Technical Manual

# Performance of Alternative Fuels at High Altitude

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UNDERSTANDING RESOURCES SOLUTIONS

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**Performance of Alternative Fuels at High Altitude**

This technical memorandum will discuss the potential implications of operating alternative fuel vehicles in a high altitude environment. This document summarizes available information regarding the performance of various alternative fuels in high altitude conditions, including documented issues and challenges, potential mitigation strategies, and other considerations. This collection of information is intended to assist fleet managers with the selection of optimal fuels suited for their specific conditions and needs. The research team made every effort to conduct a comprehensive search for information on this issue; however, this report is hardly exhaustive and should not be used as the only reference resource in the decision-making process.

High altitude affects the combustion of fuel in the internal combustion engine (ICE) through the decrease in oxygen supply. Since the air density is lower at high altitude, there is a smaller amount of oxygen in a given volume of air. Lower concentration of oxygen in the air will decrease vehicle performance. As the air density decreases, an ICE with a standard mechanical petrol carburetor will run progressively more "rich," causing a decrease in power (because the engine is getting less oxygen than needed for combustion of fuel).

Most modern vehicles with fuel injection can automatically compensate for higher altitude. The Electronic Control Module (ECM) (also called Electronic Control Unit - ECU) will adjust the fuel mixture for higher altitude to prevent the engine from "running rich" (too much fuel in the mixture, and not enough oxygen). This can be accomplished with both liquid and gaseous fuels through the use of an oxygen sensor, which ensures that a constant fuel/air ratio is maintained with altitude. However, above a certain altitude, the vehicle's performance will suffer even with automatic adjustments in fuel mixture. Due to lower air density at high altitudes, the horsepower of an internal combustion engine will decrease approximately 3.5% for each increase of 1,000 feet in altitude (see Table 1).

Generally, there are two opposing factors affecting the performance of pressurized fuel systems (such as the ones used in LPG and CNG vehicles) at high altitude: pressure difference and lack of oxygen. At high altitudes, the pressure difference between the pressurized fuel tank and the lower outside pressure decreases, increasing the ability of gas inside the canister to escape. This, in general, can make LPG and CNG to burn more efficiently, provided there is enough oxygen. However, the oxygen effect will still dominate resulting in a net loss of power for gaseous alternative fuels operated at high altitude. The lack of oxygen at high altitude will affect all ICEs in the same way, regardless of whether they are fueled by conventional or alternative fuels. However, several alternative fuels have additional considerations that need to be discussed. The use of gaseous fuels (e.g., LPG, CNG) will decrease the power of the engine by roughly 12-14 percent (regardless of altitude), because the gas occupies about 12 percent of the intake volume, and there is subsequently less air or oxygen in the combustion chamber. The liquid fuels (both conventional and alternative) do not suffer this problem. Coupling this initial 12 percent loss of power with the altitude effects, listed in Table 1, can result in significant decrease in the power of vehicles running on CNG or LPG (or any other gaseous fuel in general). The increase in altitude, however, will have the same incremental power loss effect on both conventional and alternative fuel vehicles. Thus, the same 12-14% engine power difference between gaseous and liquid fuels, observed at sea level, is expected to persist at altitude. It is important to note, however, that the factor with the biggest detrimental impact on a pressurized fuel system is not altitude, but cold temperatures.

For example, biodiesel turns into a gel at extremely cold temperatures. Possible solutions for cold weather operation of biodiesel include the use of fuel line heaters and fuel tank heaters, as well as parking the vehicle in a temperature-controlled environment (garage). It is also possible to blend biodiesel with kerosene or diesel to improve operations in cold weather.

**Table 1 – Decrease of power of ICE with altitude**

| Elevation (Feet) | Engine Power Loss |
|---|---|
| 0 | - |
| 1,000 | 3.5% |
| 2,000 | 7.0% |
| 3,000 | 10.5% |
| 4,000 | 14.0% |
| 5,000 | 17.5% |
| 6,000 | 21.0% |
| 7,000 | 24.5% |
| 8,000 | 28.0% |
| 9,000 | 31.5% |
| 10,000 | 35.0% |

To ensure better performance at high altitude, frequent engine tune-ups may be required. At high altitude, engines run colder with less oxygen. This may require the installation of spark plugs with a higher heat range (i.e. “warmer” plugs). “Warmer” spark plugs do not conduct heat away from the firing tip as quickly as “cold” plugs, which maintains a higher temperature in the combustion chamber. This tune-up, however, is not fuel-specific and applies to both conventionally- and alternatively-fueled vehicles operating at high altitudes.

The higher the altitude above sea level, the lower the octane requirement of the fuel. This can be explained by lower atmospheric pressure at high altitudes. While the static compression ratio of a given engine remains the same, the pressure developed during compression is lower at higher altitude. This is simply due to the lower initial pressure of the atmosphere. Lower compression pressure means lower octane requirement.

The octane number is actually an imprecise measure of the maximum compression ratio at which a particular fuel can be burned in an engine without detonation. Octane rating can be described by two numbers: RON (Research Octane Number) and MON (Motor Octane Number). RON simulates fuel performance under low severity engine operation, while MON simulates more severe operation that might be incurred at high speed or high load and can be as much as 10 points lower than the RON. In the United States, the mean of these two octane numbers is usually reported (calculated as (R+M)/2).

As a general rule of thumb, for every 300 meters or 1,000 feet above sea level, the RON value can go down by about 0.5 (*1*). For example, an 85 octane fuel in Salt Lake City, UT (elevation 4,200 feet) will have about the same characteristics as an 87 octane fuel in Miami, FL (sea level). This means that at higher elevations, the stability of fuel burning in the engine increases, provided that all other engine parameters remain unchanged. On the downside, under these conditions the engine may be harder to start from cold, because the fuel becomes effectively less volatile at high altitude. This affects all types of fuel, both conventional and alternative.

Natural gas presents several challenges to engine manufacturers for use as a heavy-duty, lean burn engine fuel. Natural gas can vary in composition, and the variation is large enough to produce significant changes in fuel properties and octane number. Operation at high altitude can also present challenges. The most significant effect of altitude is lower barometric pressure that can result in lower turbocharger boost at low speeds leading to mixtures richer than desired.

A group of researchers from the Colorado School of Mines, together with the engineers from Cummins Engine Co, Inc., conducted an experiment in 1997 that measured the performance and emissions of a natural gas-powered transit bus under various fuel compositions and operating conditions. The purpose of this test program was to determine the effect of natural gas composition and altitude on regulated emissions and performance of a Cummins B5.9G engine. The engine is a lean-burn, closed loop control, spark ignited, dedicated natural gas engine. For fuel composition testing, the engine was operating at approximately 1,600 m (5,280 ft) above sea level. Engine performance and emissions were measured using the EPA transient emission test for diesel and alternative fueled engines defined in the Code of Federal Regulations under 40 CFR, Part 86, Subpart N. Five different natural gas fuels were evaluated. The natural gases ranged in methane content from 76.9% to 90.3%. The total inert gas content ranged from 3.6% to 17.3%. The maximum ethane content was 5.4% (*2*).

The results of this test demonstrated that the engine was able to operate well on all gases including the lowest methane gas. Net energy based fuel economy was not affected by fuel composition. Major emissions parameters, including $CO_2$, PM, and NOx emissions were found to be unaffected by fuel composition (*2*).

The results acquired at 1,600 m (5,280 ft) were compared to results obtained at 152 m (500 ft). The test results showed rated horsepower and peak torque could be achieved at high altitude. Wide open throttle torque at speeds below peak torque speed was approximately 20% lower than at sea level, which is proportional to the difference in barometric pressure. PM and NOx emissions were not affected by operation at the higher test altitude, while $CO_2$ emissions were slightly increased at test altitude (*2*).

**Conclusion:** No adverse effects of high altitude, specific to vehicles powered by alternative fuels, were found in the literature. In fact, very limited information is available on how high-altitude conditions may affect the performance and safety aspects of alternative fuel vehicles. All the available information seems to indicate that internal combustion engines running on alternative fuels experience the same issues at high altitude that are typical to the traditional fuels. No evidence could be found that alternative fuel vehicles will suffer from additional negative effects at high elevation, besides the normally expected altitude effects (i.e. loss of engine power, lower gas mileage, etc.) that are typical to all fuel types. Finally, the performance of alternative fuels is more likely to be affected by cold weather than altitude. However there is no indication that cold weather affects alternative fuels more than conventional fuels.

**References:**

1. The Car Bibles website: http://www.carbibles.com/fuel_engine_bible_pg3.html Accessed: Feb 15, 2011.

2. Graboski, M. S., McCormick, R. L., Newlin, A. W., Dunnuck, D. L., Kamel, M. M. and Ingle, W. D. Effect of Fuel Composition and Altitude on Regulated Emissions from a Lean-Burn, Closed Loop Controlled Natural Gas Engine, SAE International, 1997.