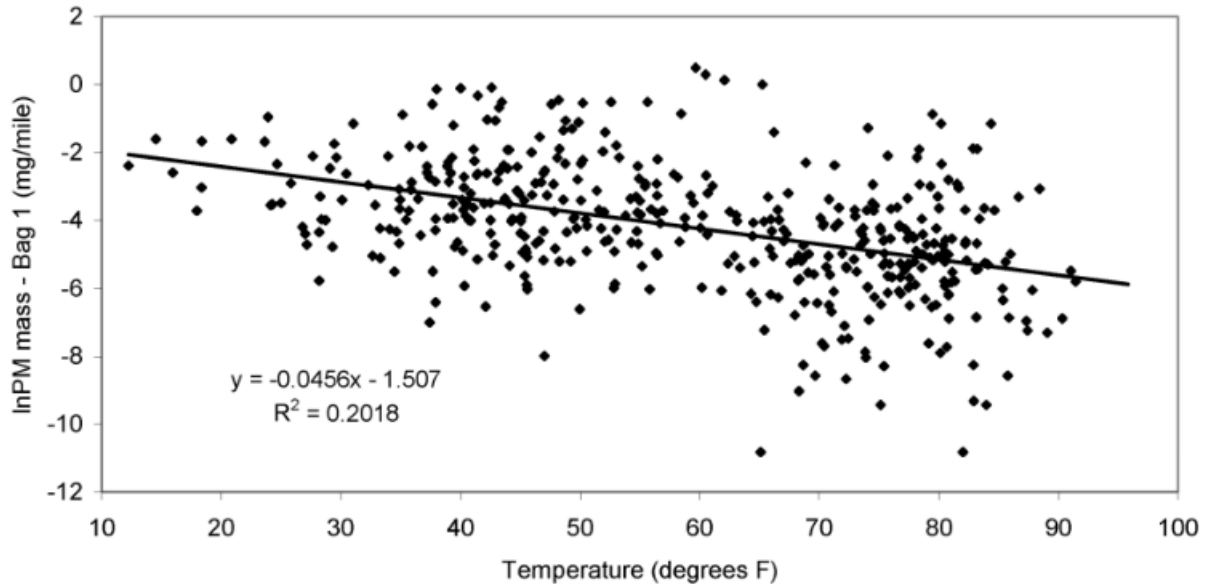
Not everyone agrees with the assessment of EPA’s researchers. Knapp et al. (1998) found that at -20 °F, most vehicles using E10 (gasoline with 10% ethanol) showed increased NO<sub>x</sub> emissions. However, at other temperatures, vehicles showed an average % reduction in NO<sub>x</sub> emissions with the same fuel type (Knapp et al., 1998, p. 646). Hall-Quinlan et al. (2023) noted that inferred mobile NO<sub>x</sub> emissions at a near-road site in Maryland were lower at higher temperatures, while CO and CO<sub>2</sub> emissions remained relatively constant (p. 2).

Yet Robertson (2019) found that each 1°C increase in temperature was associated with a 0.162% increase in CO<sub>2</sub> emissions per year per state. He also claims that a 1% increase in registered vehicles led to a 0.927% increase in emissions. He also states that the average temperature among the 48 states was 10.618°C in 2014, 11.78°C in 2015, and 12.178°C in 2016 (p. 626). If 2015 and 2016 temperatures had remained at 2014 levels, 27 and 38 million tons of CO<sub>2</sub> emissions could have been avoided (see Table 2) (Robertson, 2019, p. 625-26).

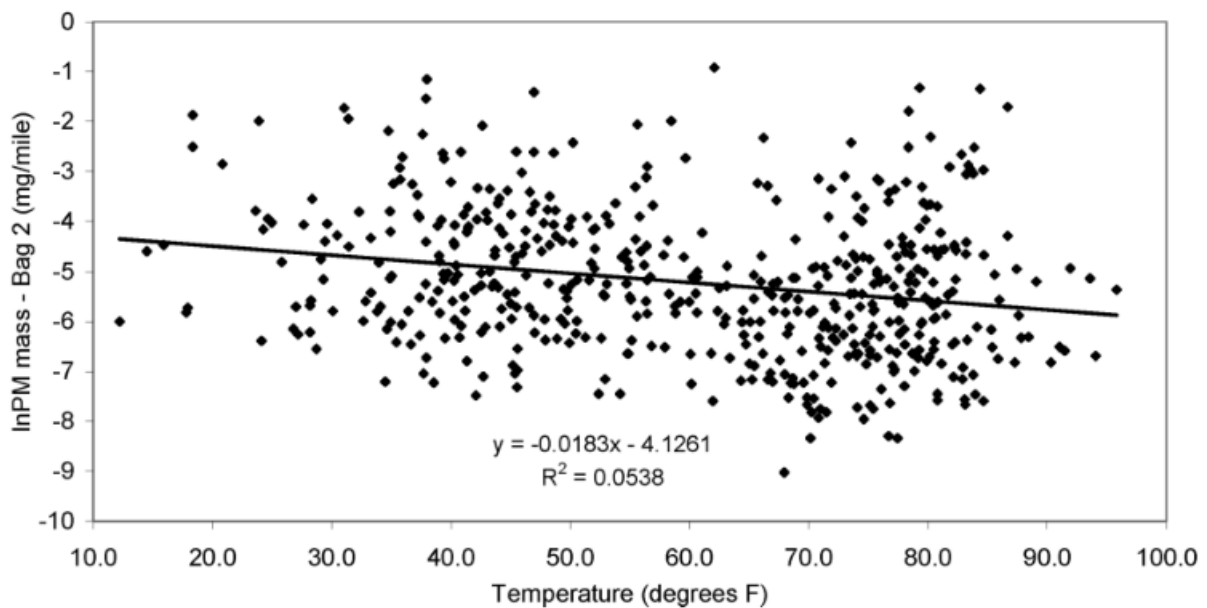
**Table 2. Predicted Millions of Metric Tons of CO<sub>2</sub> Emissions in 2015-16 (Robertson, 2019, p. 626).**

Predictor	2015			2016		
	Predicted if no change	Diff from expected	Percent diff	Predicted if no change	Diff from expected	Percent diff
Temperature	1649	27	1.6	1672	38	2.2
Vehicles	1656	20	1.2	1659	51	3.0
Median age	1676	0	0.0	1709	0	0.0
KPL	1693	-17	-1.0	1743	-33	-1.9
Insurance/\$10,000 income	1679	-3	-0.2	1705	5	0.3

In contrast, Nam et al. showed that PM emissions from gasoline-powered vehicles increased exponentially as ambient temperature decreased. They point out that PM emissions doubled for every 20 °F drop, regardless of vehicle model year. They also argue that the effects of temperature on vehicle emissions were most felt during cold start because of inefficient combustion and catalyst operation, as well as the potential to operate under fuel-rich conditions (see Figure 7 and Figure 8). Their findings were used to develop the PM emission rates for MOVES (Nam et al. pp. 4672-76).



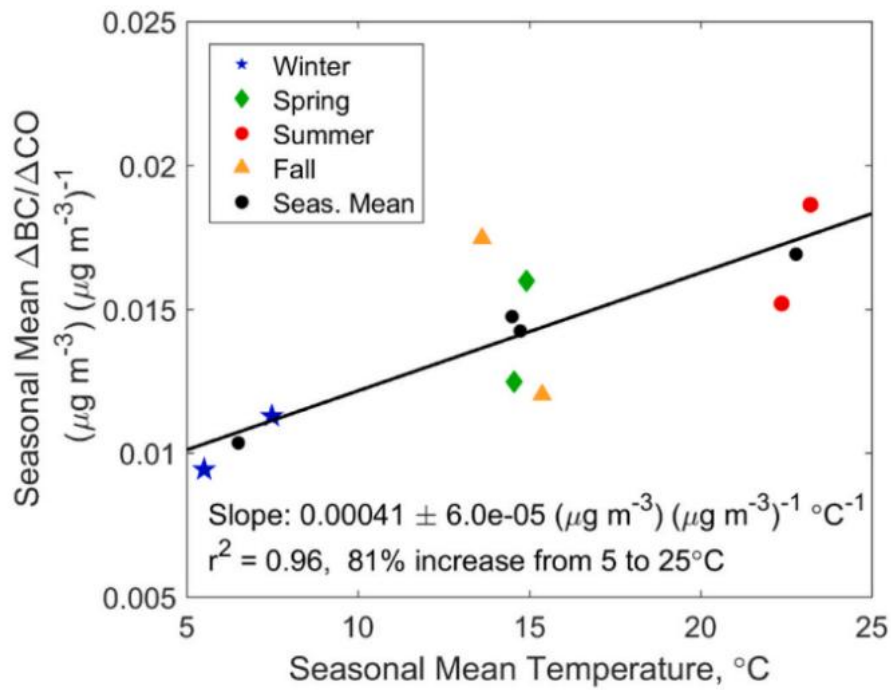
**Figure 7. Cold Start PM and Temperature (Nam et al., 2010, p. 4676).**



**Figure 8. Hot Running PM and Temperature (Nam et al., 2010, p. 4676).**

Hall-Quinlan et al. also found that black carbon ( $PM_{2.5}$ ) emissions increased by 50% as temperatures rose from  $-5^{\circ}C$  to  $20^{\circ}C$ . These observations were collected from January 2017 to December 2018 at a near-road site along I-95 in Howard County, Maryland. (2023, p. 1). As shown in Figure 9, they found that the seasonal mean (calculated from hourly emission ratios of black carbon and carbon monoxide) was at its highest in the summer and at its lowest during the winter. They point out that the “seasonal mean was strongly correlated with ambient temperature ( $r_2 = 0.96$ ) and increased by 81% from winter ( $5^{\circ}C$ ) to summer ( $25^{\circ}C$ )” (Hall-Quinlan et al.,

2023, p. 6). They also claim that “the seasonal changes in  $\Delta BC/\Delta CO$  and proximity of the NR site to a major highway suggest a temperature sensitivity in vehicular emissions, particularly those from diesel trucks” (Hall-Quinlan et al., 2023, pp. 1-6).



**Figure 9. Seasonal Variability in BC/CO Emissions (Hall-Quinlan et al., 2023, p. 7).**

# Foundational Groundwork for TA 2025-11: Using EPA MOVES to Build a Repository of Emissions Factors

The methodologies developed through this effort also informed the subsequent NCDOT Technical Assistance Request *TA 2025-11: Using EPA MOVES to Build a Repository of Emissions Factors*. In that project, the delay- and VHT-based approaches were incorporated into the development of a comprehensive emissions-factor repository, which now provides the final, standardized framework for estimating emissions across all highway specific improvement types. Collectively, the two technical assistance efforts create a cohesive and defensible foundation for integrating emissions quantification into NCDOT’s project prioritization process.

## Data Selection for a Vehicle Hours Traveled Methodology

Using existing NCDOT SPOT data to the greatest extent possible is essential for developing a reliable and defensible vehicle hours traveled (VHT) emissions formula. The SPOT dataset has already undergone extensive vetting through multiple cycles of the statewide prioritization process, rigorous review by the SPOT Workgroup, and input from key stakeholders across NCDOT and partner agencies. Leveraging this established data ensures that the VHT-based emissions formulas are grounded in information that is both technically sound and widely accepted within the prioritization framework. It also promotes consistency with existing methodologies, minimizes the risk of introducing untested assumptions, and supports seamless integration of environmental measures into the broader SPOT scoring process. See Table 3 for the data elements used as part of the VHT methodology.

**Table 3. Data for VHT Methodology**

Data Element	Highways Spreadsheet Column	Highways Spreadsheet Name	Other Source
Existing AADT	EH	Existing Volume (AADT)	--
Future AADT	GC	TTS Future Year Existing Volume - CALC	--
Net Difference in AADT	--	--	Derived from EH & GC
Project Length	DM	Grouped Project Length (Miles)	--
Net Change in VMT	--	--	Derived from EH, GC, & DM
Auto Percentage	ED	Auto %	--
Truck Percentage	EE	Truck % (FORMULA - DO NOT OVERRIDE)	--
Emissions in grams	--	--	EPA MOVES
Emissions cost	--	--	USDOT BCA Guidance

## Important Considerations for Emissions Methodologies

Findings from Table 4 demonstrate how it is important to understand how changes in vehicle speed influence emissions quantities, as emissions rates vary significantly across different speed ranges. This relationship is especially important when using VMT-based methodologies that quantify and stratify emissions by speed, allowing for a more accurate representation of real-world operating conditions. Incorporating speed-sensitive emissions behavior ensures that the resulting estimates more accurately reflect the environmental impacts of highway improvement types, particularly those that affect congestion and travel flow. This consideration also serves as a key input to the emissions accounting scenario developed under TA 2025-11: Using EPA MOVES to Build a Repository of Emissions Factors, where speed-dependent emissions factors are integrated into a standardized framework for calculating emissions across all highway SITs.

**Table 4. Considerations When Accounting for Emissions**

Studies	Key Findings
On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument Frey et al. (2003)	The average emission rate on a mass per time basis for acceleration is typically a factor of 5 greater than the idle emission rate for HC and CO <sub>2</sub> and a factor of 10 or more greater for NO and CO.
Quantification of Highway Vehicle Emissions Hot Spots Based upon On-Board Measurements Unal et al. (2004)	The peaks in CO <sub>2</sub> emission rates and fuel consumption rates occur during acceleration and higher speed driving (e.g., 0.5th and 7.5th min).
What is the optimal speed limit on freeways? Van Benthem (2015)	A 10-mph speed limit increase on highways leads to elevated pollutant concentrations of 14–24% (carbon monoxide), 8–15% (nitrogen oxides), 1–11% (ozone).
Quantifying The Environmental Effects of Speed Limit Policy - A Case Study From Michigan Chakraborty et al. (2023)	On freeways an increase in speed limit led to roughly 6,000 tons of annual increase in emissions for passenger vehicles while on non-freeways it led to roughly 8,000 tons.
Effects of Vehicle Speed and Engine Load on Motor Vehicle Emissions Kean et al. (2003)	NOx emissions increased with vehicle speed for uphill driving but not as strongly as CO emissions.

## Implementation Plan

This section presents the plan for putting the project's tools and findings into practice at NCDOT. It details the final deliverables, implementation steps, and metrics that will guide successful integration into agency workflows.

***Explanation of Deliverables.*** The final deliverables include a written report that outlines the research conducted to evaluate including the emissions resulting from vehicular delay into the prioritization process. It is part of a series of three deliverables (1) *TA2024-015: Investigation of Environmental Measures for P8.0*, (2) *TA2025-005: Investigation of Environmental Measures Using Delay (this report)*, and (3) *TA2025-11: Using EPA MOVES to Build a Repository of Emissions Factors*, that will be used to help integrate an environmental measure into the prioritization and scoring of North Carolina's highway projects.

***Influence on NCDOT.*** This project will help provide NCDOT's Office of Strategic Initiatives and Program Support with a process that can be used to estimate emissions costs or benefits stemming from highway projects evaluated in NCDOT's prioritization process.

***Implementation Process.*** The research team is currently in the process of coordinating with NCDOT's Office of Strategic Initiatives and Program Support on implementing findings from this work.

***Measures of Success.*** This research can be used to demonstrate emissions costs or benefits resulting from highway projects that are evaluated in NCDOT's prioritization process.

***Additional Assistance.*** The research team plans to work with the Office of Strategic Initiatives and Program Support on continued research to fine-tune the research approach used for the induced demand component of this research discussed in *TA2025-11*.

## Conclusions and Next Steps

This technical assistance request developed and evaluated delay-based emissions estimation approaches and conducted a targeted review of how emissions rates vary with conditions such as vehicle speeds and air temperature. To create consistency across all mobility SITs, the study also established formulas using Vehicle Hours Traveled (VHT) that can be applied to both base and build scenarios. These analytical methods were compiled into a white paper that provides recommendations for integrating delay- and VHT-based environmental measures into SPOT scoring, including guidance on weighting, costing, and placement within the prioritization workflow.

The methodologies formulated in this research became a key input to the subsequent NCDOT Technical Assistance Request TA 2025-11, *Using EPA MOVES to Build a Repository of Emissions Factors*. That follow-up effort used the delay- and VHT-based approaches from this study to create a comprehensive and standardized emissions factor repository, enabling consistent quantification of emissions across all highway SITs. Together, the two efforts produced a unified and defensible framework for emissions accounting within NCDOT's prioritization process.

More broadly, the development of this framework occurred across three sequential Technical Assistance Requests (TARs). TAR I evaluated emissions accounting practices used by other transportation agencies and recommended an approach centered on MOVES-based emissions lookup tables and initial VMT-based costing methods. TAR II extended these methods by creating three VMT-based methodologies for linear highway projects and a delay-based methodology for point projects where VMT is not the primary driver of emissions. TAR III then refined the lookup tables to incorporate emissions per minute of delay, finalized the methodologies from the earlier phases, expanded the emissions categories under review, and strengthened assumptions related to induced demand. Together, the three TARs established a complete, internally consistent, and comprehensive emissions accounting system tailored to NCDOT's prioritization needs. The results of all TARs are written about comprehensively in TA 2025-11, *Using EPA MOVES to Build a Repository of Emissions Factors*.

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