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FINAL PROJECT REPORT

EVALUATION OF THE PERFORMANCE AND AIR POLLUTANT EMISSIONS OF VEHICLES OPERATING ON VARIOUS NATURAL GAS BLENDS

Light Duty Vehicle Testing

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PREFACE

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Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blend – Light-Duty Vehicles is the final report for the Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blend project (contract number 500-07-012), conducted by University of California, Riverside. The information from this project contributes to Energy-Related Environmental Research program.

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ABSTRACT

The composition of natural gas can have an important impact on the emissions and performance of natural gas vehicles. With the expansion of natural gas production via horizontal drilling and hydraulic fracturing as well as the potential of liquefied natural gas from the Costa Azul LNG terminal in Baja California, Mexico, there is the potential for a wider range of natural gas compositions being used throughout California. This study evaluated the impact of natural gas composition on the performance and emissions of light-duty vehicles. Two natural gas light-duty vehicles were tested using the Federal Test Procedure and the Unified Cycle on a range of four different test gases. The results show that for more sophisticated, modern light-duty natural gas vehicles, fuel properties have a clear and direct impact on fuel economy and some emissions, such as carbon dioxide and non-methane hydrocarbons, but not for others, such as total hydrocarbons, nitrogen oxides, and carbon monoxide. For the fuel economy, carbon dioxide emissions, and non-methane hydrocarbon emissions, the most critical fuel properties include the energy content, the hydrogen to carbon ratio, and the level of heavier hydrocarbons in the blend.

Keywords: Natural Gas; Vehicle Emissions; Transportation; Alternative Fuels

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EXECUTIVE SUMMARY

Natural gas vehicles have been implemented in a variety of applications as part of efforts to improve urban air quality, particularly within California. Natural gas vehicles are generally believed to produce lower emissions of non-methane hydrocarbons, carbon monoxide, and nitrogen oxides. In California, for a number of years natural gas use has increased due predominantly to expanded power generation and home heating and cooking requirements. Natural gas availability in the state from a wider range of sources is also increasing, and includes the rapid development of natural gas production by horizontal drilling and hydraulic fracturing as well as the potential of liquefied natural gas from the Costa Azul terminal in Baja California, Mexico. Expanding these new sources, coupled with changes in natural gas processing to meet markets for natural gas liquids, could contribute to a wider, more varied composition of natural gas being used in California that could impact the emissions and performance of natural gas vehicles.

Previous studies of interchangeability, or the impacts of changing natural gas composition, have been conducted on small stationary source engines such as compressors, heavy-duty engines, and light-duty natural gas vehicles. Some previous studies have shown that natural gas composition can have an impact on emissions, including studies that have shown increases in oxides of nitrogen emissions with increasing Wobbe number. Wobbe number is defined as the higher heating value of a gas divided by the square root of the specific gravity of the gas with respect to air. The higher the Wobbe Number of the gas, the greater the heating value per volume of gas that will flow through a hole of a given size in a given amount of time.

Project Process

This study evaluated the impacts of changing natural gas composition on emissions and performance for light-duty vehicles. Two natural gas light-duty vehicles were tested using the Federal Test Procedure and the Unified Cycle on a range of four different test gases. The two test vehicles were a SULEV-certified 2006 Honda Civic GX (a super ultra low emission vehicle) and a ULEV-certified 2002 Ford Crown Victoria (an ultra low emission vehicle). The test gases included a baseline gas representative of those typically found in the historical marketplace, an average California Air Resources Board certification gas, a gas with high Wobbe number (1437), and a modified version of this gas blended down to a 1385 Wobbe number. The main properties of the test fuels are provided in Table ES-1. Comparisons between test gases were made for exhaust emissions, fuel economy, and horsepower.

Table ES-1: Main properties of the test fuels

Description	methane	ethane	propane	I-butane	N_2	MN	Wobbe No.	HHV	H/C
Baseline (Pipeline)	96.05	1.79	0.37	0.17	1.62	97	1345	1021	3.94
ARB Certification	90.20	4.04	2.03		3.73	86	1329	1038	3.84
High Wobbe	83.92	9.43	3.79	1.86	1.00	68	1438	1177	3.63
Modified Wobbe	84.03	6.86	3.76	1.85	3.50	68	1385	1131	3.66

Gas composition is reported on a Mole percent basis, MN= Methane Number; Wobbe No. = HHV/square root of the specific gravity of the blend with respect to air; HHV = Higher Heating Value; H/C = ratio of hydrogen to carbon atoms in the hydrocarbon portion of the blend

* Properties evaluated at 60 °F (15.6 °C) and 14.73 psi (101.6 kPa)

Project Results

Overall, the results of the study reveal that for more sophisticated modern light-duty natural gas vehicles, fuel properties still had a clear and direct impact on fuel economy and some emissions components, such as carbon dioxide and non-methane hydrocarbons, but not for other emission components, such as oxides of nitrogen, and carbon monoxide (Table ES-2).

The gases with the higher energy contents, the high Wobbe number and modified 1385 gas, provided better fuel economy on a volumetric basis, some higher power levels, and higher carbon dioxide emissions. On an energy equivalent basis, the fuel economy results showed different trends between the vehicles, with some trends of lower fuel economies for the higher energy gases for the Honda Civic and some trends of improved fuel economy for the higher energy gases for the Ford Crown Victoria. The differences in fuel economy on an energy equivalent basis indicate that there were some slight differences in the engine efficiency for the different test gases. The high Wobbe gas showed a statistically significant 7.5 percent increase in power for the Ford Crown Victoria. The Honda Civic showed a 3.6 percent increase in power for the high Wobbe gas, although this was not statistically significant. Changes in carbon dioxide emissions depended on the fuel, cycle, and vehicle, but, generally, the blends with more higher hydrocarbons, and corresponding lower hydrogen to carbon ratios, had higher carbon dioxide emissions.

The higher energy/Wobbe number gases showed some emissions trends, but these effects depended on the vehicle and driving cycle. Non-methane hydrocarbons emissions were very low in general but did increase for the high Wobbe number and modified 1385 gases for both vehicles. Carbon monoxide emissions were higher for the high Wobbe number and the modified 1385 gases under some test conditions, including the cold-start Federal Testing Procedure (FTP), the cold-start Unified Cycle (UC), and the Federal Testing Procedure weighted for the Honda Civic. Fuel composition did not have as large an impact on carbon monoxide emissions for the Ford Crown Victoria, with only higher carbon monoxide emissions for the high Wobbe number gas for the weighted Unified Cycle. Total hydrocarbons emissions had varying effects for the different vehicles. Total hydrocarbons emissions were highest for the modified gas for the Honda Civic, but these differences were not statistically significant. The

Ford Crown Victoria showed the highest total hydrocarbons emissions for the baseline gas, with the increases compared to the high Wobbe and modified gases being statistically significant. Finally, nitrogen oxides emissions trends varied between the vehicles, with the California Air Resources Board certification fuel having the highest nitrogen oxides emissions for the Honda Civic. For the Ford Crown Victoria, nitrogen oxides emissions were higher for the high Wobbe gas when compared to the baseline natural gas fuel for the Unified Cycle cold-start; however other fuels or cycle combinations did not show this trend.

In comparing the two test vehicles for the emission levels and fuel economy values, the newer technology Honda Civic showed relatively low emissions over the range of conditions evaluated in this study, consistent with its SULEV certification level. The older technology Ford Crown Victoria, however, showed relatively high nitrogen oxides emissions that were well above its certification levels. Some further testing of older technology NGVs might be warranted to further evaluate whether these vehicles maintain their performance levels over the life of the vehicle, although at the same time such vehicles will also continue to be a relatively small and declining fraction of the in-use fleet.

Table ES-2. Trends in Emissions and Performance for the Two Test Vehicles Compared with the Baseline Natural Gas.

		Honda Civic		Ford Crown Victoria	
		FTP	**UC**	**FTP**	**UC**
Fuel Economy	ARB Certification	+1.3	NS	+3.3	+3.9
Volumetric Basis	High Wobbe	+14.5	+11.3	+18	+16
	Modified Wobbe	+6.7	+10.4	+12	+14
Fuel Economy	ARB Certification	NS	-1.2	NS	NS
Energy Equiv. Basis	High Wobbe	NS	-3.9	+2.1	NS
	Modified Wobbe	-4.0	NS	NS	NS
Carbon Dioxide	ARB Certification	+1.6	+2.3	NS	NS
	High Wobbe	+4.8	+7.8	+1.6	+3.0
	Modified Wobbe	+7.6	+4.0	+2.3	NS
Nitrogen Oxides	ARB Certification	+136	NS	NS	NS
	High Wobbe	NS	NS	NS	NS
	Modified Wobbe	NS	NS	NS	NS
Carbon Monoxide	ARB Certification	NS	NS	NS	NS
	High Wobbe	+22	NS	NS	+12.6
	Modified Wobbe	+74	NS	NS	NS
Total Hydrocarbon	ARB Certification	NS	NS	NS	NS
	High Wobbe	NS	NS	-23	-29
	Modified Wobbe	NS	NS	-23	-33
Non-methane Hydrocarbon	ARB Certification	NS	NS	+99	NS
	High Wobbe	NS	+395	+261	+284
	Modified Wobbe	+2769	+656	+230	+304
		HP Test		HP Test	
Power	ARB Certification	NS		NS	
	High Wobbe	NS		+7.5	
	Modified Wobbe	NS		NS	

The numbers represent the percentage increase (+) or percentage decrease (-) for statistically significant differences; NS = no statistically significant differences; Results are considered to be statistically significant for p values ≤ 0.05 and marginally statistically significant for 0.05 <p-values ≤ 0.1, so that the probability that the compared fuel economy and emissions are the same is less than or equal to 5 percent or 5-10 percent, respectively.

Benefits for California

The results of this study provide important information about the potential impacts of bringing a broader range of natural gas with varying compositions into California. This will ensure that that bringing a broader range of energy sources into the state will not have unintended environmental and air quality impacts. These results can also be used to determine the final properties of the gas that would be needed for new natural gas sources to provide adequate performance in vehicles.

CHAPTER 1: Introduction

Natural gas (NG) is a potential alternative to conventional liquid fuels for use in automotive internal combustion engines. Natural Gas Vehicles (NGVs) are generally believed to produce lower emissions of non-methane hydrocarbons (NMHC), carbon monoxide (CO), and oxides of nitrogen (NOx) (Ma et al. 2007; Hesterberg, Lapin, and Bunn 2008; Zarante and Sodre 2009). NGVs have been implemented in a variety of applications as part of efforts to improve urban air quality, particularly within California. These vehicles are predominantly implemented in fleet applications, because travel is relatively centralized and a large refueling infrastructure is not needed. Light duty vehicles compose a significant portion of this vehicle population and also have some penetration into the private users market.

In California, natural gas use has been increasing for a number of years, predominantly from expanded power and home heating needs. As the demand for NG continues to grow, a wider range of sources will be needed to meet demand. It is also anticipated that liquefied natural gas (LNG) use globally and within California will increase over time. Global trade of LNG increased by 7.4 percent per year from 1995 to 2005, and a study by Jensen Associates estimated that LNG global trade would increase by approximately 6.7 percent per year from 2005 to 2020 under a base case scenario (Jensen Associates 2007). California currently supplies 85-90 percent of its needs with NG imported domestically from the Rockies and other southwest states such as Texas, and Canada. With the Costa Azul LNG terminal in Baja California, Mexico, it is likely that the portion of NG used from imported sources, such as the Pacific Rim, will increase, especially for regions in the southern part of the state. This new source of NG will likely differ in composition from that currently being used in the state. As new producing fields are developed in the western United States, the composition of imported domestic NG supplies could also change in the future. Additionally, some local sources of natural gas within the state have compositions that are considerably different from those throughout the rest of the State. Specifically, these sources have higher Wobbe numbers and lower methane numbers.

It is important to understand how gas composition changes might impact the performance or emissions of a NG vehicle or engine. The California Air Resources Board (CARB) is currently in amending standards for NG that can be used as a fuel in transportation applications (California Air Resources Board). Information on the impact of changing NG composition on performance and emissions can be used for regulatory development, to ensure new NG compositions do not have an adverse impact on air quality, and to evaluate the viability of using a broader mixture of NG blends in transportation applications. Several studies of interchangeability, or the impacts of changing NG composition, have been conducted in the past (Feist 2006; Feist 2003; J. Gutierrez, Hamze, and Mak 2006; J. H. Gutierrez, Saldivar, and Mora 2003). This includes the studies of NG composition effect in small stationary source engines, such as compressors, and in heavy-duty engines. These studies have shown that NG composition can have an impact on emissions. Emissions of NOx, for example, were found to increase with increasing Wobbe number in several of these studies. Studies of the impacts of NG composition on light-duty

vehicles (LDVs) have been fairly limited, with one study recently being conducted by the Southern California Gas Company at Southwest Research (SwRI). Several other older studies of LDVs have also been conducted, but many of these are from other countries and with older technology vehicles (Lee and Kim 2000; Matthews, Chiu, and Hilden 1996; Elder, Jones, and Taine 1985).

This study evaluated the impact of NG composition on the performance and emissions of light-duty vehicles. For this study, two NG LDVs were tested using the Federal Test Procedure (FTP) and the Unified Cycle (UC) on a range of four different test gases. The test gases included gases representative of those typically found in the marketplace and used for certification purposes and other gases with higher Wobbe numbers that might provide insight into the impact of a wider range of compositions. This report discusses the results of the testing for the LDVs and is part of the larger program that included the testing of heavy-duty vehicles on a chassis dynamometer, discussed in the report, *Evaluation of the Performance and Air Pollutant Emissions of Vehicles Operating on Various Natural Gas Blends – Heavy-Duty Vehicle Testing.*

CHAPTER 2:
Experimental Procedures

2.1 Test Fuels

Four different natural gas fuel blends were employed in this work. The first gas is representative of a typical southern California pipeline gas, and serves as the baseline fuel. It is identified as the Baseline gas. The second fuel is designed to be representative of the fuels used for ARB Certification, and is based on an average of fuels used for that application. This fuel is identified as the ARB Certification gas. The third fuel is a blend with a high Wobbe number that is representative of a 'hotter' gas that could be grandfathered into the marketplace in certain local regions within California or from liquefied natural gas from the Costa Azul LNG terminal in Baja California, Mexico. It is identified as the High Wobbe gas. The fourth fuel was formulated to be similar to the high Wobbe number third fuel, but it was blended with nitrogen gas (N2) to bring the Wobbe number down to 1385 while maintaining a methane number near 70. The 1385 Wobbe Number corresponds to the maximum value that can be used in the statewide gas pipeline system, as set by the California Public Utilities Commission. This fuel is identified as Modified Wobbe gas. It should be mentioned that the High Wobbe and Modified Wobbe gases were included to reflect some of the in state California gas production that can be potentially delivered unblended to compressed natural gas (CNG) refueling stations. However, at present time, the High Wobbe and Modified Wobbe gases are not reflective of most domestic NG received in California. The test fuels are presented in Table 2-1.

Table 2-1: Main properties of the test fuels

Description	methane	ethane	propane	I-butane	N_2	MN	Wobbe No.	HHV	H/C
Baseline (Pipeline)	96.05	1.79	0.37	0.17	1.62	97	1345	1021	3.94
ARB Certification	90.20	4.04	2.03		3.73	86	1329	1038	3.84
High Wobbe	83.92	9.43	3.79	1.86	1.00	68	1438	1177	3.63
Modified Wobbe	84.03	6.86	3.76	1.85	3.50	68	1385	1131	3.66

MN_{AGA}= Methane Number determined via American Gas Association calculations; Wobbe No. = HHV/square root of the specific gravity of the blend with respect to air; HHV = Higher Heating Value; H/C = ratio of hydrogen to carbon atoms in the hydrocarbon portion of the blend

* Properties evaluated at 60 °F (15.6 °C) and 14.73 psi (101.6 kPa)

2.2 Test Vehicles

Two test vehicles were utilized for this program. One vehicle was a 2006 SULEV-certified Honda Civic GX (a super ultra low emission vehicle). This represents a newer light-duty NGV technology and this vehicle is the only original equipment manufacturer (OEM) CNG vehicle that is presently being produced. The second vehicle was a ULEV-certified, 2002 OEM Ford Crown Victoria (an ultra low emission vehicle). This vehicle represents an older vehicle

technology. All vehicles acquired for testing were inspected to ensure that they are in sound mechanical and operational condition using a standard checklist.

It should be noted that three Ford Crown Victoria vehicles were tested prior to the selection of the final test vehicle. All of the Ford Crown Victoria vehicles were found to have NOx emissions multiple times higher than the standard, as shown in Table 2-2. The final Ford Crown Victoria selected for testing had the lowest NOx emissions of the vehicles that were evaluated and appeared to be the most representative of a vehicle in proper working condition. It should be noted that a Smog Check Test was also conducted on each of the three Ford Crown Victorias. While Candidate Vehicle #1 failed the Smog Check, both Candidate vehicle #2 and the final selected test vehicle passed the Smog Check test.

Table 2-2: Emissions Comparisons between Different Candidate Ford Crown Victorias and the Certification Standard.

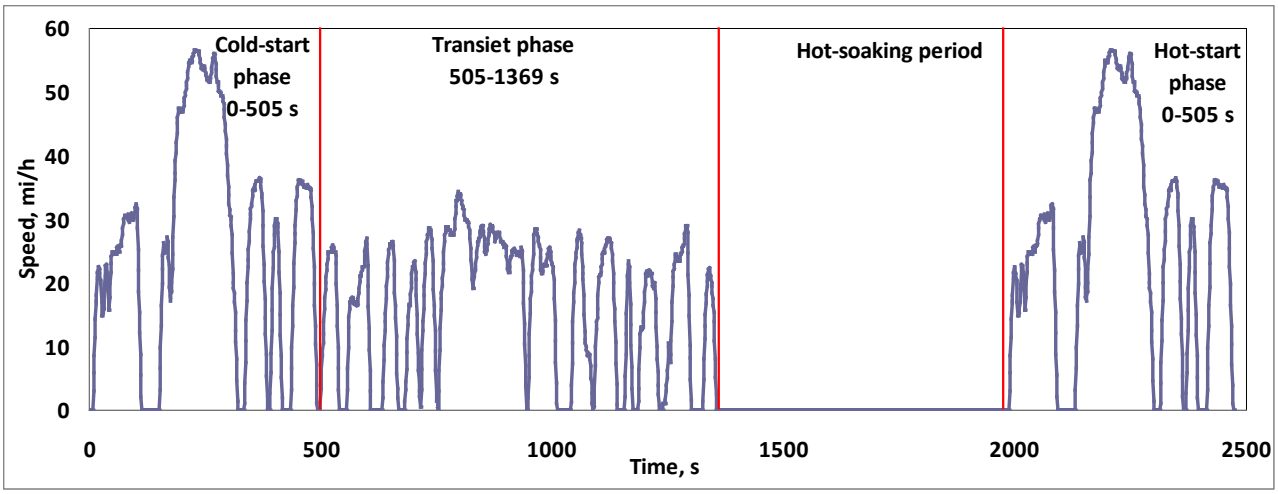
	THC g/mi	NMHC g/mi	CO g/mi	NO_x g/mi	CO_2 g/mi
Certification Standard		0.055	2.1	0.030	
Test Vehicle Selected	0.259	-0.012	0.271	0.193	334
Candidate Vehicle #1	1.066	-0.039	2.071	0.846	331
Candidate Vehicle #2	0.347	-0.013	0.491	0.383	347

2.3 Test Cycles

Each vehicle was tested on each fuel over three Federal Test Procedure (FTP) and three Unified Cycle (UC) tests. These six tests were conducted sequentially on a particular fuel. Once the vehicle was changed to operate on that fuel, the fuel was not changed to another fuel during this time. The vehicles were preconditioned over a single iteration of the first two segments of the FTP on each new fuel prior to beginning the testing on that fuel.

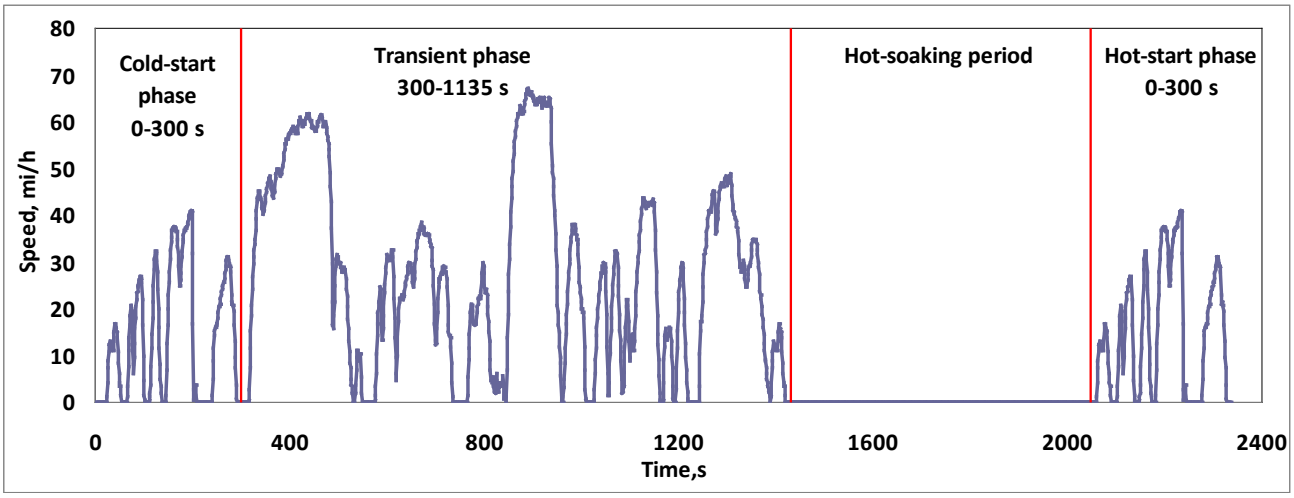
The FTP is the primary emission certification cycle for light-duty vehicles in the United States (US). The FTP cycle consists of three segments or bags representing a cold start phase, a transient phase, and a hot start phase. The cycle covers a total distance of 11.04 miles with an average speed of 21.2 mph. A speed-time trace for the FTP is provided in Figure 2-1. The vehicle is turned off for a period of 10 minutes at the conclusion of the transient phase and prior to starting the hot start phase.

Figure 2-1: FTP Cycle



The Unified Cycle (UC), shown in Figure 2-2, is a dynamometer driving schedule for light-duty vehicles that was developed by the California Air Resources Board). The UC test has three segments or three-bag structure, similar to the FTP, but it is a more aggressive driving cycle. It has a higher average speed, higher acceleration rates, fewer stops per mile, and less idle time. The UC test is run in the following manner: the cold-start phase (Bag 1) and transient phase (Bag 2) are run consecutively, followed by a ten minute hot soak, and then the hot-start phase (Bag 3), which has the same speed-time trace as Bag 1, is run.

Figure 2-2: Unified Cycle



The emissions from the individual bags for the FTP cycle are generally weighted to provide an overall emission rate for the cycle as a whole. The equation used to determine the FTP weighted emission rates is provided in equation 2-1. Overall cycle emissions for this report for the UC cycle were calculated using the same weighting as for the FTP, but using the actual mileage and emission rates from the individual UC bags.

$$Y_{wm} = 0.43\left(\frac{Y_{ct} + Y_s}{D_{ct} + D_s}\right) + 0.57\left(\frac{Y_{ht} + Y_s}{D_{ht} + D_s}\right) \quad \text{(Eq. 2-1)}$$

Where:

Y_{wm} = Weighted mass emissions of each pollutant (i.e., HC, CO, CO_2, NO_x, etc.) in grams per vehicle.

Y_{ct} = Mass emissions as calculated from the "transient" phase of the cold-start test, in grams per test phase.

Y_{ht} = Mass emissions as calculated from the "transient" phase of the hot-start test, in grams per test phase.

Y_s = Mass emissions as calculated from the "stabilized" phase of the cold-start test, in grams per test phase.

D_{ct} = The measured driving distance from the "transient" phase of the cold-start test, in miles.

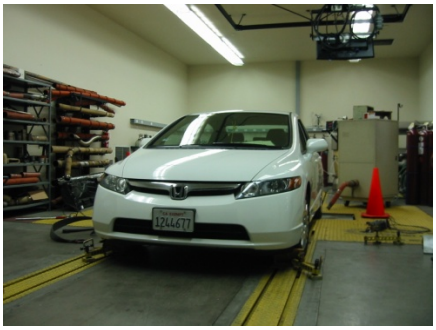
D_{ht} = The measured driving distance from the "transient" phase of the hot-start test, in miles.

D_s = The measured

2.4 Emissions Testing and Measurements

All tests were conducted in College of Engineering-Center for Environmental Research and Technology, University of California, Riverside Vehicle Emissions Research Laboratory equipped with a Burke E. Porter 48-inch single-roll electric dynamometer. For these tests, standard bag measurements were obtained for total hydrocarbons (THC), NMHC, CO, NOx and carbon dioxide (CO2). A separate analyzer was used to characterize methane (CH4) for the determination of the NMHC. Bag measurements were made with a Pierburg AMA-4000 bench. A photo of a typical vehicle set up on the chassis dynamometer is provided in Figure 2-3

Figure 2-3. Typical Setup of Test Vehicles on the Chassis Dynamometer



2.5 Power Curves

Power curves for each vehicle were conducted on a horsepower dynamometer at the Westech Performance Group in Mira Loma, California. The horsepower was determined in 500 revolutions per minute (RPM) increments from the lowest to the highest power levels for each vehicle. Two full power curves were performed for each vehicle on each fuel.

CHAPTER 3:
Light-Duty Vehicle Chassis Dynamometer Testing Results

The emissions results are presented in the following section. The figures for each emissions component show the results for each vehicle/fuel/cycle combination based on the average of tests conducted on that particular test combination. The figures show both the cold-start, or Bag 1 emissions, and the weighted emissions for each cycle. The error bars on the figures are the standard deviation over all tests for each test combination. The results for all emissions tests on the two test vehicles are provided in Appendix A.

3.1 Fuel Economy and CO_2 Emissions

The fuel economy results for all fuel/cycle combinations are presented in Figure 3-1, on a miles per volume of gas basis, and Figure 3-2, on a miles per equivalent energy basis based on the energy in a gallon of gasoline. Raw data for the weighted fuel economy, the percentage differences, and statistical analysis t-test values for the cold-start and weighted FTP and UC for both vehicles are shown in Table 3-1 for the fuel economy on a volumetric basis and Table 3-2 for the fuel economy on an energy equivalent basis, respectively. The percentage differences are all relative to the baseline NG. The statistical analyses were all comparisons relative to the baseline NG using a 2-tailed, 2 sample, equal variance t-test. For the discussion in this report, results are considered to be statistically significant for p values $\leqslant 0.10$, meaning that the probability that the compared emissions are the same is less than or equal to 10 percent.

Fuel economy on a volumetric basis is probably the most important to the NG consumer, since fuel is distributed on a volumetric basis. On a volumetric basis, the High Wobbe and Modified Wobbe gases showed higher fuel economy than the Baseline and ARB Certification gases for both the FTP and the UC cycles for both vehicles. This was due to the higher energy content of both of these fuel blends when compared to the other test gases. There is also an improvement in the fuel economy for the ARB Certification gas compared to the Baseline gas for all fuel/cycle combinations for the Ford Crown Victoria, and for the FTP for the Honda Civic. This can also be attributed to the higher energy content of the ARB Certification gas compared to the Baseline gas, although the differences are much smaller than for the High Wobbe or Modified Wobbe gases. For comparison, the High Wobbe, Modified Wobbe, and ARB Certification gases had energy contents that were 15 percent, 11 percent, and 2 percent higher than the Baseline gas, respectively.

Figure 3-1: Average fuel economy for all fuel/cycle combinations on a volumetric basis

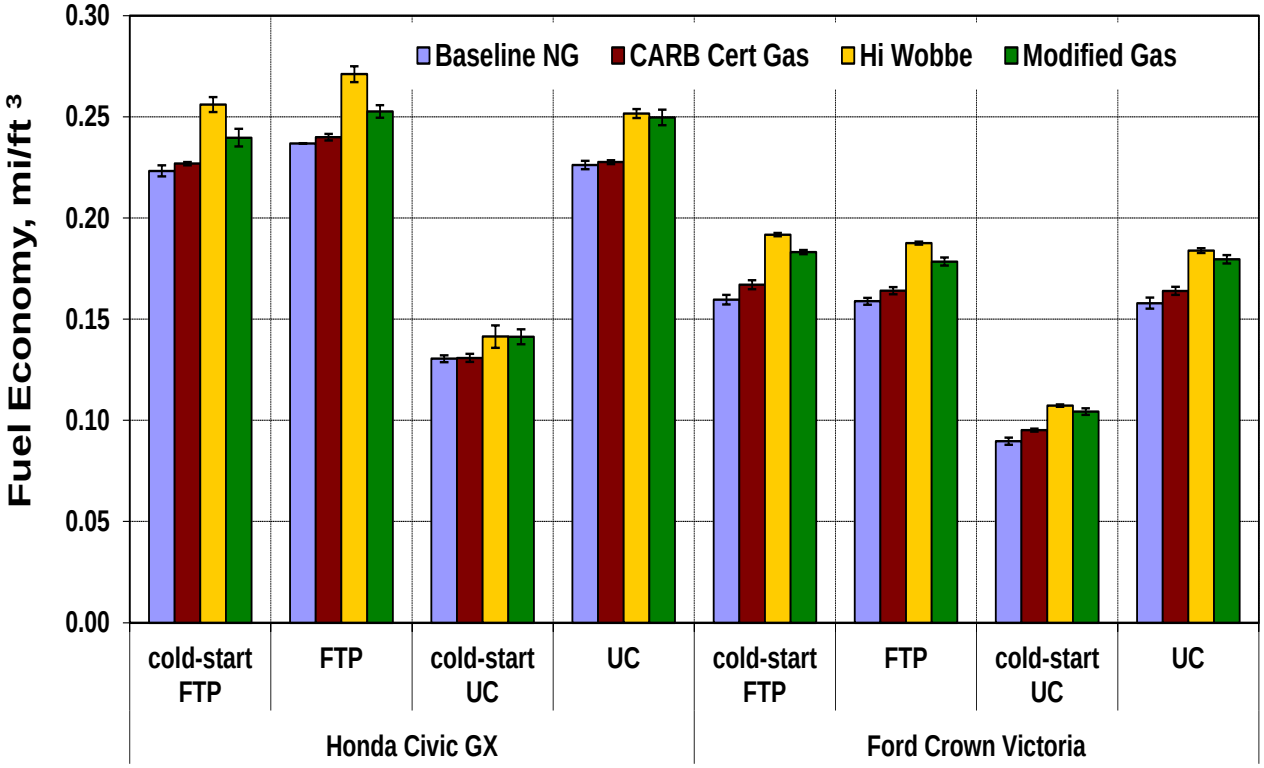


Table 3-1: Average values, Percent differences, and t-test values for fuel economy on a volumetric basis*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted Fuel Economy	Baseline NG	0.223	0.237	0.130	0.226
	ARB Certification	0.227	0.240	0.131	0.228
	High Wobbe	0.256	0.271	0.141	0.252
	Modified Wobbe	0.240	0.253	0.141	0.250
% Difference	ARB Certification	+1.6	+1.3	+0.3	+0.6
	High Wobbe	+14.7	+14.5	+8.4	+11.3
	Modified Wobbe	+7.3	+6.7	+8.3	+10.4
P-value	ARB Certification	0.098	0.031	0.772	0.321
	High Wobbe	0.000	0.000	0.012	0.000
	Modified Wobbe	0.005	0.001	0.003	0.000
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted Fuel Economy	Baseline NG	0.160	0.159	0.090	0.158
	ARB Certification	0.167	0.164	0.095	0.164
	High Wobbe	0.192	0.188	0.107	0.184
	Modified Wobbe	0.183	0.178	0.104	0.180
% Difference	ARB Certification	+4.6	+3.3	+6.1	+3.9
	High Wobbe	+20	+18	+20	+16
	Modified Wobbe	+15	+12	+16	+14
P-value	ARB Certification	0.017	0.019	0.007	0.036
	High Wobbe	0.000	0.000	0.000	0.000
	Modified Wobbe	0.000	0.000	0.000	0.000

* highlighted percentage differences are statistically or marginally statistically significant

It is also useful to look at fuel economy on an energy equivalent basis, since there might be differences in the engine efficiency on different fuels. For the Honda Civic, there was a statistically significant reduction in fuel economy on an energy equivalent basis for the

Modified Wobbe gas over the FTP and for the High Wobbe gas over the UC compared to the Baseline gas. The Ford Crown Victoria showed statistically significant improvements in fuel economy on an energy equivalent basis for the ARB Certification gas, the High Wobbe gas, and the Modified Wobbe gas for the cold start portions of both the FTP and UC. Statistically significant improvements in fuel economy on an energy equivalent basis for the Ford Crown Victoria were also found for the High Wobbe gas over the FTP and for the Modified Wobbe gas over the UC compared with the Baseline gas. It is worth noting that if the engines were optimized for the different blends, the blends with the higher methane numbers would enable higher compression ratios, which would translate to higher efficiency and correspondingly better energy equivalent fuel economy (Malenshek, M. and Olsen 2009; Bach 2008).

Figure 3-2: Average fuel economy for all fuel/cycle combinations on a gasoline energy equivalent basis

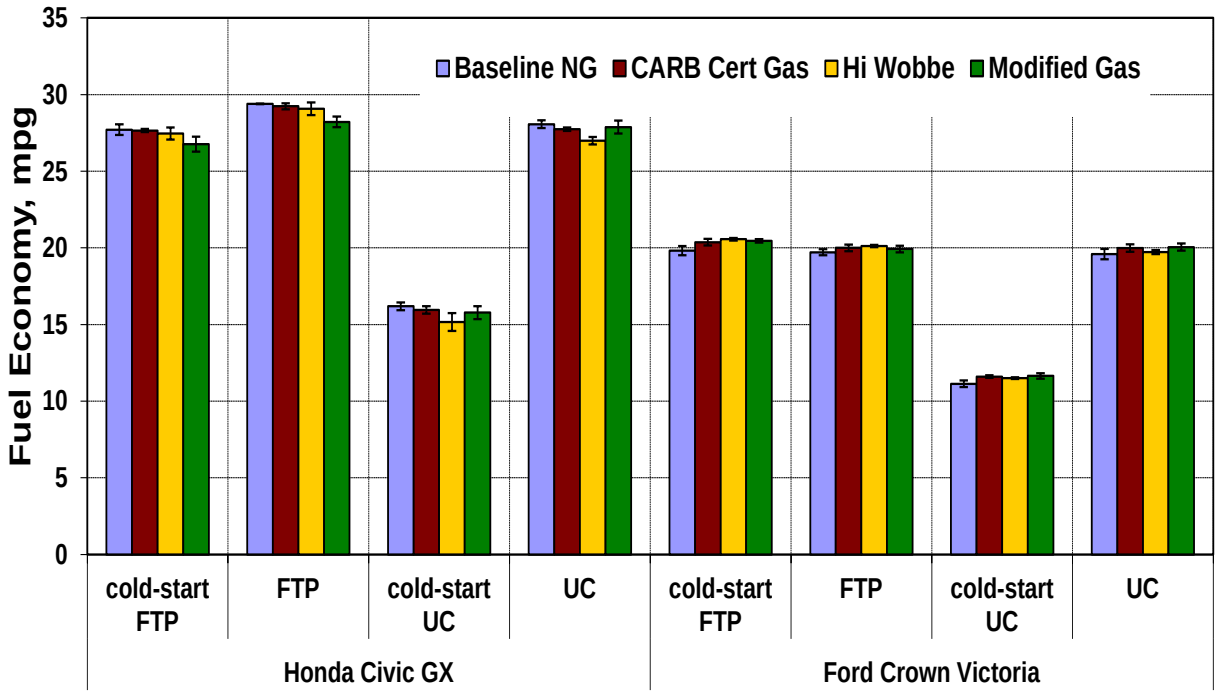


Table 3-2: Average values, Percent differences, and t-test values for energy equivalent fuel economy**

Honda Civic GX					
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted Fuel Economy (mi/ee gal.)*	Baseline NG	27.7	29.4	16.2	28.1
	ARB Certification	27.7	29.2	16.0	27.7
	High Wobbe	27.5	29.1	15.2	27.0
	Modified Wobbe	26.8	28.2	15.8	27.9
% Difference	ARB Certification	-0.2%	-0.5%	-1.5%	-1.2%
	High Wobbe	-0.9%	-1.1%	-6.3%	-3.9%
	Modified Wobbe	-3.4%	-4.0%	-2.6%	-0.7%
P-value	ARB Certification	0.792	0.253	0.218	0.098
	High Wobbe	0.458	0.258	0.021	0.002
	Modified Wobbe	0.051	0.004	0.139	0.484
Ford Crown Victoria					
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted Fuel Economy (mi/ee gal.)*	Baseline NG	19.8	19.7	11.1	19.6
	ARB Certification	20.4	20.0	11.6	20.0
	High Wobbe	20.6	20.1	11.5	19.7
	Modified Wobbe	20.5	19.9	11.6	20.0
% Difference	ARB Certification	+2.8%	+1.5%	+4.2%	+2.0%
	High Wobbe	+3.8%	+2.1%	+3.4%	+0.6%
	Modified Wobbe	+3.2%	+1.1%	+4.6%	+2.3%
P-value	ARB Certification	0.076	0.577	0.025	0.780
	High Wobbe	0.013	0.096	0.044	0.680
	Modified Wobbe	0.025	0.865	0.034	0.414

*mi/ee gal.= miles per energy equivalent gasoline gallon
** highlighted percentage differences are statistically or marginally statistically significant

CO2 emissions for all vehicle/fuel/cycle combinations are shown in Figure 3-3, while Table 3-3 presents the emission CO2 averages, percentage differences, and t-test data. As expected, the Honda Civic emitted lower levels of CO2 emissions than the Ford Crown Victoria, consistent with the Honda's higher fuel economy. CO2 emissions for the Honda Civic for the High Wobbe and Modified Wobbe gases were generally higher than those for the ARB Certification and Baseline gases. For the FTP and UC weighted emissions, these increases in CO2 were statistically significant at the 90 percent confidence level for the Honda Civic. For the Ford Crown Victoria statistically significant increases in CO2 emissions were found for High and Modified Wobbe over FTP cycle and High Wobbe for UC cycle. The ARB Certification gas also showed statistically significant increases in CO2 emissions compared to the Baseline gas for the FTP and UC weighted emissions for the Honda Civic, but for the Ford Crown Victoria these two gases were comparable. Statistically significant differences between the High Wobbe, and Modified Wobbe were also found for the Honda Civic for the cold-start phase, but not for the cold-start phase for the Ford Crown Victoria. In general, the blends with higher hydrocarbons, and corresponding lower H/C ratios, as shown in Table 2-1, had higher CO2 emissions. It is worthy to note that CO2 emissions were considerably higher during the cold-start phase of the UC cycle for the Honda Civic, which could be due to the shorter, more transient nature of this phase, or a drop in engine efficiency during cold start.

Figure 3-3: Average CO2 emissions for Honda Civic GX and Ford Crown Victoria

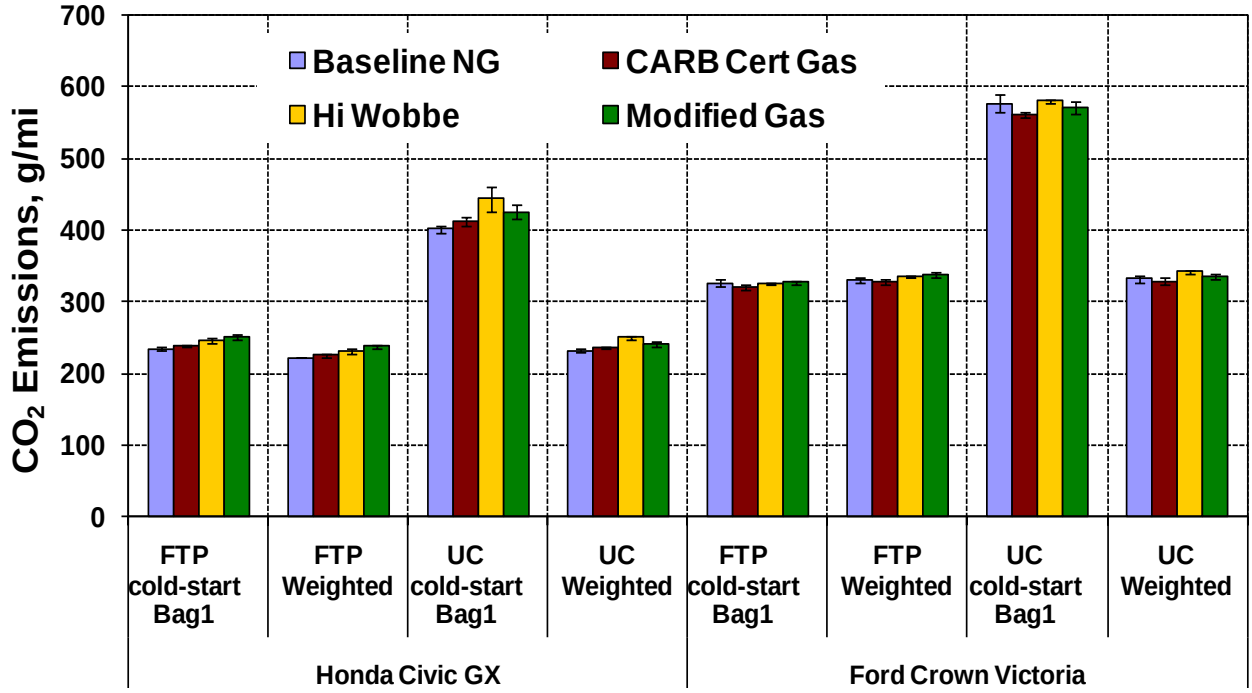


Table 3-3: Average values, Percent differences, and t-test values for CO_2 emissions*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (CO_2 g/mi)	Baseline NG	235	222	402	232
	ARB Certification	238	226	413	238
	High Wobbe	246	233	444	250
	Modified Wobbe	251	239	426	242
% Difference	ARB Certification	+1.3	+1.6	+2.6	+2.3
	High Wobbe	+4.5	+4.8	+10.4	+7.8
	Modified Wobbe	+6.8	+7.6	+5.8	+4.0
P-value	ARB Certification	0.163	0.016	0.062	0.011
	High Wobbe	0.016	0.005	0.005	0.000
	Modified Wobbe	0.007	0.000	0.010	0.007
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (CO_2 g/mi)	Baseline NG	327	330	577	332
	ARB Certification	321	329	561	329
	High Wobbe	327	335	581	342
	Modified Wobbe	328	338	572	336
% Difference	ARB Certification	-1.7	-0.4	-2.8	-0.9
	High Wobbe	-0.1	+1.6	+0.6	+3.0
	Modified Wobbe	+0.3	+2.3	-1.0	+1.0
P-value	ARB Certification	0.197	0.665	0.114	0.509
	High Wobbe	0.954	0.069	0.673	0.051
	Modified Wobbe	0.788	0.061	0.569	0.437

* highlighted percentage differences are statistically or marginally statistically significant

3.2 NO_x Emissions

Emissions of NOx are shown in Figure 3-4 for all vehicle/fuel/cycle combinations, while Table 3-4 shows the average NOx emissions, percentage differences, and t-test data. NOx emission levels with the Honda Civic were found to be significantly lower than those of the Ford Crown

Victoria. This is consistent with the difference in certification standards for the vehicles. The NOx emissions for the Ford Crown Victoria were also several times higher than its certification standard. As discussed above, preliminary tests were also conducted on two other Ford Crown Victorias. These vehicles showed higher NOx emissions compared to the vehicle actually tested. A real-time plot of the NOx emissions for the Ford Crown Victoria is provided in Figure 3 5. These data show consistently elevated NOx emissions during accelerations, even after the cold-start phase. The strong presence of emissions after the cold start phase is important, because at ambient temperatures and as the temperature in the catalyst ramps up, the catalyst reactions have a very low efficiency for eliminating exhaust pollutants. At the point where the temperature is sufficiently high to provide 50 percent efficiency on the catalyst reactions, the catalyst is considered to have reached its "light-off" temperature and it quickly rises to its typical operating efficiency. This light-off temperature is usually between 200-300°C, and is reached within the first few minutes of the cold start phase. Since the catalyst is largely inactive before the light-off temperature is reached, a large share of the overall cycle emissions are produced during this part of the cycle. Hence, the presence of significant emissions at points of the cycle where the catalyst should be well above the light-off temperature indicates an issue with the catalyst's effectiveness, poor control of the air-fuel ratio, or some other issue. Supplementary investigations by ARB did show that replacing the catalyst with a new catalyst reduced NOx emissions to below certification levels. The investigations at ARB also showed indications of a rough idle and misfires.

Figure 3-4: Average NO_x emissions for Honda Civic GX and Ford Crown Victoria

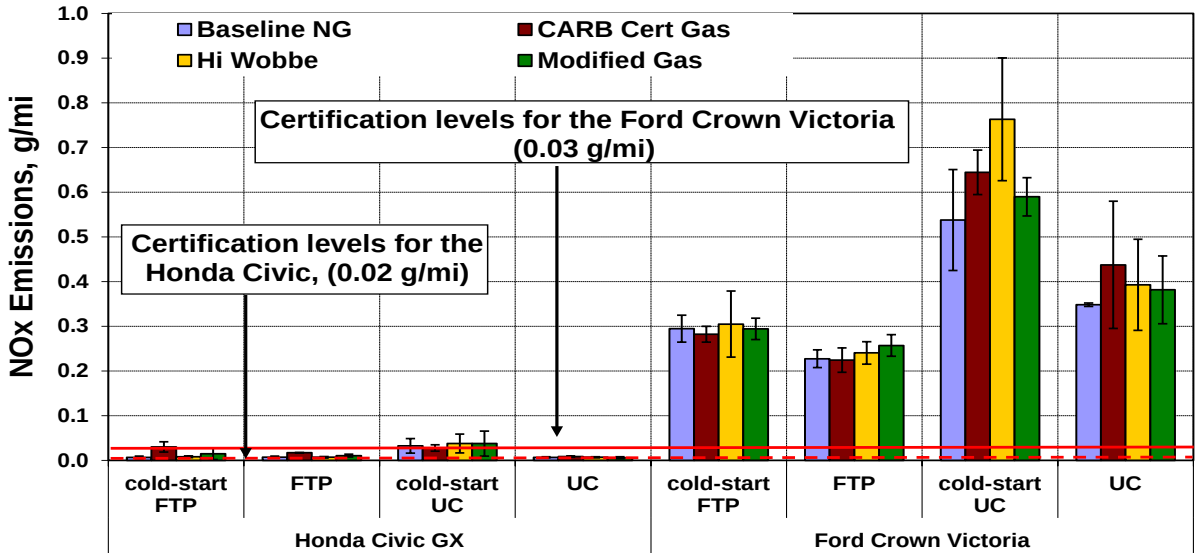
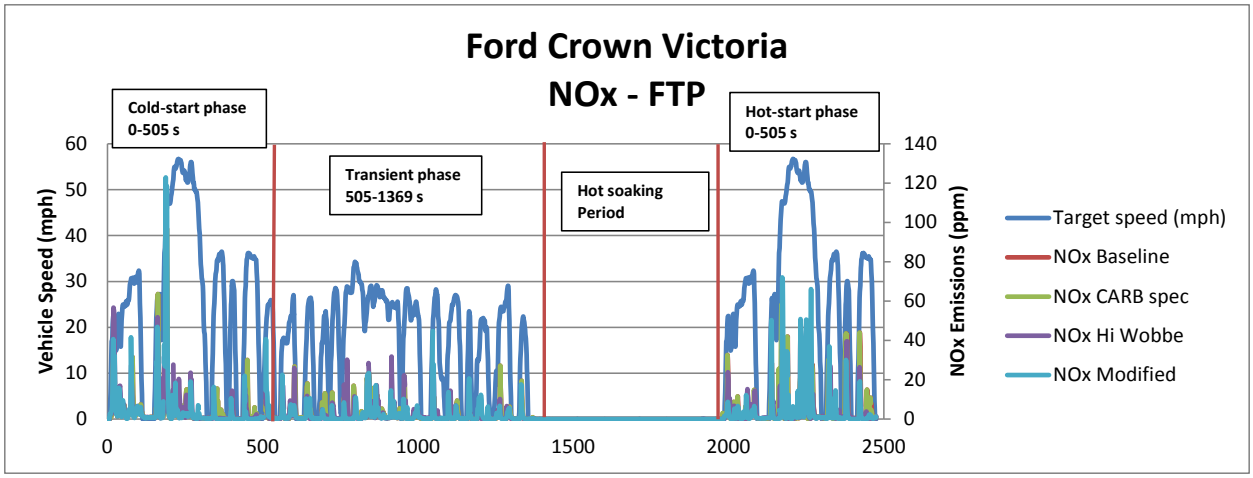


Table 3-4: Average values, Percent differences, and t-test values for NOx emissions*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (NO_x g/mi)	Baseline NG	0.006	0.007	0.032	0.007
	ARB Certification	0.030	0.017	0.028	0.008
	High Wobbe	0.008	0.007	0.038	0.007
	Modified Wobbe	0.015	0.011	0.041	0.006
% Difference	ARB Certification	+375	+136	-14	+27
	High Wobbe	+24	-5.9	+17	+2.0
	Modified Wobbe	+134	+47	+28	-15
P-values	ARB Certification	0.025	0.001	0.671	0.109
	High Wobbe	0.527	0.789	0.713	0.888
	Modified Wobbe	0.323	0.127	0.632	0.789
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (NO_x g/mi)	Baseline NG	0.294	0.227	0.538	0.348
	ARB Certification	0.282	0.224	0.644	0.437
	High Wobbe	0.305	0.240	0.763	0.393
	Modified Wobbe	0.294	0.257	0.590	0.381
% Difference	ARB Certification	-4.2	-1.4	+20	+26
	High Wobbe	+3.5	+5.7	+42	+13
	Modified Wobbe	-0.2	+13.0	+9.7	+9.6
P-values	ARB Certification	0.569	0.876	0.208	0.339
	High Wobbe	0.836	0.521	0.093	0.490
	Modified Wobbe	0.984	0.179	0.497	0.489

* highlighted percentage differences are statistically or marginally statistically significant

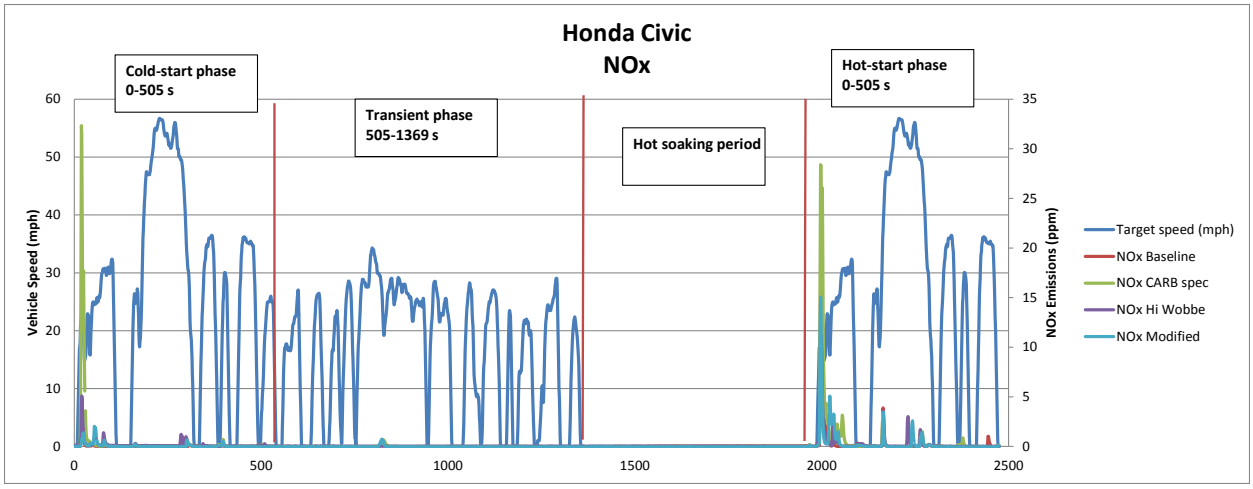
Figure 3-5. Real-Time NO_x Emissions for the Ford Crown Victoria over the FTP



Varying fuel composition had some impacts on NOx emissions, although the effects were different for the two vehicles. For the Honda Civic, the NOx emissions for the ARB Certification gas showed statistically significant increases compared to the other fuels over the FTP. The ARB Certification gas also showed slightly higher NOx emissions for the UC, but these increases were not statistically significant. Real-time NOx emissions data, as shown in Figure 3-6, show that NOx is emitted also entirely under start up conditions for the Honda Civic and shows the higher NOx for the ARB Certification gasduring that period. For the Ford Crown Victoria, statistically significant increases in NOx emissions were found for the High Wobbe gas compared to the Baseline gas for the cold-start for the UC, but not for other fuel or cycle combinations. The higher NOx emissions for the High Wobbe gas could be attributed to the increase in heavier hydrocarbons, such as ethane, propane, and butane in the fuel composition, which can cause higher adiabatic flame temperatures and thus higher thermal NOx (Naber et al. 1994; McTaggart et al. 2010).

In nearly all cases, cold-start emissions were higher than those of the weighted emissions as a result of the poor efficiency of the three-way catalyst (TWC) before the light-off temperature is reached.

Figure 3-6. Real-Time NO_x Emissions for the Honda Civic GX over the FTP.



3.3 CO Emissions

Weighted CO emissions were relatively low, with similar levels for both test vehicles, as shown in Figure 3-7. Table 3-5 shows the average CO emissions, percentage differences, and t-test data. The FTP and UC cold-start emissions for the Ford Crown Victoria vehicle were significantly higher than those emitted for the Honda Civic. This can be attributed to improvements in vehicle and catalyst technology, cold-start strategies, and/or differences in deterioration.

The effect of fuel composition on CO emissions differed between the two vehicles. Fuel composition effects were particularly noticeable for the Honda Civic. Fuels with higher levels of heavier hydrocarbon and lower methane numbers (MN), i.e., the High Wobbe number and Modified Wobbe gases, produced statistically significant increases in CO emissions compared to the Baseline NG for the cold-start FTP, the weighted FTP, and for the High Wobbe Number gas for the cold-start UC. For the Ford Crown Victoria, the fuels did not show significant differences over the FTP. Over the UC for the Ford Crown Victoria, the ARB Certification gas had the lowest CO emissions of any of the test gases for the cold-start and the High Wobbe gas showed a statistically significant increase in CO emissions compared to the Baseline gas for the weighted UC.

Figure 3-7: Average CO emissions for Honda Civic GX and Ford Crown Victoria

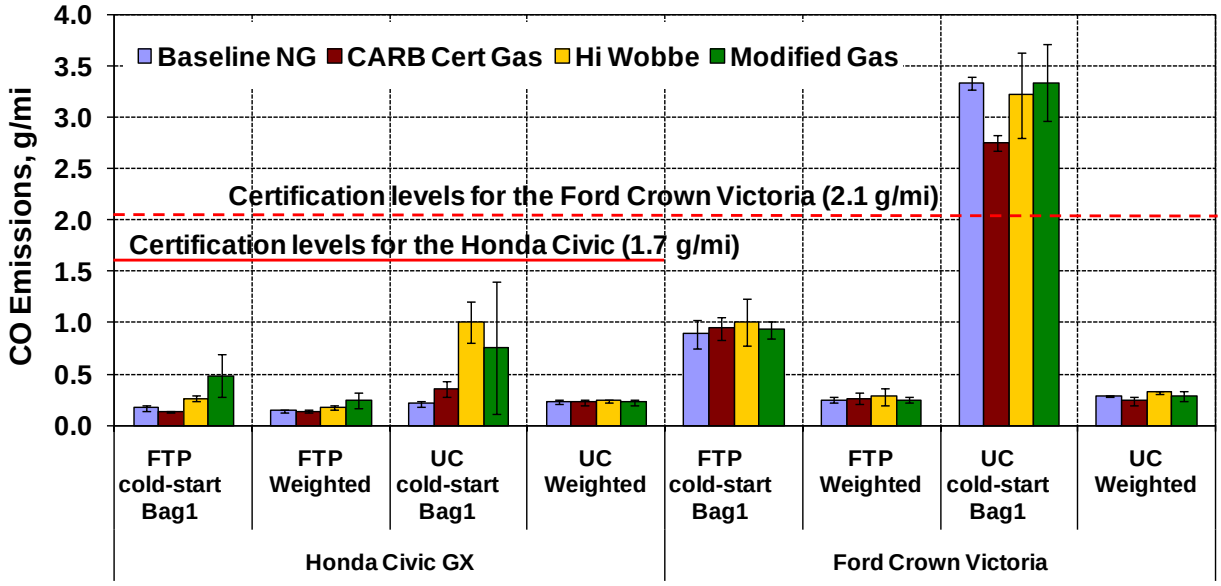


Table 3-5: Average values, Percent differences, and t-test values for CO emissions*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (CO g/mi)	Baseline NG	0.169	0.140	0.212	0.231
	ARB Certification	0.131	0.140	0.354	0.224
	High Wobbe	0.262	0.171	1.004	0.240
	Modified Wobbe	0.483	0.245	0.755	0.227
% Difference	ARB Certification	-23	-0.2	+67	-2.9
	High Wobbe	+55	+22	+374	+4.1
	Modified Wobbe	+185	+74	+256	-1.7
P-values	ARB Certification	0.118	0.979	0.013	0.753
	High Wobbe	0.018	0.066	0.000	0.589
	Modified Wobbe	0.063	0.074	0.144	0.856
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (CO g/mi)	Baseline NG	0.889	0.251	3.334	0.286
	ARB Certification	0.945	0.261	2.753	0.243
	High Wobbe	1.004	0.281	3.218	0.322
	Modified Wobbe	0.935	0.250	3.338	0.285
% Difference	ARB Certification	+6.3	+4.0	-17	-15
	High Wobbe	+12.9	+12.0	-3.5	+12.6
	Modified Wobbe	+5.1	-0.1	+0.1	-0.1
P-values	ARB Certification	0.613	0.791	0.001	0.141
	High Wobbe	0.496	0.570	0.661	0.038
	Modified Wobbe	0.645	0.994	0.986	0.988

* highlighted percentage differences are statistically or marginally statistically significant

3.4 THC Emissions

Figure 3-8 shows the THC emissions for all fuel/vehicle/cycle combinations, while Table 3-6 shows the average THC emissions, percentage differences, and t-test data. THC emissions are significantly lower for the Honda Civic than the older Ford Crown Victoria. This is consistent with the differences in the certification levels of the vehicles. The cold-start contribution to THC emissions was particularly clear for the Ford Crown Victoria. This is representative of the unreacted gaseous fuel that escaped the combustion process, since the catalyst is below the light-off temperature.

THC emissions were found to be lower for the Ford Crown Victoria for the ARB Certification, High Wobbe and Modified Wobbe gases compared to the baseline gas. These differences were statistically significant for the High Wobbe and Modified Wobbe gases, but not for the ARB Certification gas. It seems that the reduction in THC emissions is positively correlated with the reduction in MN and the higher energy content of the test fuels for the Ford Crown Victoria. The Honda Civic did not show consistent trends for THC emissions, with only reductions in THC emissions compared to the Baseline fuel for the High Wobbe fuel on the FTP cold-start and for the ARB Certification fuel on the UC cold-start being statistically significant. THC emissions for the Modified Wobbe gas were the highest for all gas over all the cycle combinations for the Honda Civic, but these differences were not statistically significant.

Figure 3-8: Average THC emissions for Honda Civic GX and Ford Crown Victoria

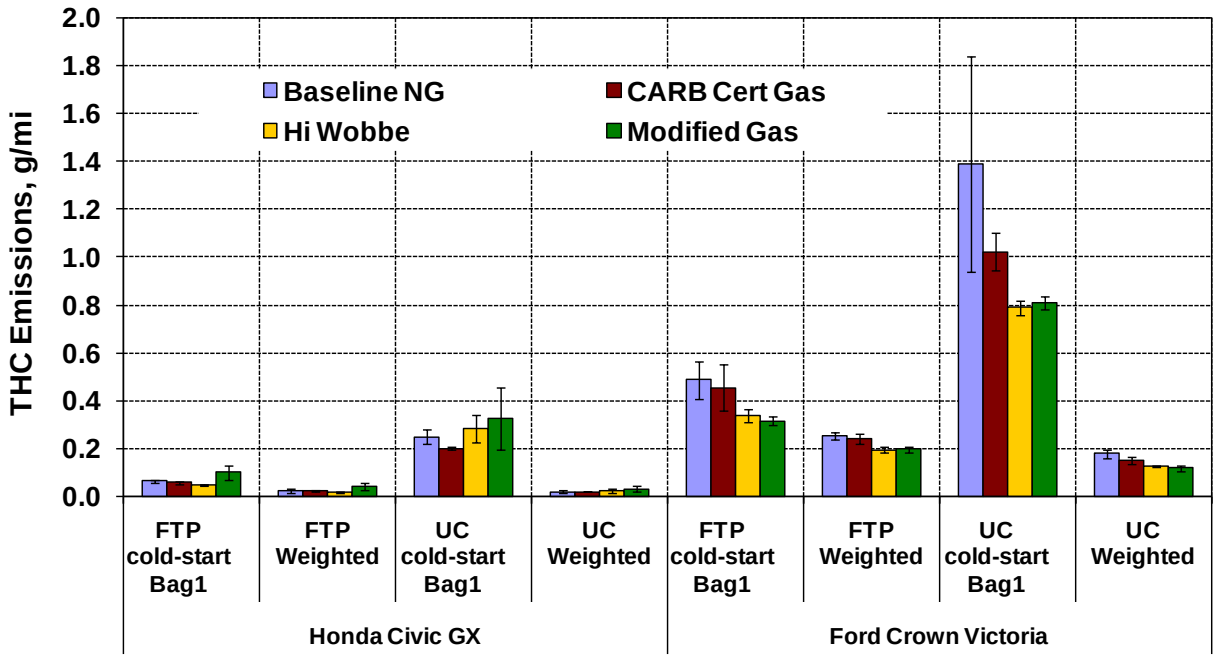


Table 3-6: Average values, Percent differences, and t-test values for THC emissions*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (THC g/mi)	Baseline NG	0.065	0.024	0.250	0.021
	ARB Certification	0.059	0.023	0.202	0.019
	High Wobbe	0.051	0.017	0.285	0.025
	Modified Wobbe	0.100	0.042	0.325	0.033
% Difference	ARB Certification	-8.8	-5.8	-19	-11.8
	High Wobbe	-21	-29	14	19
	Modified Wobbe	55	74	30	52
P-values	ARB Certification	0.355	0.753	0.039	0.482
	High Wobbe	0.041	0.163	0.336	0.437
	Modified Wobbe	0.135	0.148	0.303	0.163
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (THC g/mi)	Baseline NG	0.487	0.256	1.389	0.179
	ARB Certification	0.456	0.242	1.024	0.150
	High Wobbe	0.336	0.197	0.788	0.126
	Modified Wobbe	0.317	0.197	0.811	0.120
% Difference	ARB Certification	-6.4	-5.3	-26	-16
	High Wobbe	-31	-23	-43	-29
	Modified Wobbe	-35	-23	-42	-33
P-values	ARB Certification	0.683	0.422	0.238	0.109
	High Wobbe	0.034	0.008	0.082	0.011
	Modified Wobbe	0.022	0.006	0.090	0.012

* highlighted percentage differences are statistically or marginally statistically significant

3.5 NMHC Emissions

The experimental results showed that non-methane hydrocarbon (NMHC) emissions were especially low for both vehicles, particularly for the fuels that are comprised primarily of methane (i.e., the baseline and CARB Certification gases), as shown in Figure 3-9. Table 3-7shows the average NMHC emissions, percentage differences, and t-test data. This is consistent with expectations and indicates that the THC emissions from these vehicles are

predominantly methane. The main cases where NMHC emissions were measured above background levels (i.e., difference levels of at least ~0.010 to 0.020 g/mi) were for the High Wobbe and Modified Wobbe gases. Higher NMHC levels were seen particularly during the cold-start period of both the FTP and UC cycles for both vehicles. This can be attributed to the higher levels of NMHC in the compositions of these fuels (Table 2-1). NMHC emissions for the ARB Certification gas for the cold-start FTP and cold-start UC for the Ford Crown Victoria and the cold-start FTP for the Honda Civic were also measurable and were above those of the Baseline fuel. In comparing these fuels in Table 2-1, the ARB Certification gas also had higher levels of NMHC than the baseline gas. For the other cases, the NMHC values show either slight positive values or slight negative values depending on whether emissions measurements are above or below the background levels for a given test sequence.

Figure 3-9: Average NMHC emissions for Honda Civic GX and Ford Crown Victoria

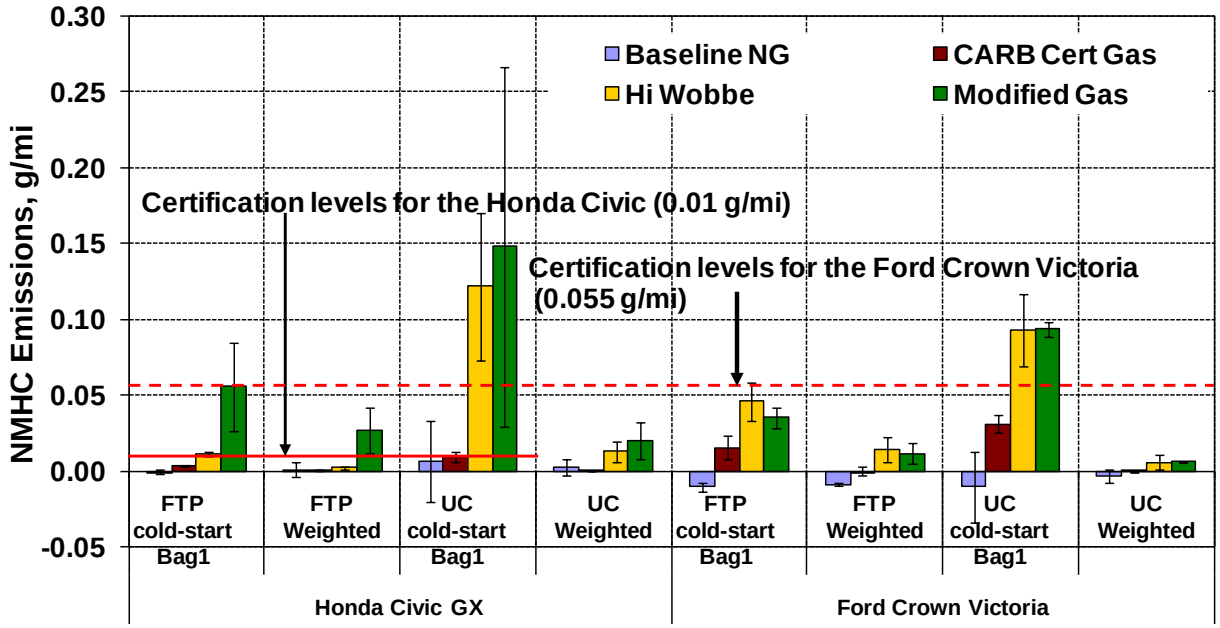


Table 3-7: Average values, Percent differences, and t-test values for NMHC emissions*

		Honda Civic GX			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (NMHC g/mi)	Baseline NG	0.000	0.001	0.007	0.003
	ARB Certification	0.004	0.001	0.010	0.001
	High Wobbe	0.011	0.002	0.122	0.013
	Modified Wobbe	0.056	0.027	0.148	0.020
% Difference	ARB Certification	+1517	+3.3	+42	-80
	High Wobbe	+4227	+137	+1681	+395
	Modified Wobbe	+20547	+2769	+2064	+656
P-values	ARB Certification	0.009	0.992	0.863	0.556
	High Wobbe	0.000	0.672	0.010	0.080
	Modified Wobbe	0.028	0.045	0.063	0.050
		Ford Crown Victoria			
		cold-start FTP	**FTP**	**cold-start UC**	**UC**
Weighted emissions (NMHC g/mi)	Baseline NG	-0.010	-0.009	-0.010	-0.003
	ARB Certification	0.015	0.000	0.031	0.000
	High Wobbe	0.046	0.014	0.093	0.006
	Modified Wobbe	0.035	0.011	0.094	0.006
% Difference	ARB Certification	+250	+99	+398	+106
	High Wobbe	+549	+261	+995	+284
	Modified Wobbe	+445	+230	+1004	+304
P-values	ARB Certification	0.006	0.007	0.042	0.280
	High Wobbe	0.002	0.008	0.006	0.085
	Modified Wobbe	0.000	0.007	0.002	0.023

*highlighted percentage differences are statistically or marginally statistically significant

3.6 Power Curves

Figure 3-10 shows the horsepower measurements for all fuel/vehicle combinations, while Table 3-8 shows the horsepower averages, percentage differences, and t-test data. The results indicated that maximum engine power output depended on natural gas composition. For the Honda Civic, the High Wobbe number gas produced approximately 3.6 percent higher engine

power compared to the Baseline gas, but this difference was not statistically significant, and the ARB Certification and the Modified Wobbe gas did not show significant power differences compared to the Baseline gas. For the Ford Crown Victoria, the High Wobbe gas resulted in significantly higher engine power (7.5 percent) compared to Baseline gas. This increase in the engine power with the High Wobbe gas is due to the higher energy content of the fuel compared to the Baseline gas. The ARB Certification and Modified Wobbe gases did not show statistically significant differences in horsepower compared to the Baseline gas, although the power for the Modified Wobbe gas was 3.0 percent higher than the Baseline gas.

Figure 3-10: Engine power output for the test vehicles fueled with different natural gas blends

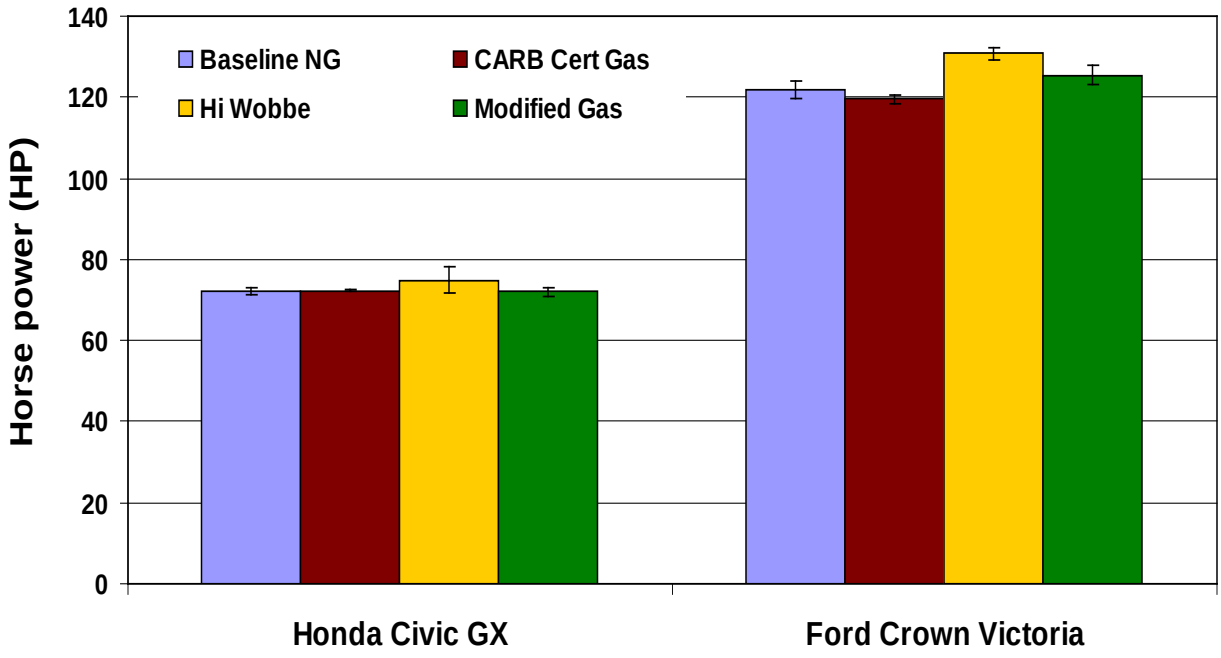


Table 3-8: Average values, Percent differences, and t-test values for horsepower measurements*

		Honda Civic GX	Ford Crown Victoria
Average HP	Baseline NG	72.3	121.7
	ARB Certification	72.2	119.5
	High Wobbe	74.9	130.8
	Modified Wobbe	72.1	125.4
% Difference	ARB Certification	-0.1%	-1.8%
	High Wobbe	3.6%	7.5%
	Modified Wobbe	-0.3%	3.0%
t-test	ARB Certification	0.614	0.208
	High Wobbe	0.763	0.002
	Modified Wobbe	0.877	0.199

*highlighted percentage differences are statistically or marginally statistically significant

CHAPTER 4: Summary

This study evaluated the impact of natural gas composition on the performance and emissions of light-duty vehicles and is part of a larger study that included testing of heavy-duty vehicles on different natural gas blends. For this study, two natural gas light-duty vehicles were tested over the Federal Test Procedure and the Unified Cycle on a range of four different test gases. The two test vehicles, a SULEV-certified 2006 Honda Civic GX and a ULEV-certified 2002 Ford Crown Victoria, were tested on four different natural gas fuel blends. Exhaust emissions and fuel economy measurements were made over the Federal Test Procedure (FTP) and the Unified Cycle (UC) driving cycles. The test fuel blends had varying methane numbers and Wobbe numbers, as well as different compositions of heavier hydrocarbons, such as ethane, propane, and butane. The test gases included a Baseline gas representative of those typically found in the marketplace, an average ARB Certification gas, a gas with high Wobbe number (1437) (High Wobbe) and a modified version of this gas blended down to a 1385 Wobbe number (Modified Wobbe).

The results of this study showed that fuel composition and engine operating conditions had an impact on the formation of exhaust emissions, fuel economy, and power output for both light-duty vehicles, although the trends were not always consistent between vehicles. The results are summarized in Table 4.1, and as follows:

- The vehicles did not show any operational issues over the range of fuels tested. The emissions levels and fuel economy values for the Honda Civic and Ford Crown Victoria were generally consistent with their certification values. Several Ford Crown Victoria's were tested for this program. The Crown Victorias all showed NO_x emissions multiple times higher than their certification levels. The nature of these unexpectedly high NO_x emissions is currently being investigated further.

- The fuel economy on a volumetric basis increased for the gas blends with higher energy contents for both vehicles. The High Wobbe and Modified Wobbe gases showed higher fuel economy on a volumetric basis than the Baseline and ARB Certification gases for both vehicles over the FTP and the UC cycle. The ARB Certification fuel also showed smaller improvements in fuel economy for most of the vehicle/cycle combinations compared to the lower energy Baseline gas. On an energy equivalent basis, the fuel economy results showed different trends between the vehicles, with some trends of lower energy equivalent fuel economy for the High Wobbe and Modified Wobbe gases (higher energy gases) for the Honda Civic and some trends of improved energy equivalent fuel economy for the High Wobbe and Modified Wobbe gases for the Ford Crown Victoria. This indicates that there were some slight differences in the engine efficiency for the different test gases.

- The CO_2 emissions were highest for the High Wobbe and Modified Wobbe gases for both vehicles and cycles. The ARB Certification gas also showed higher CO_2 emissions

compared to the Baseline gas for the Honda Civic, but for the Ford Crown Victoria these two gases were comparable. In general, the blends with more of the higher hydrocarbons, and corresponding lower H/C ratios, had higher CO_2 emissions. Carbon dioxide emissions were highest for the cold-start phase of the UC cycle.

- Varying fuel composition had an impact on NO_x emissions for both vehicles, although the effects were different for the two vehicles. For the Honda Civic, the NO_x emissions for the ARB Certification fuel were higher for both driving cycles when compared to the other fuels. These differences were statistically significant for the FTP, but not the UC. For the Ford Crown Victoria, NO_x emissions were higher for the High Wobbe gas compared to the Baseline natural gas fuel for the cold-start for the UC, but not for other fuels or cycle combinations.
- The effect of fuel composition on CO emissions was particularly noticeable for the Honda Civic. Fuels with higher levels of heavier hydrocarbon and lower methane numbers (MN) (High Wobbe and Modified Wobbe gases) produced higher CO emissions compared to the Baseline NG for the cold-start FTP, the weighted FTP, and the cold-start UC. For the Ford Crown Victoria, the fuels did not show significant differences over the FTP, but over the UC, the ARB Certification gas had the lowest CO emissions of any of the test gases for the cold-start, and the High Wobbe gas showed a statistically significant increase in CO emissions compared to the Baseline fuel for the weighted UC.
- The THC and NMHC emissions showed some differences between the gas blends for both vehicles. For the Honda, the Modified Wobbe gas showed higher THC emissions when compared to the other fuels over both driving cycles, but these differences were not statistically significant. THC emissions were highest for the Baseline fuel for the Ford Crown Victoria, with the increases compared to the High Wobbe and Modified Wobbe gases being statistically significant. NMHC emissions were only consistently above the background levels for the High Wobbe and Modified Wobbe gases, with higher emissions during the cold-start for both the FTP and UC cycles. NMHC emissions for the ARB Certification gas for the cold-start FTP and cold-start UC for the Ford Crown Victoria and the cold-start FTP for the Honda Civic were also measurable and above those of the Baseline fuel.
- The High Wobbe gas showed a statistically significant 7.5 percent increase in engine power compared to the Baseline gas for the Ford Crown Victoria. This difference can be attributed to the differences in energy content between the fuels. The engine power for the High Wobbe gas was also 3.6 percent higher than the Baseline gas for the Honda Civic, but this difference was not statistically significant. The other fuels combinations did not show statistically significant differences, although the engine power for the Modified Wobbe gas was 3.0 percent higher than the Baseline gas for the Ford Crown Victoria, consistent with the energy difference between the fuels.

Table 4-1 Trends in Emissions and Performance for the Two Test Vehicles in Comparison with the Baseline Natural Gas

		Honda Civic				Ford Crown Victoria			
		FTP c-s	FTP w	UC c-s	UC w	FTP c-s	FTP w	UC c-s	UC w
Fuel Economy	ARB Certification	+1.6	+1.3	NS	NS	+4.6	+3.3	+6.1	+3.8
Volumetric Basis	High Wobbe	+14.7	+14.5	+8.4	+11.3	+20	+18	+20	+16
	Modified Wobbe	+7.3	+6.7	+8.3	+10.4	+15	+12	+16	+14
CO_2	ARB Certification	NS	+1.6	+2.6	+2.3	NS	NS	NS	NS
	High Wobbe	+4.5	+4.8	+10.4	+7.8	NS	+1.6	NS	+3.0
	Modified Wobbe	+6.8	+7.6	+5.8	+4.0	NS	+2.3	NS	NS
NO_x	ARB Certification	+375	+136	NS	NS	NS	NS	NS	NS
	High Wobbe	NS	NS	NS	NS	NS	NS	+42	NS
	Modified Wobbe	NS	NS	NS	NS	NS	NS	NS	NS
CO	ARB Certification	NS	NS	+67	NS	NS	NS	-17	NS
	High Wobbe	+55	+22	+374	NS	NS	NS	NS	+12.6
	Modified Wobbe	+185	+74	NS	NS	NS	NS	NS	NS
THC	ARB Certification	NS	NS	-19	NS	NS	NS	NS	NS
	High Wobbe	-21	NS	NS	NS	-31	-22	-43	-29
	Modified Wobbe	NS	NS	NS	NS	-35	-23	-42	-33
NMHC	ARB Certification	+1517	NS	NS	NS	+250	+99	+398	NS
	High Wobbe	+4227	NS	+1681	+395	+549	+261	+995	+284
	Modified Wobbe	+20547	+2769	+2064	+656	+445	+230	+1004	+304

		Honda Civic				Ford Crown Victoria			
		FTP c-s	**FTP w**	**UC c-s**	**UC w**	**FTP c-s**	**FTP w**	**UC c-s**	**UC w**
Power	ARB Certification	NS				NS			
	High Wobbe	NS				+7.5			
	Modified Wobbe	NS				NS			

The numbers represent the percentage increase (+) or percentage decrease (-) for statistically significant differences; NS = no statistically significant differences

CHAPTER 5:
Conclusions and Recommendations

As the demand for natural gas (NG) in California expands, there is potential for a wider range of natural gas compositions to be used in natural gas vehicles (NGVs). It is important to evaluate whether changing compositions of NG will have adverse impacts on the emissions or performance of NGVs. While some previous studies have been conducted on the effects of natural gas fuel composition on emissions and performance, there is very limited information on the impacts of fuel composition for advanced, modern light-duty NGVs that have advanced combustion control and feedback and aftertreatment systems.

Overall, the results of the study show that for more sophisticated modern light-duty NGVs, fuel properties still had a clear and direct impact on fuel economy and some emissions components, such as CO2 and NMHC, but not for other emission components, such as THC, NOx, and CO. For the fuel economy, CO2 emissions, and NMHC emissions, the most critical fuel properties include the energy content, the H/C ratio, and the level of heavier hydrocarbons in the blend. For THC, NOx, and CO emissions, the differences in fuel impacts between the two vehicles indicate that factors other than combustion chemistry are important in understanding the effects of fuel composition for these emissions. This could include differences in vehicle technology, engine control strategy, catalyst technology, or operating condition. Further studies are needed to better understand impact of these factors on the trends in the THC, NOx, and CO emissions for the different vehicles.

The results also showed some differences in the overall performance of the vehicles. The newer technology Honda Civic showed relatively low emissions over the range of conditions evaluated in this study, consistent with its SULEV certification level. The older technology Ford Crown Victoria, however, showed relatively high NOx emissions that were well above its certification levels. Some further testing of older technology NGVs might be warranted to further evaluate whether these vehicles maintain their performance levels over the life of the vehicle, although at the same time such vehicles will also continue to be a relatively small and declining fraction of the in-use fleet.

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APPENDIX A:
Emissions Test Results[1]

Results for the Honda Civic GX

Test	Fuel	Test	Date	Mileage	THC1	THC2	THC3	THCw	NMHC1	NMHC2	NMHC3	NMHCw	CO1	CO2	CO3	COw	NOx1	NOx2	NOx3	NOxw	CO21	CO22	CO23	CO2w	FE1	FE2	FE3	FEw
FTP	baseline NG	090729_0859_FTP	07/29/2009	47,532	0.072	0.012	0.041	0.032	0.000	0.010	0.004	0.006	0.154	0.168	0.116	0.151	0.010	0.001	0.024	0.009	238	229	196	222	26.7	27.7	32.3	28.6
FTP	baseline NG	090730_0858_FTP	07/30/2009	47,547	0.057	-0.001	0.030	0.020	-0.002	-0.003	-0.004	-0.003	0.147	0.140	0.121	0.136	0.004	0.001	0.022	0.007	236	229	198	222	26.9	27.7	32.1	28.6
FTP	baseline NG	090731_0836_FTP	07/31/2009	47,563	0.065	0.001	0.024	0.021	0.001	0.000	-0.002	0.000	0.207	0.118	0.109	0.134	0.005	0.001	0.012	0.005	232	231	198	222	27.3	27.5	32.1	28.6
UNI	baseline NG	090804_0803_UNI	08/04/2009	47,594	0.232	0.001	0.063	0.017	-0.009	0.000	-0.001	-0.001	0.181	0.199	0.332	0.207	0.052	0.003	0.021	0.007	398	215	305	231	15.9	29.5	20.8	27.5
UNI	baseline NG	090805_0856_UNI	08/05/2009	47,605	0.221	0.000	0.088	0.018	-0.005	0.000	-0.003	0.000	0.241	0.266	0.267	0.265	0.039	0.004	0.040	0.008	400	215	307	230	15.9	29.6	20.7	27.5
UNI	baseline NG	090806_0914_UNI	08/06/2009	47,616	0.284	0.008	0.115	0.029	0.047	0.007	0.038	0.011	0.201	0.225	0.418	0.237	0.016	0.003	0.023	0.005	401	218	316	234	15.8	29.1	20.0	27.1
UNI	baseline NG	090807_1053_UNI	08/07/2009	47,627	0.265	0.002	0.083	0.021	-0.005	0.001	0.003	0.001	0.224	0.216	0.180	0.214	0.021	0.003	0.044	0.006	410	218	310	234	15.5	29.2	20.4	27.1
FTP	CARB Spec Gas	090811_0911_FTP	08/11/2009	47,672	0.065	0.003	0.033	0.025	0.005	0.001	0.000	0.002	0.125	0.165	0.142	0.150	0.042	0.001	0.026	0.017	237	237	201	227	27.0	27.1	31.9	28.2
FTP	CARB Spec Gas	090812_1003_FTP	08/12/2009	47,686	0.054	0.003	0.039	0.024	0.004	0.000	0.000	0.001	0.132	0.192	0.078	0.148	0.020	0.003	0.040	0.017	239	231	201	224	26.8	27.8	32.0	28.6
FTP	CARB Spec Gas	090820_0916_FTP	08/20/2009	47,717	0.057	0.000	0.032	0.021	0.003	-0.001	0.001	0.000	0.136	0.135	0.086	0.122	0.027	0.003	0.037	0.017	238	234	198	225	26.9	27.5	32.4	28.6
UNI	CARB Spec Gas	090821_0831_UNI	08/21/2009	47,731	0.208	0.002	0.093	0.019	0.006	0.000	-0.001	0.000	0.333	0.253	0.186	0.253	0.027	0.004	0.053	0.009	419	222	316	239	15.3	28.9	20.3	26.9
UNI	CARB Spec Gas	090822_1350_UNI	08/22/2009	47,753	0.205	0.003	0.093	0.019	0.011	0.000	-0.002	0.001	0.296	0.216	0.194	0.219	0.035	0.005	0.059	0.010	407	221	315	237	15.8	29.0	20.4	27.1
UNI	CARB Spec Gas	090823_1359_UNI	08/23/2009	47,786	0.193	0.003	0.092	0.019	0.012	0.000	0.001	0.001	0.434	0.188	0.182	0.200	0.021	0.004	0.036	0.007	413	221	312	237	15.5	29.0	20.6	27.1
FTP	Hi Wobbe	090824_1448_FTP	08/24/2009	47,794	0.054	0.002	0.022	0.019	0.012	0.000	0.000	0.003	0.249	0.155	0.105	0.161	0.006	0.003	0.020	0.008	243	238	204	230	27.1	27.8	32.3	28.8
FTP	Hi Wobbe	090825_1447_FTP	08/25/2009	47,807	0.047	0.001	0.019	0.015	0.010	-0.001	-0.001	0.001	0.247	0.141	0.129	0.160	0.009	0.002	0.007	0.005	244	240	206	232	27.0	27.6	32.1	28.6
FTP	Hi Wobbe	090826_1625_FTP	08/26/2009	47,821	0.051	0.002	0.021	0.018	0.012	0.000	0.001	0.003	0.291	0.186	0.133	0.193	0.008	0.002	0.015	0.007	250	243	214	236	26.4	27.2	30.9	28.0
UNI	Hi Wobbe	090829_1447_UNI	08/29/2009	47,876	0.220	0.004	0.034	0.017	0.066	0.002	0.002	0.005	0.799	0.200	0.225	0.233	0.021	0.003	0.021	0.005	427	231	330	248	15.4	28.6	20.0	26.7
UNI	Hi Wobbe	090916_0858_UNI	09/16/2009	47,995	0.306	0.009	0.069	0.029	0.144	0.008	0.026	0.016	1.016	0.180	0.359	0.236	0.061	0.004	0.014	0.007	461	233	341	252	14.3	28.4	19.4	26.2
UNI	Hi Wobbe	090917_0907_UNI	09/17/2009	47995	0.329	0.010	0.070	0.031	0.155	0.009	0.032	0.018	1.198	0.188	0.377	0.252	0.031	0.005	0.023	0.008	445	234	335	251	14.8	28.3	19.7	26.3
FTP	Modified Gas	090901_1336_FTP	09/01/2009	47,889	0.114	0.027	0.042	0.050	0.066	0.026	0.024	0.034	0.630	0.201	0.216	0.295	0.029	0.004	0.019	0.013	248	252	215	241	26.5	26.2	30.6	27.3
FTP	Modified Gas	090903_1346_FTP	09/03/2009	47,807	0.123	0.031	0.042	0.053	0.078	0.029	0.025	0.038	0.577	0.201	0.201	0.280	0.011	0.004	0.025	0.011	256	247	214	240	25.6	26.6	30.8	27.4
FTP	Modified Gas	090904_0827_FTP	09/04/2009	47,930	0.063	0.007	0.026	0.024	0.023	0.006	0.007	0.010	0.242	0.144	0.124	0.159	0.004	0.002	0.019	0.007	250	242	213	236	26.4	27.2	30.9	28.0
UNI	Modified Gas	090909_0930_UNI	9/9/2009	47,948	0.228	0.007	0.069	0.023	0.060	0.006	0.025	0.010	0.341	0.217	0.378	0.234	0.010	0.003	0.007	0.004	420	224	319	240	15.6	29.4	20.6	27.4
UNI	Modified Gas	090911_0855_UNI	9/11/2009	47,965	0.274	0.010	0.089	0.029	0.101	0.009	0.042	0.016	0.422	0.170	0.375	0.197	0.037	0.003	0.013	0.005	420	222	313	239	15.6	29.6	21.0	27.6
UNI	Modified Gas	090912_1106_UNI	09/12/2009	47,976	0.471	0.020	0.071	0.047	0.282	0.019	0.030	0.033	1.501	0.181	0.172	0.249	0.066	0.004	0.018	0.008	438	228	328	246	14.9	28.9	20.1	26.8

[1] The weighted emissions results are determined based on equation 2-1

APPENDIX B:
Results from the Ford Crown Victoria

Test	Fuel	Test	Date	Mileage	THC1	THC2	THC3	THCw	NMHC1	NMHC2	NMHC3	NMHCw	CO1	CO2	CO3	COw	NOx1	NOx2	NOx3	NOxw	CO21	CO22	CO23	CO2w	FE1	FE2	FE3	FEw
FTP	Pure CH4	100218_1251_FTP_CV	02/18/2010	66,565	0.526	0.163	0.237	0.259	-0.024	-0.008	-0.011	-0.012	0.975	0.081	0.093	0.271	0.224	0.155	0.241	0.193	326	361	290	334	19.3	17.6	21.9	18.9
FTP	Baseline NG	100311_1320_FTP_CV	03/11/2010	66,590	0.424	0.175	0.227	0.241	-0.008	-0.008	-0.007	-0.008	0.756	0.048	0.155	0.224	0.329	0.219	0.223	0.243	324	356	277	328	19.4	17.8	22.9	19.3
FTP	Baseline NG	100312_0905_FTP_CV	03/12/2010	66,604	0.461	0.186	0.224	0.254	-0.010	-0.010	-0.008	-0.009	1.028	0.041	0.163	0.282	0.273	0.207	0.256	0.234	324	355	283	329	19.5	17.9	22.3	19.3
FTP	Baseline NG	100313_1039_FTP_CV	03/13/2010	66,617	0.575	0.173	0.229	0.272	-0.013	-0.009	-0.008	-0.009	0.884	0.049	0.129	0.246	0.282	0.184	0.186	0.205	332	360	287	334	19.0	17.6	22.1	19.0
UNI	Baseline NG	100316_1105_UNI_CV	03/16/2010	66,653	1.862	0.073	0.602	0.199	0.015	0.000	0.011	0.002	3.398	0.113	0.341	0.294	0.480	0.334	0.390	0.345	565	302	468	327	11.0	21.0	13.5	19.4
UNI	Baseline NG	100320_0856_UNI_CV	03/20/2010	66,680	0.969	0.082	0.552	0.159	-0.015	-0.002	-0.019	-0.004	3.331	0.114	0.173	0.282	0.466	0.344	0.379	0.353	590	312	484	338	10.6	20.3	13.1	18.7
UNI	Baseline NG	100321_0923_UNI_CV	03/21/2010	66,691	1.336	0.078	0.637	0.179	-0.032	-0.004	-0.030	-0.007	3.274	0.120	0.148	0.281	0.667	0.319	0.470	0.347	577	307	483	332	10.8	20.7	13.1	19.1
FTP	CARB spec	100322_1438_FTP_CV	03/22/2010	66,710	0.501	0.188	0.195	0.256	0.020	-0.004	0.002	0.002	0.920	0.044	0.087	0.238	0.300	0.250	0.233	0.255	319	355	284	328	19.9	18.1	22.6	19.5
FTP	CARB spec	100323_0906_FTP_CV	03/23/2010	66,723	0.347	0.179	0.196	0.219	0.006	-0.007	-0.003	-0.003	0.848	0.036	0.092	0.221	0.264	0.188	0.199	0.207	319	353	282	326	20.0	18.2	22.7	19.6
FTP	CARB spec	100324_1327_FTP_CV	03/24/2010	66,737	0.519	0.166	0.214	0.253	0.020	-0.006	-0.001	0.000	1.067	0.102	0.167	0.322	0.282	0.194	0.183	0.210	326	361	285	333	19.5	17.8	22.5	19.2
UNI	CARB spec	100325_0907_UNI_CV	03/25/2010	66,750	0.932	0.073	0.599	0.152	0.025	-0.002	0.001	0.000	2.732	0.142	0.255	0.282	0.689	0.314	0.350	0.335	566	307	487	332	11.2	20.9	13.1	19.3
UNI	CARB spec	100326_1233_UNI_CV	03/26/2010	66,762	1.057	0.052	0.534	0.136	0.032	-0.001	-0.005	0.001	2.684	0.064	0.127	0.202	0.591	0.362	0.400	0.377	557	300	474	325	11.4	21.4	13.5	19.7
UNI	CARB spec	100327_0900_UNI_CV	03/27/2010	66,763	1.082	0.084	0.502	0.163	0.036	-0.002	-0.002	0.000	2.844	0.100	0.156	0.244	0.653	0.591	0.682	0.600	561	307	484	332	11.3	20.9	13.2	19.3
FTP	Hi Wobbe	100328_0858_FTP_CV	03/28/2010	66,791	0.352	0.125	0.174	0.186	0.043	-0.004	0.009	0.009	1.248	0.108	0.167	0.363	0.246	0.183	0.254	0.216	325	368	288	337	20.2	18.0	22.9	19.6
FTP	Hi Wobbe	100329_1110_FTP_CV	03/29/2010	66,805	0.305	0.142	0.200	0.192	0.035	-0.003	0.013	0.010	0.794	0.048	0.055	0.206	0.388	0.232	0.237	0.266	328	364	285	335	20.1	18.2	23.1	19.7
FTP	Hi Wobbe	100330_0828_FTP_CV	03/30/2010	66,818	0.351	0.152	0.217	0.212	0.060	0.007	0.026	0.024	0.971	0.048	0.162	0.273	0.280	0.222	0.238	0.239	327	366	282	334	20.1	18.1	23.4	19.7
UNI	Hi Wobbe	100331_1107_UNI_CV	03/31/2010	66,831	0.826	0.065	0.446	0.130	0.065	0.446	0.130	0.000	3.371	0.152	0.154	0.319	0.803	0.487	0.510	0.505	580	319	501	345	11.3	20.7	13.2	19.1
UNI	Hi Wobbe	100401_1408_UNI_CV	04/01/2010	66,843	0.771	0.059	0.472	0.123	0.106	0.001	0.032	0.008	2.743	0.169	0.222	0.304	0.876	0.325	0.526	0.367	579	316	484	341	11.3	20.9	13.6	19.4
UNI	Hi Wobbe	100402_1244_UNI_CV	04/02/2010	66,854	0.767	0.060	0.484	0.126	0.107	0.000	0.043	0.009	3.541	0.164	0.225	0.342	0.610	0.281	0.404	0.306	584	315	493	341	11.2	21.0	13.4	19.4
FTP	Modified	100403_0920_FTP_CV	04/03/2010	66,872	0.311	0.142	0.193	0.191	0.028	-0.004	0.010	0.007	0.862	0.012	0.101	0.215	0.302	0.256	0.309	0.281	329	371	299	342	19.9	17.8	22.0	19.2
FTP	Modified	100404_0955_FTP_CV	04/04/2010	66,886	0.337	0.136	0.185	0.192	0.036	-0.003	0.009	0.008	1.023	0.040	0.131	0.271	0.267	0.207	0.253	0.232	328	364	288	336	19.9	18.1	22.8	19.6
FTP	Modified	100405_1453_FTP_CV	04/05/2010	66,899	0.303	0.152	0.243	0.209	0.042	0.004	0.030	0.019	0.920	0.085	0.102	0.265	0.313	0.212	0.299	0.257	326	364	290	336	20.1	18.1	22.6	19.6
UNI	Modified	100406_0756_UNI_CV	04/06/2010	66,913	0.779	0.069	0.406	0.127	0.089	0.001	0.015	0.006	2.908	0.083	0.263	0.238	0.634	0.444	0.366	0.449	575	310	488	335	11.3	21.3	13.5	19.6
UNI	Modified	100407_1428_UNI_CV	04/07/2010	66,924	0.828	0.059	0.468	0.127	0.099	0.000	0.020	0.006	3.546	0.150	0.160	0.327	0.586	0.389	0.354	0.396	579	315	486	340	11.2	20.9	13.5	19.3
UNI	Modified	100408_0757_UNI_CV	04/08/2010	66,935	0.824	0.041	0.404	0.106	0.093	0.000	0.018	0.006	3.561	0.115	0.102	0.291	0.548	0.280	0.366	0.299	561	307	495	332	11.6	21.5	13.3	19.8