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Real-time black carbon emission factor measurements from light duty vehicles

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Abstract

Eight light-duty gasoline low emission vehicles (LEV I) were tested on a Chassis dynamometer using the California Unified Cycle (UC) at the Haagen-Smit vehicle test facility at the California Air Resources Board in El Monte, CA during September 2011. The UC includes a cold start phase followed by a hot stabilized running phase. In addition, a light-duty gasoline LEV vehicles and ultra-low emission vehicle (ULEV), and a light-duty diesel passenger vehicle and gasoline direct injection (GDI) vehicle were tested on a constant velocity driving cycle. A variety of instruments with response times ≥ 0.1 Hz were used to characterize how the emissions of the major PM components varied for the LEVs during a typical driving cycle. This study focuses primarily on emissions of black carbon (BC). These measurements allowed for the determination of BC emission factors throughout the driving cycle, providing insights into the temporal variability of BC emission factors during different phases of a typical driving cycle.

1 Introduction

Black carbon (BC), the main refractory and strongly absorbing component of soot, constitutes a substantial fraction of primary particulate matter (PM) and is emitted by both anthropogenic and natural combustion sources. BC has adverse impacts on human health,[1] contributes to visibility degradation,[2] and influences climate by scattering and absorbing solar radiation[3] and acting as cloud condensation nuclei.[4] One important source of primary anthropogenic BC in urban areas is motor vehicles, with vehicular primary particulate emissions dominated by BC and particulate organic matter (POM, defined as the sum of particulate organic carbon and non-carbon components). Although light-duty gasoline vehicles (LDGVs) currently contribute less than 5% of $PM_{2.5}$ emissions, they can lead to high $PM_{2.5}$ concentrations near major roadways.[5] Current regulations, such as the low-emission vehicle II (LEV II) standards, focus primarily on particle mass, with less emphasis placed on composition and size of vehicle particulate emissions, even though the latter are important considerations when assessing the environmental and health effects of PM. Accurate quantification of emission factors (EFs) or emission rates (ERs) of BC are central to development of composition-specific emissions inventories for use in models and future air quality regulations. To facilitate improvements in the spatial resolution of BC emissions modeling, accurate measurements of BC and ancillary species that are sufficiently fast (response times on the order of seconds) to capture the wide variations in emitted species concentrations throughout vehicle testing are necessary as these parameters change rapidly throughout a typical driving cycle. Such real-time measurements allow for the relation of broad aspects of driving behavior, such as acceleration, directly to emissions.

Here, results are reported from a study conducted in September 2011 in which eight LDGV's were tested on a Chassis dynamometer using the California Unified Cycle (UC) at the Haagen-Smit vehicle test facility at the California Air Resources Board (CARB) in El Monte, CA. The eight in use vehicles (requisitioned for this study) all met emission requirements for LEV I. Additionally, four different types of light duty vehicles (LEV I, ULEV, GDI and diesel) were tested on a constant velocity cycle. Real-time measurements of BC and other non-refractory PM (NR-PM) components and of gas-phase CO_2 concentrations were made, thereby allowing for quantification of EF_{BC}'s throughout the driving cycle for each of the vehicles tested. Measurements here can be contrasted with most past measurements in which EF_{BC}'s were averaged over the entire driving cycle or specific subset periods, although there are a few studies[6, 7] that have quantified BC concentrations for individual vehicles in real-time during a cold-start driving cycle (see Table 3) and fast-response instruments (≤ 1 second) are often used during engine testing. The current study provides insights into the variability of not just BC concentrations, but of BC EFs throughout a driving cycle that bulk measurements cannot distinguish and also addresses some of the differences in EFs reported between previous field studies (e.g. on-road or tunnel sampling) and dynamometer studies.

2 Experimental

2.1 Vehicle Testing

Each full test day, the eight LEV vehicles (Table 1) were tested on a Chassis dynamometer, which mimics road load typically experienced by vehicles, following the UC. The UC is a predetermined driving cycle with a 300-second "cold start" phase followed by a 1135-second "hot stabilized running" phase. Cold start consists of starting the vehicle after letting it sit overnight at ~24 °C, followed by a period of small accelerations. Hot stabilized running has two periods of hard acceleration and a maximum velocity of 67.2 mph. In addition to the UC tests, four different types of light duty vehicles (LEV I, ULEV, GDI and diesel) were tested on a steady-state cycle, which begins with a cold-start (although not necessarily following the overnight conditioning) followed by a 30-minute 60 mph constant velocity phase.

Emissions from the vehicle tailpipe were sampled into a constant volume sampler (CVS) and further diluted by a secondary dilution system (SDS),[8] with a total dilution factor of ~60 (a factor of 12 in the CVS and an additional factor of 5 in the SDS). A primary goal of the testing, the subject of future work, was to characterize the variations in the gas-particle partitioning of POM under atmospherically-relevant dilution conditions and concentrations, upon modification of the ambient relative humidity, or upon the addition of non-vehicle "flame" soot (see Supporting Information). Since BC is non-volatile and since the real-time measurements were made under dry conditions, such modifications beyond the CVS will not affect the measured EF_{BC} values, although can influence POM measurement. As a result, of these post-emission modifications, real-time BC measurements are available for all test days, but POM and bulk BC measurements from only a subset of days are used here (specifically days without RH modification or non-vehicle soot addition). The diluted sample air was mixed under turbulent conditions in a residence time chamber (RTC). The overall residence time through the CVS and the SDS+RTC was around 1.2 minutes. Because the RTC is turbulent, extremely rapid (seconds) fluctuations in concentrations associated with changes in driving conditions are smoothed out while slower (10s of seconds) variations are retained. Given this smoothing, the current study provides information as to how emissions of BC depend on general driving conditions during the UC, but does not capture very fast transients that can be seen during bench engine testing. The absolute average PM concentrations out of the SDS+RTC during UC tests ranged from 1-5 $\mu g\ m^{-3}$.

2.2 Instrumentation

Real-time measurements (i.e. response time ≥ 0.1 Hz) of particulate light absorption and light extinction coefficients (b_{abs} and b_{ext}, respectively), NR-PM concentrations and size distributions, gas-phase CO_2 and other specific trace gases (particularly organic acids and aldehydes), were made from the SDS+RTC for each vehicle tested throughout each driving cycle (Figure S1). Bulk PM from all vehicles tested over the course of a day was also sampled from the SDS+RTC onto a quartz-fiber filter for offline analysis. This study focuses only on the PM and CO_2 emissions, and mainly the BC component. Measurements directly from the CVS were made by CARB staff and included real-time gas-phase CO_2 and bulk sampling of particles from all vehicles onto a filter each test day for offline bulk chemical analysis. Key instrumental details are provided below, with full descriptions given in the supporting information.

The b_{abs} and b_{ext} (in Mm^{-1}) from the SDS+RTC were measured at 532 nm using a home-built cavity ring-down and photo-acoustic spectrometer (CRD-PAS), with an accuracy of ±2% (b_{ext}), ± 10% (b_{abs}) and a time resolution of 0.4 Hz.[9] Real-time BC concentrations are calculated from the b_{abs} as [BC] = b_{abs}/MAC, where MAC is the mass absorption coefficient for BC (MAC_{BC}), equal to 7.75 (± 1.5) $m^2\ g^{-1}$ at 532 nm.[10] The MAC_{BC} is nearly constant over the range of particle sizes sampled here.[10] Real-time concentrations of particulate organic matter (POM), and other NR-PM components from the SDS+RTC were measured using an Aerodyne High Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS, henceforth AMS)[11] with an instrument accuracy of ± 20% and a time resolution of 0.1 Hz (Collier et al., In preparation). CO_2 was measured from the SDS+RTC in real-time in two ways: using a standard CO_2 analyzer (LI-6262 CO_2/H_2O Gas Analyzer; Licor, Inc.) and, because the Licor was available for only a subset of the sampling campaign, non-conventionally using the AMS (Supporting Information) with an uncertainty of 10% for the CO_2 concentrations. Importantly, the real-time [CO_2] from the AMS compared well with the Licor, within 6%, on average (Figure S2). CO_2 was measured from the CVS using a non-dispersive infrared (NDIR) spectroscopy method. The dilution-adjusted AMS [CO_2] agreed with the all-test average CVS NDIR [CO_2] within 8%, providing confidence that the use of the AMS in this non-conventional manner is justified.

Bulk, daily average elemental carbon (EC) and particulate organic carbon (POC) concentrations and relative fractions were determined from the collected filter samples from either the CVS or SDS+RTC using a Thermo-Optical Analyzer (Desert Research Institute) and the IMPROVE_A protocol,[12] with overall precisions of ± 5-10% for POC and ± 20% EC.[13] EC is operationally defined as carbonaceous material that combusts at high temperatures in an oxygen-containing atmosphere, whereas BC is defined as light absorbing components of soot. For this study EC and BC are considered to be equivalent.

2.3 Emission Factor Calculations

Emission factors are defined here as the amount of BC emitted (in mg) per kg of fuel burned and emission rates are the amount of BC emitted per mile driven. Vehicle emissions models, such as the EPA's Motor Vehicle Emission Simulator (MOVES), rely on accurate quantification of EFs and ERs. Real-time EF_{BC} values were calculated as:

$$EF_{BC} = w_C \left[\frac{b_{abs}}{MAC \cdot [CO_2]} \right] 10^6 = w_C \left[\frac{[BC]}{[CO_2]} \right] 10^6 \qquad (3)$$

where w_c is the mass fraction of carbon in fuel (assumed to be 0.85)[14] and [BC] (in μg m^{-3}) and [CO_2] (in g-C m^{-3}) are the background corrected concentrations, which have been synchronized in time and where the [BC] has been averaged to the same time-base as the [CO_2] (0.1 Hz). Equation 3 assumes the majority of fuel carbon is converted to CO_2, consistent with observations. The background [BC] was zero, except for the tests that added non-vehicle soot, in which case the added [BC] was subtracted.

Emission rates were calculated as:

$$ER_{BC} = \frac{EF_{BC}}{MPG \times \rho_{gasoline}} \quad (4)$$

where MPG is the vehicle-specific fuel economy (in miles per gallon with an assumed gasoline density, $\rho_{gasoline}$, of 720 kg m^{-3}). The overall uncertainty in EF_{BC} comes from uncertainty in the *MAC* (± 19%), b_{abs} (± 10%), [CO_2] (± 10%) and the carbon content of the gasoline fuel (± 5%). An additional uncertainty for tests with added non-vehicle background BC results from baseline subtraction and is estimated to be ± 5% for high emitting vehicles and ± 23% for low emitting vehicles over the entire UC. (Note that "high" and "low" are used here to characterize the range of EF_{BC} and ER_{BC} from the tested vehicles, and splits the 8 vehicles into two groups). The propagated uncertainty is ± 24% for days without background BC, ± 25% for high emitting vehicles on days with non-vehicle BC, and ± 33% for low-emitting vehicles on days with non-vehicle BC.

3 Results

3.1 Average BC Emission Factors

All-test averages and box-and-whisker plots of EF_{BC} and ER_{BC} (averaged from real-time data) for eachLEVs tested on the UC are shown in Figure 1. The daily (all tests) average real-time [BC] from the SDS+RTC compared well with the [EC] in the CVS, agreeing on average to within 12% (excluding one anomalous test day when one vehicle malfunctioned during testing, thus strongly affecting the bulk EC measurement). The consistency between the thermal [EC] measured in the CVS and the daily averaged [BC] indicates that particle mass losses in the CVS and the SDS+RTC were minimal.

Typically, BC emissions are largest during the cold start phase, consistent with previous dynamometer studies.[6, 14-17] For example, the averaged ER_{BC} ranged from 0.61 – 5.3 mg $mile^{-1}$ during cold start but only 0.03 – 0.7 mg $mile^{-1}$ for hot stabilized. Reasons for this difference include reduced volatilization of gasoline fuel and wall impingement characteristic of LDGVs during cold start. .

3.2 Real-time BC Emission Factors

A key aspect of this study is the ability quantify EF_{BC} and ER_{BC} throughout the UC driving cycle. Figure 2 shows that there is a great deal of variability in the EF_{BC} during a given phase. Consistent with the average EF_{BC} and ER_{BC} values, the vehicle-specific maximum in the real-time EF_{BC} for properly functioning vehicles occurred during the cold start phase (60-360 seconds; Figure 2), ranging from 7.8 to 75.5 mg-kg^{-1}. Two additional peaks in EF_{BC} occurred during the hot-stabilized phase (360-1435 seconds), the first concurrent with a "hard" acceleration (at ~400 seconds) and the second, typically larger peak, with another hard acceleration (at ~920 seconds). This is consistent with the second acceleration during the hot stabilized phase being more rapid than the first (by 43%) and suggests that the EF_{BC} is most sensitive to the air-to-fuel ratio in the engine, with peaks corresponding to fuel-rich conditions (i.e. during the cold start phase and during hard accelerations). Unlike EF_{BC} (and [BC]), the [CO_2] peaked during all accelerations (not just hard accelerations), and overall exhibited greater consistency between tests that occurred on different days for a given vehicle.

The timing and magnitude of maximum EF_{BC}'s during a typical driving cycle may be used to inform spatially resolved models. The real-time EF_{BC}'s reveal that a major proportion of BC emissions would likely occur in the morning within approximately the first five minutes of driving (i.e. cold start) and in locations prone to hard accelerations (e.g. freeway entrances). Although modeling tools (such as MOVES) take increased PM emissions into account during cold start, the models could benefit from the enhanced time resolution provided by these real-time EF_{BC} or real-time ER_{BC} measurements since primary PM emissions tend to have sharp spatial gradients.[18] The real-time behavior implies that local air quality of neighborhoods adjacent to major roadways and freeway entrances will be most affected by LDGVs in the morning driving commute.

3.3 Malfunctioning Vehicle

Results from the Taurus provide for an interesting case study because the Taurus engine began malfunctioning on 9/15 (after 3 sampling days), as indicated by the "check engine" light turning on. Although engine diagnostics that would elucidate the nature of the engine malfunction are not available, it is evident that after at this point the Taurus EF_{BC} increased substantially and became more variable (Figure 2c). However, despite this malfunction, the ER_{BC} values for the Taurus are still well below the expected range of "smoker" vehicles.[8, 19-21] Before malfunctioning, the Taurus exhibited the typical three peak structure in [BC], reaching a maximum of 10 μg m^{-3} (Figure 3). Just after malfunctioning, there were many more peaks in [BC] and the maximum concentration after the SDS+RTC reached 200 μg m^{-3}. Later tests (Figure 2c and 2f) similarly evidenced greater variability and higher [BC] than the properly operating vehicle, with an average EF_{BC} that was a factor of 6 higher than the other vehicles (Figure 1). In contrast to properly functioning vehicles, the post-malfunction Taurus BC emissions did not depend on the driving phase and were more sensitive to all periods of acceleration in the hot running phase, not just the two hard accelerations. This indicates that malfunctioning vehicles might not only have higher peak *EF* and *ER* values compared to properly functioning vehicles, but that they will emit BC throughout a typical drive cycle. This would in turn alter the spatial pattern of BC emissions for such vehicles.

3.4 BC/TC and EC/TC

The real-time measurements (for tests performed with no added non-vehicle soot) demonstrate that BC dominates the total carbon (TC = BC + POC or EC + POC), with an all-vehicle full test average BC/TC = 0.75 ± 0.03 ($1\,\sigma_{\bar{x}}$) (Figure 4) and cold start and hot running values of 0.83 and 0.73, respectively. The very large BC fraction is consistent with the observation of very small average particle single scatter albedo (SSA) values (0.05 and 0.23 during cold and hot phases, respectively, and where SSA is the fraction of total light extinction due to scattering). The BC/TC (from the AMS and PAS and sampled from the SDS+RTC) compared well with the EC/TC (from thermal optical analysis and sampled from the CVS), with EC/TC = 0.80 on the single day where the measurements could be directly compared. The campaign average EC/TC from the CVS was similarly high (0.79). The slightly higher BC/TC could result from the additional dilution in the SDS relative to the CVS and consequent increased partitioning of semi-volatile POM species into the gas phase,[22] although the difference is small and within uncertainties, suggesting minimal influence of this additional dilution on the POM. The BC/TC ratio was relatively consistent between driving cycles for most vehicles, although the Pathfinder and Solara had somewhat large, although highly variable bursts of POM during cold-start, with an average cold-start BC/TC for these vehicles of 0.64 to 0.68, respectively. The relatively high

BC/TC ratios observed here are consistent with some previous dynamometer studies,[8, 16, 17] but not with others[6, 15, 20] (Table 3). Further, these dynamometer results can be compared with recent (post-2000) on-road and tunnel studies in which BC/TC or EC/TC ratios have been reported for LDGVs specifically, with values of 0.40±0.05,[14] 0.16±0.05,[23] 0.50±0.1,[24] and 0.5±0.6[25] (most on-road studies are unable to clearly distinguish the LDGV contribution). The discrepancy between the relatively high EC/TC values in some dynamometer studies (including this one) but not others for similar model years could be in part due to the relatively small number of vehicles tested, although the consistently high BC/TC values for all vehicles tested would argue against this. The comparably large BC/TC ratio observed here could result from the relatively high dilution ratios used here, although the similarity of the SDS (total dilution factor ~60) and CVS (dilution factor ~12) EC/TC suggests this is not the case. Nonetheless, the possibility that the comparatively low EC/TC ratios in some studies result from smaller dilution factors cannot be ruled out. It is possible that our observations differ from the on-road studies because of substantial contributions from older, high-emitting vehicles in on-road studies, which often emit more unburned lubricating oil[26], or from contributions from non-tailpipe sources (e.g. organic compounds from road dust).[27]

3.5 Constant velocity (steady state operation)

EF_{BC}'s and ER_{BC}'s for the constant velocity tests were averaged from the start of the constant period until the end of the test (Table 2). Average ER_{BC}'s for LEVs are much lower during the steady state test than during either the cold start or hot stabilized phases of the UC, consistent with Schauer et al.,[16] and likely as a result of vehicles operating at stoichiometry (i.e. low load) during steady-state operation even at high speeds. Interestingly, steady-state EF_{BC}'s for the SULEV GDI were substantially larger than for the other LEVs equipped with standard multi-port fuel injection, consistent with previous studies.[28] As expected, EF_{BC} for the diesel vehicle, which was not equipped with a diesel particle filter, was substantially larger than the GDI, ULEV, and LEV vehicles.

The average PM emission rate (BC + POM) from the GDI was 2.0 mg mile^{-1}, comparable to previous studies.[28, 29] The observed GDI ER_{PM} meets current PM standards (10 mg mile^{-1}) and the first phase of proposed PM standards under LEV III (3 mg mile^{-1}), but exceeds the second phase of proposed PM standards (1 mg mile^{-1}).[5] Even though the GDI ER_{PM} meets current standards, the substantially larger ER_{PM} values for the GDI compared to the LEV suggests that any shift towards GDI vehicles (driven by their increased fuel economy relative to multi-port fuel injection) could lead to an increase in PM emissions from gasoline vehicles.

4 Discussion

4.1 Comparison with Dynamometer studies

The average ER_{BC} values for all vehicles from this study compare reasonably well with results obtained from the majority of previous dynamometer studies, both for individual phases and averaged over the entire cycle[6, 8, 15, 16, 30] (Table 3). For example, the overall ER_{BC} reported in Fujita et al.[15] of 1.2 mg mile^{-1} is between the high and low emitters tested here. However, the ER_{BC}'s from high and low emitters are lower than those reported in Schauer et al,[16] likely because their vehicles started at lower cold start temperatures.

4.2 Comparison with On-Road and Tunnel studies

The average EF_{BC} values here are substantially smaller than the mean EF_{BC} values reported in on-road and tunnel studies that distinguish LDVs, by factors of 2-10 (for the high emitters here) and 10-60 (for the low emitters here) (Table 3). This is true even though the vehicles sampled in the on-road and tunnel studies typically do not operate under cold-start conditions and therefore should, in principle, emit less BC. Our EF_{BC}'s are, in particular, much lower than the median values reported in Park et al.[31] and Liggio et al.[32] The average EF_{BC} here is 5.2 mg kg^{-1} for properly functioning vehicles, compared with a median EF_{BC} = 61 mg kg^{-1} from Liggio et al.[32] for a highway dominated by gasoline-powered vehicles (or ~75 mg kg^{-1} extracted for just the LDGVs) and a range of 10-30 mg kg^{-1} from Park et al. for LDGV vehicles operating under various conditions (e.g. idling vs. fast acceleration vs. high speed cruising).[34]

A possible reason for these differences is that the mean EF_{BC} values in on-road and tunnel studies are skewed towards higher values by very high-emitting vehicles, including older vehicles and malfunctioning vehicles. Dynamometer studies indicate that the ER_{BC}'s of vehicles with older model years are substantially higher than those from newer vehicles. For example, in one study the average ER_{BC} from vehicles with model years 1980-1990 was around 4 times higher than from vehicles with model years 1990-2000, but with a much smaller decline in going from 1990-2000 to 2000-newer.[6] This is likely due to implementation of improved emission control technologies in newer vehicles, allowing for more ideal fuel-to-air ratios. Thus, the oldest vehicles sampled in the on-road studies (with median vehicle ages of ~10 years)[33] likely push the average EF_{BC} upwards. However, most of the on-road/tunnel studies in Table 3 report measurements from the mid-2000's, and thus most of the vehicles sampled should have been from the mid-1990's into the 2000's, not all that different from the vehicles tested in the current study. It is possible that the small fleet of vehicles sampled in the current study happened to have emissions substantially lower than a typical on-road vehicle, although this seems unlikely since the vehicles tested were actual in-use vehicles (requisitioned for this study) and since the average EF_{BC} from even the malfunctioning vehicle was only 24 mg kg^{-1}. However, since the tested vehicles were all classified as LEV I, and therefore utilize advanced emission control technologies, it is possible they have lower EF_{BC}'s than some in-use vehicles.

On-road malfunctioning vehicles, including smokers,[8, 19-21] may also drive up the average EF_{BC}. Interestingly, the average EF_{BC} of the malfunctioning, high-emitting vehicle tested in this study was at the lower end of reported mean and, for the few studies that report it, median on-road EF_{BC} values. It seems unlikely that there would be enough malfunctioning vehicles on the road to substantially influence the median (especially for studies conducted in locations that require periodic vehicle emissions testing, such as California). Additionally, studies that report both the mean and the median[31, 32] indicate that the mean is only around 2-3 times higher than the median. The median should be more characteristic of the behavior of the average vehicle, and thus there remains an apparent inconsistency between our dynamometer results on the on-road and tunnel studies.

Notably, the GDI vehicle tested in this study emitted substantially more BC than the LEVII vehicles and exceeds the proposed LEV III standard. However, the influence of GDI vehicles is likely minimal for the on-road and tunnel studies because the fraction of GDI vehicles in the U.S. fleet is negligible for model years 2007 and older,[34] and most on-road and tunnel studies listed in Table 3 took place before 2007.

The real-time observations demonstrate that BC emissions are sensitive to driving behavior, in particular acceleration, and it is possible that the UC may not accurately reflect the driving behavior (i.e. the frequency of aggressive accelerations) observed in on-road studies. However, Liggio et al. measured emissions from vehicles traveling on a straight stretch of highway. We observed that, for a given vehicle, the EF_{BC} was substantially lower during steady, high velocity operation compared to the cold start or hard accelerations during the hot running phase. Thus, it seems reasonable to expect that the median EF_{BC} values from Liggio et al. should, in principle, be lower than that measured during the UC here, which is not the case.

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Supporting Information

Information regarding methodologies and instrumentation. This information is available free of charge via the Internet at http://pubs.acs.org/.

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Table 1. Summary of results for LEVs tested on the Unified Cycle.

Model and Year	Phase	*N*	EF_{BC} (mg BC kg^{-1} fuel)		ER_{BC} (mg BC mile^{-1})		SSA[%]	Max EF_{BC}[*]
			Mean	Median	Mean	Median		
Ford Windstar 1998	Combined	5	1.5±0.4	0.94	0.21±0.06	0.14	0.30±0.04	7.8±1.3
	Cold Start		4.0±0.9	3.07	0.93±0.22	0.71	0.04±0.04	
	Hot Running		0.54±0.14	0.54	0.07±0.02	0.07	0.36±0.90	
Chevy Cavalier 2001	Combined	3	3.3±0.6	3.72	0.40±0.08	0.45	0.26±0.06	60.0±21.7
	Cold Start		14.3±5.0	10.19	2.7±1.0	1.93	0.05±0.04	
	Hot Running		0.42±0.13	0.35	0.05±0.01	0.04	0.24±11.8	
Toyota Tacoma 2003	Combined	6	8.1±1.2	8.49	1.24±0.20	1.21	0.10±0.02	35.3±6.0
	Cold Start		17.4±2.8	17.89	4.0±0.6	4.12	0.01±0.02	
	Hot Running		5.4±0.7	5.44	0.73±0.10	0.74	0.07±0.48	
Cherokee Laredo 2002	Combined	6	4.3±0.8	3.69	0.92±0.21	0.79	0.20±0.04	34.2±14.0
	Cold Start		11.2±4.2	7.56	3.6±1.4	2.44	0.05±0.02	
	Hot Running		1.83±0.35	1.58	0.35±0.07	0.30	0.22±0.89	
Nissan Pathfinder 2003	Combined	6	7.2±1.2	7.33	1.24±0.21	1.26	0.24±0.04	60.5±14.6
	Cold Start		26.4±6.0	26.29	6.7±1.5	6.64	0.03±0.02	
	Hot Running		1.07±0.14	1.03	0.17±0.02	0.16	0.29±0.93	
Chevy S-10 2002	Combined	6	1.92±0.25	2.01	0.25±0.03	0.26	0.20±0.02	11.8±5.7
	Cold Start		6.2±0.8	6.29	1.26±0.15	1.27	0.06±0.02	
	Hot Running		0.75±0.10	0.72	0.09±0.01	0.09	0.19±0.88	
Ford Taurus[$] 1997	Combined	5	24.1±8.1	18.16	3.5±1.2	2.57	0.09±0.05	79.9±27.4
	Cold Start		36±16	19.29	6.8±3.5	4.21	0.07±0.03	
	Hot Running		21.0±6.2	21.69	2.2±0.7	2.45	0.04±0.31	
Toyota Solara 2003	Combined	3	0.76±0.10	0.69	0.10±0.02	0.09	0.29±0.06	13.3±6.0
	Cold Start		2.8±0.7	2.34	0.61±0.16	0.51	0.09±0.05	
	Hot Running		0.29±0.04	0.32	0.03±0.00	0.04	0.44±4.37	

[$] Vehicle malfunctioned

[*] Maximum value observed during a test, typically during the cold start period

[%] SSA = single scatter albedo

Table 2. Results from the constant velocity tests.

Make/Model	Model Year	MPG	RH	Times previously started on test day	EF_{BC} (mg kg^{-1})	ER_{BC} (mg $mile^{-1}$)	EF_{OM} (mg kg^{-1})	ER_{OM} (mg $mile^{-1}$)
Chevy Cavalier (LEV)	2001	37	Ambient	0	0.50	0.04	0. 11	9.0×10^{-3}
Chevy Cavalier (LEV)	2001	37	Ambient	1	0.18	0.01	0.06	4.6×10^{-3}
Hyundai Sonata (GDI, SULEV)	2011	50	High RH	0	33	1.80	1.9	0.11
Hyundai Sonata (GDI, SULEV)	2011	50	Ambient	0	36	1.97	1.6	0.09
Hyundai Sonata (ULEV)	2008	39	Ambient	0	0.93	0.07	0.13	9.3×10^{-3}
Hyundai Sonata (ULEV)	2008	39	High RH	3	0.45	0.03	0. 39	0.03
Volkswagen Jetta (Diesel)	2004	47	Ambient	0	120	6.9	7.1	0.41

Table 3: Comparison of black carbon emission factors and rates for LEVs with other studies.

Study & Type	Year of Measurements or Vehicle Model Years	BC Emission Factor (mg kg^{-1})	BC Emission Rate (mg mile^{-1})	BC/TC or EC/TC ratio
Dynamometer Studies				
This Study (Low)[#] Combined[%]	1998 - 2003	1.90 (± 0.52)	0.24 (± 0.06)	0.75 (±0.03)° 0.80 (±0.08)[&]
This Study (High)[$] Combined	1997-2003	10.47 (± 3.98)	1.65 (± 0.51)	
This Study (Low)[#] Phase 1[^]	1998-2003	6.82 (± 2.59)	1.38 (± 0.46)	
This Study (High)[$] Phase 1	1997-2003	21.7 (± 2.29)	5.33 (± 0.88)	
This Study (Low)[#] Phase 2[+]	1998-2003	0.5 (± 0.05)	0.06 (± 0.01)	
This Study (High)[$] Phase 2	1997-2003	7.03 (± 2.19)	0.87 (± 0.47)	
Fujita et al. (2007) Combined[15]	1990-2001		1.2	0.23
Schauer et al. (2008) Combined[16]	1995-1999		3.9	0.34-0.84
KCS (2006) Phase 1[6]	1990-2000/ 2000-2003		4.4/3.6	0.36 – 0.38°
KCS (2006) Phase 2[6]	1990-2000/ 2000-2003		0.7/0.3	
Robert et al. (2007) Overall[8]	1996-2003		0.40	0.68
Geller et al. (2006) (New European Driving Cycle)[30]	2001		0.76	0.28
On-road and Tunnel Studies				
Kittelson et al. (2006)[17]	1984-1999		2.0	0.64
Grieshop et al. (2006) (tunnel)[25]	2002	26.6		0.46
Zielinska et al. (2004)[20]	1982-1996		4	0.40
Ning et al. (2008) (on road)[23]	2004-2005	20.5		0.16±0.05
Liggio et al. 2012 (on road)[32]	2010	115 (Median = 59)		
Strawa et al. 2010 (tunnel)[24]	2006	22		0.50±0.1
Park et al. 2011 (on-road)[31]	2007	60 (Fast Acc.) (Median = 20)		
Miguel et al. 1998 (tunnel)[35]	1996	30		
Geller et al. 2005 (tunnel)[36]	2004	30.4		
Kirchstetter et al. 1999 (tunnel)[14]	1997	35		0.40±0.05

% Averaged over the entire UC.
\# Average for the 4 vehicles with the lowest average EF_{BC}.
$ Average for the 4 vehicles with the highest average EF_{BC}.
° BC/TC single-day average over all vehicles, sampled from the SDS (N_{days}=2).
& EC/TC single-day average over all vehicles, sampled from the CVS (N_{days}=1).
^ Phase 1 = cold start
\+ Phase 2 = Hot running

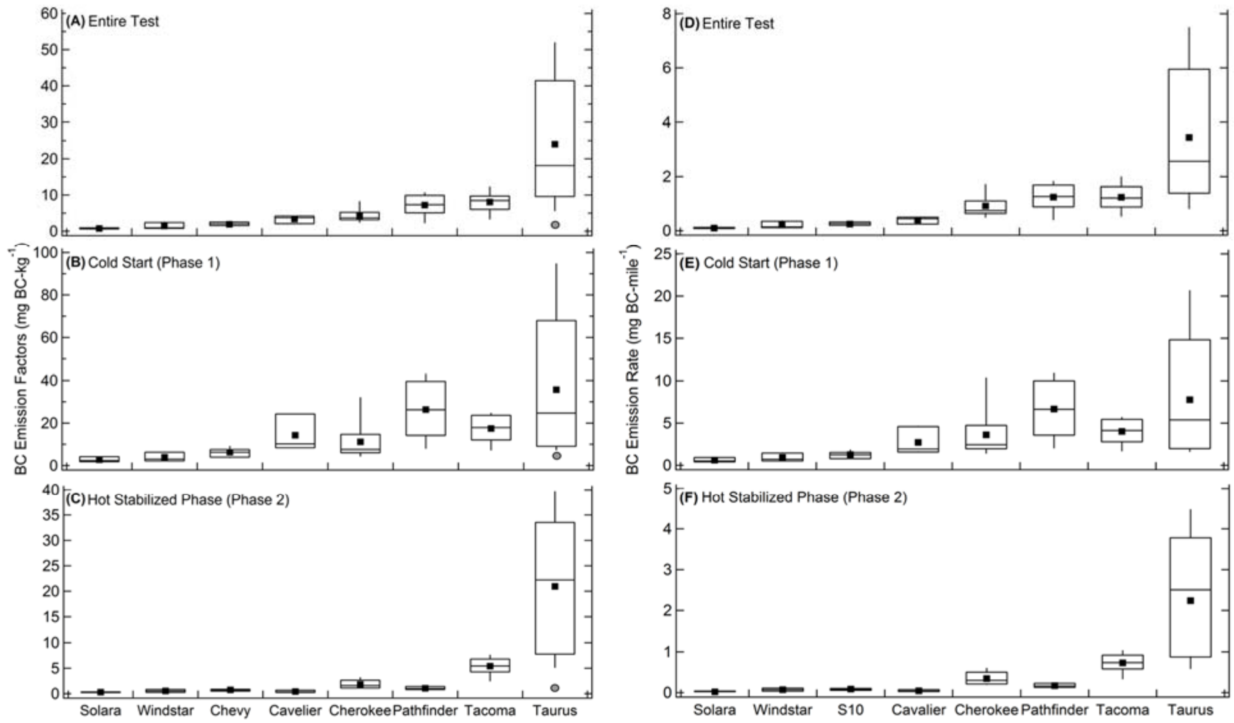

Figure 1. Black carbon emission factors (left panels) and emission rates (right panels) for all LEVs tested using the Unified Cycle. Results are shown for (A and D) overall, (B and E) Cold Start/Phase 1 and (C and F) Hot Running/Phase 2 EFs and ERs. The box and whisker plots show the mean (■), median (-), lower and upper quartile (boxes) and 9th and 91st percentile (whisker). The test vehicles are organized from lowest to highest overall emission factors. The Taurus malfunctioned after only one test; the gray circle indicates the EF_{BC} prior to the malfunction.

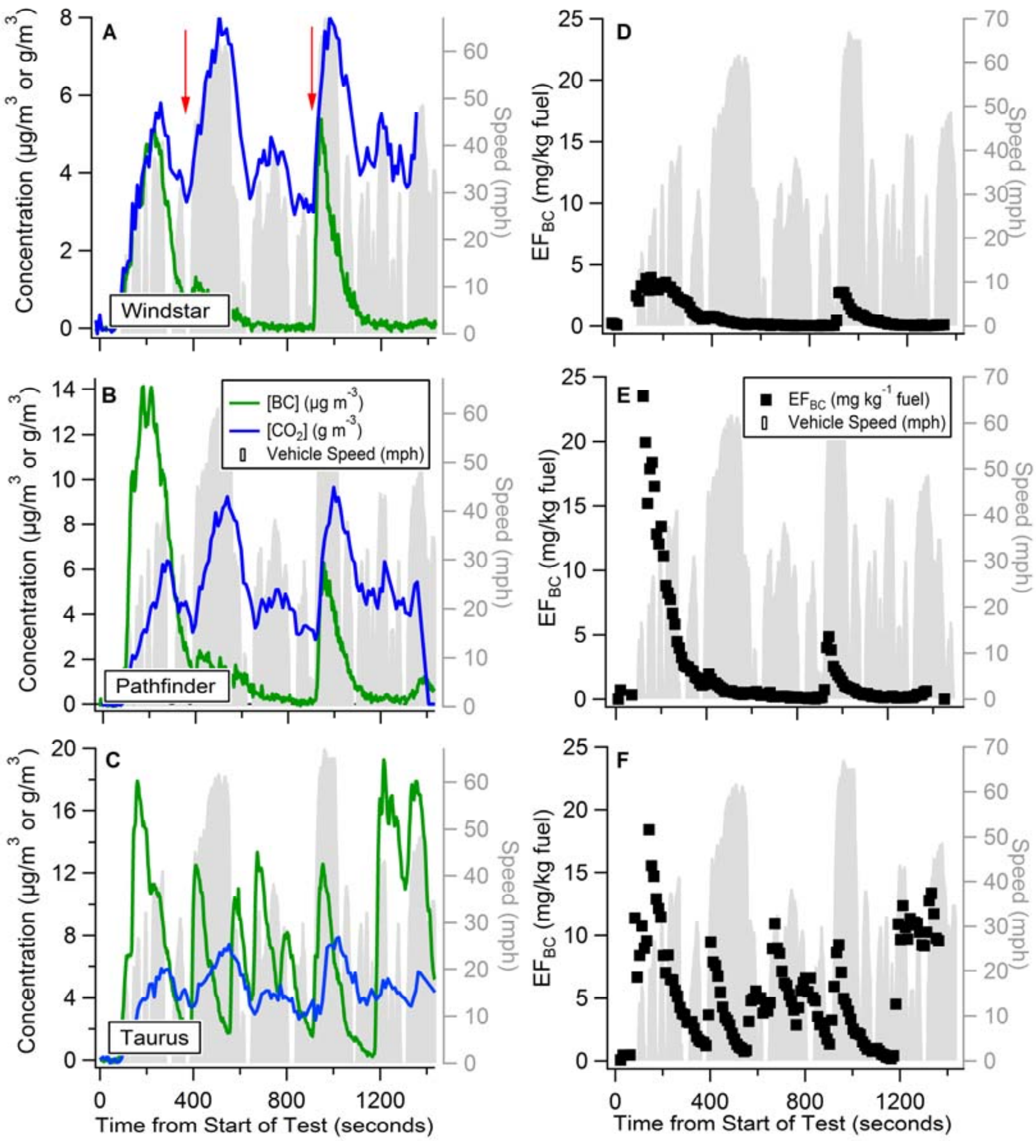

Figure 2. Real-time BC (green lines) and background-subtracted CO_2 (blue lines) concentrations (Panels A-C) and emission factors (black points; Panels D-F) during a base case UC test on Sept. 20th for three LEVs: (A,D) Ford Windstar, (B,E) Nissan Pathfinder and (C,F) post-malfunction Ford Taurus. The vehicle speed is shown for reference (grey lines). The red arrows indicate the occurrence of the first and second hard accelerations. The delay in at the beginning is due to the residence time in the CVS and the SDS+RTC; the speed profile has been shifted accordingly.

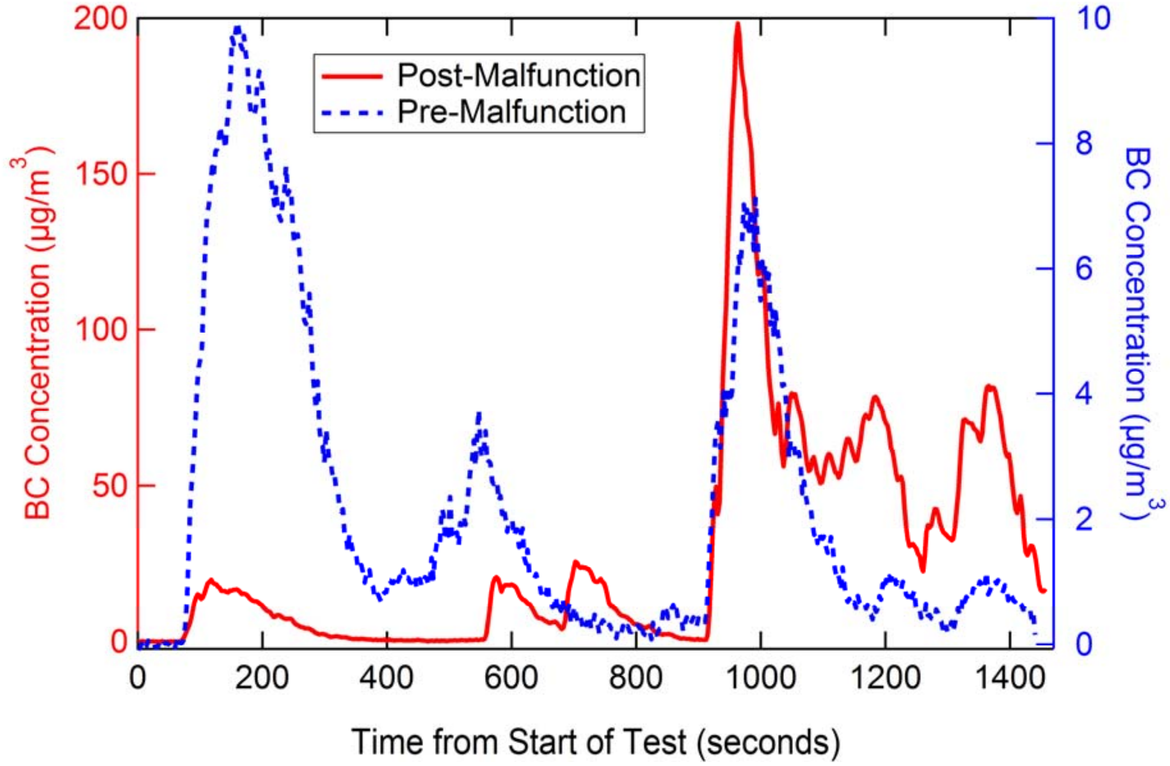

Figure 3. Real-time BC concentrations from the Ford Taurus (LEV) during the UC before (Sept. 9th; blue line) and after (Sept. 15th; red line) malfunctioning. Note the difference in scales for the two axes.

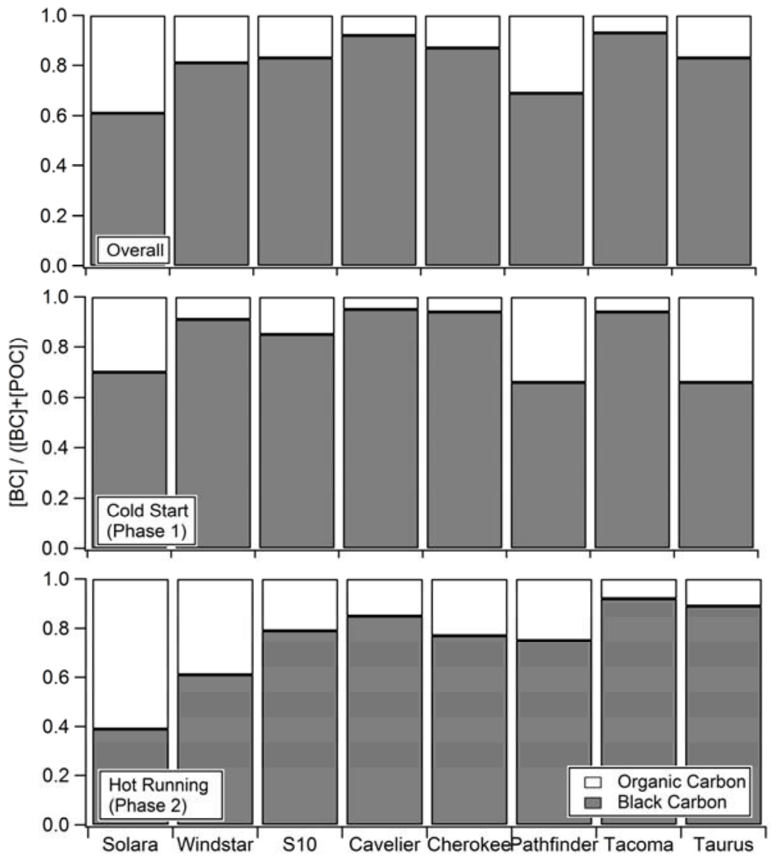

Figure 4. Average BC to total carbon (=BC + POC) ratios for LEVs determined from the real-time instrumentation (i.e. PAS and AMS), excluding the days on which non-vehicle BC was added to the SDS.

TOC Art

3.33" X 1.64"