

1 **THE PROBLEM OF COLD STARTS:**
2 **A CLOSER LOOK AT MOBILE SOURCE EMISSIONS LEVELS**
3

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21 **ABSTRACT**

22 While the phenomenon of excess vehicle emissions from cold-start conditions is well known, the
23 magnitude and duration of this phenomenon is often unclear due to the complex chemical processes
24 involved and uncertainty in the literature on this subject. This paper synthesizes key findings regarding
25 the influence of ambient and engine temperatures on light-duty vehicle (LDV) emissions. Existing
26 literature, as well as analytical tools like the U.S. Environmental Protection Agency’s Motor Vehicle
27 Emission Simulator (MOVES), indicate that while total vehicle emissions have dropped significantly in
28 recent years, those associated with cold starts can still constitute up to 80% for some pollutant species.
29 Starting emissions are consistently found to make up a high proportion of total transportation-related
30 methane (CH₄), nitrous oxide (N₂O), and volatile organic compounds (VOCs). After three to four
31 minutes of vehicle operation, both the engine coolant and the catalytic converter have generally warmed,
32 and emissions are significantly lower. This effect lasts roughly 45 minutes after the engine is shut off,
33 though the cooling rate depends greatly on the emission species and ambient temperature. Electrically
34 (pre-)heated catalysts, using the bigger batteries available on hybrid drivetrains and plug-in vehicles, may
35 be the most cost-effective technology to bring down a big share of mobile source emissions. Trip chaining
36 (to keep engines warm) and shifting to non-motorized modes for shorter trips, where the cold start can
37 dominate emissions, are also valuable tactics.
38

39 **INTRODUCTION**

40 Vehicle cold starts are an important source of major air pollutants, including uncombusted hydrocarbons
41 (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM). In the first minutes
42 of engine operation, when engine block and coolant temperatures are low, incomplete combustion results
43 in significantly higher emissions than at ordinary operating temperatures (Cao, 2007). This effect is
44 magnified by the modern catalytic converter, which was adopted as a standard vehicle feature in order to
45 control these three pollutants and improve air quality (CARB 2012). Each of these pollutant species
46 carries potentially serious health and environmental costs. HC, for example, is part of a broader category
47 known as volatile organic compounds (VOCs), which can cause headaches, nausea, and kidney and liver
48 damage, and various VOCs are carcinogenic for humans (EPA, 2012). CO inhibits oxygen intake and can
49 be fatal at large doses. Prolonged exposure to NO_x can result in chronic bronchitis, asthma, and other
50 respiratory problems. The mortality impacts of these pollutants can be in the tens of thousands of dollars
51 per ton emitted, and depends in large part on how many humans are exposed (EPA, 2013).

52
53 Due to serious air pollution, particularly in California’s Los Angeles region, the U.S. Environmental
54 Protection Agency (EPA) has been regulating the light-duty vehicle fleet’s emissions of these substances
55 since 1968, and began regulating PM with the 1994 model year. More recently, the EPA has also cut by
56 around three-quarters the allowable sulfur content in gasoline for on-road use, and recent LEV III
57 standards are expected to continue to decrease tailpipe emissions (EPA, 2014). While gasoline blends
58 have gotten cleaner over the years, and catalytic converters do filter a substantial portion of primary
59 pollutants (largely CO, NO_x, and HC, after reaching approximately 400°F) (Reif, 2015), lower running
60 emissions during engine operation mean that increased starting emissions make up a large and growing
61 share of total vehicle emissions. In the case of PM, the catalytic converter does relatively little, but high
62 vehicle operating temperatures are still key to low-emissions operation.

63
64 This paper quantifies the cold-start effect for U.S. light-duty fleet conditions. A literature review first
65 summarizes key relationships between temperature and tailpipe and evaporative emissions. Next, the
66 proportion of total light-duty vehicle emissions attributable to cold starts is calculated using the EPA’s
67 Motor Vehicle Emission Simulator (MOVES) (EPA, 2011). Finally, this paper highlights other relevant
68 emissions considerations, such as evaporation and re-suspension, as well as various strategies for
69 reducing cold-start emissions. Excess emissions attributable to cold starts vary widely by pollutant
70 species, accounting for 10 to 30% of total mobile source emissions in most cases. For both fine and
71 coarse PM, the proportion is about 10 to 20% of combined starting and running emissions. This does not
72 reflect brake and tire dust or re-suspension, which are major sources of PM air pollution, as discussed
73 toward the end of this paper.

74 75 **Defining Cold Starts**

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

82
83 The EPA (1993) defines a “hot start” as one during which both engine and catalytic converter are near
84 operating temperatures. A hot start thus requires that the previous trip be at least four minutes long (two
85 minutes to heat the catalyst and another two to reach at least 140°F coolant temperature, assuming a
86 typical internal combustion engine) and the soak length be no more than 45 minutes, after which the
87 catalytic converter has cooled considerably (EPA, 1993). Catalytic converters require extremely high
88 temperatures to operate at intended efficiency (Reif, 2015), so they drop below their optimal temperatures
89 much more quickly than the engines.

90
91 A “warm start” occurs when the engine is still hot but the catalytic converter is cool, and a cold start
92 occurs when both engine and catalytic converter have cooled to within 10 degrees Fahrenheit of the
93 ambient temperature (EPA, 1993). The EPA also defines a cold start in terms of time passed since engine
94 operation: it is any start that occurs at least one hour after the end of the preceding trip for catalyst-
95 equipped vehicles (EPA, 1994), which covers the vast majority of the current vehicle fleet since the EPA
96 has required catalytic converters on nearly all light-duty vehicles built since 1975.

97
98 These cold-, warm-, and hot-start definitions mask considerable variation between vehicles, across
99 starting ambient temperatures, and after different soak lengths (engine-off times). In truth, many
100 definitions of a cold start, including in official documents, are vague. For example, the EPA (1993) also
101 considers a start “cold” “if it is preceded by a long uninterrupted soak, such as those starts that occur after
102 an overnight soak”. U.S. law (CFR 2013) requires a soak time between 12 and 36 hours prior to testing

103 for cold-start emissions. These regulations also specify that “a set of cold start criteria based solely on
104 ambient temperature exceeding engine coolant temperature will not be acceptable.” Fortunately, there are
105 several methods for quantifying cold start emissions more specifically, in the lab and using publicly
106 available tools and data sets.

107

108 **QUANTIFYING COLD START EMISSIONS**

109 The most accurate way to measure the magnitude of vehicle emissions in general, and those attributable
110 to cold starts in particular, is through repeated testing of vehicles under real-world driving conditions
111 using sophisticated sensing technology. Unfortunately, this is expensive and time-consuming, and
112 existing research tends to focus on a single pollutant or a small sample of vehicles (e.g., Robinson et al.
113 [2010], Lee et al. [2012], Kleeman et al. [2000]). Nevertheless, this study builds on prior laboratory work
114 and clarifies our current understanding by first summarizing the relevant literature on cold starts.
115 Relevant parameters, as well as specific emissions rates, were sought for all criteria pollutants, with
116 emphasis on PM and SO₂, due to these species’ disproportionate health and environmental costs.

117

118 The synthesis of existing work is augmented by emissions estimates developed using EPA’s MOVES
119 model. MOVES is a powerful tool for anticipating emissions based on a variety of parameters, including
120 time of day, month of the year, pollutant species, and emissions process. Unlike previous programs, such
121 as VT-MICRO and CMEM, MOVES explicitly models starting emissions separately from running
122 emissions (Fujita et al., 2012). A single weekday in many US metropolitan areas represents millions of
123 vehicle-miles traveled (VMT) across a variety of roadway types, speed profiles, and vehicle attributes,
124 and thus a large city’s or region’s total mobile-source emissions are substantial.

125

126 In this study, default MOVES data were used to develop county-wide emissions inventories for regulated
127 pollutants, air toxics, and greenhouse gases (as CO₂ and CO₂eq). Comparisons of running versus starting
128 emissions quantify the relative importance of vehicle cold starts with regard to each pollutant species.
129 Base estimates come from a single scenario: a weekday in July 2010 in Travis County, Texas (which
130 contains the City of Austin).

131

132 The simulation was then expanded to encompass the month of January, and other years (ranging from
133 year 2000 to 2025), in order to reveal seasonal and longer-term variations in emissions levels – and the
134 relative importance of cold start conditions, due to changes in fuel composition and vehicle technologies.
135 Finally, emissions were simulated for other counties, around the U.S., to appreciate regional variations.

136

137 **Existing Estimates of Cold Start Emissions**

138 Measuring cold-start emissions changes due to temperature variation and other factors presents a
139 significant challenge. It can take up to 12 hours to fully cool an engine to steady state, but heat loss is
140 most significant in the first two hours after shutdown. Start-up emissions produced after the engine has
141 been off for even 15 minutes can be high. According to the EPA (2011), a hot start after a soak period of
142 three minutes results in average increases of less than 10% in CO, HC, and NO_x emissions, per mile
143 traveled (as compared to hot running levels). After just 45 minutes, the catalytic converter has cooled
144 significantly, and CO and HC are halfway back to cold-start levels, while NO_x has recovered more than
145 85% of the difference.

146

147 This raises a key question: How long are engines off? The EPA (1993) found that almost 40% of real-
148 world soak times in Baltimore, Maryland lay between 10 minutes and two hours. Similar findings come
149 from the more recent Commute Atlanta study (Guensler et al., 2007), with 16.1% of the Georgia region’s
150 soak times lying within the 0 to 5 minute interval and 17.9% lying between 8 and 24 hours (the two most
151 common bins). Intermediate soak lengths, between 5 minutes and two hours duration, accounted for over
152 43% of Atlanta’s LDV starts (Guensler et al., 2007).

153

154 Some emissions come simply from starting the engine. For example, Gaines et al. (2013) found that a hot
155 start emits more HC than ten minutes of idling, and more CO than idling the engine for 45 minutes and
156 longer. André and Joumard (2005) estimated a broad distribution (by species) for what they call “cold
157 start distances,” with an average of 5.2 km (3.2 miles) at 20°C (68°F). In other words, it may take 3.2
158 miles of driving before emissions rates of some pollutants stabilize when ambient temperature is 68°F.
159

160 This is particularly important in densely developed settings, because many automobile trips are short in
161 distance and duration, so a significant share of urban driving takes place while the engine is cold – and
162 human exposure (in denser settings) is relatively high. Research in Europe suggests cold start emissions
163 may comprise as much as 50% of urban driving emissions (Sérié and Joumard, 1998). The U.S. 1995
164 Nationwide Personal Transportation Survey revealed that nearly half of all person-trips were three miles
165 or less (de Nazelle et al., 2010). And the median LDV trip distance in the 2009 NHTS is just 4.0 miles,
166 with 43.4% of all personal-vehicle trips being less than 3.2 miles in length (USDOT, 2010). At these
167 relatively short distances, most pollutant species would not have stabilized at low, hot-running levels
168 before the engine is turned off and begins cooling again. All this suggests that cold starts deserve special
169 attention by travelers and policymakers, especially in regions and neighborhoods where most vehicle-trips
170 are relatively short (and engines cold).
171

172 However, these results vary across studies. Surveying a representative sample of late-model vehicles
173 from the Swiss fleet at 25°C (77°F) and 28 km/h (17 mph), Favez et al. (2009) estimated an average “cold
174 distance” of just 1 km (0.6 miles), with a maximum of 3 km (1.9 miles). Chen et al. (2011) reported a
175 120-second cold start duration (which is typically 1 mile or less of travel distance on local streets, where
176 most trips begin), and noted that gasoline blended with 20-30% ethanol can lower HC, CO, and NO_x
177 emissions during cold starts.
178

179 Defining cold start in terms of associated PM emissions and PM size distribution, Robinson et al. (2010)
180 measured cold start times between 165 and 230 seconds using a 1999 Toyota Sienna minivan at
181 temperatures ranging from 68°F to 99°F (i.e., 20°C to 37°C). In this case, times reflect primarily those
182 required to heat the engine, since the catalytic converter has little effect on PM emissions. The cold start
183 durations in this study suggest “cold distances” of 2 miles or less, given operating speeds at the start of
184 most vehicle trips.
185

186 In terms of specific emission species, Lee et al. (2012) produced estimates using a specially equipped
187 1999 Dodge Grand Caravan SUV. By comparing the emissions bagged during the first and third phases
188 of the U.S. federal test procedure (FTP) for vehicle emissions (which are identical except for the engine
189 temperature at the beginning of the phase), they estimated that a cold engine emits 3.46 gm/mi (gpm) of
190 CO, or *nearly three times* what a warm engine produces. The cold engine was also responsible for 0.79
191 gpm of NO_x and 0.48 gpm of total hydrocarbons (THCs). These values are *nearly double and nearly*
192 *quadruple* the respective rates for the warmed/hot engine in their test chamber (Lee et al., 2012). They
193 also found minimal PM (as PM₁₀ and PM_{2.5}) emissions, under the detection threshold for most driving
194 cycles, and so concluded that MOVES’ PM estimates may be biased high. On the other hand, Nam et al.
195 (2008) estimated that approximately 30% of total vehicle PM emissions occur during cold start, and
196 found that Phase 1 (cold-start) emissions were 7.5 times those of Phase 3. Kleeman et al. (2000) noted
197 that PM size distribution varied little between their samples of the cold and hot start portions of the FTP
198 driving cycle.
199

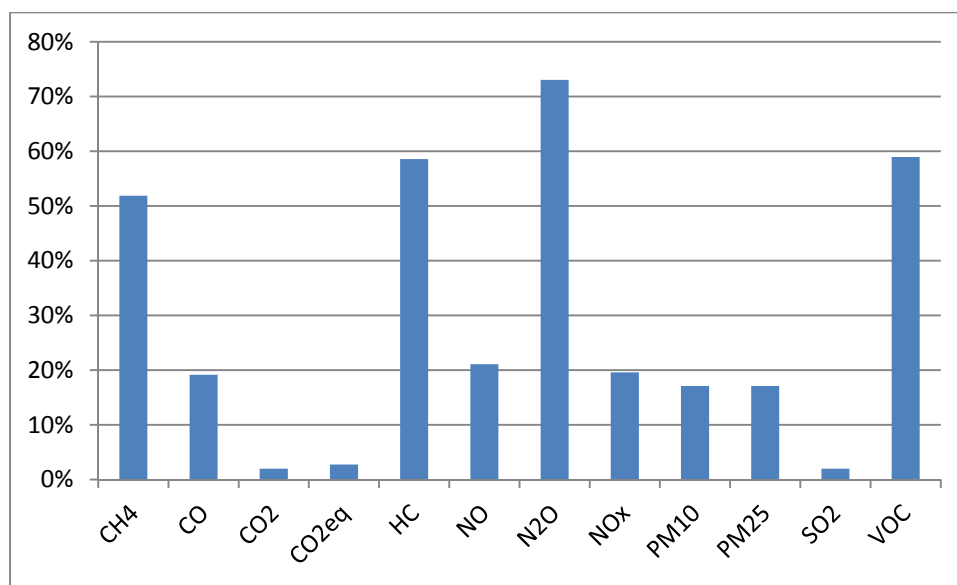
200 Diesel combustion is relatively fuel-efficient, especially for heavy-duty applications. For the same engine
201 load, diesel engines emit less CO, HC, and CO₂ than gasoline-fuelled engines, but emit much more PM.
202 Conventional port fuel injection (PFI) gasoline engines emit at least 90 percent less PM than diesel
203 engines, per mile of travel, which is why until recently there has been little regulation of PM in gasoline
204 engines. Newer gasoline direct injection (GDI) technologies offer better fuel economy and increased

205 power, but emit significantly more PM than PFI vehicles (Myung and Park, 2012) - perhaps on the order
206 of 14 mg/mi during the first 505 seconds of the FTP (Zhang and McMahon, 2012), as compared to Lee et
207 al.'s (2012) estimate of just 1 mg/mi with an older, PFI vehicle.
208

209 These experimental results are useful, but many of them focus on a small sample of vehicles at a constant,
210 moderate ambient temperature. What about the big picture of vehicle emissions across an entire
211 metropolitan area? The following section considers an alternative approach to quantifying cold start
212 emissions using a simulation tool developed by the U.S. Environmental Protection Agency.
213

214 MOVES Estimates of Cold Start Emissions

215 The default database built into MOVES, aggregated at the county level, provides a sense of the proportion
216 of emissions species that result from cold starts, rather than from the more common "hot running" of
217 engines. Figure 1 shows the percentage of total running and starting emissions (which include
218 evaporative emissions during engine operation, but not brake or tire-wear emissions) that are due to
219 vehicle starts, as estimated for a typical weekday in July 2010 in Austin, Texas' Travis County. Clearly,
220 methane (CH₄) and other HCs (which overlap most VOC species) and NO₂ are strongly affected by
221 starting conditions. Catalytic converters are designed to reduce CO and NO_x, though MOVES' CO
222 estimates do not suggest that converters are appreciably more effective at reducing CO and NO_x than they
223 are at reducing PM (which is removed by a heated engine, thanks to more complete combustion). Since
224 CH₄, HC (as VOC) and N₂O appear as dominant species in cold-start emissions, these three species are
225 the focus of much of the rest of this paper. CO is also included because it is among the primary pollutants
226 regulated by the EPA since 1968, along with HC and NO_x. Methane is not currently regulated from
227 mobile sources, but is a powerful greenhouse gas. In addition, short-term exposure to concentrations of
228 15% can cause dizziness and headaches (Wisconsin DHS, 2012).
229

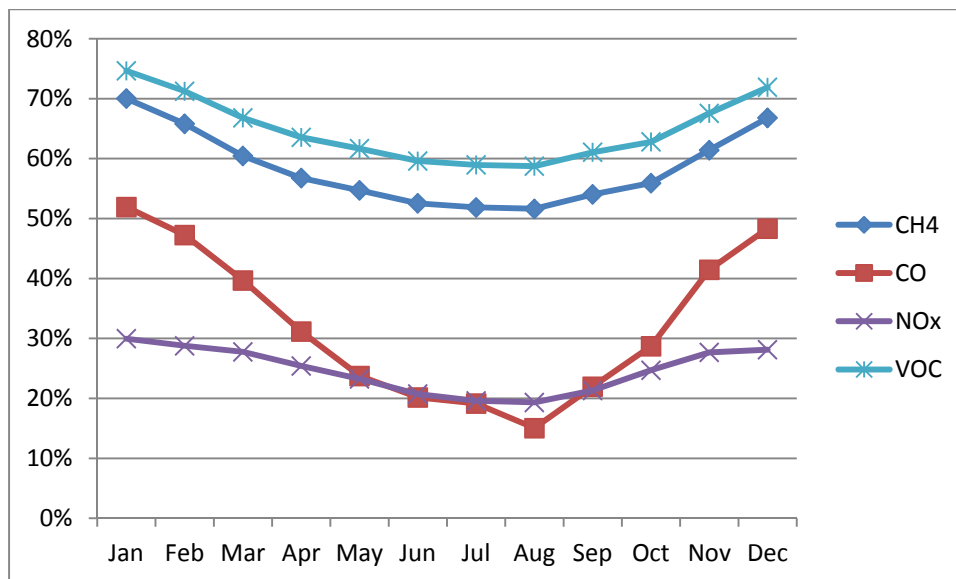


230
231 **FIGURE 1 Percentage of running and starting emissions attributable to starts (MOVES output).**
232 **Travis County, Texas, July 2010 weekday, LDVs only**
233

234 Ambient Temperature Effects

235 Temperature affects vehicle emissions in at least two opposing ways: lower ambient temperatures raise
236 cold-start emissions for most pollutant species, while higher engine or ambient temperatures increase
237 evaporative emissions of gasoline (which are included in MOVES' running emissions while the engine is
238 running, but continue throughout the day, especially in hot weather). This is illustrated in Figure 2, which
239 shows cold start emissions shares falling substantially during summer months. This is partly due to

240 summer starts resulting in lower absolute emissions, and partly because of increased evaporative and
 241 running emissions in hotter weather.
 242



243 **FIGURE 2 Percentage of key running and starting emissions attributable to cold starts over**
 244 **months of the year (MOVES output). Travis County, Texas, 2010 weekday, LDVs only**
 245
 246

247 The technologies being used for significant reductions in overall vehicle emissions over the last four
 248 decades have resulted in dramatic cold-weather effects: modern gasoline vehicles now emit about 15
 249 times more CO and 35 times more HC when started at -4°F as compared with 73°F (i.e., -20°C to +23 °C)
 250 (Weilenmann et al., 2009). Only CO₂ (the primary greenhouse gas of anthropogenic origin) does not
 251 show a strong inverse relationship with ambient temperature (Sentoff et al., 2010).
 252

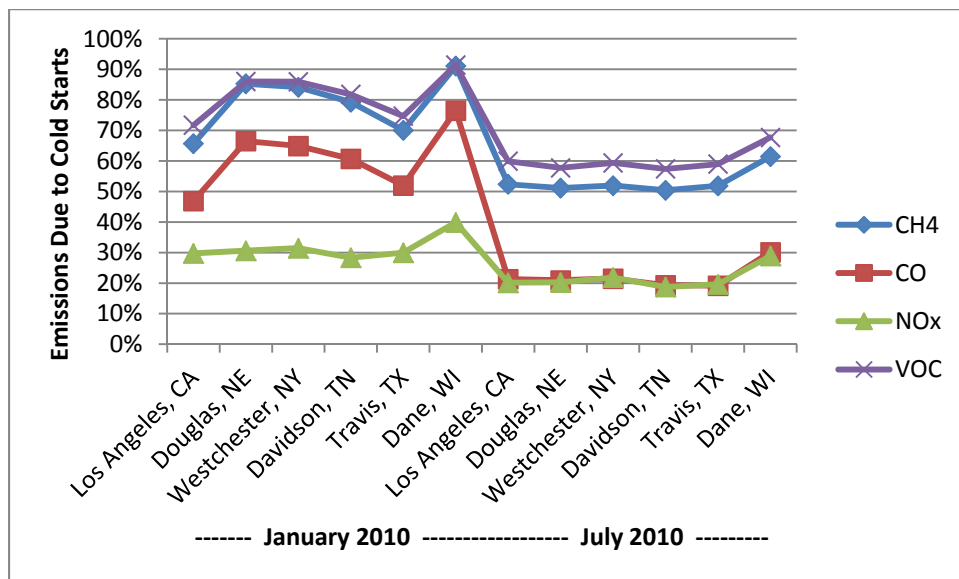
253 In Robinson et al.'s (2010) measurements of cold start times, they found that lower ambient temperatures
 254 did not increase starting PM emissions rates per minute or per mile, but resulted in longer times to warm
 255 the engine, which generated higher total PM emissions. Nam et al. (2010) found that cold-start per-mile
 256 PM emissions approximately doubled for every 20°F drop in ambient temperature. In terms of other
 257 species, Weilenmann et al. (2005) found that cold ambient temperatures have a “disproportional” effect
 258 on HC emissions, a moderate impact on CO, and little to no effect on NOx emissions, which are relatively
 259 low (as a share of total emissions, as shown in Figure 1) and essentially constant. Figure 3 summarizes
 260 those results.
 261

262 Such numbers are important because many real-world conditions fall outside formal test procedures’
 263 prescribed temperature intervals. For example, Lejon et al. (2010) note that European emissions tests
 264 generally call for an ambient temperature between 68 and 86°F, even though the average annual
 265 temperature across the continent is closer to 50°F, and in northern EU countries the average lies below
 266 41°F. Fortunately, Dardiotis et al. (2013) recently found that, despite cold start emissions being 2 to 11
 267 times higher at 19°F than at 72°F, modern gasoline engines emit substantially less than current legislation
 268 requires, even at the colder temperature.
 269

270 Geographic Variability

271 Travis County, Texas provides an interesting test case, but does not necessarily represent the reality of
 272 other metropolitan areas. Figure 3 shows cold start emissions of methane, CO, NOx, and VOCs for
 273 several other counties across different regions of the country. With one exception (Dane County,

274 Wisconsin, which contains the city of Madison), cold start shares are relatively consistent across regions.
 275 Cold-start emissions shares during January are almost uniformly higher than those during July.
 276

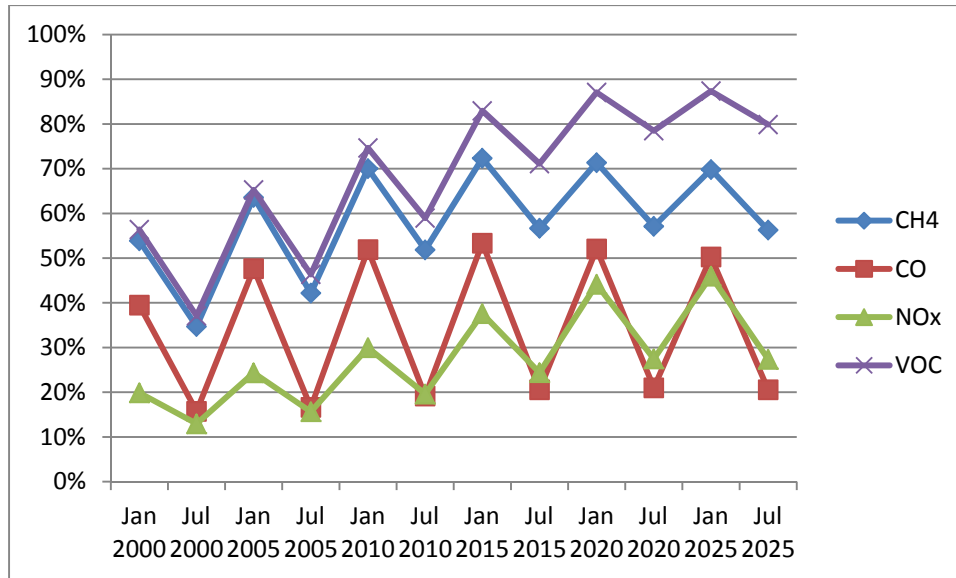


277
 278 **FIGURE 3 Cold start emissions shares across U.S. regions (MOVES output), 2010 weekdays,**
 279 **LDVs only**

280
 281 **Evolution over Time**

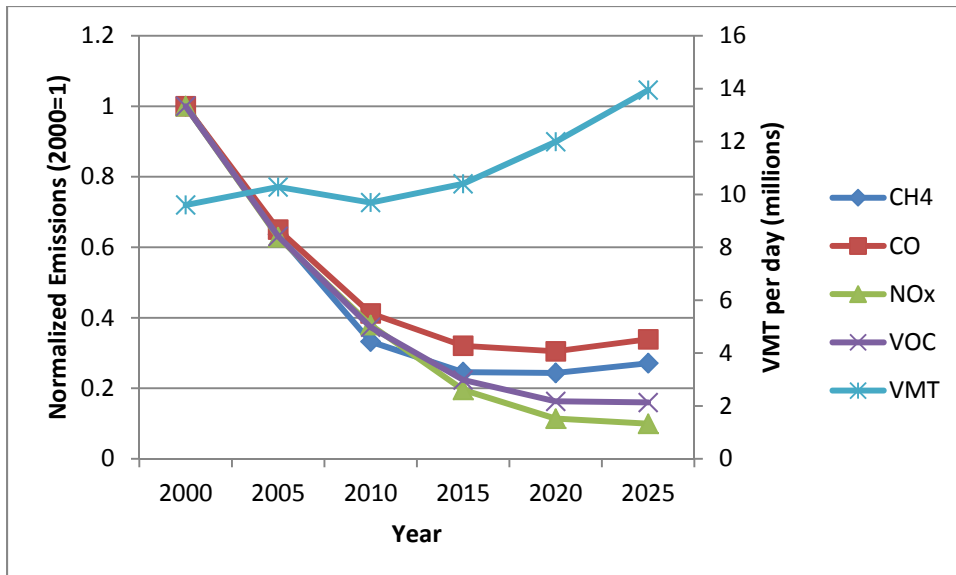
282 Figure 4 illustrates the evolution of cold-start LDV emissions across years, with winter versus summer
 283 season variations, for Travis County. As expected, each of the four species exhibits a higher cold start
 284 share in winter due to lower ambient temperatures. The MOVES model forecasts cold-start shares to rise
 285 over time, reaching 80 to 90 percent in the case of VOCs in year 2025. Fortunately, this sharp increase in
 286 shares is due to significant reductions in running emission rates. In fact, the U.S. expects significant
 287 continuing reductions in both starting and running emissions across its LDV fleet, which should translate
 288 to lower overall emissions in Travis County as well. For example, Travis County’s mobile-source
 289 emissions of NOx and VOC are expected to fall 93 and 95 percent, respectively, between 2000 and 2025,
 290 while VMT is expected to rise 45 percent.

291

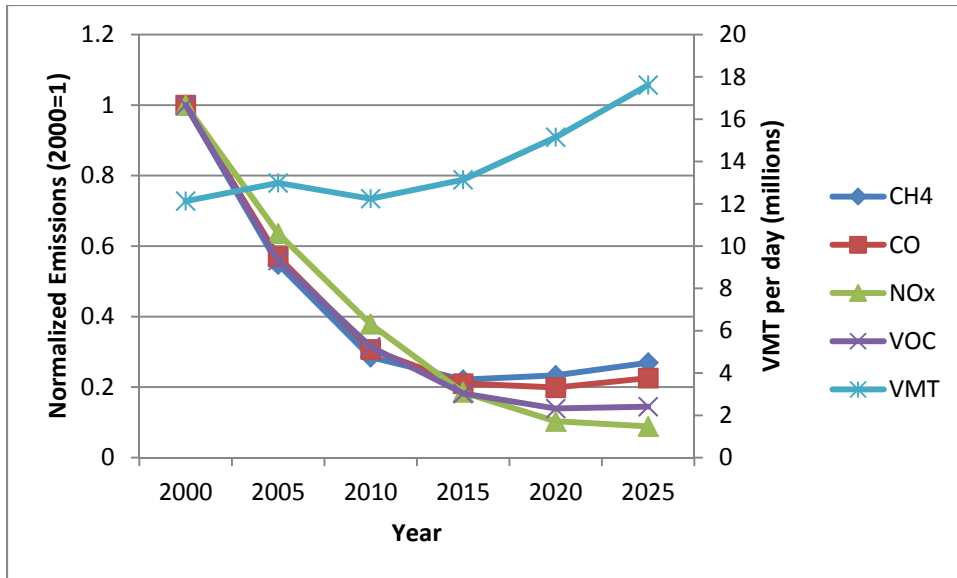


292 **FIGURE 4 Evolution of Travis County weekday cold start emissions proportions, 2000-2025**

293
 294
 295 Figures 5 and 6 depict this evolution over time by comparing normalized running plus starting emissions
 296 totals from 2000 through 2025 at 5-year intervals. Anticipated mobile-source emissions from LDVs drop
 297 dramatically on each of these species over time, despite a 40 to 50 percent increase in total VMT over the
 298 25-year period considered.
 299



300 **FIGURE 5 Normalized running plus starting LDV emissions totals over time (MOVES output),**
 301 **January weekday, Travis County, Texas (y = 1.0 serves as reference for year 2000)**
 302
 303



304 **FIGURE 6 Normalized running plus starting LDV emissions over time (MOVES output), July**
 305 **weekday, Travis County, Texas (y = 1.0 serves as reference for year 2000)**
 306

307
 308 **Strategies for Reducing Cold Start Emissions**

309 Several strategies exist for reducing cold-start emissions. For example, since starting emissions shares are
 310 most significant on shorter trips, de Nazelle et al. (2010) considered the environmental benefits of shifting
 311 to alternative modes, like biking and walking, for journeys less than 3 miles in distance. They found that
 312 the associated emissions reductions exceeded those associated with many projects funded by the federal
 313 Congestion Mitigation and Air Quality (CMAQ) Improvement Program, including natural gas buses,
 314 hybrid fleet vehicles, and tolled freeway lanes.

315
 316 Other changes can also prove very valuable. For example, a fleet shift toward hybrid electric vehicles can
 317 delay need for and use of a catalytic converter until it is pre-heated. Fully electric vehicles may shift
 318 travel-related emissions to remote power-generating units or even ultimately derive their power from
 319 clean renewable feedstocks (Nichols et al., 2014). Systems of shared autonomous vehicles may also
 320 reduce the incidence of cold starts by avoiding engine cool-down periods, and thus yield significant
 321 emissions savings (Fagnant and Kockelman, 2014).

322
 323 Along with these potential mode shifts and vehicle-type shifts, the key is to warm the catalytic converter
 324 as quickly as possible, reducing the level of cold-start emissions in conventional vehicles. While many
 325 drivers may assume it is best to idle the engine for a time before driving the vehicle, initial idling is only
 326 advisable in extreme cold in order to prevent engine damage. In milder weather, idling contributes to
 327 higher emissions than warm-up driving, and does not heat the emissions control equipment as quickly as
 328 driving (even slowly) for the first few minutes (Sentoff et al., 2010).

329
 330 Since the operating temperature of the catalytic converter is crucial, one simple idea is to relocate the
 331 converter closer to the engine, so that it will warm up more quickly. This has proven an effective strategy
 332 in reducing emissions, but in the past has introduced unwanted heat into the passenger compartment
 333 (Burch et al., 1995). More recently, exhaust temperatures have dropped and the catalyst has been placed
 334 closer to the engine (Presti and Pace, 2011).

335
 336 Catalytic converter technologies also continue to improve. For example, Nissan has developed a
 337 hydrocarbon trap, using an innovative blend of silver and zeolite, which significantly reduces tailpipe
 338 emissions by trapping some of the elevated hydrocarbons emitted by a cold engine (Hamada, 2009). As

339 this technology matures, it may become a standard feature of new vehicles, while adding relatively little
340 to the purchase price. Alternatively, car companies have long experimented with battery-powered pre-
341 heaters, but concerns about energy efficiency and equipment durability have prevented widespread
342 adoption. Recent improvements in battery technology have helped to make this a feasible option with
343 little additional fuel consumption, especially in hybrid electric vehicles (Presti and Pace, 2011).

344
345 One particularly promising idea is the use of innovative thermal materials in the catalytic converter to
346 retain heat longer and reduce the rate of engine cooling. National Renewable Energy Laboratory tests
347 showed that a prototype maintained high converter temperatures for 17 hours, as compared to 25 minutes
348 for conventional converters (Burch et al., 1995). A more recent study, using a phase-change heat storage
349 material, obtained reductions of 64% for CO and 15% for HC after a 500-second pre-warming period
350 (Gumus, 2009). This pre-warming involved the discharge of stored heat from the heat storage medium,
351 and did not require engine idling, so the catalyst's improved performance came without idling's added
352 emissions and engine wear.

353
354 This novel use of materials may eventually prove unnecessary, as computers are integrated into every
355 aspect of engine operation. Computerized fuel injection already helps optimize gas mileage and may also
356 be used in the future to minimize emissions in the minutes following a cold start (Spiegel, 2014).

357

358 **OTHER CONSIDERATIONS**

359 **Evaporative Emissions**

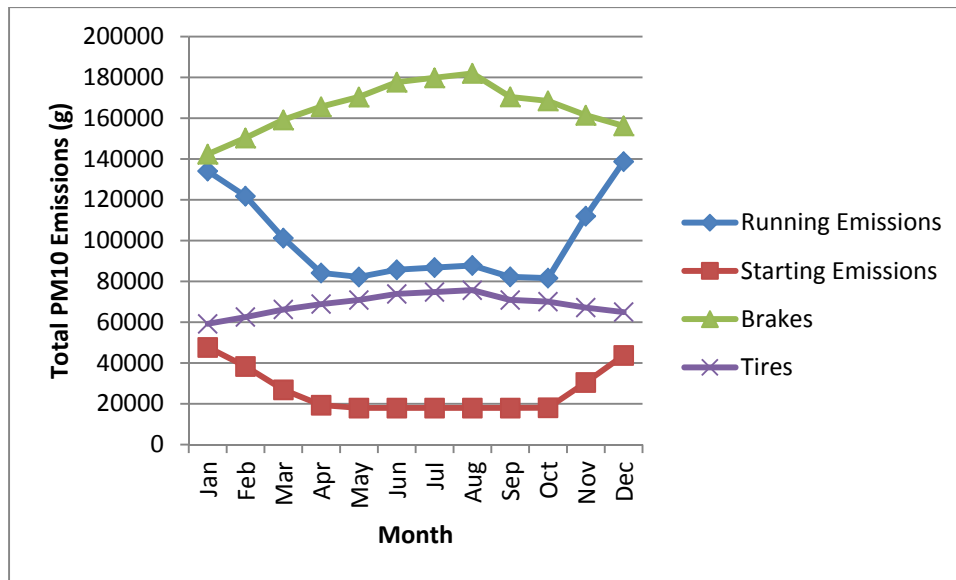
360 Another major source of vehicle emissions is evaporation of unburned gasoline from parked vehicles.
361 This is particularly a problem during summer months, when ambient temperatures can exceed 100°F and
362 engine components remain at an elevated temperature much longer than in the winter. It is estimated, for
363 instance, that 19% of gasoline VOC emissions in the UK are due to evaporation (Boulter et al., 2009).
364 The EPA estimates that a typical 2002 model car emits 4.3 grams per day of VOC, simply sitting parked,
365 which is more than 10% of total average weekday emissions for this species. An approximately equal
366 proportion can be attributed to the "hot soak" period, when the vehicle is off but its engine is still hot
367 (EPA, 2004). This is the rationale behind testing gas tank caps during mandatory vehicle emissions
368 inspections in many jurisdictions (e.g., Texas DPS [2011] and Fischer [2014]).

369

370 **Additional Sources of Particulate Matter**

371 While PM10 and PM2.5 emissions from internal combustion engines are a cause for concern, vehicle
372 brake wear typically generates more PM10, on average, even during winter months, as shown in Figure 7.
373 Tire wear and tear is also important to track, contributing more PM10 than starting emissions. Such
374 contributions to total PM pollution are significant, and are relatively unaffected by changes in engine
375 technology. Tires may experience less wear if (unless, for example, battery-powered vehicles accelerate
376 more intelligently than conventionally designed and driven vehicles via use of significantly lower
377 weightsuch). Interestingly, in the warmer months of summer, when more efficient engine processes cause
378 both starting and running PM emissions to decline, brake and tire-related PM actually increase.

379



380
 381 **FIGURE 7 Total grams of PM10 from light-duty gasoline vehicles in Travis County, Texas**
 382 **(MOVES output) 2010 weekdays, LDVs only**
 383

384 PM is also susceptible to re-suspension. After such matter has finally settled onto the road surface, it may
 385 be lofted into the atmosphere again via air turbulence caused by passing vehicles (Boulter et al., 2009).
 386 This source of PM pollution is especially important for human exposure and thus human health, since it
 387 keeps particles at low altitudes, within range of the human respiratory system, with potentially serious
 388 consequences.

389
 390 To summarize, while engine and converter temperatures are key to cold start emissions of ICEs, and cold
 391 start emissions are a significant share of mobile source emissions, many other considerations are at play.
 392 Month to month temperature variations, trends in vehicle technologies and regulations, other types of
 393 emissions (e.g., evaporative and re-suspended PM), and a variety of emissions-abating strategies merit
 394 attention.

395 396 CONCLUSIONS

397 This paper synthesizes a variety of current knowledge about cold start emissions for motor vehicles.
 398 Simulations performed using EPA’s MOVES program suggests that, regardless of geographic location or
 399 time of year, CH₄, N₂O, and VOC constitute a significant cost of cold engine starts. Looking toward the
 400 future, the same top pollutants continue to appear, but absolute levels of emissions decline substantially.
 401 Other potential sources of vehicle power, such as electricity, are undergoing their own sharp reductions in
 402 pollutant emissions. This could have major implications for the future of transportation.

403
 404 Going forward, a key policy question is: which approach is most promising for emissions-related health
 405 and environmental benefits? With the relatively recent introduction of hybrid electric vehicles, battery
 406 technology has advanced dramatically. These new battery packs have sufficient power to pre-heat the
 407 catalytic converter, thereby resolving the difficulties of either relocating the cat or searching for a suitable
 408 heat-storage medium (which typically stores heat for 10 to 20 hours after vehicle shutoff, and so does not
 409 resolve all cold-start emissions incidents).

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416

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