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1 Assessing the climate trade-offs of gasoline direct 2 injection engines

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24 **TOC/ABSTRACT ART**

27 **ABSTRACT**

28 Compared to port fuel injection (PFI) engine exhaust, gasoline direct injection (GDI) engine
29 exhaust has higher emission of black carbon (BC), a climate-warming pollutant. However, the
30 relative increase in BC emissions and climate trade-offs of replacing PFI vehicles with more fuel
31 efficient GDI vehicles remain uncertain. In this study, BC emissions from GDI and PFI vehicles
32 were compiled and BC emissions scenarios were developed to evaluate the climate impact of GDI
33 vehicles using global warming potential (GWP) and global temperature potential (GTP) metrics.
34 From a 20-year time horizon GWP analysis, average fuel economy improvements ranging from
35 0.14-14% with GDI vehicles are required to offset BC-induced warming. For all but the lowest
36 BC scenario, installing a gasoline particulate filter with an 80% BC removal efficiency and <1%
37 fuel penalty is climate beneficial. From the GTP-based analysis, it was also determined that GDI
38 vehicles are climate beneficial within <1-20 years; longer time horizons were associated with
39 higher BC scenarios. The GDI BC emissions spanned two orders of magnitude and varied by
40 ambient temperature, engine operation, and fuel composition. More work is needed to understand
41 BC formation mechanisms in GDI engines to ensure that the climate impacts of this engine
42 technology are minimal.

1. INTRODUCTION

In 2013, emissions from light-duty vehicles accounted for approximately 16% of the total greenhouse gas emissions in the United States, amounting to slightly more than one billion metric tons of CO₂-equivalents¹. Beginning in 2011, the United States Corporate Average Fuel Economy (CAFE) standards were tightened to reduce CO₂ emissions from fuel combustion. It is predicted that by 2017, fleet-average fuel economy will exceed 38 mpg and will continue to increase by 5% per year until 2025, at which point minimum fuel economy must reach 55 mpg^{2,3}. In recent years, the spark ignition gasoline direct injection (GDI) engine, an alternative to the traditional port fuel injection (PFI) engine, has gained popularity as means of meeting these CAFE standards while simultaneously increasing specific power⁴, especially when coupled with turbocharging⁵. These engines can also be designed to operate with higher biofuel blends (up to 85% ethanol) to further reduce CO₂ emissions. GDI-equipped vehicles are being rapidly integrated into the vehicle fleet; in the United States, between model years 2009 and 2015 the percentage of new vehicles with GDI engines increased from <5% to 46%⁶, and it is projected that in 2020 GDI-equipped vehicles will represent over 50% of the on-road vehicle fleet^{7,8}. However, the main trade off of replacing PFI engines with GDI engines is a substantial increase in exhaust particulate matter (PM) emissions^{9–12}, a problem previously associated with diesel fuel combustion. A significant fraction of the GDI exhaust PM_{2.5} is black carbon (BC), a pollutant with large positive radiative forcing due to its ability to absorb incoming sunlight and reduce surface albedo on snow¹³. Previous studies have reported the fraction of elemental carbon (considered here to be analogous to BC) in the GDI exhaust PM_{2.5} to range from 2–29%¹⁴ with elemental to organic carbon (EC/OC) ratios for GDI engine exhaust PM ranging from 0.5–20^{12,15,16}. Compared to PFI engines, which currently make up the bulk of the North American vehicle fleet, similar BC-to-PM_{2.5} ratios have been observed¹⁷;

66 however, GDI engine exhaust contains higher total concentrations of BC ^{17–21}. For example, real-
67 world BC emissions from a 2013 GDI were in the 73rd percentile of the Toronto fleet ²¹.

68 GDI engine exhaust PM is primarily formed due to incomplete fuel volatilization causing fuel
69 impingement on cylinder and piston surfaces, and incomplete fuel mixing with air resulting in
70 pockets of fuel-rich combustion. The extent of fuel-air mixing can be further affected by injection
71 system design. There are two major classes of injection systems for GDI engines: spray-guided
72 and wall-guided, which differ in where the fuel is injected into the cylinder, the piston head design,
73 and the fuel injection strategy. For spray-guided systems (Figure 1A), some of the fuel is directed
74 towards the spark plug for ignition, while the remaining fuel is dispersed into the remainder of the
75 cylinder. Wall-guided systems (Figure 1B) primarily rely on piston head geometry for fuel-air
76 mixing; the fuel spray is injected near the wall towards the piston head where it is redirected
77 towards the spark plug for ignition. Less fuel-air mixing time is available with GDI engines
78 compared to PFI engines, in which fuel mixes with the air intake upstream of the exhaust cylinder
79 (Figure 1C). Commercially available GDI vehicles have been mostly equipped with wall-guided
80 systems; however, there has been some movement towards spray-guided systems in lieu of wall-
81 guided systems due to their potential to reduce the number of particles emitted ^{22–24} and black
82 carbon ²⁵, likely due to improved fuel-air mixing with the spray-guided design.

83 Given that GDI vehicles will generally reduce CO₂ emissions per vehicle distance travelled
84 while simultaneously increasing BC emissions, an assessment of the climate trade-off is needed to
85 ensure that integration of GDI vehicles will result in a net reduction of CO₂-equivalent emissions.
86 In this study, BC emission rates (ERs) from our previous study ²¹ and from the literature were
87 compiled. From these emission rates, BC emissions scenarios were constructed to determine the
88 fuel economy improvements needed to offset the increase in black carbon using both global

warming potential (GWP) and global temperature potential (GTP) metrics. Briefly, GWP and GTP are metrics for calculating the climate forcing from a unit mass emission of a species relative to the climate forcing from an equivalent mass emission of CO₂. The GWP is a measure of the radiative forcing integrated over a given time horizon, while the GTP is an end-point metric of the temperature change at the end of a given time horizon. The development, equations, and uncertainties associated with these metrics in the context of BC are discussed in detail elsewhere^{13,26–28} and summarized in the Supporting Information. Additionally, a trade-off assessment of gasoline particulate filter fuel penalty and BC reduction efficiency is discussed. Four emissions scenarios were chosen to represent the broad range of reported BC emissions, which were reported across variable ambient temperatures, vehicle operation, and fuel compositions.

2. METHODS

2.1 Black carbon emission rates

In addition to the black carbon emission factors from Zimmerman et al.²¹, emission rates (mg BC/mile) were compiled from the published literature^{17–21,25,29,30}. Only emissions from North American commercially available vehicles were considered. In Zimmerman et al.²¹, fuel-based BC emission factors were originally reported (mg BC/kg fuel burned). To convert to distance-based emission rates, real-time fuel economy data from an on-board diagnostics logger (OBD-II, ELM327) was used. For all other studies, BC emissions were originally reported on a distance-travelled basis. In most of the published studies, specific vehicle fuel economies and the relationship between fuel economy and vehicle operation were unreported.

A summary of the distance-based BC emission factors (emission rates, mg/mile) for GDI and PFI vehicles is provided in Figure 2, sorted by vehicle model year (MY). All available BC emission factors were included independent of engine operation, measurement environment

(laboratory, real-world), temperature and relative humidity. However, only emissions from vehicles fuelled with 10% ethanol or less were included^{17–21,25,29,30}. The effect of fuel properties on BC emissions is considered separately in the discussion.

Figure 2 shows individual reported BC emission rates along with box-whisker averaging of the BC emission rates for PFI and wall-guided GDI engines. Due to the paucity of published data on spray-guided GDI engine emissions, this engine type was excluded from the averaging and subsequent analysis. A detailed list of the individual studies used to develop Figure 2 as well as pertinent experimental details are provided in the Supporting Information.

2.2 Climate trade-off analysis: GWP and GTP

To quantify the climate impact of the fuel economy/black carbon trade-off, four BC emission scenarios were developed using the data from Figure 2 representative of the range of BC emissions reported (Table 1). To address the uncertainty in the difference between GDI and PFI BC emissions, a Monte Carlo sampling procedure was employed³¹. A similar analysis approach has been used to quantify uncertainty in forest fire emissions^{32,33}, air toxics emissions³⁴ and global black carbon inventories³⁵. Briefly, one GDI and one PFI BC emission rate was selected randomly and the difference was computed. This was repeated 100,000 times to generate a distribution of solutions. From this distribution we generated four emissions scenarios: scenario A (“mean ΔBC ”), the average ΔBC from the Monte Carlo analysis, scenario B (“low ΔBC ”), the 25th percentile of the Monte Carlo distribution, scenario C (“high ΔBC ”), the 75th percentile of distribution, and scenario D (“extreme ΔBC ”), the 95th percentile of the distribution. The four BC emission rate scenarios were then converted into CO₂-equivalent emissions using global warming potential (GWP) data for a 20-year time horizon¹³. Subsequently, the required percent fuel economy improvement to offset the black carbon emissions was calculated by comparing the increase in

136 CO₂-equivalent emissions from BC (CO₂ g-eq/mile) to the reduction in CO₂ emissions by reducing
137 fuel consumption by a given percentage. Here, the baseline fuel economy was assumed to be 21.4
138 miles per gallon, the average fuel economy of the in-use United States light-duty fleet in 2014³⁶.
139 A CO₂ emission factor was calculated assuming a fuel carbon content of 8887 g/gallon⁶. Details
140 of this assessment illustrated with a sample calculation are provided in the Supporting Information.

141 The GWP provides the radiative forcing due to a pulse emission integrated over the time
142 horizon and use of this metric to compare short-lived (BC) and long-lived (CO₂) species may
143 significantly overestimate the impact of the short-lived species²⁸ (see Supporting Information for
144 an expanded discussion of this effect). To further explore the trade-off, an analysis was also
145 conducted using the global temperature potential (GTP) metric. In contrast, the GTP is an end-
146 point metric that provides the global mean temperature change for a given year after the emissions
147 and thus does not reflect the higher time-integrated-based impact of short-lived species, such as
148 BC, in the preceding years. A detailed discussion of the advantages and drawbacks of the GWP
149 and GTP metrics is analyzed in detail elsewhere^{13,37} and is also summarized in the Supporting
150 Information for completeness. Additionally, many GWP and GTP analyses assume a pulse
151 emission at the beginning of the time horizon vs. a sustained emission over a specified period. For
152 example, in the case of a new car purchasing scenario (i.e., buying a GDI in lieu of a PFI vehicle),
153 an appropriate sustained emission period might be 10-15 years, roughly the average lifetime of a
154 new vehicle^{28,38}. Thus, to determine a more conservative estimate of the climate trade-offs of GDI
155 engines, the GTP-based analysis assumed a 10 year sustained emission period based on available
156 data²⁸. The underlying assumption here is that the BC emissions will drop back down for the
157 subsequent car purchased due to improved vehicle technologies.

The climate trade-off analysis follows the approach outlined in Boucher and Reddy²⁸ where they define a parameter X to assess whether a trade-off situation is beneficial or detrimental to climate (Eq. 1), where ΔBC is the net increase in BC emissions from purchasing a GDI vehicle instead of a PFI vehicle (from Table 1) and ΔCO_2 is the reduction in CO_2 emissions by improving fuel economy with GDI.

$$(1) \quad X = GWP_{BC}(t = 100 \text{ years}) \frac{\Delta_{BC} (mg/mile)}{\Delta_{CO_2} (mg/mile)}$$

Boucher and Reddy²⁸ also demonstrate that the critical value of X at a given time horizon t is inversely proportional to the GTP of “normalized” BC (GTP_{nBC} , Eq. 2). As defined by Boucher and Reddy²⁸, normalized BC (nBC) is a hypothetical BC-like short-lived species that has the same lifetime as BC, but the same 100-year absolute GWP as CO_2 (i.e., 100 year $GWP_{nBC} = 1$).

$$(2) \quad X_{limit}(t) = \frac{1}{GTP_{nBC}(t)}$$

As the parameter X as defined in equation (1) is based on the 100 year GWP of BC, it follows that the critical value of X is inversely proportional to the GTP of the hypothetical “normalized” BC, which has the same 100 year GWP as CO_2 . Using the GTP_{nBC} values from Figures 4 and 6 in Boucher and Reddy²⁸ for a 10 year sustained release period, Eq. (1) and Eq. (2) were equated and the critical required improvement in fuel economy was calculated for Scenarios A through D (Table 1) for time horizons ranging from 1-40 years. A sample calculation is provided in the Supporting Information.

3. RESULTS AND DISCUSSION

3.1 Global warming potential (GWP)

Figure 3 illustrates the trade-off analysis of BC emissions and fuel economy for scenarios A through D. The fuel economy gain needed to offset BC-induced warming is represented as the

181 intercept with the x-axis (net zero CO₂-equivalent emissions). The average fuel economy gains
182 needed to offset the BC emissions ranged from 0.14% for the low Δ BC emissions scenario (B) to
183 14% for the extreme Δ BC scenario (D). The bounded regions in Figure 3 represent the reported
184 uncertainty associated with the BC GWP. Incorporating this uncertainty into the estimate, the
185 required fuel economy gains to offset the BC-induced warming range from 0.04% (negligible) for
186 the low Δ BC emissions scenario (B) to 26% for the extreme Δ BC scenario (D).

187 To determine the expected fuel economy improvements from purchasing a GDI vehicle,
188 we utilized data from Appendix I of the annual United States Environmental Protection Agency
189 (US EPA) report on fuel economy data from 1975 to 2015 (Table 2)⁶, which provides average fuel
190 economy data by model year and engine type. The fuel economies reported in Table 2 are
191 “adjusted” fuel economies, which are the US EPA’s estimate of real-world fuel economy
192 performance. Here, we consider two case studies: one in which an in-use PFI-equipped vehicle is
193 replaced with a new GDI-equipped vehicle (Case 1A,1B), and another in which a consumer buys
194 a new GDI-equipped vehicle in lieu of a new PFI-equipped vehicle (Case 2). In the replacement
195 cases (Case 1A, 1B), replacing a 2005 model year PFI-engine-equipped vehicle with a 2015 GDI
196 vehicle, unsurprisingly, results in large fuel economy gains ranging from 9-14%. However, when
197 comparing the fuel economy gains from replacing a fleet-standard PFI vehicle 5 years newer, the
198 impact is less substantial. Choosing to replace a 2010 PFI-engine-equipped vehicle with a 2015
199 GDI vehicle only results in fuel economy improvements of up to 4% for highway driving and
200 negligible changes for city and combined driving. In a new car purchase scenario (Case 2), the
201 average 2015 model year PFI-engine-equipped vehicle is more fuel efficient than a 2015 GDI
202 vehicle by margins ranging from 7-12%. This is possibly due to the fact that GDI-equipped

203 vehicles have higher brake specific fuel consumption than their PFI counterparts⁶ (i.e., a GDI
204 vehicle likely has a more powerful engine than a PFI vehicle with equivalent fuel economy).

205 On a 20-year timescale, we estimate from our GWP-based calculation (Figure 3) that
206 replacing older PFI-equipped vehicles, such as a fleet-average 2005 PFI vehicle, with a new fuel
207 efficient GDI-equipped vehicle (Case 1A) should result in a net climate benefit across all scenarios.
208 The climate impacts of choosing to replace a 2010 PFI-equipped vehicle with a new GDI vehicle
209 are less clear based on this analysis, as we found that replacing 2010 PFI vehicles should only
210 reduce CO₂-equivalent emissions for scenarios A through C. When considering a new car
211 purchase (Case 2), given that fleet-average 2015 model year PFI vehicles achieve comparable or
212 better fuel economy than GDI vehicles, purchasing the PFI vehicle will always result in lower
213 CO₂-equivalent emissions due to the added value of the avoided black carbon. While we only
214 discuss fleet-averages in this simple assessment, our analysis highlights the need to carefully
215 compare the fuel economy-black carbon trade-off when evaluating impact of a vehicle on climate.

216 **3.2 Global Temperature Potential (GTP) Analysis**

217 Figure 4 shows the GTP-based trade-off analysis of BC emissions and fuel economy for scenarios
218 A through D. This assessment assumed a sustained release period of 10 years (roughly the lifetime
219 of a single vehicle) using GTP values published in Boucher and Reddy²⁸ (data is re-created in the
220 Supporting Information). For time horizons ranging from 1 through 40 years, the minimum
221 improvement in fuel economy required to offset the increase BC emissions (by equating equations
222 (1) and (2) and solving for ΔCO_2 , repeating for $n=1, 2, \dots, 40$ years) was calculated. An example
223 of this calculation is provided in the Supporting Information. As an example of the realistic fuel
224 economy gains with GDI engine technology, the estimated fuel economy improvements achieved

225 by replacing a fleet-average 2005 (Case 1A) and 2010 PFI vehicle (Case 1B) with a 2015 GDI
226 vehicle (see Table 2, combined fuel economy) are overlaid on Figure 4.

227 For all scenarios in this example, the climate benefit has some dependence on the
228 considered time horizon, which is defined here as the time beginning from the point of vehicle
229 purchase. For scenario A (mean ΔBC), replacing an older PFI vehicle with a GDI vehicle is only
230 climate-detrimental for 2 (Case 1A) to 17 years (Case 1B) after vehicle purchase, beyond which
231 the increase in BC is offset by the overall reduction in fuel consumption. Similarly, the time
232 horizon beyond which the replacement becomes climate beneficial ranges from <1 year (Case 1A)
233 to 4 years (Case 1B) for scenario B (low ΔBC), from 7.5 (Case 1A) to 24 years (Case 1B) for
234 scenario C (high ΔBC), and 18 (Case 1A) to 40 years (Case 1B) for scenario D (extreme ΔBC).
235 Given the lower probability of the “extreme ΔBC ” scenario, we suggest that for time horizons
236 exceeding 20 years, replacement of 2010 or earlier PFI vehicles with more fuel efficient GDI
237 vehicles will eventually start yielding climate benefits 20 years after purchase. Further, greater
238 climate benefits will eventually occur if the GDI vehicle is operated for longer than the 10-year
239 vehicle lifetime used in this analysis. However, for a new car purchase decision (Table 2, Case 2),
240 choosing a PFI-vehicle is recommended to minimize overall climate impacts.

241 3.3 Impact of gasoline particulate filters (GPFs)

242 Many studies have investigated the installation of gasoline particulate filters (GPFs) to reduce BC
243 and total particle emissions from GDI vehicles^{20,39–43}. Particulate filters have been very effective
244 at reducing PM and BC emissions from diesel vehicles; however, developing effective GPFs may
245 require overcoming several technical challenges. GDI-equipped vehicles emit less exhaust PM
246 than diesel vehicles, resulting in a situation where GPFs may initially have a very low filtration
247 efficiency due to the longer time needed to build up a soot layer within the filter⁴¹. Gasoline engine

248 exhaust is also approximately 300 °C hotter than diesel exhaust, and these higher temperatures
249 may favour more frequent passive regeneration events, limiting the buildup of PM in the filter⁴⁴.

250 Commercial installation of diesel particulate filters, which have a similar operating
251 principle as GPFs, has typically resulted in fuel penalties in the range of 2-3%^{45,46}. In contrast,
252 several studies have found that GPFs can be installed without compromising overall vehicle fuel
253 economy^{39,43,47-49}, in which case installation of a GPF is always climate beneficial and may also
254 offer significant health benefits by the reduction of ultrafine particles and PM_{2.5}. However, a recent
255 study by Chan et al.⁴⁴ observed a 1.9% reduction in fuel economy during an aggressive highway
256 driving cycle (US06), possibly due to high exhaust flow rates during aggressive driving conditions.
257 If GPF installation results in a similar fuel penalty to those of diesel particulate filters, this may
258 offset the climate benefits of reducing the BC emissions. This is explored in Figure 5, using the
259 same BC emission scenarios (Table 1) and the 20-year average GWP. Fuel penalties ranging from
260 0.5%-3% were considered and the critical GPF filtration efficiency for net zero CO₂-equivalent
261 emissions was calculated. Details of the calculation are provided in the Supporting Information.

262 On a 20-year time horizon the critical GPF BC removal efficiency to offset the increase in
263 CO₂ from a fuel penalty varies significantly by BC emissions scenario. For scenario A (mean
264 Δ BC), the reduction in BC emissions will not compensate for the fuel penalty if this penalty
265 exceeds 1% (i.e., installing a GPF is not climate beneficial). For 0.5% and 1% fuel penalties, GPF
266 BC removal efficiency must exceed 40% and 80%, respectively. For scenario B (low Δ BC), the
267 CO₂ emissions incurred from a small 0.5% fuel penalty would not offset the removal of BC (i.e.,
268 BC emissions are too low to warrant GPF installation if fuel economy is compromised). For
269 scenarios C (high Δ BC) and D (extreme Δ BC), installing a GPF with BC filtration efficiency of at
270 least 60% should offset the CO₂ increase for the fuel penalties equal to or less than 2%. Chan et

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271 al.⁵⁰ have reported BC removal efficiencies with a GPF ranging from 57% (-7 °C, US-06 drive
272 cycle) to 89% (-7 °C, FTP-75 drive cycle), suggesting this level of removal is achievable.
273 Conversely, manufacturers striving to reduce the climate impact of vehicles may find inclusion of
274 a GPF as a more easily achievable opportunity than reducing fuel efficiency by an additional 0.5-
275 3%. For example, if a GPF can be developed without a fuel penalty as suggested in the early
276 literature^{39,43,47-49}, then installation of GPFs might offset part of the 2025 requirements for
277 improved fuel efficiency. As such, continued GPF research with a focus on minimizing fuel
278 penalty is recommended. Given the potential technical challenges of commercial GPF design,
279 engineering strategies to reduce BC in absence of a GPF is also desirable, such as a reduction in
280 BC by moving towards spray-guided direct injection technology.

281 3.4 Fuel properties and GDI BC emissions

282 The GDI BC emissions in Figure 2 span approximately two orders of magnitude, suggesting that
283 BC emissions are dependent on external factors such as fuel composition. The most investigated
284 fuel property when considering particle phase GDI engine emissions is the effect of ethanol and
285 other biofuels. Ethanol blending in gasoline has been largely motivated by perceived reductions in
286 greenhouse gas emissions when ethanol is produced from renewable sources. If ethanol could be
287 used to formulate new fuels with higher octane numbers, significant reductions of CO₂ emissions
288 could be achieved⁵¹. However, ethanol is currently blended into gasoline stocks to achieve only
289 fuels with standard octane numbers (87, 89, and 91 anti knock index). Additionally, the impact of
290 ethanol on PM emissions from GDI vehicles is highly variable and there is no general consensus
291 on its impact. While many studies report universal PM (and by extension BC) reductions from
292 biofuel use^{11,12,15,52}, others report both increases and decreases in PM emissions depending on
293 engine operation or blend level^{16,29,53-56}. Furthermore, the range of benefit is large and inconsistent

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294 across the same blend levels from different studies. Part of the variability may be explained by fuel
295 injection spray effects. A recent study of fuel effects on the spray wall impingement in an optically
296 accessible wall guided GDI engine that found that spray wall impingement of E100 (pure ethanol)
297 was less sensitive to coolant temperature than pure indolene fuel⁵⁷. Also, the normalized
298 vaporization duration was shorter for E100 compared to E0 (indolene). The inconsistent effects of
299 ethanol addition require greater investigation when considering that replacing gasoline with
300 ethanol has been shown previously to result in a net decrease in lifecycle greenhouse gas emissions
301 ⁵⁸.

302 As an example, in Zimmerman et al.²¹, it was observed that increasing the ethanol content
303 of gasoline from 0 to 10% (on a volumetric basis) resulted in a 114% increase in elemental carbon
304 (EC) concentration (considered here to be equivalent to BC) during a simulated highway cruise
305 operation. Using the laboratory EC emission factors reported in Zimmerman et al.²¹ (45 mg/kg
306 fuel for E0, 95 mg/kg fuel for E10), the 20 and 100 year GWPs of BC from Bond et al.¹³, and an
307 overall 19% reduction in life-cycle greenhouse gases from replacing gasoline with ethanol ⁵⁸, the
308 net climate impact of ethanol can be roughly assessed. Details of this calculation are provided in
309 the Supporting Information. In this example it was determined that on average, the 114% increase
310 in EC measured in Zimmerman et al.²¹ should offset the greenhouse gas benefits of ethanol on a
311 20-year time horizon, but not on a 100-year time horizon (Supporting Information, Figure S1).
312 However, this is only one example, and further assessments are needed make more conclusive
313 statements on the climate impacts of GDI vehicles using ethanol-blended fuels.

314 The effect of ethanol on GDI BC engine emissions may also be convoluted by the impacts
315 of other fuel properties, such as aromatic content and blending technique (i.e., splash vs. match
316 blending). In Karavalakis et al.³⁰, fuel aromatic content was systematically increased from 15% to

317 35% and the impact on PN, PM and black carbon emissions was measured. They found that that
318 increasing fuel aromatics from 15% to 35% resulted in a 395% increase in PM, a 266% increase
319 in PN, and a 154% increase in black carbon, suggesting that aromatic compounds are precursors
320 for soot formation. Ramos¹⁶ also observed that doping commercially-available E0 gasoline with
321 10% toluene, a common fuel aromatic, resulted in approximately 70% higher particle number
322 emissions, and when doping E10 with 10% toluene, particle number emissions further increased
323 by 64%, potentially suggesting a synergistic effect that is not currently understood. Differences in
324 blending techniques between studies may also influence results, as “splash” blended fuels may
325 have different hydrocarbon profiles and vapor pressures than fuels produced using match
326 blending⁵⁹.

327 In California, regulations on reformulated gasoline mandate a maximum aromatics content of
328 25% by volume; no such regulation exists federally in the United States or in Canada. Of the
329 studies used to compile the BC emission scenarios, over half were conducted in California, thus
330 our scenarios would be disproportionately influenced by data reported from this state, where fuel
331 aromatics are lower. In contrast, a commercially-available summer-blend premium 91 octane fuel
332 sample in Toronto, Canada contained 43% aromatics by volume (fuel analysis in Supporting
333 Information). The BC emissions data from two separate Canadian studies were roughly an order
334 of magnitude higher than those from California studies, suggesting that understanding the impact
335 of fuel properties on BC emissions, which may vary significantly by region, is critical to
336 developing a more precise climate trade-off analysis of GDI engine emissions.

337

338

3.5 Implications

From this study, it was determined that a broad range of fuel economy improvements (0.04% to 26%) with GDI vehicles are required to offset the BC-induced warming. This large range was primarily due to the large uncertainty in the impacts of GDI engines on BC emissions. From the more complex GTP-based analysis with a sustained emission release scenario of 10 years, it was determined that replacing a fleet-average pre-2010 PFI vehicle with a fleet-average GDI vehicle will generally offer climate benefits within 20 years of putting the vehicle into use. As such, detrimental climate impacts due to the integration of the current generation GDI vehicles into the fleet will likely still be observed over the near-term, especially for new car purchase scenarios, where PFI vehicles outperform GDI vehicles on the basis of fuel economy and BC emissions.

Generally, installing a gasoline particulate filter with a <1% fuel penalty would result in a net climate benefit for filtration efficiencies exceeding 80%. However, if BC emissions are sufficiently small (scenario B) then installation of a GPF is never advantageous to climate if there is any associated fuel penalty. However, given that preliminary implementations of GPFs suggest that negligible fuel penalties are possible, we suggest a more holistic regulatory approach that also considers a reduction in BC as an offset to the demands for greater fuel efficiency by 2025. Furthermore, if GPFs can be implemented with a negligible fuel penalty, there may be considerable co-benefits to human health by a reduction in vehicle exhaust PM. This could also be achieved through modifications to GDI engine design that promote less PM and BC formation.

The climate trade-off analysis conducted in this study lacked precision due to the broad range of reported BC emissions from GDI vehicles, combined with the uncertainty of the GWP and GTP metrics. In this study we were also limited to data from integrated drive cycles and we

361 were not able to isolate the impacts from specific vehicle operation. Additionally, one study
362 suggests higher BC emissions under cold temperatures³⁹, but we did not model this specific effect
363 due to limited data. We also were unable to account for the cooling effects of organic aerosol
364 emissions due to a lack of available data. Future studies that include the effects of organic carbon
365 cooling, that focus on cold temperature data or on BC emissions during specific vehicle operation
366 where fuel economies are reported would greatly enhance our understanding of the climate trade-
367 offs of GDI engines.

368 Of greatest significance to BC emissions were fuel properties, in particular total aromatic
369 content, which may vary substantially by geographic area. As such, it is recommended that
370 additional GDI emissions studies in regions where total fuel aromatics are high, or studies of a
371 broader range of fuel types are needed to better understand the potential range of BC emissions.
372 Additionally, more studies of the impacts of spray-guided or advanced GDI engines on BC
373 emissions are needed to verify if this engine technology results in lower BC emissions than the
374 wall-guided GDI design. In this study, the BC emissions data from spray-guided GDI engines
375 were too limited to develop an emissions scenario. It is expected that as spray-guided injectors are
376 increasingly used in GDI engines or as GDI engine technology develops, BC and PM emissions
377 may be significantly reduced. As such, it is recommended that these metrics be revisited when
378 more data is available from engines with advanced injection strategies.

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383 Scholarship.

SUPPORTING INFORMATION

A tabulated list of black carbon emission factors included in the scenarios, a discussion of the global warming potential (GWP) and global temperature potential (GTP) metrics, sample calculations for the climate trade-off assessments, and a fuel sample analysis of summer-grade commercial fuel from Toronto, Canada is provided.

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Figure 1: Injection systems for A) spray-guided and B) wall-guided GDI engines (adapted from Zhao et al.⁴ compared to C) the injection system for a typical PFI engine where fuel is injected into the air intake manifold. Blue arrow: air intake, orange arrow: exhaust outflow.

Figure 2: Summary of literature reported black carbon (BC) emission rates for 2007-2013 model year vehicles with port fuel injection (PFI, yellow), wall-guided gasoline direct injection (WG-GDI, purple), and spray-guided gasoline direct injection (SG-GDI, blue) engines (left) and a box-whisker plot of PFI and WG-GDI emission rates. The line is the median value, the gray marker is the arithmetic mean, the box ends are the 25th and 75th quartiles, whiskers extend to the 10th and 90th percentiles, and outliers are denoted as markers beyond the whiskers.

582

583 **Figure 3:** Climate trade-off analysis of increased black carbon emissions vs. improved fuel economy on a 20-year
 584 time horizon. Labels A, B, C, and D correspond to the emissions scenarios described in Table 1. Dashed lines represent
 585 upper and lower GWP uncertainty bounds from Bond et al.¹³ (Average GWP = 3200, Lower = 270, Upper = 6200).
 586 The fuel economy gain needed to offset BC-induced warming is represented as the intercept with the x-axis (net zero
 587 CO₂-equivalent emissions)

588

589 **Figure 4:** Required fuel economy improvement to offset the increase in BC emissions for scenarios A (mean, red
 590 bars), B (low BC, purple bars), C (high BC, blue bars) and D (extreme BC, gold bars) (see Table 1 for emission
 591 scenario details). Gray and green lines: fuel economy improvements (“Adjusted Combined”) by replacing a fleet-
 592 average 2005 (gray) and 2010 (green) PFI vehicle with a GDI vehicle.

593

594

595 **Figure 5:** Required BC removal efficiency for a GPF to offset fuel penalties ranging from 0.5-3% for emission
596 scenarios A (mean, red bars), B (low BC, purple bars), C (high BC, blue bars) and D (extreme BC, gold bars) (see
597 Table 1 for emission scenario details. Analysis uses 20-year average GWP from Bond et al.¹³ (Average 20-year GWP
598 = 3200).

Table 1: Black carbon emission rate (ER) scenarios developed from the data in Figure 2. Scenarios were developed using a Monte Carlo method (n=100,000) in which we randomly selected one WG-GDI ER and one PFI ER and calculated the difference ($\Delta BC\ ER = WG-GDI_{ER} - PFI_{ER}$).

Scenario	$\Delta BC\ ER$ (mg/mile)	Description
A: Mean	1.26	Mean ΔBC emissions from the Monte Carlo analysis
B: Low BC	0.18	25 th percentile of ΔBC emissions from the Monte Carlo analysis
C: High BC	3.36	75 th percentile of ΔBC emissions from the Monte Carlo analysis
D: Extreme	15.9	95 th percentile of ΔBC emissions from the Monte Carlo analysis

Table 2: Average adjusted (Adj) city, highway (Hwy), and combined (Comb) fuel economy in miles per gallon (MPG) for the U.S. 2005, 2010, and 2015 PFI vehicle fleet and 2015 GDI vehicle fleet⁶. All values are for vehicles with variable valve timing and multi-valve systems. The relative change in fuel economy for different vehicles is also summarized.

	2005 PFI (PFI-1)	2010 PFI (PFI-2)	2015 PFI (PFI-3)	2015 GDI	Case 1: % change, replace PFI-1 with GDI	Case 2A: % change, buy GDI instead of PFI-2	Case 2B: % change, buy GDI instead of PFI-3
Adj City (MPG)	20.7	22.9	25.8	22.6	+9%	-1%	-12%
Adj Hwy (MPG)	28.7	31.2	35.3	32.6	+14%	+4%	-7%
Adj Comb (MPG)	24.6	27.0	30.4	27.4	+11%	+1%	-10%