Assessment of Automobile Start and Idling Emissions under Utah Specific Conditions:

Cold Start, Hot Start, and Idle Emissions as Measured on Northern Utah Vehicles

Project Final Report

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by

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Executive Summary

The state of Utah, like many other states, municipalities, and countries rely on mobile source control programs for significant reductions in oxides of nitrogen (NO_x) and hydrocarbons or volatile organic compounds (VOCs or HCs) into their air sheds. These plans often include programs to address cold starts, anti-idling ordinances and public awareness campaigns. Unfortunately, there is not an abundance of available published research demonstrating the benefits or penalties of such programs, especially at ambient and fleet conditions relative to northern Utah.

In order to assess the utility of such programs and quantify start and idle emissions relative to a vehicle fleet representative of Utah's population centers, parallel studies were conducted at Utah State University's Utah Water Research Laboratory (UWRL) and Weber State University's National Center for Automotive Science and Technology (NCAST). Over 70 different vehicles representing the tiered vehicle profile typical to northern Utah were tested between November 2014 and June 2016 at both UWRL and NCAST. Autologic 5-Gas Analyzers were used to measure tailpipe concentrations of NO_x, HCs, CO (carbon monoxide), and carbon dioxide (CO_2). Supporting data measured include system temperatures, flow rates, RPMs, and drive cycle conditions using appropriate scan tools. The established sampling protocols measured emissions during cold start conditions (engine off $\geq$ 12 hrs) followed immediately by drive a drive cycle or an extended idle period, which in turn was followed up with variable hot start scenarios (after 5, 10, 20 minute off periods) and subsequent idle periods, with a drive cycle conducted between each hot start examination.

The cold start studies found that, averaged across all the Tiers, the cold start emissions peaked in less than one half a minute and were optimized (95% of peak value) after 1½ to 2½ minutes, confirming that lengthy "warm up" periods are not required for effective catalytic converter performance. Hot start emissions were found to average about 5-10% of the typical cold start emissions for most the Tiers examined. Similarly, on average, idling for five minutes resulted emissions were approximately three, four, and ten times the emissions for NOx, VOCs, and CO, respectively, as observed for the scenario in which the vehicles were started after being shut off and in park for five minutes (5-min hot start). The magnitude of the proportionality factor tended to increase for most vehicles as the time periods increased to 10 and 20 minutes.

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Introduction

Several areas of Northern Utah have documented $PM_{2.5}$ and ozone problems. The areas of Utah include Box Elder, Cache, Davis, Salt Lake, Toole, Utah, and Weber Counties. These areas exceed the National Air Quality Standards set by the Environmental Protection Agency (EPA), especially in the winter season (Utah, 2014). The state of Utah has focused on reducing automobile emissions as a significant components of the plans to improve the air quality in the affected airsheds as about half of the wintertime emissions of nitrogen oxides (NOx) and volatile organic compounds (VOC, also referred to as hydrocarbons) come from mobile sources (Utah, 2014).

The start cycle of vehicles is known to have increased emissions of hydrocarbons (HC) and carbon monoxide (CO) because the engine uses an enriched fuel mixture to avoid misfires due to condensation on the cylinder walls. Some of this extra fuel does not participate in combustion, increasing emissions when engine block and coolant temperatures are low (Dardiotis et al., 2013; Cao, 2007). Additionally, CO and HC are not oxidized in the vehicles exhaust treatment system during the period immediately after start-up (Bielaczyc et al., 2014). Sentoff demonstrated that HC emissions during a cold start are one to two orders of magnitude higher than those produced during a warm idle (Sentoff et al., 2010).

NOx is normally produced during driving conditions when the engine is under load, running a lean fuel mixture, and operating at high temperatures. Zhang demonstrated that there are significant increases in NOx emissions with higher vehicle specific power (VSP) associated with grades greater than 5% (Zhang and Frey, 2006). Developed by Jiménez et al (1999), VSP is a relationship between aerodynamic drag, acceleration, rolling resistance, road grade, and vehicle mass; essentially a measure of the load on the vehicle engine. However, during a cold start the catalytic converter and other emission control equipment do not work efficiently until sufficient has warmed up has occurred, possibly leading to increased NOx emissions similar to CO and HC (EPA, 2014).

The Motor Vehicle Emission Simulator (MOVES) model developed by the EPA adjusts emission rates based on time since the last start, or soak time (EPA, 2015). A soak time of at least 12 hours is considered a *cold start* and the MOVES model adjusts emissions down for hot starts based on the time since the last start. A start is considered *hot* if the previous trip is at least

4 minutes long with a soak time of less than 45 minutes (EPA, 1993). Following MOVES, a hot start with five minutes or less soak time emits only 5% of HC compared to a cold start, 3.4% of the CO, and 9.3 % of the NO_x. These adjustments vary through eight soak time increments in the model (EPA, 2015).

As new emission standards (e.g. Tier III) lower the running emissions of light duty vehicles, the starting emissions will make up a growing percentage of total emissions. Some research suggests that cold start emissions can make up over 50% of urban driving emissions as the majority of trips are less than three miles in length (Reiter and Kockelman, 2016, Bielaczyc et al., 2014, and Favez et al., 2009). Additionally, Fan and Li (2013) report that for modern vehicles, the first 20 seconds of a short trip can account for 80-90% of the HC emissions for a given trip.

The fuel enrichment during a starting cycle is amplified during cold starts at lower ambient temperatures because more fuel is needed to compensate for colder, higher density air resulting in longer run times with rich fuel and longer times required for proper emission control equipment operation (Sentoff et al., 2010). Bielaczyc et al. (2014) showed that one or two cold starts are experienced by each passenger car on most days, with around 69% of all trips starting with a cold or cool start, meaning that in regions where temperatures are regularly below freezing a vehicle may experience one or two sub-freezing cold starts on a significant number of days each year. The number of sub-freezing cold starts performed may be significant when the large emission increases due to these starts is considered. Sentoff et al. (2010) found that cold start peaks for CO almost double when temperature decreased from 25°C to 10°C, and the magnitude of HC peaks were three times larger across the same temperature range (Sentoff et al., 2010). Ludykar et al. (1999) showed CO emission factors increased by 2.6x, HC emissions increased by 8x, and NOx emissions were unaffected when the ambient temperature fell from 22°C to -7°C. As temperatures were further decreased to -20°C, the emission factors increased, but by significantly smaller increments (Ludykar et al., 1999). Similarly, Dardiotis et al. (2013) reported that as ambient temperatures decreased from 22°C to -7°C, CO emissions increased by 11x, HC increased by 6.5x, and NOx emissions were variable. Cook et al. (2007) found HC emissions increased by 4x to 10x, depending on vehicle type, when ambient temperatures decreased from 10°C to -7°C (Cook et al., 2007). Bielaczyc et al. (2014) found HC emissions increased by about 6x and CO increased by 8x when ambient temperature drops from 24°C to -

7°C. Interestingly, Bielaczyc et al. (2014) reported NOx emissions actually decreased by a small amount over the same temperature decrease (Bielaczyc et al., 2014). Weilenmann et al. (2009) found similar trends in HC and CO emission increases over the same temperature drop, with increases even more pronounced when temperatures were further decreased to -20°C. Over the total temperature drop from 23°C to -20°C, HC emissions increased by 35x and CO by 15x. NOx showed no obvious trend with values varying widely among the tested vehicles (Weilenmann et al., 2009). More recently, George et al. (2015) showed total volatile organic compounds (VOC, also known as HCs) emissions increased by about 10x when ambient temperature dropped from 24°C to -7°C.

In recognition of the above research, the EPA uses a large compilation of these and other available data to model vehicle emissions for the MOVES model. In the MOVES model, emission rates are adjusted based on ambient temperatures (EPA, 2014). The base temperature is 24°C and both CO and HC emissions adjust higher as ambient temperatures fall. CO in vehicles older than 2010 emit 20 g of CO at 24°C, increasing to 40 g at -4°C and 80 g at -18°C. For newer vehicles manufactured since 2010 the values are lower but have the same trend. At 24°C, 10 g CO are emitted during a cold start, increasing to 25 g at -4°C and 40 g at -18°C. HC show similar behavior with older vehicles, 2010 and older, emitting 3 g HC for a cold start at 24°C, 7 g HC at -4°C, and 15 g of HC at -18°C. The newer vehicles have lower emission rates for HC and are also less dependent on temperature. 3 g HC are emitted at 24°C, increasing to 5 g at -4°C, and 8 g of HC at -18°C. NO$_x$ emissions are shown to be less sensitive to temperature and are modeled as a linear line with 0.1 g NO$_x$ emitted at 24°C and 0.6 g NO$_x$ at -18°C (EPA, 2014).

The study documented herein was conducted to measure the differences in emissions between cold starts, hot starts (with soak times of 5, 10, and 20 minutes), and continuous idling under Utah-specific winter conditions by testing a sample set of over 50 vehicles representative of the actual vehicle fleet in Northern Utah. Additionally, a single vehicle, a 2007 Dodge RAM 1500, was measured multiple times to examine the affect of differing ambient temperatures on cold start emissions for comparison against the MOVES algorithms.

Methodologies

Vehicle Selection

It was desired to have a pool of vehicles for this study that was representative of the vehicle fleet in Northern Utah. This study looked only at light duty gasoline vehicles, which are less than 8,500 lbs. gross vehicle weight (EPA, 2015). In order to achieve a representative sample, vehicle registration data from 2013 were analyzed for the previously mentioned seven northern Utah counties to determine the local vehicle age distribution. Vehicles categories were broken down by age and registration population into the Tier classifications indicated by the EPA (EPA, 2016). The vehicles tested were selected to match the tier distribution based on fleet population in Northern Utah. The project proposal called for at least 50 total vehicles to be tested, and in the end 71 total vehicles were examined. All of the test vehicles were solicited from the local population to reflect current, in-use vehicles. Table 1 shows the number of vehicles in each tier through Northern Utah and indicates how many of each tier were actually tested. A number of the vehicles had check engine lights or mechanical problems.

Table 1. Vehicle tiers and number of vehicles tested.

Tier	Model Years	Fleet Population	Sample Goal	Actually Tested
Pre-0	1980 and older	22,447 (1%)	1 (2%)	3 (4%)
0	1981-1993	92,827 (6%)	3 (6%)	4 (6%)
1	1994-2000	372,927 (24%)	12 (24%)	16 (23%)
NLEV	2001-2003	271,522 (17%)	8 (16%)	12 (17%)
2	2004-2016	811,802 (52%)	26 (52%)	36 *51%)
Total	**-----**	**1,571,525**	**50**	**71**

The vehicle selected for repetitive cold start measurements over a wide range of ambient temperatures was a 2007 Dodge Ram 1500 pickup equipped with a 5.7 L V8 engine and an automatic transmission. At the start of the testing, the pickup had an odometer reading of approximately 135,000 miles and at the conclusion of the testing it read approximately 153,000 miles.

Sampling Protocol

Vehicle testing was conducted primarily from November until April in order to get cold temperatures that are normal during Northern Utah winters. However, over the test periods, the winters were relatively mild with the average temperature for the tests of 5.9°C. Ambient temperatures for the tests ranged from -8.2°C to 15.6°C. Twelve replicate measurements on the 2007 Dodge pickup were conducted from December 2014 to January 2016 over an ambient temperature range of -6.8 ^{o}C to 33^{o}C. Measurements were conducted the Utah State University Utah's (USU's) Water Research Laboratory in Logan, Utah and the Weber State University's (WSU's) National Center for Automotive Science and Technology in Ogden, Utah. In order to achieve the cold start measurements, the vehicles being tested were parked at the test location for at least a twelve hour soak period (EPA, 2015) and typically tested in the morning hours. The monitoring equipment (below) was installed and initiated before vehicle ignition. The vehicle emissions and operating conditions were monitored for at least five minutes, or until equilibrium in emissions were observed and then the instruments were disconnected. Equilibrium was defined as when the measured concentrations reached a 95% reduction compared to the peak observed concentration or if the specified level of reduction was not achieved, equilibrium was estimated when the concentration curve approached consistency.

The vehicles were then taken on a drive cycle to simulate a typical trip and allow the engine and catalyst to reach full operating conditions. The drive cycle was 4.7 miles long with a mix of residential streets and a state highway. Speed limits ranged from 25 to 50 miles per hour (mph). The drive cycle included several traffic-regulated stops and various grades. The vehicle was then returned to the test location after the drive cycle, turned off, allowed to cool for five minutes, and then started. This start represented 5-minute hot start conditions. The drive cycle was sequentially repeated and hot starts were repeated for 10- and 20-minute soak times. Idle emissions were measured for the vehicles by monitoring emissions for at least five minutes after the emissions approached equilibrium following each start scenario.

Instrumentation

Autologic Applus 5-Gas portable AutoGas analyzers (model 310-0220) were used to quantify the automobile exhaust – one each at USU and WSU. Via an inserted metal probe and flexible umbilical, the device continually monitored tailpipe concentrations of oxygen (O_2), carbon dioxide (CO_2), CO, HC (as propane), and NOx (as NO), and gave concentrations or mixing ratios in percent (CO, CO_2, O_2) or parts per million (HC, NOx). The AutoGas sampler was zeroed after every vehicle and calibrated approximately every three vehicles. The calibration gas was an Airgas brand mixture with 3190 ppm propane, 7.96 % CO, 12.00% CO_2, and 2961 ppm NO. The 5-gas analyzer provided data approximately every second.

External surface temperatures of various engine and exhaust components were measured using type K thermocouples and a Campbell Scientific data logger model 21X. Temperatures taken included oil pan temperature, catalytic converter shell temperature, exhaust temperature and ambient temperature. Sampling frequency was also every second.

Engine operating parameters were monitored using a Dyna-scan module collect data from vehicles with onboard diagnostic (OBD II) computers (model year 1996 and newer). Parameters collected from the vehicles computer included coolant temperature, engine revolutions per minute (RPM), derived catalytic converter temperature, and oxygen sensor information. The data available from the on board computer varied from vehicle to vehicle depending on year and manufacturer. Sampling frequency also varied depending on vehicle, but was usually typically one second intervals. For older vehicles without OBD II computers, the engine RPM was logged manually every thirty seconds during the test period.

Volumetric exhaust flowrate measurements were also determined to convert the concentration data into mass flowrate units (e.g. grams per sec). Specifically, for each vehicle algorithms were developed for relating real-time monitored RPMs to volumetric exhaust flowrate. The exhaust velocities from the tailpipes were measured using a metal vane anemometer (Extech Instruments, Model 407113) that recorded velocity and temperature every two seconds. For some of the earlier vehicles tested, a Kestrel pocket weather meter (model 4000) was used to measure exhaust velocity. This exhaust velocity was used in conjunction with measured tailpipe cross sectional area to calculate exhaust flowrate. A linear curve was fit to a plot of engine RPMs versus exhaust flowrates such that exhaust flowrate could be estimated based on in-test engine RPM observations. Figure 1 show select examples of RPM vs. exhaust flowrate and the fitted relationships.

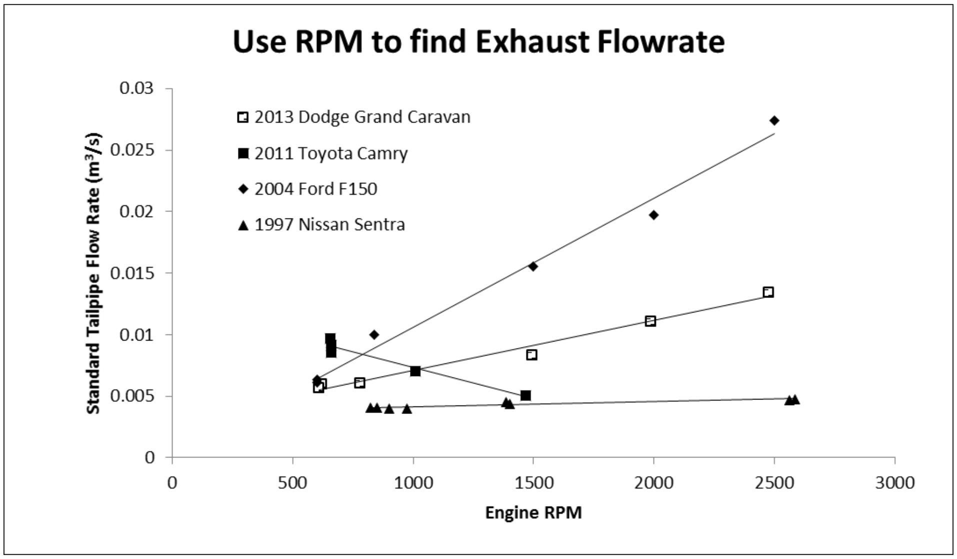

Figure 1. Converting engine RPM to exhaust flowrate.

As can be seen in Figure 1, most vehicles displayed an expected increased exhaust flowrate with increasing engine RPMs. Some vehicles, however, notably four cylinder engines, showed decreasing flowrate with RPMs. This is a result of an air injection system that uses a fan to force more air through the exhaust system in order to warm up the catalytic converter more quickly. These vehicles have decreasing exhaust flowrate up to a certain RPM and then exhaust flow increases with RPM. For these vehicles only the linear region associated with lower RPMs is shown in Figure 1, and was used in subsequent calculations since the vehicles were only tested at idle RPMs.

As previously mentioned, a vehicle's start period was considered complete when the emission rate stabilized at 5% of the peak starting value. In Figure 2, the 2007 Dodge Ram 1500 shows a typical hydrocarbon (HC) cold start emission rate. As can be seen at about 65 seconds, the emission rate reached 5% of the peak emission rate, the cold start was considered complete, and the vehicle was considered to be in the idling phase. In contrast, the 1998 Subaru Outback tested never reached the desired equilibrium value as the emission rate never fell to 5% of the peak value. Overall, about 77% of all emission rate curves had the starting period defined using the 5% of peak emission rate method.

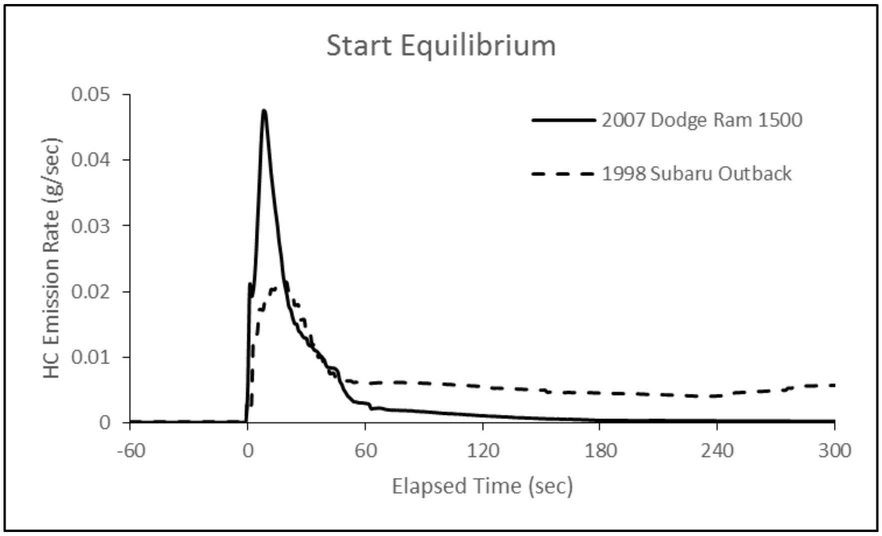

Figure 2. Examples of cold start equilibrium determinations.

Results and Discussion

Cold and Hot Start Comparisons

Pre-Tier 0

Three pre-Tier 0 (older than 1980) vehicles were tested, resulting in emission rates that were about one order of magnitude higher than the other cars tested and are therefore presented as a separate discussion. These vehicles did not have catalytic converters and were carbureted rather than fuel injected. The results for these vehicles are shown in Figure 3 and the compiled Table 2 (at the end of this subsection). As can be seen in Figure 3, with the exception of CO, the emission rates do not change much between a cold start and any of the hot starts. The Pre-Tier 0 cold start emissions averaged 8.10 g, 0.06 g, and 60.1 g for HCs, NOx, and CO, respectively (Table 2). Across all the hot start scenarios, the parallel emissions averaged 6.80 g, 0.16 g, and 13.8 g, respectively. This is likely due to the absence of an operating catalytic converter. The starting emissions for these older vehicles were also one order of magnitude higher than emissions of any other tier of vehicles tested. It is of interest to note that one of the other vehicles tested, a 1996 Subaru Outback (Tier 1), had emissions similar to the pre-Tier 0 vehicles. Park et al. (2011) and others have shown that about 5% of light duty vehicles are high emitters with emissions often more than 5 times the fleet average. It is important to remember that even though these high emitting vehicles are not a large percentage of the vehicle fleet, they will have a large effect on the fleet wide emissions.

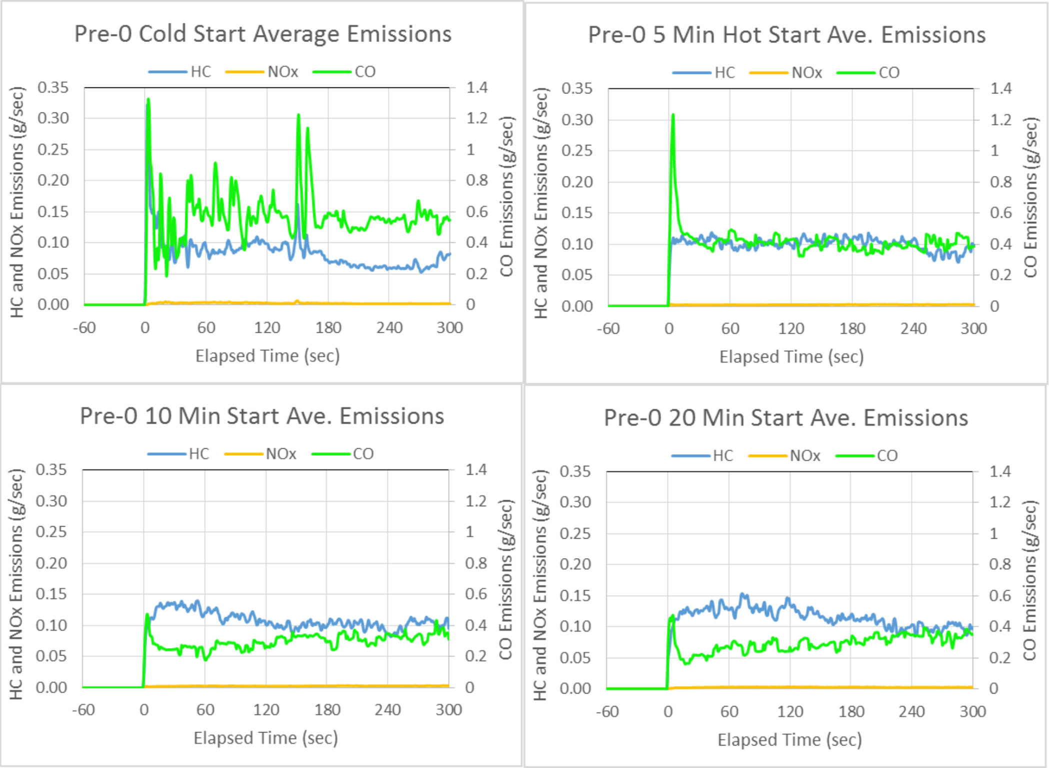

Figure 3. Average cold and hot start emission rate profiles for pre-tier 0 vehicles.

Hydrocarbons

Figure 4 shows the average HC emission rate profiles for Tier 0, Tier 1, NLEV, and Tier 2 vehicles tested, and, again, Table 2 shows the compiled peak emissions, emissions per start and time averaged idle for each tier. In Figure 4, it can be seen that, as was expected, the cold start emission profiles were greater in magnitude than any of the hot start emissions. It can also be seen that, in general, the newer model year vehicles also equilibrated quicker and at lower concentrations across all of the hot start periods. The time to equilibrium, or the time for the vehicle to emit at what may be considered stable, idle-type levels, also becomes shorter for hot starts (Figure 4, Table 2). For example, Tier 2 vehicles showed it took an average of 107 seconds to reach idle (HC equilibrium) conditions after a cold start, but only 64 seconds following a 20 minute hot start. By comparison, for Tier 1 vehicles, the average cold start equilibrium time was found to be 156 seconds and 48 seconds for a 20 minute hot start. As can also be seen in Table 2, the newer vehicles (NLEV and Tier 2) showed little change in HC equilibrium times across the different hot start scenarios (averaging 64 seconds).

Figure 5 shows a bar graph of average starting HC emissions (in total grams) segregated by Tier category. The total grams per start were calculated as the summed area under curves for each vehicle as indicated in Figure 4. It should be noted that the y-axis scale on the graph is logarithmic and the error bars indicate the 95% confidence interval about the average. These formats are consistent throughout all the bar graphs subsequently presented herein.

As can be seen in Figure 5, the observed average emissions were typically higher for the older vehicles across all start conditions tested (general downward slope from left-to-right). An exception seems to be the cold start NLEV HC emissions appeared higher rate than Tier 0 emissions. However, these differences were not significant at the 95% confidence interval, although all of the tested vehicles Tier 0 and newer showed statistically lower cold start emissions than the Pre-Tier 0 vehicles.

The average cold start HC emissions for Tier 0 vehicles were 0.78 ± 0.44 g, with Tier 1 and NLEV vehicles averaging slightly higher (1.39 ± 0.32 g and 0.98 ± 0.35 g, respectively) and Tier 2 vehicles averaging slightly lower at 0.46 ± 0.16 g HC per cold start. For comparison, the values reported herein are slightly lower, but within range of EPA estimates of 1.9 to 3.6 g HC per cold start for Tier 0 vehicles depending on the year and 0.6 to 0.8 g of HC for Tier 2 vehicles (EPA, 2015).

The average cold start HC emissions were found to be about 10 times higher that hot starts for newer vehicles (Tier 1 and newer) and close to double Tier 0 vehicles (Figure 5). As previously mentioned, no significant differences were observed among any of the Pre-Tier 0 start scenarios. Sentoff et al. (2010) found similar results for Tier 1 vehicles, with HC emissions up to 10 times higher for cold starts compared to hot starts. Similarly, the EPA (2015) estimated that a hot start with a soak time of 20 minutes should produce about one quarter of the emissions compared to a cold start (or 4x). As can be derived from Figure 5, this study found cold start HC emissions were about double for Tier 0 vehicles and 10 to 12 times higher for the newer vehicles compared to a 20 minute hot start (Table 2).

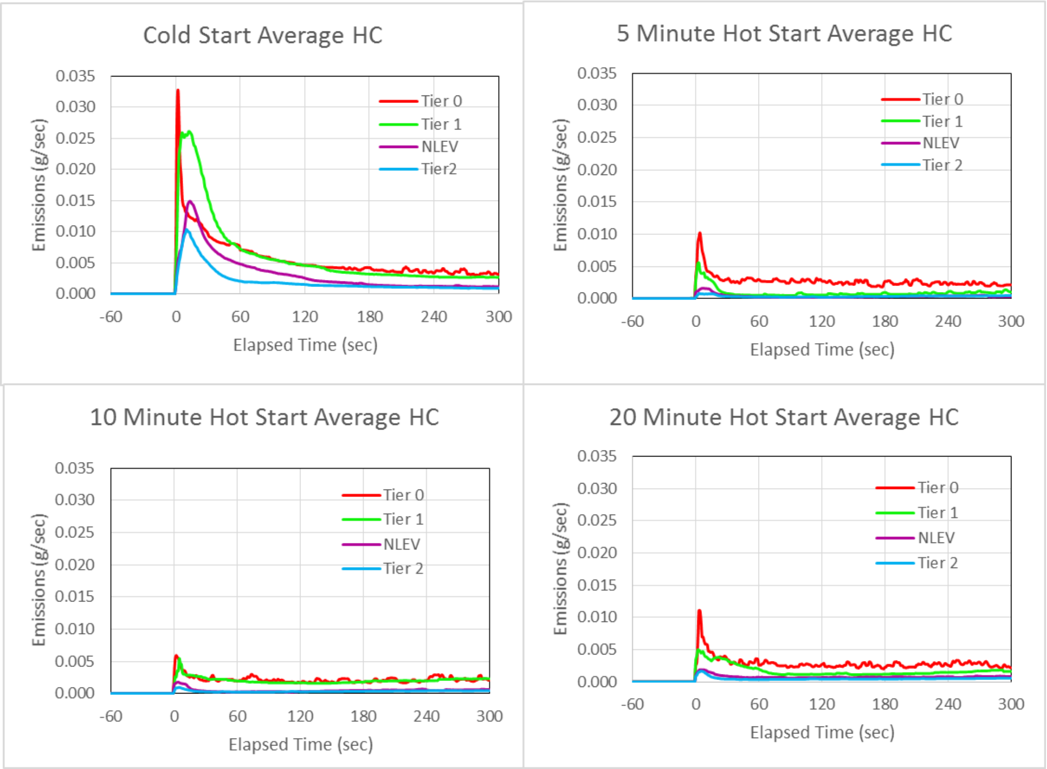

Figure 4. Average HC emission rate profiles.

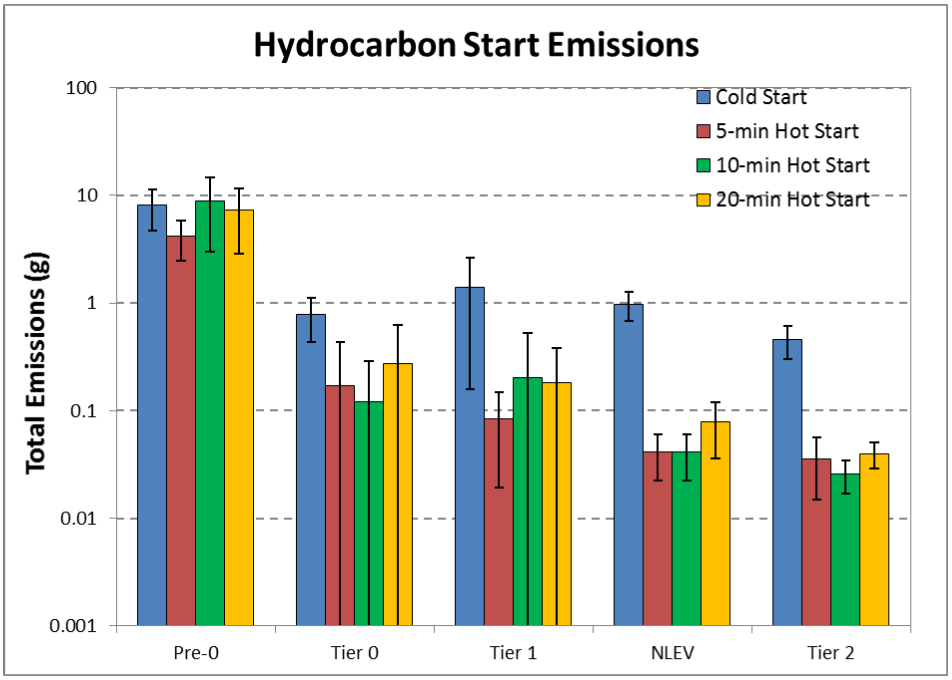

Figure 5. Average HC emitted per start type for each Tier type.

Oxides of Nitrogen (NOx)

Average emission rate profiles for NOx are given in Figure 6. Table 2 also shows the total NOx emissions for each start and idle scenario for each Tier of vehicles tested. As shown in Figure 6, the average emission rate profiles for NOx were much more variable between tiers and start conditions than the HCs. Additionally, the magnitude of the NOx emissions rates was found to be more than an order of magnitude lower than the HC emissions. As summarized by Boulter et al. (2013) and Cooper and Alley (2011), NOx production from automobile engines is maximized at the high temperature and slightly fuel-lean conditions. In other words, NOx production typically increases as engine work and load increases, so moderately low NOx emission can be expected for low-work start and idling situations. Additionally, of the summed "NO_x", nitric oxide (NO) content is expected to significantly dominate the nitrogen dioxide (NO_2) content in "fresh" automobile exhaust (Boulter et al., 2013). NOx emissions are also known to be reduced, to diatomic nitrogen (N_2) before the catalyst by controlling the air/fuel ratio, exhaust gas recirculation and ignition timing (Dardiotis et al., 2013). NOx is then reduced by the catalytic converter as long as exhaust temperatures are high enough (Dardiotis et al., 2013). All of these factors contribute to the variability in NOx emissions during starts depending on each vehicles operating parameters during the start and subsequent idle cycles.

In general, as can be seen in Figure 6, NOx emission rates for hot starts were found to be lower than for cold starts. The NOx emission rate for cars older than model year 2000 (Tiers 0 and 1) also shows an increase after idling for a few minutes for both hot and cold starts. This increase in NOx after a period of idling is hypothesized to be due to the catalyst cooling off during idle conditions enough that NOx removal efficiency is decreased. Similarly, Sentoff et al. (2010) tested a 1999 vehicle and found that idle NOx emissions increased after about 300 seconds.

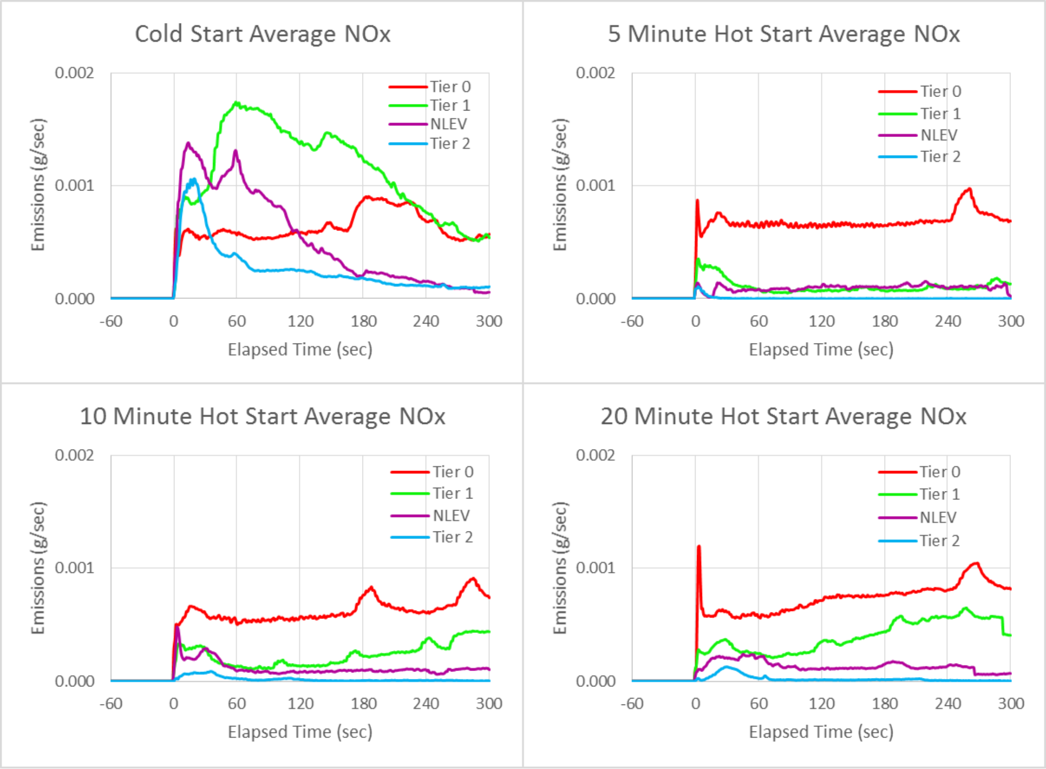

Figure 6. Average NOx emission rate profiles.

Figure 7 shows a bar chart displaying the average start emissions for NOx for each tier of vehicle. For Tier 0 vehicles, the EPA (2015) estimates that a cold start produces about 1.0 g of NOx and Tier 2 vehicles produce 0.16 to 0.32 g of NOx depending on the specific model year. This study found average NOx emissions for a cold start Tier to be 0.05 ± 0.02 g for Tier 0 vehicles, 0.24 ± 0.17 g for Tier 1, 0.13 ± 0.08 g for NLEV, and 0.05 ± 0.02 g for Tier 2. Across all of the Tiers, this study found average NOx emissions for cold starts to be from two to twenty times lower than that estimated by the MOVES model. The observed average for Tier 0 should the greatest deviation; however, the relatively small sample population tested as a part of this study (four vehicles) may not be sufficiently representative of the local vehicle fleet.

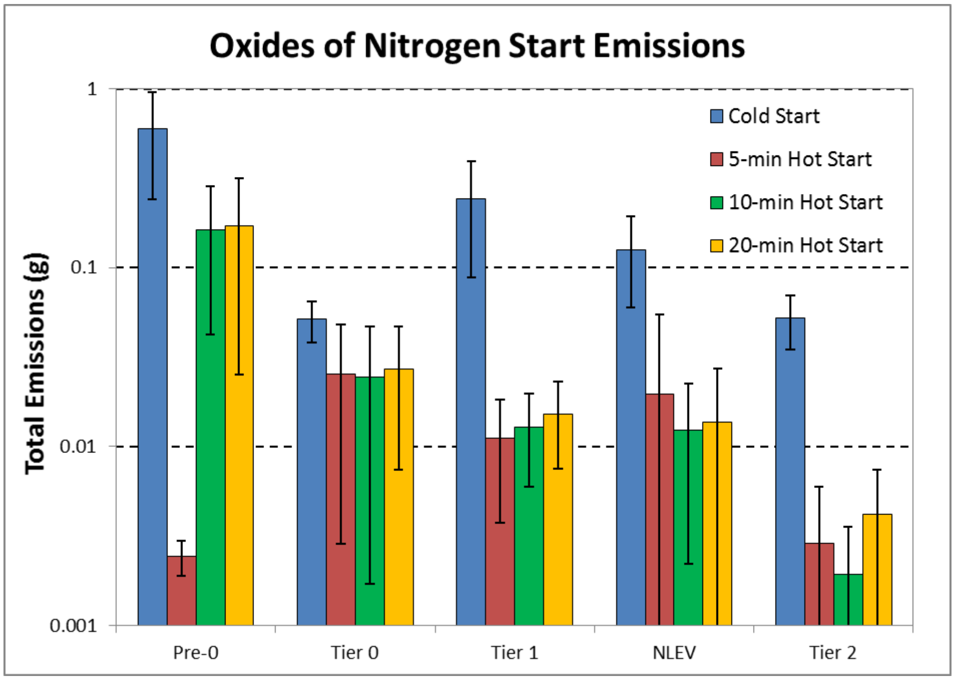

Figure 7. Average NOx emitted per start.

Figure 7 (and Table 2) also shows a comparison of the 5-, 10-, and 20-minute hot start NOx emissions compared to the cold start NOx emissions. For Tier 0 vehicle hot starts were about half of the values for cold starts, but these differences were not significant at the 95% confidence interval. Additionally, it is of interest to note that the emissions were about the same for all three hot start soak times. For the newer Tier 1, NLEV and Tier 2 vehicles there were also small differences between the NOx emissions of all three hot start scenarios, but the cold start protocol emitted approximately 20 times more NOx than the hot starts for Tier 1 vehicles, six times more NOx than the hot starts for NLEV, and 18 times more for Tier 2. The MOVES model adjusts NO emissions for soak time with a cold start emitting three times as much as a 20 minute hot start and ten times as much as a 5 minute hot start (EPA, 2015). Comparing the data from this test to the EPA data, the newer vehicles tested emitted much less NOx than the EPA models predicted, NLEV vehicles emitted similar to the predictions, and older Tier 0 models emitted more than the EPA predicted based on soak times.

Carbon Monoxide

CO peaks during a cold start because of incomplete combustion of the enriched fuel mixture used during a vehicle's start (Dardiotis et al., 2013). Sentoff et la. (2010) found that CO peaks and reduces back to baseline levels in about 90 seconds after the vehicle starts as the catalyst warms up and becomes more efficient. Similarly, this study found times to reach equilibrium for cold starts ranging from 43 seconds for Tier 2 to 179 seconds for Tier 0 (see Table 2). Time to equilibrium was much faster for hot starts since the catalyst was already warmed up, ranging from 15 seconds to 52 seconds.

Figure 8 shows the average emission rate profiles for CO for all of the tiers and starting conditions tested. Not unexpectedly, even cold start CO emissions show improvement with each successive Tier category, reflecting the emission improvements with each new vehicle generation. As can also be seen in Figure 8, the emission rate profiles for CO are reduced considerably for all tiers during hot starts, with the emissions for Tier 1, NLEV, and Tier 2 vehicles all having similar hot start emission profiles for CO.

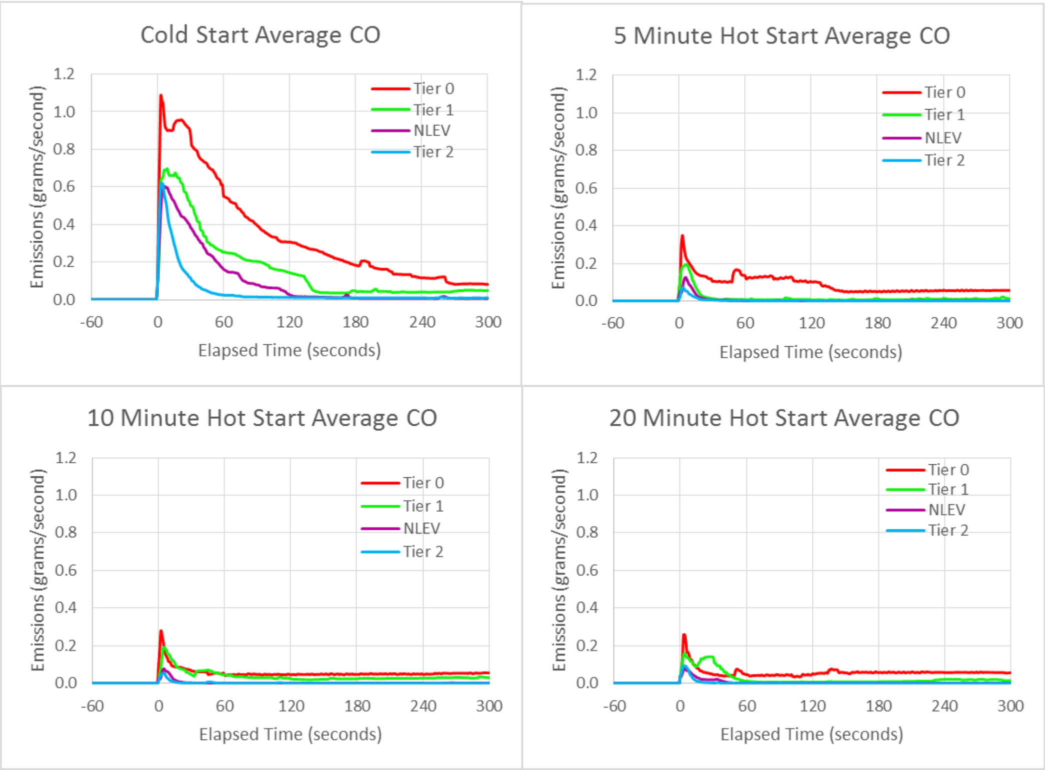

Figure 8. Average CO emission rates.

As shown in Figure 9 and explicitly given in Table 2, for the fleet test in this study, it was found that average cold start CO emissions were 98 ± 77 g for Tier 0 vehicles, 46 ± 12 g for Tier 1, 35 ± 22 g for NLEV, and 9 ± 3 g CO for Tier 2 (Figure 9). These cold start emissions were somewhat higher, but generally within the given statistically uncertainty, than the EPA estimates of 18-52 g for Tier 0 vehicles, 7-12 g of CO for NLEV, and 5-6 g CO for Tier 2 (EPA, 2015). Furthermore, as can be seen in Figure 9, the cold start CO emissions from the newest vehicle class (Tier 2) were also statistically lower than the CO emissions from all of the other tested vehicle tier categories.

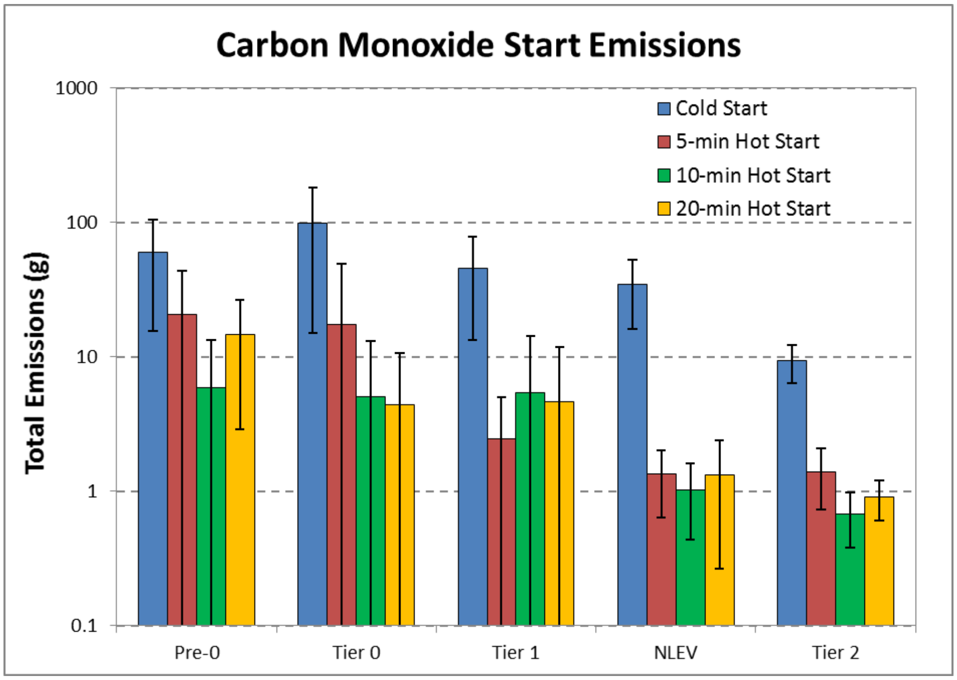

Figure 9. Average CO emitted per start.

As can also be seen, the start emissions for CO across all tiers were statistically similar for all three hot soak times. Tier 0 CO emissions fell from 98 g for a cold start to about 6 g for the hot start, showing an approximately 94% reduction. Tier 1 and NLEV showed similar reductions from about 30 g for cold starts to about 1 g for the hot starts (97% reduction). Tier 2 dropped from much lower levels of about 9 g for a cold start to about 1 g for hot starts (89% reduction). Once again, this was somewhat different than the EPA estimates for the effect of different soak times on CO emissions. The EPA (2015) estimates that emissions will drop by a about 80% going from a cold start to a 20 minute hot start, smaller than the reductions observed in this study. For a 5 minute soak; however, the EPA (2015) estimates a reduction in CO emissions on the order of 97%, similar to the findings for NLEV and Tier 1 in this study.

Table 2: Average emissions for each tier of vehicles tested.

	Pre-Tier 0 (≤1980)			**Tier 0 (1981 - 1993)**			**Tier 1 (1994 - 2000)**			**NLEV (2001 - 2003)**			**Tier 2 (2004 - 2016)**		
Count	3			4			16			12			36		
Average Mileage (miles)	256667			235424			170986			117757			51922		
Mileage Range (miles)	170,000-300,000			180,023-274,327			69,054-241,235			25,445-170,776			46-170,000		
	HC	**NO**	**CO**	**HC**	**NO**	**CO**	**HC**	**NO**	**CO**	**HC**	**NO**	**CO**	**HC**	**NO**	**CO**
Cold Start															
Peak Emiss (g/s)	0.39	0.01	1.92	0.03	0.001	1.09	0.03	0.003	0.75	0.02	0.002	0.74	0.01	0.002	0.59
Time to Equil (sec)	96	146	96	92	89	179	156	211	117	195	160	80	107	74	43
CS Emiss (g)	8.10	0.60	60.1	0.78	0.05	98.2	1.39	0.24	45.8	0.98	0.13	34.7	0.46	0.05	9.35
CS 5-min Idle Emiss (g)	25.4	0.77	164	1.20	0.22	30.2	0.80	0.19	12.5	0.28	0.03	2.69	0.25	0.03	2.34
5-min Hot Start															
Peak Emiss (g/s)	0.14	0.01	2.29	0.01	0.001	0.35	0.01	0.001	0.23	0.002	0.0004	0.15	0.002	0.0002	0.14
Time to Equil (sec)	43	64	26	27	33	55	34	43	24	71	48	32	66	28	52
5-m Hot Start Emiss (g)	4.17	0.16	20.8	0.17	0.03	17.6	0.08	0.01	2.47	0.04	0.02	1.34	0.04	0.003	1.41
5-min Idle Emiss (g)	29.7	0.85	120.8	0.74	0.21	15.2	0.25	0.04	2.38	0.14	0.01	2.87	0.11	0.001	0.41
10-min Hot Start															
Peak Emiss (g/s)	0.15	0.005	0.60	0.01	0.001	0.29	0.01	0.001	0.23	0.004	0.001	0.13	0.002	0.0001	0.09
Time to Equil (sec)	73	59	15	35	36	33	44	49	24	42	37	32	65	31	31
10-m Hot Start Emiss (g)	8.91	0.16	5.89	0.12	0.02	5.06	0.20	0.01	5.04	0.04	0.01	1.03	0.03	0.002	0.63
10-min Idle Emiss (g)	61.6	1.82	179.6	1.25	0.38	29.1	1.13	0.15	12.1	0.30	0.05	6.58	0.27	0.005	0.53
20-min Hot Start															
Peak Emiss (g/s)	0.17	0.004	0.88	0.01	0.002	0.26	0.01	0.001	0.22	0.004	0.001	0.13	0.003	0.0002	0.20
Time to Equil (sec)	59	59	21	63	40	37	48	54	26	76	46	28	64	43	37
20-m Hot Start Emiss (g)	7.31	0.17	14.7	0.27	0.03	4.43	0.18	0.02	4.36	0.08	0.01	1.34	0.04	0.004	0.91
20-min Idle Emiss (g)	133	3.35	365	3.13	0.92	64.3	1.74	0.52	11.4	0.77	0.22	1.62	0.78	0.01	0.63

Idle Compared to Hot Starts

An equally important objective of this study was to compare the tailpipe emissions of the targeted pollutants as a function of the hot start (soak) period compared to pollutant emissions is the vehicles were allowed to idle for the same time periods. In other words, would the average vehicles emit more if the vehicles were shut off and restarted, accepting the noted “peak” upon initiating the start, after the selected time period or left idling for that period.

Figure 10 (and Table 2) shows the average HC emissions for each of the vehicle Tiers for 5-, 10-, and 20-minute hot starts compared with idling for the same time period. As before, the error bars indicate the 95% confidence interval and the y-axis scale is shown as a logarithmic scale. As shown, the trends clearly indicate that relative to average HC emissions, it is better to turn off and restart the vehicle even for short stops. Further, all emissions tended to decrease with newer vehicle ages. The difference between re-starting and idling becomes more statistically significant for the newer vehicles (NLEV and Tier 2) and especially for the longer 20-minute idle period. Even considering the confidence intervals, letting the vehicle idle for 20 minutes produces about 10 times more hydrocarbons than restarting the vehicle. This trend can also be seen in the shorter soak periods of five and ten minutes; however, the confidence intervals tend to overlap by the 5-minute start and idle time. Gaines et al. (2012) estimated that ten minutes of idling was equivalent to one restart on a 2011 (Tier 2) vehicle. This is different than the results presented here wherein the HC emissions for restarting were found to be about 11% of that produced by idling for 10 minutes: 0.03 g vs. 0.27 g (see Table 2).

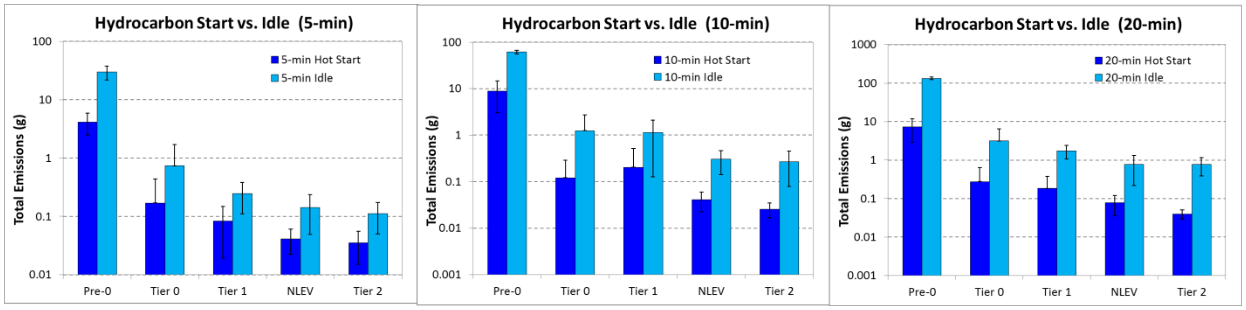

Figure 10. Comparison of HC emissions between hot starts and idling for similar time periods.

Figure 11 contrasts the average NOx emissions from idling for five, ten, or twenty minutes and the emissions for restarting the vehicle after the corresponding soak time. The NOx emissions were generally more than an order of magnitude lower than the HC emissions, but, overall, showed the same general decrease with newer vehicle age. The NOx emissions during the idling scenarios were generally higher than for restart (hot soak) scenarios, with the exception the very newest vehicles (NLEV and Tier 2) during the shortest dwell time (five minute). It should be noted that the error bars are relatively larger for NOx emissions showing that for most scenarios in this study the differences between restarting and idling are not statistically significant. This may be due to the fact, as previously, that NOx is produced mainly when the engine is under load and is produced at lower rates when the vehicle is idling. For NOx, Gaines et al. (2012) concluded that 1.7 minutes of idling was equivalent to one hot start for NOx emissions (Gaines et al., 2012). This is relationship partially confirmed by data collected in this study showing for short term (5-minute) when considering the 95% confidence intervals, but the data shown in Figure 11 indicates that as the dwell time increases, less NOx is emitted from restarting as opposed to idling

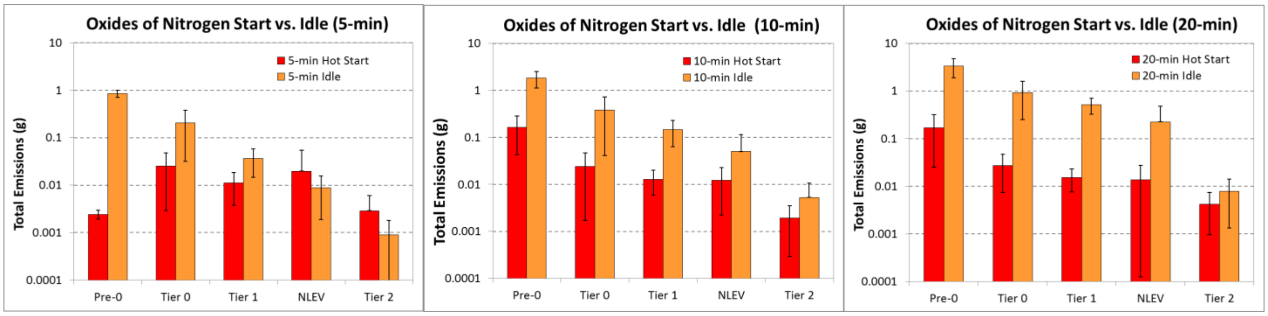

Figure 11. Comparison of NOx emissions between hot starts and idling for similar time periods

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Figure 12 shows the CO emissions for stopping and restarting the vehicle (hot soak scenario) compared to idling the vehicle for the same amount of time. Once again the error bars indicate the 95% confidence interval and are quite large indicating a wide range of values for CO emissions. It must be pointed out that the observed CO emissions were generally an order of magnitude great than the HC emissions and two orders of magnitude greater than the NOx emissions. Similar to the HC and NOx emission, the observed CO idle emissions averaged greater than the start emissions, with the consistent exception of the Tier 2 vehicles in which the start emissions showed higher average values. However, the overall CO emissions showed less relative difference between idling and restarting than both HC and NOx, especially in the newer vehicles, and were generally indifferent at the 95% significant level. Gaines et al. (2012) showed that a Tier 2 vehicle could idle for up to 28 minutes and emit less CO than a single restart. This also agrees with the current study, wherein 20 minute idle CO emissions averaged lower than restart scenario.

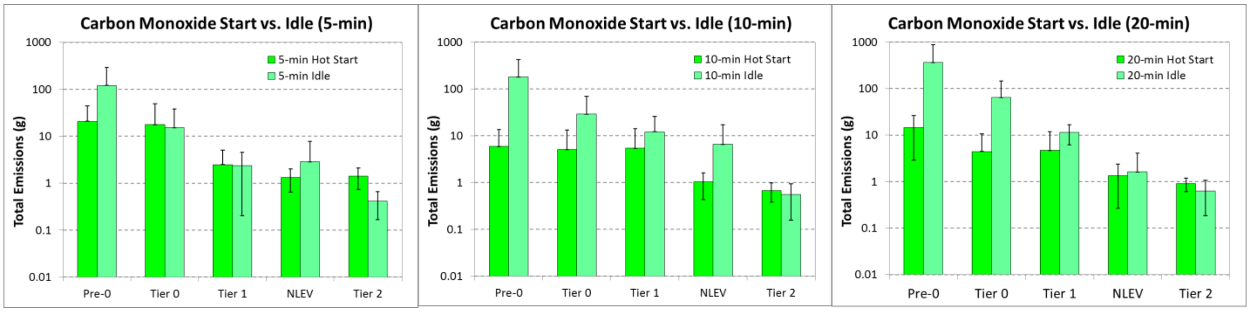


Figure 12. Comparison of CO emissions between hot starts and idling for similar time periods.

Ambient Temperature Impacts on Cold Start Emissions

Hydrocarbons

Lower ambient temperatures during cold starts can result in increased tailpipe HC emissions in a number of ways. During very cold ambient temperature starts, engines will use highly enriched air/fuel mixtures to prevent condensation on cylinder walls and to compensate for denser air (Sentoff et al., 2010 and Cao, 2007). Also, HC will not be oxidized in the vehicles catalytic converter until the exhaust temperature increases to above 200 ^{o}C, which will require longer time periods at power ambient temperatures (Favez et al., 2009; Bielaczyc et al., 2014).

Figure 13 shows the HC emissions produced during cold start phase plotted with respect to ambient temperature. Also shown are the parallel times to equilibrium (seconds) and emissions as derived for the selected vehicle from the EPA MOVES software. As can been, the HC emissions increased by approximately 8x when ambient temperatures dropped from 24^{o}C to -7^{o}C, and followed a reasonable (R^2 = 0.8516) exponential relationship (see Equation 1).

$$HC(in\ grams) = 0.9906\,e^{-0.065°C} \qquad \textit{Equation 1}$$

These results correspond very well with the results of many previous studies which should increases in the range of 4x to 10x across similar temperature changes (Ludykar et al., 1999; Cook et al., 2007; Sentoff et al., 2010; Dardiotis et al., 2013; Bielavzyc at al., 2014; and George et al., 2015). Both the MOVES model and the vehicle tested for this study showed increased HC emissions with lower ambient temperatures; however, the MOVES model uses curve showing a slightly greater dependence on ambient temperature than was observed for the vehicle tested during this study.

Also shown on Figure 13 are the observed equilibration times for the cold starts for the 2007 Dodge Ram. The equilibration times all fall within a range of about 40 to 70 seconds with a moderate trend (R^2 = 0.4509, not shown) seemingly indicating shorter equilibrations time at higher ambient temperatures. This shorter time may correspond with shorter catalytic converter warm up time or a faster time to stoichiometric air/fuel ratios leading to more complete combustion.

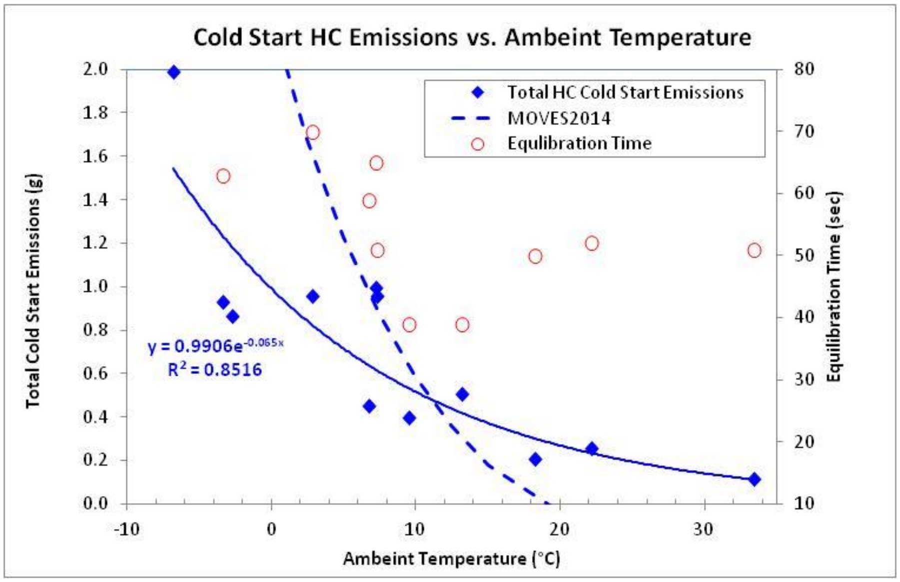


Figure 113. Total cold start HC emissions as a function of ambient temperature.

Oxides of Nitrogen

NOx emissions are controlled in gasoline engines by the catalytic converter and some combustion characteristics such as air/fuel ratio and ignition timing. In new gasoline vehicles, the catalyst is able to reduce NOx emissions to low levels a few seconds after a cold start; however, cold starts at low ambient temperatures can have an effect on emissions. Engine out NOx can increase with colder ambient conditions due to modified air/fuel ratio, exhaust gas recirculation valve operation and ignition timing. Lower ambient temperatures will also increase the time required for the catalytic converter to reach operational temperatures, leading to longer periods of increased NOx emissions (Dardiotis et al., 2013). NOx emissions may be lowered during low ambient temperature cold starts; however, because many vehicles use a very rich air/fuel ratio when starting at low ambient temperature conditions leading to low combustion temperatures and low NOx emissions. A variety of engine control strategies including exhaust recirculation valve operation and ignition timing can vary from vehicle to vehicle and can effect NOx emissions in contrasting ways, leading to large differences in NOx emissions from vehicle to vehicle and at different ambient temperatures (Dartiotis et al., 2013).

Figure 14 shows the NOx emissions for the cold starts conducted at different temperatures and also the corresponding equilibration times. The tests showed the observed NOx emissions were higher increase at warmer ambient temperatures, approximately doubling as the temperature increased from -7°C to 33°C. A linear fit to the data (see Equation 2) suggested the cold start NOx emissions increased by the relative small rate of change of +0.7 mg per °C with a correlation (R^2) of 0.7044.

$$NOx(in\ grams) \quad = \quad 0.0007(°C) + 0.0297 \qquad\qquad \textit{Equation 2}$$

This is notably different than the EPA MOVES model which adjusts comparative NOx emissions by -9.0 mg per °C, a steeper slope and in the opposite direction. However, the low rate of change and opposite observed here is not uncommon and was previously discussed by other researchers (Ludykar et al., 1999; Weilenmann et al., 2009; Dardiotis et al., 2013, and Bielaczyc et al., 2014).

Figure 14 also shows the observed NOx emission equilibration times with respect to temperature. As can be seen, the equilibration times for NOx were relatively unchanged over the entire temperature range. This suggests that the time to reach NOx equilibrium (<60 seconds) was independent across the ambient temperatures observed.

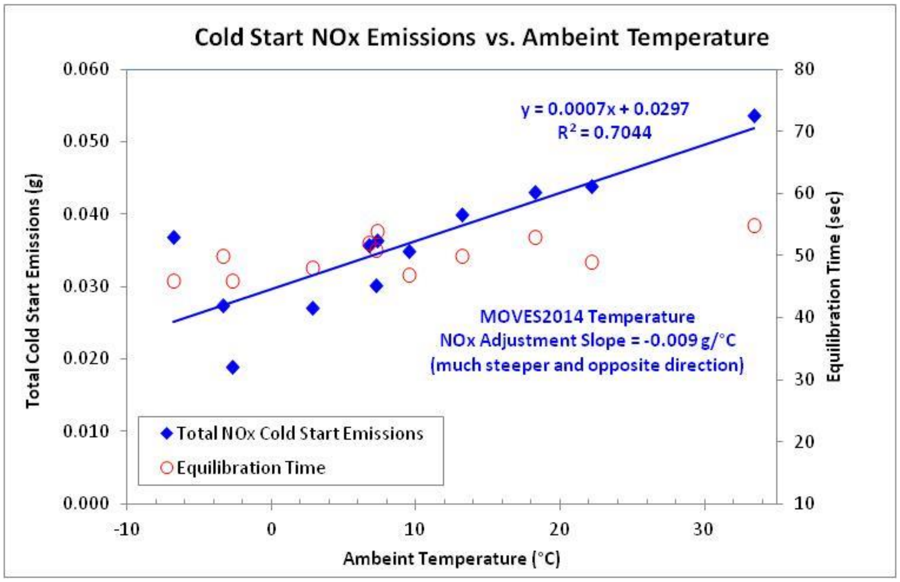


Figure 114. Total cold start NOx emissions as a function of ambient temperature.

Carbon Monoxide

The increase in CO emissions seen during cold starts as the ambient temperature decreases is similar to the HC emission increase and is based mostly on incomplete combustion of a rich air/fuel mixture. CO emissions for cold starts at different ambient temperatures were also measured for the same 2007 Dodge Ram 1500. These results are illustrated in Figure 15, with CO emissions at -7°C (66.2 g CO) found to be about 6 times more than those observed at 24°C (9.9 g CO). Similar to the HC emissions, the observed relationship between cold start CO emissions and ambient temperature was adequately ($R^2 = 0.8324$) modeled with an exponential relationship (see Equation 3).

$$CO(in\ grams) \quad = \quad 36.97\, e^{-0.063°C} \qquad \textit{Equation 3}$$

This relationship is similar to emission algorithms used within the MOVES model (see dashed line on Figure 15). The study described herein was able to examine emissions at higher temperatures (to 33°C) and verified increased sensitivity to temperature at lower temperatures with the curve leveling out at warmer temperatures. As with HC and NOx, the results of this study also closely reflected the results of many documented previous studies (Ludykar et al., 1999; Weilenmann et al., 2009; Sentoff et al., 2010; Dardiotis et al., 2013; and Bielaczyc et al., 2014).

Equilibration times for CO closely followed the same trend as CO emissions (Figure 15), with times being much shorter at higher ambient temperatures. Once again all of the equilibration times were less than 60 seconds, even at low ambient temperatures, indicating that the vehicles tailpipe emissions reached idle values with very little warm-up time.

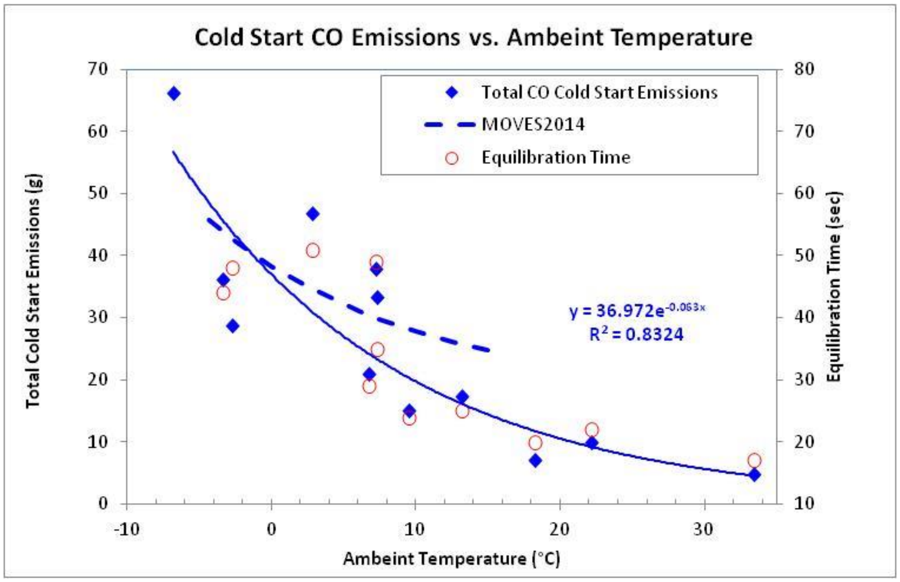


Figure 115. Total cold start CO emissions as a function of ambient temperature.

Conclusions

For this study, over 70 vehicles, broken down by EPA emission tier categories, were analyzed during cold start, hot start, and idling phases to quantify hydrocarbon (HC), oxides of nitrogen (NOx), and carbon monoxide (CO) emissions. With the exception of Pre-Tier 0 vehicles, it was shown that cold starts have much higher emission rates compared to hot starts, with some vehicles emitting twice (mainly, Pre-Tier 0 and Tier 0 vehicles) and some up to ten times more HC, NOx, and CO during a cold start. In general, cold start HC emissions were on the order of 1 to 10 g, with older vehicles generally having the higher emissions. However, at the 95% confidence interval cold start HC were indistinguishable among the Tier 0 through Tier 2 vehicles. Similar trends were also observed for NOx and CO with cold start concentration ranges of 0.1 to 1 g and10 to 100 g, respectively. During the hot start tests, most of the tested vehicles showed statistically similar emissions grouped by the pollutants and Tier level for the 5, 10, and 20-minute hot starts. Furthermore, the newer vehicles (Tier 1, NLEV, and Tier 2) consistently were found to have statistically lower emission rates during the hot starts than the cold starts.

It was also found that most vehicles do not need an extended warm up time to reach emissions equilibrium (nominally 95% reduction from peak values). Almost all vehicles tested reached equilibrium within two minutes or less after a cold start, and the equilibrium wasreached even faster following a hot start. In comparing idling a vehicle or re-starting the vehicle after a short stop of 5, 10, or 20 minutes it was found that for hydrocarbon emissions it was always better to turn the vehicle off and restart it. On average, vehicles emitted four times more HC by idling rather than restarting after a short, 5-minuite stop. The results for NOx and CO were less consistent (3x and 10x, respectively), as some newer vehicles showed similar emissions for idling and restarting.

All of the cold start time to equilibrium and the hot start versus idle data were compiled into total average data and we developed into a public awareness poster/flyer. The goal of the poster was to answer two questions: (1) How long does my car need to warm up after a cold start, and (2) During short stops, it is better to let my engine idle or shut it off and restart it? A copy of the flyer can be found in the Appendix of this document or can be provided as a PDF file by contacting the authors.

The tailpipe emissions of a single U.S. EPA Tier 2 vehicle (Dodge Ram 1500 pickup) were repeatedly monitored for cold start emissions as a function of varying ambient temperatures ranging from -7°C to 33°C (19°F to 91°F). Colder ambient temperatures were shown to produce higher HC and CO emissions in general with HC and CO emissions increasing by factors of 18 and 14, respectively, when ambient temperatures dropped from 33°C to -7°C and followed predictable exponential relationships (refer to Equations 1 and 3). These results followed previous studies by other researches and are similar to the algorithms used within EPA’s MOVES model. In contrast, the observed NOx emissions were found to be much more insensitive to variations in ambient temperatures, but did show a slight decrease with decreasing temperatures (Equation 2). The MOVES algorithms, similar to the HC and CO emissions, shows an increase in NOx emissions with decreasing temperatures, but also at a much lower rate of change than the HC and CO. The varying nature of NOx emissions with different ambient temperature is, however, documented in other research studies and has been shown to be highly variable in both direction and slope depending on vehicles cold start fuels and emission management strategies. In summary, the temperature dependency of the cold start emissions observed for the 2007 Dodge Ram 1500 tested within this study supported the relationships used by the EPA's MOVES model for HC and CO emissions. The observed NOx emissions were found to have an opposite slope to the MOVES model, but the actual rate of change with temperature was relatively low (0.0007 g of CO per °C).

References

Bielaczyc, P., A. Szczotka, and J. Woodburn. 2014. Cold Start Emissions of Spark-Ignition Engines at Low Ambient Temperatures as an Air Quality risk. *Archives of Environmental Protection* 40:86-100. doi:10.2478/aep-2014-0026.

Boulter, P.G., J. Borken-Kleefeld, and L. Ntziachristos. 2013. The evolution and control of NOx emissions from road transport in Europe. In Urban Air Quality in Europe. M. Vianna (ed). Hdb Env Chem (2013) 26:31-54. Doi: 10.1007/698_2012_162. Spinger-Verlag Berlin Hedelberg.

Cao, Y. 2007. Operation and Cold Start Mechanisms of Internal Combustion Engines with Alternative Fuels. SAE Technical Paper. 2007-01-3609. doi:10.4271/2007-01-3609.

Cook, R., J. Touma, A. Fernandez, D. Brzezinski, C. Bailey, C. Scarbro, J. Thurman, M. Strum, D. Ensley, and R. Baldauf. 2007. Impact of Underestimating the Effects of Cold Temperature on Motor Vehicle Start Emissions of Air Toxics in the United States. *Journal of the Air &Waste Management Association* 57:1469-1479. doi:10.3155/1047-3289.57.12.1469.

Cooper, C.D. and F.C. Alley. 2011. Air Pollution Control: A Design Approach. Waveland Press, Inc. Long Grove, IL. ISBN 1-57766-678-X. pp 573-612.

Dardiotis, C., G. Martini, A. Marotta, and U. Manfredi. 2013. Low-temperature cold-start gaseous emissions of late technology passenger cars. *Applied Energy* 111:468-478. doi:10.1016/j.apenergy.2013.04.093.

Fan, Q., and L. Li. 2013. Study on first-cycle combustion and emissions during cold start in a TSDI gasoline engine. *Fuel* 103: 473-479. doi:10.1016/j.fuel.2012.07.025.

Favez, J.-Y., M. Weilenmann, and J. Stilli. 2009. Cold start extra emissions as a function of engine stop time: Evolution over the last 10 years. *Atmospheric Environment* 43: 996-1007. doi:10.1016/j.atmosenv.2008.03.037.

Gaines, L., E. Rask, and G. Keller. 2012. Which is Greener: Idle, or Stop and Restart? Comparing Fuel Use and Emissions for Short Passenger-Car Stops. Transportation Review Board Annual Meeting Proceedings. https://anl.box.com/s/q13vvdjic1jbz6lqa7m9u1nthfq5u0n9 (Accessed 08/30/16).

George, I., M. Hays, J. Herrington, W. Preston, R. Snow, J. Faircloth, B. George, T. Long, and R. Baldauf. 2015. Effects of Cold Temperature and Ethanol Content on VOC Emissions from Light-Duty Gasoline Vehicles. *Environmental Science and Technology* 49: 13067-13074. doi:10.1021/acs.est.5b04102.

Jiménez, J.L., P.M. McLintock, G.J. McRae, D.D. Nelson, M.S. Zahniser. 1999. Vehicle Specific Power: A useful parameter for remote sensing and emission studies. Ninth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 1999.

Ludykar, D., R. Westerholm, and J. Almen. 1999. Cold start emissions at +22, -7 and -20^{o}C ambient temperatures from a three-way catalyst (TWC) car: regulated and unregulated exhaust components. *The Science of the Total Environment* 235: 65-69.

Park, S., K. Kozawa, S. Fruin, S. Mara, Y. Hsu, C. Jakober, A. Winer, and J. Herner. 2011. Emission Factors for High-Emitting Vehicles Based on On-Road Measurements of Individual Vehicle Exhaust with a Mobile Measurement Platform. *Journal of the Air & Waste Management Association* 61: 1046-1056. doi:10.1080/10473289.2011.595981.

Reiter, M., and K. Kockelman. 2016. The problem of cold starts: A closer look at mobile source emission levels. *Transportation Research Part D* 43:123-132. doi:10.1016/j.trd.2015.12.012.

Sentoff, K., M. Robinson, and B. Holmen. 2010. Second-by-Second Characterization of Cold-Start Gas-Phase and Air Toxic Emissions from a Light-Duty Vehicle. *Transportation Research Record: Journal of the Transportation Research Board* 2158: 95-104. doi:10.3141/2158-12.

U.S. Environmental Protection Agency (EPA). 1993. Federal Test Procedure Review Project: Preliminary Technical Report. U.S. EPA report 420-R-93-007.

U.S. Environmental Protection Agency (EPA). 2014. Emission Adjustments for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES2014. Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency. EPA-420-R-14-012.

U.S. Environmental Protection Agency (EPA). 2015. Exhaust Emission Rates for Light-Duty On-road Vehicles in MOVES2014. Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency. EPA-420-R-15-005.

U.S. Environmental Protection Agency (EPA). 2016. Light-Duty Vehicles and Light-Duty Trucks: Tier 0, Tier 1, and National Low Emission Vehicle (NLEV) Implementation Schedule. U.S. EPA Office of Transportation and Air Quality report EPA-420-B-16-009.

Utah Air Quality Board (Utah). 2014. Utah State Implementation Plan (SIP). www.deq.utah.gov (Accessed 9/1/2016).

Weilenmann, M., J.Y. Faves, and R. Alvarez. 2009. Cold-Start Emissions of Modern Passenger Cars at Different Low Ambient Temperatures and Their Evolution over Vehicle Legislation Categories. *Atmospheric Environment* 43: 2419-2429. doi:10.1016/j.atmosenv.2009.02.005.

Zhang, K., and C. Frey. 2006. Road Grade Estimation for On-Road Vehicle Emissions Modeling Using Light Detection and Ranging Data. *Journal of the Air & Waste Management Association*. 56:777-788.

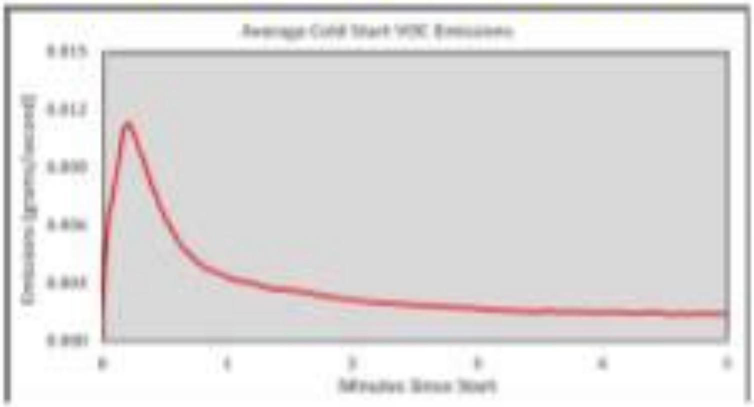
APPENDIX

Public Awareness Warm-up and Idle Poster/Flyer

To Idle or Not To Idle…

Automobiles are significant sources of Volatile Organic Carbon (VOC) Oxides of Nitrogen (NO_x) and Carbon Monoxide (CO)

Question 1: How long does my engine need to warm up after a "cold start" (engine off for more than 12 hours)?



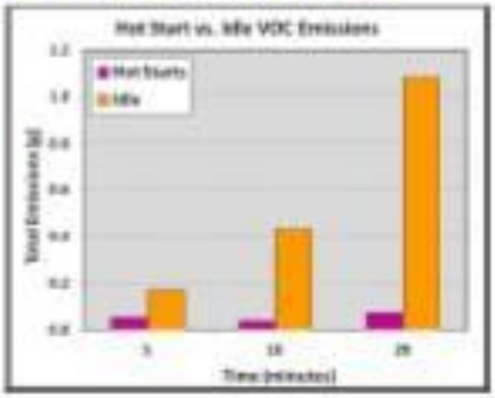
Warming up the engine by idling for more than 2-3 minutes IS NOT needed. After start, warm up the engine by driving it normally.

Question 2: During short stops, is it better to let my engine idle or shut off and restart it?

Always turn off your engine when the vehicle's transmission is in the "Park Position". When the engine is warm, idling for 5 minutes produces…

- *4 times more VOC*
- *3 times more NO_x and*
- *10 times more CO*

than restarting the engine and the differences become even greater for longer time periods



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