Effect of Ambient Temperature and Fuel on Particle Number Emissions on Light-Duty Spark-Ignition Vehicles

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ABSTRACT

To better understand the impact of ambient temperature and fuel on the emissions of ultrafine particles from spark ignition light-duty vehicles, experiments were conducted to examine the impact of ethanol-gasoline mixtures, compressed natural gas (CNG), and ambient temperature, on the size distribution and number emissions of particles. Vehicles were tested on a chassis dynamometer under controlled conditions of ambient temperature spanning from 60 to 85°F. A dual fuel vehicle operating with CNG and 6% ethanol-gasoline blends (E6); and a flex fuel vehicle operating with four different ethanol-gasoline blends E6, 35% ethanol (E35), 65% ethanol (E65) and 85% ethanol (E85) was evaluated to understand fuel effects. Changes in vehicle operating temperature, which included the combustion air temperature, over the ranges of 60 to 85°F showed no clear impact on fine particle emissions. Likewise, no significant changes in particle number or particle size distributions were observed between CNG and E6 fuels. However, tests with the flex fuel vehicle, which were able to examine higher ethanol concentrations in the fuel showed large decreases in particle number emissions as ethanol levels increased to E65 and E85.

Keywords: Particle number; Size distribution; EEPS; Fuel; Source emissions.

INTRODUCTION

Fine particles are commonly defined as those particles with aerodynamic diameters lower than 2.5 µm; ultrafine particles are considered those with aerodynamic diameters smaller than 0.1 µm (Morawska et al., 2008). Ultrafine particles are commonly measured in terms of number rather than mass and tend to dominate particle number size distributions. Ultrafine particles from natural and anthropogenic sources are always present in the atmosphere and can easily enter the respiratory system, depositing in the lungs with the potential to enter the blood stream by passing through the lung-blood barrier (Gilmour et al., 2004; Kapnos et al., 2004; Chio and Liao, 2008; Araujo, 2011). Respiratory diseases have been linked with air pollution and more specifically with particulate matter exposure; recent studies have shown that ultrafine particles, in addition to known respiratory complications, could affect the cardiovascular and neurological systems, the liver and other organs (Gilmour et al., 2004; Morawska et al., 2008; Terzano et al., 2010). Ultrafine particles are likely to be deposited in the pulmonary region, which can facilitate entryway into the cardiovascular system, subsequently causing alterations in blood coagulation, triggering autonomic nervous system reflexes altering cardiac function.

Several studies have shown that particle size and composition varies according to the type of fuel and engine, including recently developed fuel alternatives such as compressed natural gas (CNG), biodiesel and bioethanol (Agarwal, 2007; Sawyer, 2010). Particulate matter (PM) emissions have been an issue for diesel engines (Myung et al., 2009), nevertheless, the use of Diesel Particulate Filters (DPF), has contributed to important decreases in particulate matter emissions (Biswas et al., 2009). Although particle size distributions for diesel engines using DPF look more similar to those for gasoline-powered engines, emissions of ultrafine particles are of greater concern for gasoline engines (Harris and Mariq, 2001; Lee et al., 2008). Particle diameters emitted from diesel engines are usually above 50 nm (Myung et al., 2009). In general, diesel engine emissions contain...
particles with greater aerodynamic diameters compared to emissions from gasoline and CNG-powered vehicles; thus, particle mass distributions are important for diesel emissions, whereas particle number distributions are of great concern for gasoline and CNG-powered vehicles (Morawska et al., 2008). Although ultrafine particle emissions from gasoline and CNG-powered vehicles are similar (Ristovski et al., 2000), blending conventional gasoline with ethanol leads to reductions in these emissions (Lee et al., 2009a; Lee et al., 2009b); however, that is at the expense of increases in emissions of toxic gases such as acetaldehyde and formaldehyde (Corrêa and Arbilla, 2005). Since ultrafine particle emissions depend highly on engine operation mode, these results are given as average particle number concentrations over the duration of a driving cycle. Only one study (Myung et al., 2009) showed measurable differences between time-resolved particle number distributions for different gasoline-ethanol blends following driving cycles common in Asian countries. Several studies have shown that there is an important increase in gas and particle exhaust emissions during cold start and during this period of engine operation, there is an indirect relation between ambient temperature and ultrafine particle emissions (Mathis et al., 2005). Results from hot start tests have shown similar behavior of PM10 emissions with extreme changes in ambient temperature (Mulawa et al., 1997). On the other hand, results from hot start tests in diesel-powered light-duty vehicles have shown that there is almost no variation of ultrafine particle emissions even with drastic changes in ambient temperature (Ristimäki et al., 2005).

The purpose of this study is to evaluate the effect of changes in ambient temperature and fuel in emissions of ultrafine particles from light-duty vehicles. The ambient temperature tested were 60°F, 75°F and 85°F; and the tested fuels include conventional gasoline, gasoline-ethanol blends from 6%, 35%, 65% and 85% ethanol content and CNG.

METHODS

Fuel Blends, Testing Vehicles, and Additional Equipment

Tests were conducted using a commercially available blend of 94% gasoline, 6% ethanol (E6); a commercially available blend of 15% gasoline, 85% ethanol (E85); and blends formulated, via splash mixing, on site of 65% gasoline, 35% ethanol (E35), and 35% gasoline, 65% ethanol (E65). In addition, commercially available compressed natural gas (CNG).

Vehicle Preparation and Driving Cycle

For liquid fuel vehicles, old fuel was drained completely and new test fuel was added to run a 25-mile road prep. After the 25-mile road prep, the fuel system was drained again and the fuel tank was filled to 40% of the fuel tank capacity with the new test fuel. CNG fuel tank was filled before tests for CNG fuel vehicle. The vehicle was warmed up with the FTP phase 1 driving cycle for 505 seconds and left idling prior to emission sampling.

After the warm up cycle, the vehicle setup for a hot-start modified LA92 driving cycle without engine cranking,
composed of three consecutive Unified LA92 driving cycles, each of which had an approximate duration of 1435 seconds, a distance of 9.82 miles, and an average speed of 24.61 mph, for a total testing time of 4305 seconds (71.8 minutes). The driving cycle schematic can be seen in Fig. 1(a). Table 1 shows the complete testing schedule, with all tested vehicles and their respective fuel and ambient temperature. The testing procedure followed in this study can be found in “CALIFORNIA EVAPORATIVE EMISSION STANDARDS AND TEST PROCEDURES FOR 2001 AND SUBSEQUENT MODEL MOTOR VEHICLES” elaborated by the California Air Resources Board.

**Ambient Temperature Effect Evaluation**

The effect of operating the vehicles on ultrafine particulate matter emissions at different ambient temperatures was evaluated for three vehicles independently. The Chevrolet Cavalier – Dual fuel was tested while operated with E6 and CNG fuels at ambient temperatures 60, 75 and 85°F; the Honda Civic – CNG was operated with CNG at the same ambient temperatures 60, 75 and 85°F, while the Ford Escape - Hybrid was operated with E6 at the same ambient temperature conditions mentioned above. The tests were conducted at temperatures 60, 75 and 85°F according to the test cell air conditioning capabilities.

![Fig. 1.](image)

**Fig. 1.** a) Driving cycle used for testing (Unified LA92), compared to b) Particle number concentration emissions per second as a function of time for Chevrolet Cavalier tests at 75°F for duplicate runs 8 and 14 with E6 fuel and c) Particle number concentrations per second as a function of time for Chevrolet Impala tests at 75°F for duplicate runs 7 and 9 with E6 fuel.
Table 1. Testing schedule and specifications.

<table>
<thead>
<tr>
<th>Date</th>
<th>#</th>
<th>Vehicle</th>
<th>Fuel</th>
<th>Temperature (°F)</th>
<th>Std Dev (°F)</th>
<th>Nominal Temperature (°F)</th>
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<td>1</td>
<td>Ford Escape Hybrid</td>
<td>Gasoline 94% - Ethanol 6%</td>
<td>59.61</td>
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<td>Gasoline 35% - Ethanol 65%</td>
<td>75.97</td>
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Fuel Effect Evaluation

The effect of using different fuels on particle emissions from vehicles was evaluated for two vehicles independently. The Chevrolet Cavalier – Dual fuel was operated with E6 and CNG fuels in order to assess the difference in particle emissions from combustion of gasoline and CNG; while the Chevrolet Impala – Flex fuel was operated with E6, E35, E65 and E85 fuel blends, in order to assess the effect of ethanol content on gasoline-ethanol blends in particle emissions.

RESULTS AND DISCUSSION

Test Repeatability

Duplicate tests were performed for the Chevrolet Impala – Flex fuel at an ambient temperature of 75°F, operating with E6, E35 and E65 fuel blends and for the Chevrolet Cavalier- Flex fuels at an ambient temperature of 75°F, operating with E6 fuel. Fig. 1 compares the Unified LA92 driving cycle with particle emissions as a function of time for both the actual and duplicate tests for the Chevrolet Impala and Chevrolet Cavalier at an ambient temperature of 75°F with E6 fuel and shows good agreement between duplicates. The results from the Chevrolet Cavalier (Fig. 1(b)) do show more variability between the repeated tests, which is an indication of a number of factors that could not be controlled during testing, including: variability in driver technique, changes in atmospheric pressure and relative humidity, and subtleties in vehicle operation. While these factors, and likely others, can affect vehicle emission characteristics, the overall scale of emissions are in agreement and these sensitivities are accounted for in the reported uncertainties for each of the test conditions.

Particle emissions results were calculated as the arithmetic average of particle number concentrations per second for the three consecutive Unified LA92 cycles, therefore the time axis extends only to about 1,415 seconds, the duration of one Unified LA92 cycle. The concentrations in the time series figures are reported in particles per second in order to allow for an easy comparison across cycles and technologies. The emission rates were calculated by multiplying the EEPS reported particle concentration by the tunnel constant flow rate. The results from Fig. 1 show good agreement between both tests for the Chevrolet Cavalier and Chevrolet Impala – Flex fuel operating with E6 fuel at 75°F, confirming the repeatability of the performed tests. When feasible, the E6 duplicate runs for the Chevrolet Cavalier and Chevrolet Impala were included in the figures to show the repeatability of all the measurements as long as they did not clutter the figures. In addition, nearly all results exceeded the average of the dynamic blank results seen in Fig. 2(a). Dynamic blank tests were performed with no engine in operation, for the whole duration of a driving cycle, with only dilution air entering the sampling train. Although dilution air passes through particle filters, it is almost impossible to remove all particles, especially ultrafine particles, from
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ambient air. Fig. 2(a) shows the scale of the background tunnel concentration as compared to an example test run shown in Fig. 2(b), giving the reader the context for the reported measurements. In general, the background levels are more than an order of magnitude less than measured concentrations.

**Fig. 2.** a) Average size distribution as a function of particle diameter for blank tests compared to b) the average size distributions for Chevrolet Impala tests at 75°F for duplicate runs 13 and 25 with E65 fuel.

**Ambient Temperature Effect in Particle Number Emissions from Light-duty On-road Vehicles**

Fig. 3(a) shows the average of particle number concentrations detected by the EEPS throughout the whole test. For all tests, uncertainties were estimated as the standard deviation of the three individual Unified LA92 cycles. The EEPS results were segregated into three different particle bin sizes: diameters lower than 45 nm, between 52.3 and 93.1 nm, and between 107.5 and 523.3 nm, thus making it easier to compare emissions of nanoparticle, ultrafine, and fine particle ranges. Results reported in Fig. 3(a) show that average particle number emissions per mile from the Escape Hybrid operating on E6 fuel in the 0–45 nm and the 52.3–93.1 nm bin sizes are greater to those in the 107.5–523 nm bin size for the three different temperatures; this difference is more than one order of magnitude in average. However, in general, average particle number emissions, in all bin sizes, showed little variation at the three different temperatures. Detailed averaged particle number concentrations per mile for the three different bin sizes evaluated in this test are presented in Table 2. Particle number concentrations per second as a function of time obtained for the Civic CNG and the Cavalier dual fuel vehicles operating on CNG at different ambient temperatures showed little variations throughout the whole test, as observed in Figs. 4(a) and 4(b). Moreover, particle number size distributions obtained from the same vehicles, shown in Figs. 5(a) and 5(b), confirm this observation. From these results it can be concluded that slight temperature variations such as the analyzed in this study, do not clearly affect particle number emissions from light-duty spark-ignition vehicles. As stated previously in similar studies on light-duty vehicles operating on petroleum diesel fuel (Ristimäki et al., 2005), changes in ambient temperature have little influence in time based particle number concentration emissions per mile testing on driving cycles with hot starts.

**Fuel Effect in Particle Number Emissions from Light-duty On-road Vehicles**

Fig. 3(b) shows the differences in average particle number concentrations per mile obtained for different blends of gasoline and ethanol fuels at the same ambient temperature for the Impala flex fuel vehicle operating on E6, E35, E65 and E85 fuel blends. Particle number emissions per mile for the 0–45 nm bin size are higher compared to the other bin sizes, presenting similar trends as shown in Fig. 3(a); however, particle number emissions per mile of E65 and E85 blends are considerably lower compared to E6 and E35.
blends. In general, average particle number emissions, in bin sizes 0–45 nm and 52.3–93.1 nm, showed little variation at the three different temperatures. Nonetheless, total particle number emissions for particle diameters between 107.5 and 523.3 nm showed a decrease of almost an order of magnitude when increasing ambient temperature for the hybrid vehicle test operating on E6. Given the higher oxygen content of ethanol compared to gasoline, this decrease may be related to an increased yield in the combustion reaction. There are a number of mechanisms that could cause this decrease, however, further investigation would be required to describe this observation. Detailed averaged particle number concentrations per mile for the three different bin sizes are summarized in Table 2. Fig. 6(a) shows particle number concentrations per second as a function of time obtained from the Cavalier dual fuel vehicle operating on E6 and CNG fuels. From this figure it is clear that there is no significant difference in particle number emissions per second from the different tested fuels. This observation can be confirmed by the particle number size distributions per mile shown in Fig. 7(a), even with the uncertainties associated to these measurements. On the other hand, Fig. 6(b) presents significant differences between time based particle number emissions per mile obtained from operating the Impala flex fuel vehicle with E65 and E85 fuel blends compared to E6 and E35. The same differences can be observed in particle number size distributions per mile shown in Fig. 7(b) where E65 and E85 distributions are considerably different, which is clearer for particle diameters above 10 nm. Previous studies reported similar trends comparing blends of gasoline and ethanol fuels with ethanol content not higher than 10% in volume with E85 blends (Lee et al., 2009a; Lee et al., 2008; Myung et al., 2009). However, this study also assessed intermediate blends E35 and E65, which allows a better view of determining a breaking point in ethanol fuel content in the blends, in terms of particle number emissions. As proposed earlier, based on Fig. 3(b), the observed decreases in particle emissions may be associated with the
Table 2. Average particle concentration by vehicle, fuel and temperature.

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<tr>
<th>Vehicle</th>
<th>Fuel</th>
<th>Temperature</th>
<th>Average Particle Concentration (#/mile)</th>
<th>ST Dev</th>
<th>Average Particle Concentration (#/mile)</th>
<th>ST Dev</th>
<th>Average Particle Concentration (#/mile)</th>
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<td></td>
<td></td>
<td>Condition</td>
<td>(0–45.3 nm)</td>
<td></td>
<td>(52.3–93.1 nm)</td>
<td></td>
<td>(107.5–523.3 nm)</td>
<td></td>
</tr>
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<td>E6</td>
<td>T60</td>
<td>1.0E+12</td>
<td>4.9E+10</td>
<td>8.2E+10</td>
<td>6.1E+10</td>
<td>1.7E+11</td>
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<td>NG</td>
<td>T75</td>
<td>4.6E+11</td>
<td>6.6E+11</td>
<td>2.2E+10</td>
<td>8.5E+09</td>
<td>1.2E+10</td>
<td>2.1E+09</td>
</tr>
<tr>
<td>Honda Civic</td>
<td>NG</td>
<td>T85</td>
<td>1.1E+11</td>
<td>1.7E+10</td>
<td>2.2E+10</td>
<td>3.5E+09</td>
<td>1.4E+10</td>
<td>1.1E+09</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of average particle concentrations as a function of time for natural gas powered vehicles a) Honda Civic and b) Chevrolet Cavalier, at temperatures 60, 75 and 85°F.
higher oxygen content in E65 and E85 fuel blends. Since there is an increasing trend of using more ethanol in gasoline-ethanol fuel blends, the results shown in this research highlights the benefits of using blends with ethanol contents higher than 65% in volume in terms of nanoparticle, ultrafine and fine particle emissions and the human health and climate change impacts associated with these particles. Nonetheless, it is recommended to keep in mind that using E85 fuel blends increases formaldehyde and acetaldehyde emissions (Corrêa and Arbilla, 2005); therefore, reductions in particle emissions are at the expense of increasing the health risk and ozone forming potential associated with these species.

DISCUSSION

The purpose of this study was to examine the effect of ambient temperature and fuel type on emissions of ultrafine particles in spark-ignition vehicles. The study shows that ambient temperature changes ranging from 60, 75 and 85°F do not clearly have an effect in ultrafine particle number concentrations as a function of time for hot start chassis dynamometer tests, which was confirmed for vehicles fueled with CNG, and E6. Nonetheless, total particle number emissions for particle diameters between 107.5 and 523.3 nm showed a decrease of almost an order of magnitude when increasing ambient temperature for the hybrid vehicle test operating on E6. As mentioned before, this decrease could be associated with the volatilization of species present in particles within that diameter range, most likely organics, which may happen at temperatures above 85°F. Nevertheless, total particle emissions from other vehicles tested with fuels E6 and CNG did not show the same trend, thus refuting this idea. It is important to mention that the temperature values chosen for this study were limited by the temperature control capacity of the air conditioning unit installed at the test cell.

With respect to fuel type, there were no significant differences in particle number concentrations as function of testing time or total particle number emissions, when comparing conventional gasoline blended with 6% in volume of ethanol (E6), and compressed natural gas (CNG).
Nevertheless, comparison of particle number emissions in a flex fuel vehicle operating on different conventional gasoline/ethanol blends at 0, 6, 35, 65 and 85% in volume showed decreases in such emissions, clearly observed for E65 and E85 fuel blends. This trend was clear for both particle number concentrations as a function of time, and total particle emissions throughout the whole test, where it was clear that total particle number emissions of the vehicle operating with E6 and E35 fuels were very similar, but more than an order of magnitude greater than those operating with E65 and E85. Since total particle emissions of these blends were very similar with each other, it does not make a great difference using E65 or E85 to benefit in terms of lower particle number emissions. Prior studies mention a direct relation between oxygen content in fuel and quality of combustion, resulting in decreases in most air pollutants linked to incomplete combustion, including particle emissions (Niven, 2005; Canakci et al., 2013; Costagliola et al., 2013), but there were no results indicating a correlation between oxygen content in fuel and ultrafine particle emissions. The results of this study suggest that there is not a linear relation between ethanol content in fuel and ultrafine particle emissions, and that further research must be conducted with controlled fuel formulation, engine type, driving cycle, ambient temperature and dilution conditions, complemented by a broad knowledge of cylinder combustion dynamics, chemical mechanisms and complex computational modelling (Bayraktar, 2005; Ginnebaugh et al., 2010) in order to understand this phenomena.

From the results of this study it can also be concluded that blending conventional gasoline with more than 65% in volume of ethanol decreases the health risk associated with exposure to ultrafine particles emitted from spark-ignition engines. In addition, it has been proven that emissions of hazardous species such as benzene, butadiene, toluene, xylenes, PAHs, etc. also decrease with the use of blends of gasoline and ethanol (Graham et al., 2008; Karavalakis et al., 2012; Bielaczyc et al., 2013), which would lower even more the health risk of SI engine emissions in general. Nevertheless, emissions of carbonyl species tend to increase for gasoline/ethanol blends with higher ethanol content (Graham et al., 2008; Karavalakis et al., 2012; Bielaczyc et al., 2013), and these species are known to be highly toxic and even carcinogenic (Grosjean et al., 2001); furthermore, carbonyl species have an important ozone forming potential (Bakeas et al., 2003). Based on these facts, the overall
Fig. 7. Effect of different fuel types on average size distribution as dN/dLog(Dp) at temperature 75°F for vehicles a) Chevrolet Cavalier operating on E6 and CNG, and b) Chevrolet Impala operating on E6, E35, E65 and E85.

impact of using gasoline/ethanol blends on human health is difficult to assess. For instance, emission of air pollutants greatly depends on engine type and age, driving conditions, fuel composition, etc. (Jamriska and Morawska, 2001; Heeb et al., 2003; Martyr and Plint, 2007); ozone forming potential of carbonyl species depends on background concentrations of other VOCs, NOx, and solar radiation intensity (Schifter et al., 2007; Yanowitz and McCormick, 2009; Ginnebaugh et al., 2010); and although it is known that exposure to ultrafine particles has an impact on human health (Wichmann et al., 2000; Araujo, 2011; Buonanno et al., 2014), there are still many uncertainties about this topic concerning the chemical composition of these particles; in addition, particle number concentrations are more important near roadways than away from them (Knibbs et al., 2011).

CONCLUSION

Given the increasing trend of using higher contents of ethanol in gasoline-ethanol fuel blends, the results of this research highlight the benefits of using this biofuel in terms of reduction in ultrafine particle emissions, noticeable for blends with at least 65% ethanol in volume. Subsequently, impacts on human health and climate associated with such particles may be reduced. Nonetheless, it is recommended to keep in mind that reductions in ultrafine particle emissions through the use of gasoline/ethanol blends come at the expense of increases in carbonyl species emissions (Corrêa and Arbilla, 2005); which may result in an increasing health risk associated with direct exposure to these species and their indirect effect due to their high ozone forming potential.

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SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aqqr.org.

REFERENCES


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SUPPLEMENTAL MATERIALS

Effect of Ambient Temperature and Fuel on Particle Number Emissions on Light-Duty Spark-Ignition Vehicles

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SUPPLEMENTAL FIGURE CAPTIONS

Supplemental Figure S0. A schematic of the dilution tunnel sample system showing the layout of test vehicle and instrumentation.

Supplemental Figure S1ab. a) Ambient temperature effect on fine particle and CO emissions for Chevrolet Cavalier – Dual fuel tests operating on E6 at temperatures 60, 75 and 85°F for the three different bin sizes (0–45, 52.3–93.1 and 107.5–523.3 nm). b) Fuel effect on fine particle and CO emissions for Chevrolet Cavalier – Dual fuel tests operating on E6 and CNG fuels at 75°F for the same three different bin sizes.

Supplemental Figure S2ab. a) Ambient temperature effect on fine particle and CO emissions for Chevrolet Cavalier – Dual fuel tests operating on CNG at temperatures 60, 75 and 85°F for the three different bin sizes (0–45, 52.3–93.1 and 107.5–523.3 nm). b) Ambient temperature effect on fine particle and CO emissions for Honda Civic – CNG tests operating on CNG at temperatures 60, 75 and 85°F for the same three different bin sizes.

Supplemental Figure S3ab. a) Average NOx emission rates compared to b) average HC emission rates for all the tests.

Supplemental Figure S4ab. Comparison of Log of average particle concentrations as a function of time for temperatures 60, 75 and 85°F for vehicles a) Chevrolet Cavalier and b) Ford Escape operating with E6 fuel.

Supplemental Figure S5ab. Effect of ambient temperature changes on average size distribution as dN/dLog(Dp) as a function of particle diameter for vehicles a) Chevrolet Cavalier and b) Ford Escape operating with E6 fuel.
Supplemental Figure S0

CLOSED TEST CELL WITH TEMPERATURE CONTROL
Supplemental Figure S1ab

**a)**

![Bar chart showing total particle number concentration and average CO concentration for different groups labeled as Cavalier E6 T85, Cavalier E6 T75 (8), and Cavalier E6 T85. Each group is divided into bins of different sizes.](image)

**b)**

![Bar chart showing total particle number concentration and average CO concentration for different groups labeled as Cavalier E6 T75 (8), Cavalier E6 T75 (Dip, 14), and Cavalier NG T75.](image)

- **Legend:**
  - Bin size 0 - 45 nm
  - Bin size 52.3 - 93.1 nm
  - Bin size 107.5 - 523.3 nm
  - Average CO emissions
Supplemental Figure S2ab

![Graph showing total particle number concentration and average CO concentration for different vehicle models and bin sizes.]
Supplemental Figure S4ab

Chevrolet Cavalier - E6

![Graph a)

Ford Escape - E6

![Graph b)
Supplemental Figure S5ab

*Chevrolet Cavalier - E6*

![Graph a)](image)

*Ford Escape - E6*

![Graph b)](image)