

Gasoline Anti-Knock Index Effects on Vehicle Net Power at High Altitude

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ABSTRACT

Automakers are designing smaller displacement engines with higher power densities to improve vehicle fuel economy, while continuing to meet customer expectations for power and drivability. The specific power produced by the spark-ignited engine is constrained by knock and fuel octane. Whereas the lowest octane rating is 87 AKI (antiknock index) for regular gasoline at most service stations throughout the U.S., 85 AKI fuel is widely available at higher altitudes especially in the mountain west states.

The objective of this study was to explore the effect of gasoline octane rating on the net power produced by modern light duty vehicles at high altitude (1660 m elevation). A chassis dynamometer test procedure was developed to measure absorbed wheel power at transient and stabilized full power operation. Five vehicles were tested using 85 and 87 AKI fuels. Turbocharging, natural aspiration, gasoline direct injection, and port fuel injection technologies were evaluated using this group of vehicles.

All vehicles in the study had some reduction in net power when operated on 85 AKI fuel compared to 87 AKI fuel. Vehicles with turbocharged engines had a greater net power loss using 85 AKI fuel compared to vehicles with naturally aspirated engines. Engine control system data provided strong evidence that all vehicles were able to detect the earlier onset of knock when operated on 85 AKI fuel, and used different engine control settings for knock avoidance.

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INTRODUCTION

In 2010, the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) introduced a final rule to jointly regulate greenhouse gas emissions and corporate average fuel economy [1]. In 2012, the EPA and NHTSA finalized a new rule to extend this national program by increasing the fleet average fuel economy to 54.5 mpg by 2025 [2]. These challenging regulations have accelerated the development of fuel efficient powertrain and vehicle technologies.

The spark-ignited gasoline engine is likely to remain the dominant powerplant for passenger vehicles in the United States for years to come. Technology advances such as gasoline direct injection, variable

valve actuation, cylinder deactivation, and engine stop-start at idle have all contributed to fuel efficiency gains for gasoline engines. Automakers are also designing smaller displacement engines with higher power densities to reduce vehicle weight and improve fuel efficiency while continuing to meet customer expectations for power and drivability. A common approach to increase power density is through the use of turbocharging. About 20% of new light-duty vehicles are equipped with turbocharged engines in the U.S. today, and market penetration is expected to grow dramatically [3,4,5,6,7].

Downsized turbocharged engines utilize boosted charge air to deliver the performance of larger engines, but typically with lower compression ratio due to the constraints of knock and available fuel

octane [8]. Knock can lead to engine component damage. Avoiding knock by retarding spark timing can lead to excessive exhaust gas temperatures that may cause thermal damage to the catalytic converters used for emissions control. The fundamental tradeoffs between fuel octane rating, spark timing, equivalence ratio (enrichment), compression ratio, boost pressure, charge air temperature, power, efficiency, and knock are well understood. But modern electronically controlled engines employ numerous control strategies often utilizing knock sensor feedback. Generalizations regarding the effect of fuel octane on the observed performance of modern engines are therefore elusive. The research community has extensively explored the critical role that fuel octane rating plays in the design, operation, efficiency and emissions of modern spark-ignited engines [8,9,10,11 and their incorporated references].

The minimum octane rating for U.S. gasoline is currently being debated, as automakers design and develop the next generation of fuel-efficient engines. Whereas the lowest octane rating of regular gasoline is 87 AKI at most service stations throughout the U.S., 85 AKI fuel is prevalent in some higher altitude regions such as the mountain west states. The use of 85 AKI fuel dates back to vehicles that had naturally aspirated engines equipped with carburetors and lacked electronic knock detection systems [12]. Historically, with those older technology engines, 85 AKI fuel at high altitude was found to have equivalent anti-knock performance compared to 87 AKI fuel at sea level conditions.

The octane-high altitude paradigm has changed with modern engine technology that uses adaptive controls and altitude compensation to minimize fuel enrichment and optimize spark timing. The objective of this study was to explore the effect of gasoline octane ratings on the net power produced by modern light duty vehicles at high altitude conditions. Vehicle tests were performed in a chassis dynamometer laboratory located at 1660 m (5440 feet) elevation above sea level and 83 kPa nominal barometric pressure. This study contributes new information:

- The effect of gasoline octane rating (AKI) on full power vehicle operation was quantified at high altitude.
- Transient full power operation was compared to stabilized full power operation.
- The effect of gasoline octane rating on net power was determined for a variety of model year 2015 engine technologies.

Five vehicles were tested using 85 AKI and 87 AKI fuels. A chassis dynamometer test procedure was developed to measure absorbed net power at the drive wheels. Data analysis included examination of transient and stabilized full power, operational anomalies, and control system adaptation differences for the test fuels. A statistical analysis was performed to compare net power differences over the speed range of each engine. This report summarizes testing and analysis performed by SGS North America, Inc. (SGS) to investigate the effects of gasoline octane rating on vehicle performance at high altitude, and was sponsored by the United States Council for Automotive Research (USCAR) Fuels Working Group (FWG).

CHASSIS DYNAMOMETER TEST PROCEDURE

Engine dynamometer test stands are commonly used to map power and torque curves over the speed range. Net power ratings are typically determined using the procedures in the SAE J1349 standard for net power rating [13] which establishes testing uniformity to minimize lab-to-lab differences. However, testing modern electronically-controlled automotive engines on the engine dynamometer without manufacturer involvement is a complex matter because:

- The engine must be removed from the vehicle.
- Proprietary information may be needed to replicate microcontroller and sensor interconnections and network communications (anti-theft, safety interlocks, engine-transmission communications, etc.).
- Components such as the engine fan, intercoolers, heat exchangers and ancillaries may be required for net power rating tests, and these components must be set up to replicate in-vehicle performance.

As an alternative to engine dynamometer testing, complete vehicles were tested on a chassis roll dynamometer to map power for this study. Chassis dynamometer testing was deemed to be a much faster and more cost effective approach that enabled fuel effects to be compared in repeatable back-to-back tests. Complete vehicles were tested without modification, so the test approach accounted for all components affecting net power thus eliminating the need to replicate ancillary systems.

A test procedure was developed to approximate SAE J1349 on the chassis dynamometer. The test procedure and trial runs are discussed in this section. Engine brake power was not readily measured during chassis dynamometer testing, as the flywheel was not accessible and torque meter installation would be intrusive. Therefore wheel power (WP) was used as the primary measure of vehicle net power. WP was equivalent to the brake power minus the driveline/tire losses that occurred during operation on the chassis dynamometer. WP was calculated from the dynamometer roll tractive force and the roll speed. An equal and oppositely directed force occurred at the contact surface of the vehicle tires.

Whereas it would be possible to estimate engine brake torque using the gear ratios for each vehicle, this approach yields an indirect measure because there would be driveline efficiency assumptions. Rather, WP provided a direct laboratory measure of net power and was used as the primary power metric for this study.

In order to allow maximum power mapping over the speed range of the engines, vehicles equipped with manual transmissions were selected for the study. Manual transmissions had the following distinct advantages over automatics:

- Testing was performed in a fixed gear, thereby eliminating shift dynamics and unintended down-shifts that may be encountered using automatic transmissions.

- Testing in a fixed gear eliminated concern about the automatic transmission torque converter lock-up function which may vary and would be detrimental to test repeatability.

Laboratory Equipment

Testing was performed by SGS Transportation, at the Environmental Testing Center located in Aurora, Colorado. The laboratory is located at 1660 m elevation (5440 feet), with a nominal barometric pressure of 83 kPa.

The laboratory featured four Burke Porter AC dynamometers, all with 48-inch (1.22 m) diameter rolls and wheel centering mechanisms. Multiple dynamometers were used to facilitate vehicle fuel conditioning, but all power mapping tests for a particular vehicle model were performed using the same dynamometer to control laboratory variability.

The test procedure was developed using the model year 2015 Dodge Dart described in the next section. Vehicles were tested in a closed chamber with air temperature and humidity control. A high velocity road speed fan was used to provide full frontal and underbody air flow (Figure 1). The fan speed was set to a constant nominal air velocity of 129 kph (80 mph) for all tests to reduce variability and to prevent vehicle overheating. Vehicle test speeds were up to 161 kph (100 mph) on the dynamometer.

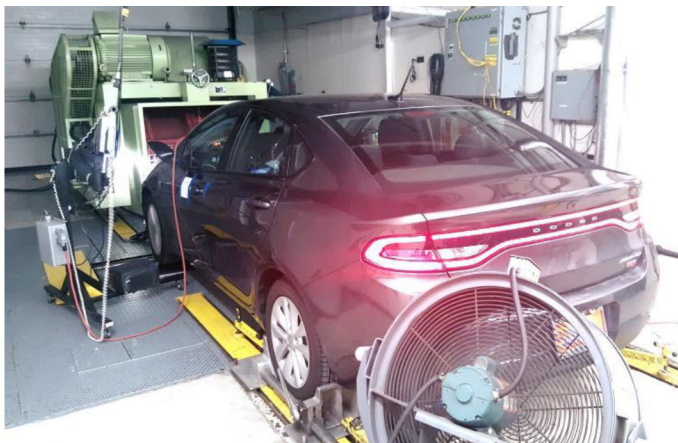


Figure 1. Vehicle Test Set-up in the Chassis Dynamometer Laboratory

Vehicle Preparation

The vehicles were prepared to prevent heat damage during sustained high power operation. The following precautions were taken to ensure plastic body panels, engine and exhaust sensor connectors and wiring did not sustain any thermal damage during testing:

- The hood was removed for heat dissipation. Light duty vehicles are normally tested with the hood raised for emissions certification tests performed at low power. Full power testing at high speed required much higher air flow rates and hood removal for safety.
- Air flow was directed at selected engine and exhaust sensors, as is common practice for engine stand rapid aging tests.

- Heat resistant insulation was added to protect plastic components adjacent to the turbocharger and exhaust pipes.
- Insulation was added between the tailpipe and plastic underbody and bumper panels. A fan was used to dissipate heat at the rear of the vehicle (Figure 1).

The vehicles were instrumented and the following data were acquired for safety monitoring and test analysis purposes:

- A K-type thermocouple was strapped to the upper radiator hose, insulated, and used to measure engine coolant outlet temperature. An alarm trigger was added to alert the driver of excessive temperatures to prevent coolant boiling.
- A K-type thermocouple was inserted through the oil dipstick tube to monitor oil sump temperature and ensure the engine was not being stressed beyond normal operating limits.
- A K-type thermocouple was used to monitor tailpipe-out exhaust gas temperature.
- The test cell ambient air temperature was measured to verify compliance with SAE J1349 intake air limits and to calculate power corrections for the naturally aspirated engines.
- Local barometric pressure was measured in the test cell and used to calculate power corrections for naturally aspirated engines.
- Supported SAE J1979 On Board Diagnostics (OBD) sensor channels were logged to record engine speed, vehicle speed, and other signals. The OBD data were for indication and trend analysis. There was no attempt to independently verify or calibrate the OBD sensors.

The OBD sensor data were used to compare engine control system responses to the test fuels. The sensor measurements were used to study trends but were not intended to prove the underlying cause of the net power differences observed for the two fuels. The OBD data logger was a passive device conforming to industry standards and did not influence vehicle operation.

No safety alarms or vehicle overheating events occurred during vehicle testing.

Consideration of SAE J1349 for Test Procedure Development

A test procedure was developed to approximate SAE J1349 on the chassis dynamometer. SGS adopted the standards defined in SAE J1349 that could be practically implemented. Full compliance to SAE J1349 was not possible for this study, because the standard is applicable for engine power ratings in the engine dynamometer lab, and tests are to be performed at barometric pressure greater than 90 kPa.

There was no intention to establish advertised engine power ratings for comparison to other laboratory results. Rather, the intention of this study was to compare gasoline octane rating (AKI) effects on net power under high altitude conditions. Comparison of the fuel effects was made possible through careful experimental design, and by adopting relevant requirements and control parameters from the SAE

J1349 standard. This section provides a summary of some of the SAE J1349 provisions that were adopted or alternatives that were used where compliance was not possible.

Net Power

For reasons discussed previously, WP was used as the primary measure for this study and represents uncorrected net wheel power. WP was an alternative to engine brake power used for engine dynamometer stand testing.

Corrected Net Power

Power corrections were made for naturally aspirated vehicles to standardize results for test-to-test variations in barometric pressure and ambient intake air temperature per SAE J1349-5.5 and 7.2.1. The power corrections were not used for the purposes of normalizing the high altitude results back to reference conditions, as this was prohibited per SAE J1349-5.6.

No power corrections were made for the turbocharged vehicles, in conformance with SAE J1349-5.5.2. Power correction was not appropriate because the vehicles were equipped with compensation devices (wastegated turbochargers and other controls) that affected the power produced.

Corrected Net Power Formula

Power corrections were made for vehicles with naturally aspirated engines using a formula substantially similar to SAE J1349-5.6.1 Eq. 12. However, instead of normalizing the indicated power to a 99 kPa reference, results were normalized to 83 kPa (corresponding to the nominal barometric pressure at the test lab). The purpose of this correction was to account for test-to-test variations in barometric pressure (P_o) and ambient air temperature (T_o) adjacent to the air intake in the test chamber.

$$WPC = WP * \left(\frac{83}{P_o}\right)^{1.2} \left(\frac{T_o + 273}{298}\right)^{0.6}$$

Through data analysis, SGS independently confirmed that the power corrections were appropriate for vehicles with naturally aspirated engines. Power corrections were generally about 0 to 1% (well under the 3% limit in SAE J1349-5.5.3) and significantly reduced repeat test variation at high engine speeds.

Barometric Pressure, Ambient Air Temperature and Humidity

The nominal barometric pressure at the lab was 83 kPa. A target temperature of 32°C was chosen for the test chamber air, with a tolerance of ±3°C. Temperature was held under the 35°C limit from SAE J1349-5.1. Humidity inside the chamber was controlled to a nominal absolute humidity level of 7.2 g/kg (50 grains/lb) of dry air.

Gasoline Fuel Properties

The properties of each test fuel used for this study were in conformance with 'Regular Fuel Grade' found in SAE J1349-5.2.

Test Points

Power was mapped in 250 or 500 rpm increments, in sequence from 1500 rpm to rated speed, subject to vehicle and dynamometer maximum speed limitations (per SAE J1349-7.5.2).

Stabilized Net Power

For steady state testing a 60 second stabilization period was followed by a 60 second log period for each engine speed, per SAE J1349-7.4.1 and 7.5.3. The resulting measurement was designated as "stabilized net power" and "Metric 3" in this paper. Engine speeds were well within the ±1% stabilization tolerance of SAE J1349-7.4.3. Control temperatures were generally within the ±2°C stabilization tolerance. Torque measurements on the chassis dynamometer often exceeded the ±1% tolerance specified for engine testing, likely due in part to powertrain controller, vehicle drive shaft and tire harmonic oscillations. Dyno roll torque variation was much larger than the roll speed variation ([Appendix A](#)). The naturally aspirated vehicles had lower torque variations than the turbocharged vehicles. The naturally aspirated vehicles produced torque variations under ±2% at low speeds and under the ±1% tolerance at mid-range and high speeds. The power oscillations evident in the time domain data were highly dependent on the vehicle under test, and therefore were not solely attributed to torque measurement noise or the signal filtering method.

Transient Net Power

Transient testing was performed at 1500, 2000, 3000, 4000 and 5000 rpm (or max engine speed) for each vehicle in the study, per SAE J1349-7.4.2. The vehicle was instantly commanded from a no-load stabilized condition to full-load while holding speed constant. Upon reaching 90% of stabilized power, a five second timer was followed by a 10 second data log per SAE J1349-7.5.3. The resulting measurement of momentary WP at this condition is designated as "transient net power" and "Metric 2". Transient net power was generally found to be significantly higher than stabilized net power. This is because fuel enrichment or spark timing retard may be employed as thermal protection strategies under stabilized conditions, to prevent damage as the engine runs continuously at full power. Transient net power is encountered during vehicle accelerations, whereas sustained high power operation is often associated with high road grade, cargo and tow weights.

Performance Metrics and Drive Cycle

Net power (and knock tendency) at transient full load operation may be different than at stabilized full load operation. This issue is acknowledged in J1349 Section 9: "These transient effects may permit the creation of control algorithms that temporarily increase brake horsepower and are representative of the power the end-user would obtain under similar, transient conditions. The traditional, steady-state test condition may yield lower net brake horsepower and torque for the same engine." Typical control algorithms include the use of spark timing retard and fuel enrichment to thermally protect the engine and catalysts under sustained high-power engine operation. Fuel enrichment will also reduce knock tendency under steady state full power conditions. All vehicles in the study utilized these type of control algorithms

For these reasons, the chassis dynamometer test procedures for this study incorporated both transient and stabilized operation at full power. A combined transient and stabilized segment is shown in [Figure 2](#). With the dynamometer operating in fixed speed control mode, the vehicle was instantly commanded from no-load to full-load by fully actuating the accelerator pedal. The absorbed wheel power climbed rapidly during this event. Power peaked shortly after the command, and then decayed to a stabilized value as thermal protection strategies were employed.

Three metrics were used to capture these transient performance and net power effects, and are illustrated on two time scales in [Figure 2](#):

- **Metric 1: Time to 90% of stabilized power.** This metric was used to provide qualitative information on transient performance for the turbocharged vehicles, giving an overall indication of load acceptance as the turbocharger spooled up after full load was commanded. Metric 1 was the time to achieve 90% of the lowest stabilized power observed for all tests run on the two fuels, at a given engine speed and for a specific vehicle. The 90% power threshold was calculated during post processing and held constant for all tests and fuels run on the vehicle.
- **Metric 2: Transient net power.** This metric was used to explore fuel effects during transient full power operation at five engine speeds. The metric was calculated using the time periods specified in SAEJ1349-7.4.3.
- **Metric 3: Stabilized net power.** This metric was used to quantify net power over the speed range of the engine. The effect of fuel AKI on knock tendency or power was not necessarily greatest at the peak torque speed, due to many electronic control system calibration possibilities. Therefore testing was conducted at a minimum of 12 engine speeds. The stabilization and calculation time periods from SAEJ1349-7.4.3 were used.

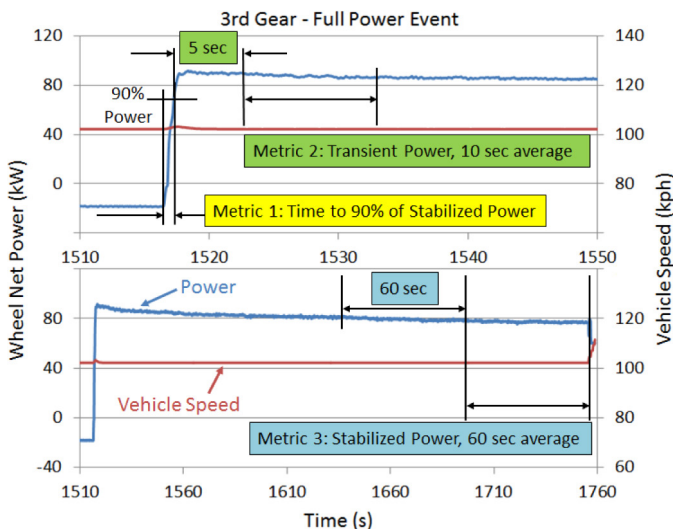


Figure 2. Metrics for Transient Performance and Net Power

The AKI of the fuel did not affect the transient load acceptance of the turbocharged vehicles. Therefore, for brevity Metric 1 results are not reported in this paper. Metric 2 and Metric 3 were used for a statistical analysis of wheel net power.

Preliminary tests were run to find vehicle speed and gear combinations that produced viable engine test speeds for each vehicle. Gear choice was constrained by excessive wheel slip on the dynamometer and a top dynamometer speed of 160 kph (100 miles/hour) due to equipment and laboratory safety limits. The test procedure was designed to detect small changes in power measurement at the interface between the drive-wheel and the chassis dynamometer. The vehicle was aligned and strapped in place by following standard procedures used for emissions testing such that tire contact force was controlled in the experiment [14].

A time-scripted dynamometer drive cycle was constructed for each vehicle to map the transient events and stabilized events in a single run (see example in [Figure 3](#)). Time scripting was used in favor of a stability tolerance gate to promote good test repeatability. Nevertheless, conformance with the stability criteria was factored into the drive cycle design. The drive cycle duration was approximately 1 hour and 40 minutes with the following features:

- Vehicle warm-up of 10 minutes at 96 kph (60 mph), compliant with SAE J1349-9.2.1.
- Five transient segments:
 - With the vehicle in a fixed gear, engine operation was changed from a no-load stabilized condition to full-load while holding engine and vehicle speed constant. This event is also known as load acceptance testing.
- Minimum of 12 full load steady state segments:
 - With the vehicle holding at full load, the dynamometer roll speed (vehicle speed) was changed to map power at successive engine speeds following stabilization.
- Cool-down periods serving two purposes: to provide a consistent no-load condition prior to each transient segment and to avoid thermal damage to the vehicle components and body parts.

The steps in [Figure 3](#) represent different engine speed mapping points. The drive cycle segments for each vehicle are shown in [Appendix B](#).

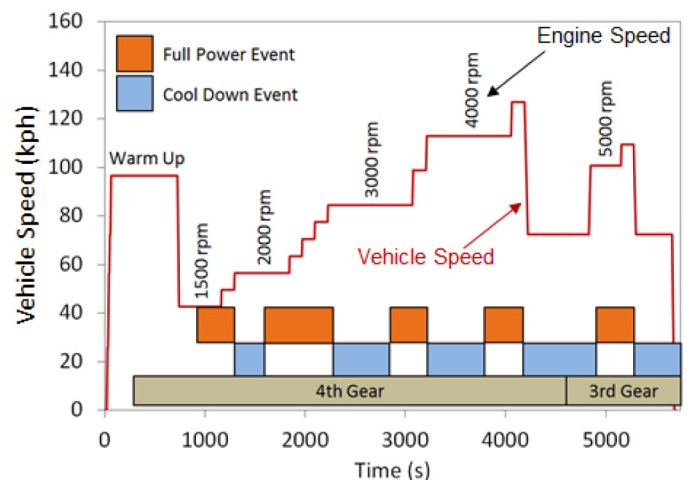


Figure 3. Chassis Dynamometer Drive Cycle - Dodge Dart

Test Repeatability and Wheel Slip

The Dodge Dart was run ten times over the dynamometer cycle shown in Figure 3 to explore test repeatability. These trial results were used to establish the number of replicates needed for evaluating the fuel effects.

There was evidence of wheel slip on the dynamometer even at steady state operation (Figure 4). The upper graph shows that following application of full load, the OBD vehicle speed sensor was about 0.5 kph (0.3 mph) higher than the roll speed indicating wheel slip. The speed discrepancy became greater with increasing power as shown in the lower graph.

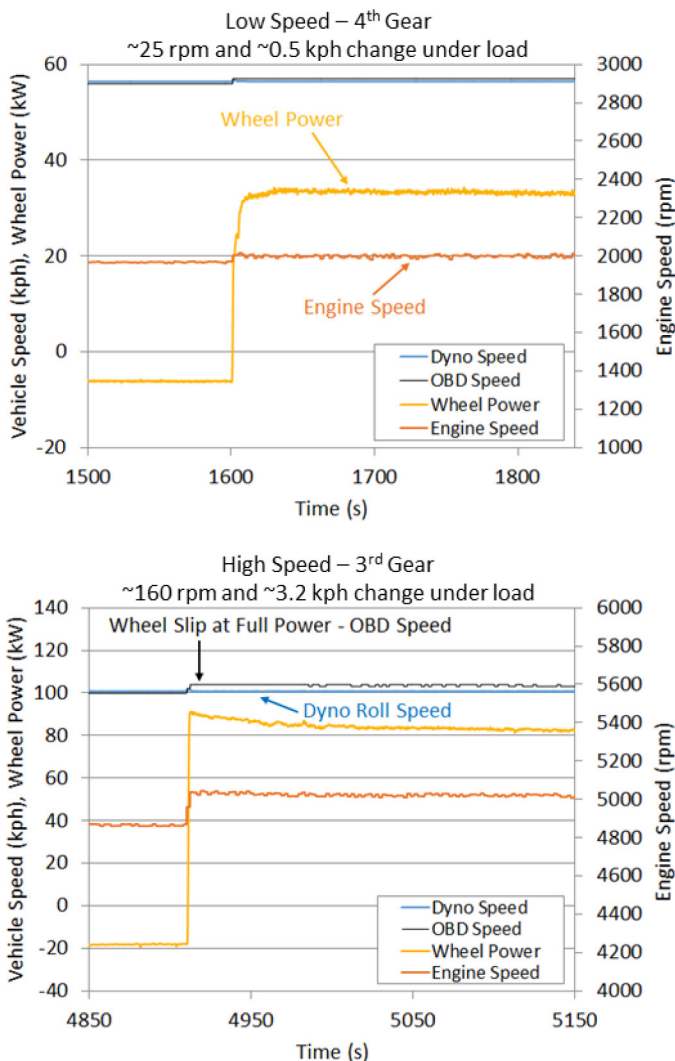


Figure 4. Wheel Slip during Full Power Events, at 2000 rpm (upper) and 5000 rpm (lower) Nominal Engine Speeds

The amount of wheel slip was found to be very repeatable from test-to-test. The results from ten measurements at each engine speed are shown in Figure 5. The variance of the measurements indicated that the wheel slip did not have a primary influence on stabilized net power measurement as shown in Appendix A. Whereas the highest variation in engine speed and wheel speed occurred at 5000 rpm due to wheel slip, the measured wheel power was more repeatable at this speed compared to lower speeds (COV of 1.7%). The data were

analyzed in a similar manner for all the test vehicles in the study, to verify that wheel slip was repeatable and was not adversely impacting the wheel power measurement. The COV was 0.12% and 0.07% on average for the Dodge Dart engine and vehicle speed, respectively.

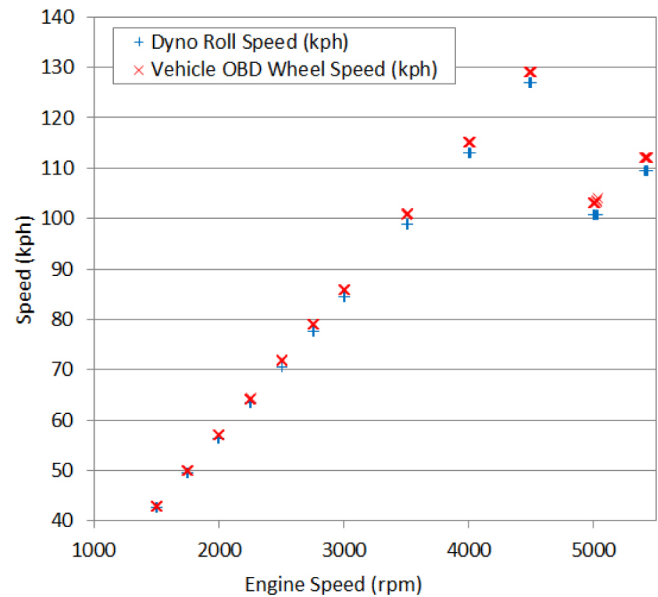


Figure 5. Wheel Slip Repeatability at Stabilized Net Power - 10 Tests

The wheel power COV generally improved as speed increased. Following implementation of the chassis dynamometer test procedures discussed here, the wheel power COV was further reduced as is evident via comparison with the fuel test results for the Dodge Dart (Appendix E).

TEST VEHICLES

SGS selected five vehicles to represent a range of engine technologies present on late model cars and light duty trucks. The vehicles were chosen from a list of candidate vehicle models provided by the USCAR FWG. SGS established the following criteria for vehicle recruitment:

- Minimum odometer of 6,400 km (4,000 miles)
- Never been in an accident and clean CarFax history
- No active or pending engine diagnostic codes
- No powertrain-related repairs
- Serviceable and safe tires of the correct size for the vehicle model
- No significant modifications by previous owner and no aftermarket equipment
- Manual transmissions
- No all-wheel drive vehicles (to allow testing on 2WD dynamometer)
- At least one vehicle with a turbocharged engine
- At least one vehicle with gasoline direct injection fuel system
- At least one light duty truck or sport utility vehicle

All five vehicles were from the 2015 model year and were acquired from the public fleet (Table 1). Three vehicles had turbocharged and intercooled engines and two were naturally aspirated. Three vehicles

had PFI and two had GDI fuel systems. All four aspiration-type and fuel injection-type combinations were represented. All vehicles were equipped with manual transmissions in order to perform maximum power mapping over the engine speed range. The Ford Focus had 5 speeds, and all others had 6 speed transmissions.

Table 1. Vehicles Tested

Year, Make and Model	Series	Displacement (L)	Cylinders and Induction	Fuel Injection	Emission Cert. Level	Compression Ratio
2015 Dodge Dart	Aero 4-Door Sedan	1.4	I-4 Turbo	PFI	Tier 2 Bin 5	9.8:1
2015 Ford Focus	SE 4-Door Hatchback	2.0	I-4 Nat. Asp.	GDI	Tier 2 Bin 3	12.0:1
2015 Chevrolet Cruze	ECO 4-Door Sedan	1.4	I-4 Turbo	PFI	Tier 2 Bin 4	9.5:1
2015 Volkswagen Golf	GTI S 4-Door Hatchback	2.0	I-4 Turbo	GDI	Tier 2 Bin 2	9.6:1
2015 Toyota Tacoma	TRD Pro 4-Door Dbl. Cab	4.0	V-6 Nat. Asp.	PFI	Tier 2 Bin 5	10.0:1

The Dodge Dart and Volkswagen Golf GTI had the highest power densities in the study, at 85 and 78 kW/liter respectively (Table 2). The Toyota Tacoma was chosen to include a truck with a larger-bore V6 engine. Knock tendency can increase with bore diameter, but may have been somewhat offset by this engine's lower power density of 44 kW/liter.

Table 2. Advertised Rated Power, Specific Power and Odometer for Test Vehicles

Year, Make and Model	Advertised Rated Net Power kW@RPM (HP@RPM)	Advertised Rated Torque Nm@RPM (lb-ft@RPM)	BMEP at Rated Torque bar (psi)	Specific Power kW/L (HP/L)	Specific Torque Nm/L (lb-ft/L)	Starting Odometer km (miles)
2015 Dodge Dart	119 @ 5500 (160 @ 5500)	249 @ 2500 (184 @ 2500)	22.4 (325)	85 (114)	178 (131)	21417 (13308)
2015 Ford Focus	119 @ 6500 (160 @ 6500)	198 @ 4450 (146 @ 4450)	12.4 (180)	60 (80)	99 (73)	10842 (6737)
2015 Chevrolet Cruze	103 @ 4900 (138 @ 4900)	201 @ 1850 (148 @ 1850)	18.0 (261)	74 (99)	144 (106)	39006 (24237)
2015 Volkswagen Golf	157 @ 4500 (210 @ 4500)	350 @ 1500 (258 @ 1500)	22.0 (319)	78 (105)	175 (129)	21778 (13532)
2015 Toyota Tacoma	176 @ 5200 (236 @ 5200)	361 @ 4000 (266 @ 4000)	5.6 (80.9)	44 (59)	91 (67)	30943 (19227)

TEST FUELS

The USCAR FWG specified and ordered the 85 and 87 AKI E10 fuels used for this study. The fuel specification and blending approach was the same as the CRC E-108 study [10] and the fuels were obtained from the same supplier (Gage Products Co., Ferndale, MI). From the CRC E-108 report, "Care was given to meet the targeted respective 85 and 87 AKI octane ratings of the two fuels while

minimizing differences in density, volatility, energy content and any other properties that may influence the combustion process and result in changes to engine efficiency and emissions." Approximately 4.5 volume% n-heptane and 0.4 volume% ethanol were added to the 87 AKI E10 blend to generate the 85 AKI E10 blend.

The fuels were shipped in drums from the supplier directly to SGS. The supplier's certificates of analysis were delivered with each fuel. A sample of each test fuel was taken by SGS and independently analyzed by the SGS Oil, Gas and Chemicals Division in Deer Park, Texas. The analysis results are shown in Table 3. SGS-OGC test results for octane, density and net heat of combustion closely matched the results reported on the supplier's COA. The 85 AKI and 87 AKI fuels had nearly the same energy density. Differences in fuel property measurements from those expected with addition of the n-heptane and ethanol were within the reproducibility limits of the specified test method.

Table 3. Test Fuel Properties

Property	ASTM Method	85 AKI Result		87 AKI Result	
		COA	SGS	COA	SGS
Research Octane Number	D2699	87.5	87.4	90.3	90.2
Motor Octane Number	D2700	82.5	82.8	84.3	84.5
Antiknock Index (R+M)/2	-	85.0	85.1	87.3	87.4
Sensitivity (R-M)	-	5.0	4.6	6.0	5.7
Density @ 15.56°C, g/ml	D4052	0.7337	0.7338	0.7389	0.7398
Net Heat of Combustion, MJ/kg	D240	42.22	42.37	41.98	42.17
Carbon Content, wt%	D5291	81.86	-	81.96	-
Hydrogen Content, wt%	D5291	14.45	-	14.47	-
Oxygen Content, wt%	D4815	3.69	-	3.57	-
Ethanol Content, vol%	D4815	9.82	-	9.6	-
Sulfur Content, ppm	D5453	< 1	-	< 1	-
RVP @100°F, kPa	D5191	56.77	-	58.15	-
Aromatic Content, vol%	D1319	9.1	-	12.7	-
Olefin Content, vol%	D1319	6.2	-	6.6	-
Saturate Content, vol%	D1319	74.9	-	71.1	-
Distillation, 10%, °C	D86	56.2	-	56.8	-
Distillation, 50%, °C	D86	99.8	-	103.8	-
Distillation, 90%, °C	D86	157.4	-	157.8	-

EXPERIMENTAL DESIGN AND ANALYSIS APPROACH

The independent variables for this study were the vehicle model (5 vehicles tested), the fuel type (85 AKI and 87 AKI fuels), and engine speed. The dependent variables were transient net power and stabilized net power.

For each vehicle, the fuel type was alternated for consecutive test sequences. A rigorous fuel drain, refill and conditioning process was performed to minimize carry-over effects from the previous fuel. The process consisted of the following steps and required about 3 to 4 hours to complete:

1. Drain fuel from rail or fuel supply line
2. Key on for 30 seconds to confirm tank empty using fuel gage
3. 25% fill with new fuel
4. Start and idle for 2 minutes
5. EPEFE cycle (10xWOT) run and idle for fuel adaptation [15]

6. Drain fuel
7. 25% fill with new fuel
8. Start and idle for 2 minutes
9. Drain fuel
10. 100% fill with new fuel
11. LA4 prep cycle for fuel conditioning

Data collected during the test procedure development were used to estimate that six replicates were needed for each vehicle-fuel combination in order to detect small power differences. A test plan was created to randomize test order within the practical constraints of a laboratory operation. The fuel type was alternated for consecutive test days. The order of vehicle testing was random on a given day. Dart, Focus and Cruze testing was completed over a one month period. The Golf and Tacoma testing began three weeks later and was completed in eleven days.

Due to the length and cost of the fuel change process described, a “pairwise-alternating” test sequence was adopted as outlined in Table 4. The fuel type was changed once per day, and Test #1 and Test #2 dyno test cycles were performed on the same day. The vehicle warm-up was performed before Test #1 and Test #2, to ensure similar vehicle operation and temperature conditioning prior to making the power measurements.

Table 4. Test Sequence for Each Vehicle

Test Order	6 Repeat Tests for each Vehicle-Fuel Combination Fuel Change and Dyno Set-up is Pairwise Alternating
Day 1	Fuel A: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel A
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle
Day 2	Fuel B: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel B
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle
Day 3	Fuel A: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel A
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle
Day 4	Fuel B: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel B
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle
Day 5	Fuel A: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel A
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle
Day 6	Fuel B: Drain/Fill/Conditioning Process
	Vehicle Warm-up
	Test #1 Transient + Net Power Dyno Test Cycle
	Brief soak period and vehicle refueling using Fuel B
	Vehicle Warm-up
	Test #2 Repeat of Transient + Net Power Dyno Test Cycle

A pairwise t-test was performed to confirm that there was no statistically significant difference between the stabilized net power measurements made for Test #1 and Test #2 (Table 5). Based on this confirmation, the pairwise-alternating test sequence in Table 4 was adopted and Test #1 and Test #2 results were treated as equivalent observations in the statistical analysis.

Table 5. Test Order Analysis - Pairwise t-Test Results for Stabilized Net Power (kW)

H0: Mean of Paired Differences (Test #1 - Test #2) = Zero			
H1: Mean of Paired Differences (Test #1 - Test #2) not equal to Zero			
p-value (probability of Type I Error)			0.408
Confidence that Mean of Paired Differences (Test #1 - Test #2) not equal to Zero			59.2%
Summary Statistics			
	Test #1	Test #2	Paired Differences
Mean	85.005	85.061	-0.056294
StDev	37.524	37.582	1.3007
Count	366	366	366

Statistical Analysis and Outliers

A statistical analysis was performed to determine if the fuel AKI effects on net power were statistically significant. An analysis was performed independently for stabilized net power and transient net power responses.

The wheel net power measurements were centrally distributed and approximated a Gaussian distribution, enabling the use of statistical methods with normality assumptions (Figure 6).

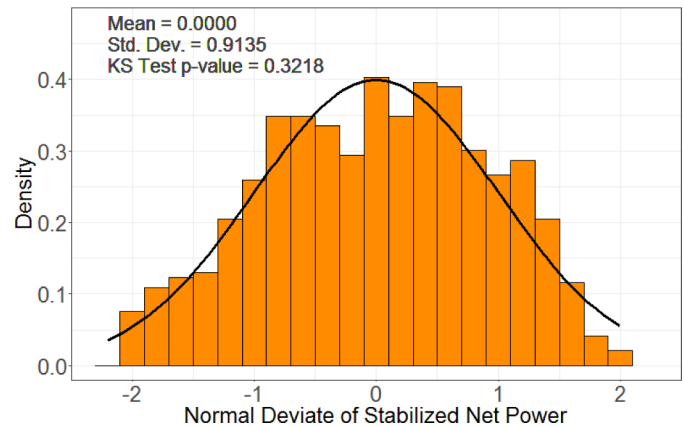


Figure 6. Normalized Distribution of Stabilized Net Power Measurements for All Vehicles and Tests, Compared to Normal Probability Density Function

The analysis approach focused on individual vehicle effects. No attempts were made to pool the data to make conclusions about the test fleet.

A two-tailed Student's t-test was performed to compare the difference in mean values at each engine speed. There were six observations for each vehicle-fuel combination. The hypotheses tested were:

- Null Hypothesis H0: (85 AKI Mean Net Power - 87 AKI Mean Net Power) = 0. A small p value (≤ 0.05) indicates strong evidence against the null hypothesis, so it would be rejected.