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The problem of cold starts: A closer look at mobile source emissions levels

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ABSTRACT

While the phenomenon of excess vehicle emissions from cold-start conditions is well known, the magnitude and duration of this phenomenon is often unclear due to the complex chemical processes involved and uncertainty in the literature on this subject. This paper synthesizes key findings regarding the influence of ambient and engine temperatures on light-duty vehicle (LDV) emissions. Existing literature, as well as analytical tools like the U.S. Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES), indicate that while total vehicle emissions have dropped significantly in recent years, those associated with cold starts can still constitute up to 80% for some pollutant species. Starting emissions are consistently found to make up a high proportion of total transportation-related methane (CH_4), nitrous oxide (N_2O), and volatile organic compounds (VOCs). After 3–4 min of vehicle operation, both the engine coolant and the catalytic converter have generally warmed, and emissions are significantly lower. This effect lasts roughly 45 min after the engine is shut off, though the cooling rate depends greatly on the emission species and ambient temperature. Electrically (pre-)heated catalysts, using the bigger batteries available on hybrid drivetrains and plug-in vehicles, may be the most cost-effective technology to bring down a sizable share of mobile source emissions. Trip chaining (to keep engines warm) and shifting to non-motorized modes for shorter trips, where the cold start can dominate emissions, are also valuable tactics.

Introduction

Vehicle cold starts are an important source of major air pollutants, including uncombusted hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM). In the first minutes of engine operation, when engine block and coolant temperatures are low, incomplete combustion results in significantly higher emissions than at ordinary operating temperatures (Cao, 2007). This effect is magnified by the modern catalytic converter, which was adopted as a standard vehicle feature in order to control these three pollutants and improve air quality (CARB, 2012). Each of these pollutant species carries potentially serious health and environmental costs. HC, for example, is part of a broader category known as volatile organic compounds (VOCs), which can cause headaches, nausea, and kidney and liver damage; various VOCs are carcinogenic for humans (EPA, 2012). CO inhibits oxygen intake and can be fatal in large doses. Prolonged exposure to NO_x can

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result in chronic bronchitis, asthma, and other respiratory problems. The mortality impacts of these pollutants can be in the tens of thousands of dollars per ton emitted, and depend in large part on how many humans are exposed (EPA, 2013).

Due to serious air pollution, particularly in California's Los Angeles region, the U.S. Environmental Protection Agency (EPA) has been regulating the light-duty vehicle fleet's emissions of these substances since 1968, and began regulating PM with the 1994 model year. More recently, the EPA has also cut by around three-quarters the allowable sulfur content in gasoline for on-road use, and recent LEV III standards are expected to continue to decrease tailpipe emissions (EPA, 2014). While gasoline blends have gotten cleaner over the years, and catalytic converters do filter a substantial portion of primary pollutants (largely CO, NO_x, and HC, after reaching approximately 400 °F) (Reif, 2015), lower running emissions during engine operation mean that starting emissions make up a large and growing share of total vehicle emissions. In the case of PM, the catalytic converter does relatively little, but high vehicle operating temperatures are still key to low-emissions operation.

This paper quantifies the cold-start effect for U.S. light-duty-fleet conditions. A literature review first summarizes key relationships between temperature and tailpipe and evaporative emissions. Next, the proportion of total light-duty vehicle emissions attributable to cold starts is calculated using the EPA's Motor Vehicle Emission Simulator (MOVES) (EPA, 2011). Finally, this paper highlights other relevant emissions considerations, such as evaporation and re-suspension, as well as various strategies for reducing cold-start emissions. Excess emissions attributable to cold starts vary widely by pollutant species, accounting for 10–30% of total mobile source emissions in most cases. For both fine and coarse PM, the proportion is about 10–20% of combined starting and running emissions. This does not reflect brake and tire dust or re-suspension, which are major sources of PM air pollution, as discussed toward the end of this paper.

Defining cold starts

An internal combustion engine's (ICE's) chemical processes are complex, making it difficult to pinpoint what constitutes a cold engine start in a way that is scientifically and practically meaningful. As the terminology "cold start" implies, the key factor is the difference in temperature from regular operating conditions (for both the engine and catalytic converter). A reasonable starting point is to ask, "At what temperatures do fuel consumption and emissions profiles become qualitatively different from those of a vehicle at steady operating temperature?"

The EPA (1993) defines a "hot start" as one during which both engine and catalytic converter are near operating temperatures. A hot start thus requires that the previous trip be at least 4 min long (2 min to heat the catalyst and another two to reach at least 140 °F coolant temperature, assuming a typical internal combustion engine) and the soak length (engine-off time) be no more than 45 min, after which the catalytic converter has cooled considerably (EPA, 1993). Catalytic converters require extremely high temperatures to operate at intended efficiency (Reif, 2015), so they drop below their optimal temperatures much more quickly than the engines.

A "warm start" occurs when the engine is still hot but the catalytic converter is cool, and a cold start occurs when both engine and catalytic converter have cooled to within 10 °F of the ambient temperature (EPA, 1993). The EPA also defines a cold start in terms of time passed since engine operation: it is any start that occurs at least one hour after the end of the preceding trip for catalyst-equipped vehicles (EPA, 1994), which covers the vast majority of the current vehicle fleet since the EPA has required catalytic converters on nearly all light-duty vehicles built since 1975.

These cold-, warm-, and hot-start definitions mask considerable variation between vehicles, across starting ambient temperatures, and after different soak lengths. In truth, many definitions of a cold start, including in official documents, are vague. For example, the EPA (1993) also considers a start "cold" "if it is preceded by a long uninterrupted soak, such as those starts that occur after an overnight soak". U.S. law (CFR, 2013) requires a soak time between 12 and 36 h prior to testing for cold-start emissions. These regulations also specify that "a set of cold start criteria based solely on ambient temperature exceeding engine coolant temperature will not be acceptable." Fortunately, there are several methods for quantifying cold start emissions more specifically, in the lab and using publicly available tools and data sets.

Quantifying cold start emissions

The most accurate way to measure the magnitude of vehicle emissions in general, and those attributable to cold starts in particular, is through repeated testing of vehicles under real-world driving conditions using sophisticated sensing technology. Unfortunately, this is expensive and time-consuming, and existing research tends to focus on a single pollutant or a small sample of vehicles (e.g., Robinson et al., 2010; Lee et al., 2012; Kleeman et al., 2000). Nevertheless, this study builds on prior laboratory work and clarifies our current understanding by first summarizing the relevant literature on cold starts. Relevant parameters, as well as specific emissions rates, were sought for all criteria pollutants, with emphasis on PM and SO_2, due to these species' disproportionate health and environmental costs.

The synthesis of existing work is augmented by emissions estimates developed using EPA's MOVES model. MOVES is a powerful tool for anticipating emissions based on a variety of parameters, including time of day, month of the year, pollutant species, and emissions process. Unlike previous programs, such as VT-MICRO and CMEM, MOVES explicitly models starting emissions separately from running emissions (Fujita et al., 2012). A single weekday in many US metropolitan areas repre-