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ABSTRACT

An appropriate test procedure, based on a duty cycle representative of real in-use operation, is an essential tool for characterizing engine emissions. A study has been performed to develop and validate a snowmobile engine test procedure for measurement of exhaust emissions.

Real-time operating data collected from four instrumented snowmobiles were combined into a composite database for analysis and formulation of a snowmobile engine duty cycle. One snowmobile from each of four manufacturers (Arctic Cat, Polaris, Ski-Doo, and Yamaha) was included in the data collection process. Snowmobiles were driven over various on- and off-trail segments representing five driving styles: aggressive (trail), moderate (trail), double (trail with operator and one passenger), freestyle (off trail), and lake driving. Statistical analysis of this database was performed, and a five-mode steady-state snowmobile engine duty cycle was developed.

A test procedure, based on this five-mode duty cycle, has been defined, addressing requirements specific to snowmobile engines. A round-robin testing program was conducted by International Snowmobile Manufacturers Association (ISMA) member companies to validate and further develop this test procedure. Supporting emissions test results and analysis are presented on two snowmobile engines tested at six different laboratories.

THE 1990 AMENDMENTS TO THE CLEAN AIR ACT broadened the scope of U.S. EPA rulemaking authority to include nonroad engines and vehicles. Similar actions are under consideration world-wide. This attention has encouraged the emission testing of snowmobile engines, most of which had previously been done using the J1088 small utility engine test procedure due to the lack of a specific snowmobile engine test procedure.

In response to the developing interest in snowmobile emissions, the International Snowmobile Industry Association (forerunner of the International Snowmobile Manufacturers Association, or ISMA, which represents all snowmobile manufacturers) launched an effort to develop a representative test procedure for the measurement of exhaust emissions from snowmobile engines. Southwest Research Institute (SwRI) was contracted to determine operating parameter data for snowmobiles under a variety of real-world operating conditions. SwRI applied statistical analysis to this database to determine representative operating points and weight factors, which were used to create a five-mode test cycle. This cycle was combined with the emissions measurement procedure defined in the U.S. EPA Marine Spark-Ignition Engine rule (40 CFR Part 91)(1)[*] to create a representative snowmobile emission test procedure. Round-robin testing was conducted on two snowmobile engines to refine and validate the procedure.

BACKGROUND — SNOWMOBILE ENGINES

Conventional snowmobiles are powered by two-stroke cycle spark-ignited engines, which offer the high power output and light weight necessary to achieve acceptable driveability of a tracked vehicle through heavy snow. Two-stroke engines also offer excellent cold weather starting in temperatures as low as –40°C. When properly tuned, these engines have a torque curve uniquely suited for a belt-type continuously variable transmission drivetrain.

A snowmobile engine is typically configured with two or three cylinders in line, using crankcase compression charging, loop scavenging, and a pulse-tuned exhaust system. Cooling is by either air or liquid. The induction system is either piston port, rotary valve, or reed type, and the fuel system typically employs either carburetion or electronic fuel injection. The exhaust system is usually composed of one or more tuned pipe(s) followed by a muffler.

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[*] Subscript numbers in parentheses indicate references at end of paper.

The tuned pipe is vital to a snowmobile's performance. The pipe is composed of a divergent cone followed by a center section and a convergent cone, and functions by reflecting pressure waves in the exhaust system. When the exhaust port opens, a pressure wave enters the divergent cone, and an expansion wave is reflected back into the cylinder, which evacuates the exhaust and draws fresh charge into the cylinder and exhaust port. When the pressure wave reaches the convergent cone, a pressure wave is reflected back toward the cylinder, which forces most of the fresh charge in the exhaust port back into the combustion chamber. This design offers maximum charging efficiency and lower brake-specific emissions at peak power. A well designed muffler is located downstream of the tuned pipe for noise suppression.

At lower engine speeds, the timing of these pressure waves is no longer optimal, resulting in a loss of engine torque. Since the performance of the engine is dependent on speed, the engine is said to have a *power band*. The clutch on the snowmobile is designed to maintain engine speed in this power band most of the time, to achieve maximum vehicle performance.

Hydrocarbon (HC) emissions from snowmobile engines generally originate from scavenging losses, which occur when fresh charge escapes from the combustion chamber during the scavenging process. Snowmobile engines run rich of stoichiometric to reduce peak combustion temperatures and prevent piston seizure. This results in increased emissions of carbon monoxide (CO). Lastly, at low throttle settings, increased residual exhaust in the cylinder can produce occasional misfires, emitting some additional hydrocarbon. The lubricating oil is also burned in the combustion chamber, and occasionally produces a visible exhaust plume; however, lubricating oil makes an insignificant contribution to hydrocarbon emissions. Two-stroke engines operate with low effective compression ratios, rich fuel air mixtures, and high residual exhaust concentrations. All these factors contribute to lower peak combustion temperatures, resulting in very low emissions of oxides of nitrogen (NO_x).

Most advances in snowmobile engine technologies over the last twenty years have had a positive effect on emissions. These included improved scavenging, mechanical oil injection, electronic fuel injection, exhaust valves, electronic ignition, altitude compensating carburetors, and liquid cooling.

DEVELOPMENT OF SNOWMOBILE ENGINE TEST CYCLE

The International Snowmobile Industry Association (ISIA) contracted with Southwest Research Institute to determine operating parameter data for snowmobiles, based on on-board measurement of engine speed, torque, and other parameters, under a variety of representative operating conditions. Four snowmobiles were provided by Arctic Cat, Bombardier (Ski-Doo), Polaris, and Yamaha. The snowmobiles were instrumented with portable data acquisition systems designed for field operation. Testing was conducted in the Michigan Upper Peninsula, near Houghton, from February 27 through March 3, 1995. Snowmobiles were driven over various on- and off-trail segments representing five driving styles: aggressive (trail), moderate (trail), double (trail with operator and one passenger), freestyle (off-trail), and lake driving. Following collection, snowmobile data were collated and analyzed to develop a representative snowmobile engine test cycle.

SNOWMOBILES TESTED – Each of the four manufacturers provided a snowmobile which was considered representative of current industry sales. Arctic Cat described its Panther model as a family/rental unit. Polaris described its XLT model as a trail/high-performance unit. Yamaha described its Vmax 600V as a sports model. Ski-Doo described its Formula S as a sport/utility model. Details of snowmobiles tested are summarized in Table 1. All four snowmobiles were powered by 2-stroke engines.

INSTRUMENTATION – The snowmobile powertrain consists of a transversely-mounted engine, coupled to a belt-type continuously variable transmission consisting of a drive clutch and a driven clutch. The driven clutch transmits power to the track through a driven shaft (jackshaft), which is parallel to the engine at the rear of the engine compartment. The driven shaft is connected to a chain reduction unit, which drives the rubber track that propels the snowmobile. Each of the four snowmobiles was instrumented to measure:

Table 1. Snowmobiles Tested

Manu-facturer	Arctic Cat	Polaris	Ski-Doo	Yamaha
Model	Panther	XLT	Formula S	Vmax 600V
Model Year	1995	1995	1995	1994
Capacity, riders	2	1	1	1
Engine Manufac-turer	Suzuki	Fuji	Rotax	Yamaha
Displace-ment, cc	440	579	503	600
No. of Cylinders	2	3	2	2
Cooling System	Fan	Liquid	Fan	Liquid
Induction System	1 Mukini carburetor	3 Mukini carburetors	2 Mukini carburetors	2 Mukini carburetors
Weight, lbs (dry)	509	504	430	507

- Engine speed, rpm
- Driven shaft speed, rpm
- Driven shaft torque, lb-ft
- Throttle position, % of max.
- Steering angle, degrees
- Exhaust temperature, °F
- Ambient temperature, °F

The primary goal of the project was to obtain information about engine operation under representative operating conditions. Ideally, this would be obtained by direct measurement of engine speed and torque. Due to the close-coupling of the engines to the drive clutch, there was insufficient space available for installation of a strain-gauge to measure engine output shaft torque. Instead, torque measurement was accomplished using strain gauges mounted on the driven shaft. Following removal and surface preparation of the driven shafts, paired strain gauges were applied 180° apart. This arrangement allowed the compressive and tensile strains which result from shaft bending to cancel each other, so that the gauge sets sensed torsional strains only. Strain gauges utilized were self temperature compensated. Torque information was transmitted from the instrumented shaft to an underhood receiver using an RF-type torquemeter.

Engine speed was measured by conditioning the pulsed output from each snowmobiles alternator/lighting coil and supplying this signal to the data recorder, which converted the frequency input to rpm. Driven shaft speed was measured with an Arctic Cat-supplied, 6-tooth, magnetic pickup assembly, which also utilized a conditioning circuit to supply a pulsed signal to the data recorder.

Steering and throttle position measurements were obtained using rotary potentiometers. Temperatures were measured with 3.2 mm, closed-end, Type K thermocouples. Operating data were recorded at 5 Hz using a Campbell Scientific data recorder.

FIELD TESTING PROGRAM – Snowmobile engine operating conditions vary widely, depending on the type of riding done. In addition, the speed and riding style of a group, trail condition, and terrain type also greatly influence snowmobile operation. The condition of the snow, whether hard-packed or fresh, also affects engine load. Some snowmobiles can accommodate two riders, which increases engine load significantly, compared to single rider operation.

It was estimated by ISIA that approximately 90 percent of snowmobile operation is on-trail, and that off-trail operation represents only about 10 percent of operation. A field test program was designed to acquire operating data under the most typical types of operation including:

- Trail riding, straight
  - moderate and aggressive riding styles
- Trail riding with hills and turns
  - moderate and aggressive riding styles
- Lake riding, moderate speeds
- Lake riding, higher speeds
- Freestyle riding, off-trail.

Data with double rider operation was also obtained.

Testing was conducted in the Michigan Upper Peninsula near Houghton, from February 27 through March 3, 1995. This area was selected due its excellent snow conditions and its very extensive snowmobile trail system. Data were taken on the Keweenaw Trail and the South Gay Trail. Lake runs were performed on the southern section of Torch Lake, adjacent to the Keweenaw Trail.

Operating cycle data were obtained on each sled, operated in turn by its company representative, over the same trail segments. All drivers were given the same driving instructions in attempts to achieve reasonably consistent operation from sled-to-sled. Forty-one data files were generated at the winter site.

ANALYSIS OF REAL-TIME OPERATING DATA – Operating data collected from the four instrumented snowmobiles were combined into a composite database and categorized into five driving styles: aggressive (trail), double (trail with one passenger), freestyle (off-trail), lake driving, and moderate (trail). The three primary response variables (speed, power, and torque) were normalized so that all the data could be compared on similar scales. The analysis of the data included an investigation of whether the measured data from the snowmobile runs required a smoothing treatment. Also, weighting factors were used on the composite database to reflect the estimated percentage of time drivers operate their snowmobiles in each of the five defined driving styles. Following the smoothing and driving style weighting analyses, a series of frequency histograms were generated on the composite database for normalized speed and normalized torque response variables in order to locate conditions best representing snowmobile operation.

COMPUTATIONS FOR NORMALIZING VARIABLES – In order to merge all the snowmobile data into a composite database, the response variables were normalized to individual snowmobile target values. Three response variables were considered in the normalization process: power, speed and torque. Each of these three responses was computed from the measured data values for each snowmobile run using the following conversion formulas:

$$\text{Normalized Speed} = \text{Engine Speed}/s$$

$$\text{Normalized Power} = [(\text{Driven Shaft Speed} * \text{Driven Shaft Torque})/5252]/p$$

$$\text{Normalized Torque} = [(\text{Driven Shaft Speed} * \text{Driven Shaft Torque})/\text{Engine Speed}]/t$$

where s, p, and t are constants representing maximum steady speed, power, and torque by snowmobile model.

Rated speed and power of an engine are defined by its manufacturer from laboratory test data. However, in a field study, each engine and drivetrain combines to produce a measurable maximum steady torque and speed. Therefore, for this study, we defined rated speeds and torques as the maximum steady torque and speed observed for each engine-drivetrain combination. This was preferred to deriving these constants from manufacturer ratings because constants derived from the field data accurately reflect the performance of these specific engines as operated at the winter site.

Separate relative frequency histograms were generated for the normalized speed, power, and torque response variables. Generically, the histogram divides the response variable into equal intervals and counts the number of observations (frequency) in each "bin." This bin count is then divided by the total number of observations to produce a percentage of the total (relative frequency) occupying each bin. Thus, the x-axis represents the bin intervals and the y-axis represents the percentage of observations in each bin.

Figures 1 through 6 illustrate the relative frequency histograms for the normalized speed data. The entire database is represented in Figure 1, where the majority of the data are in the 70 to 90 percent normalized speed range. The data are broken down by driving style in Figures 2 through 6. Notice that the distributions of freestyle and lake driving are similar, with a large part of their data clustered around 1.0 (100% of maximum steady speed). Also, note the differences in moderate and aggressive driving. As expected, normalized speed for moderate driving is grouped around 60 to 80 percent, while the aggressive driving style has data gathered nearer to 80 to 100 percent of maximum steady speed.

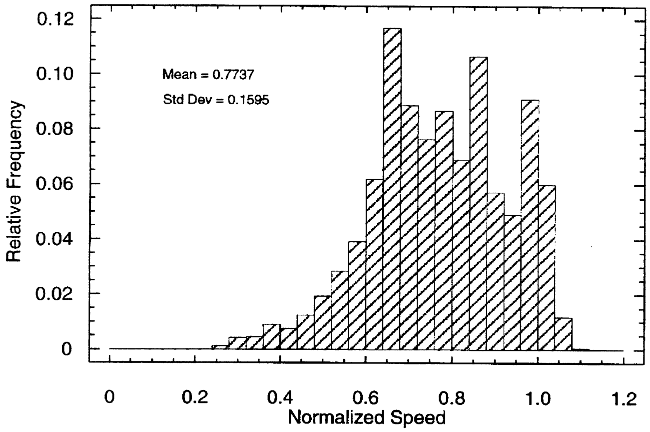

Figure 1. Relative Frequency Histogram for Normalized Speed - All Data

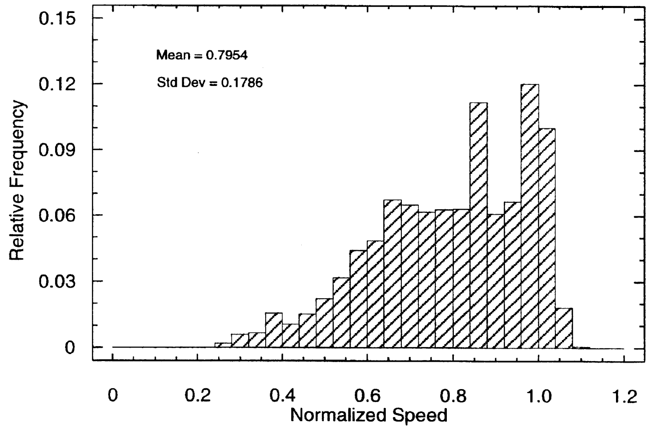

Figure 2. Relative Frequency Histogram for Normalized Speed - Aggressive Driving

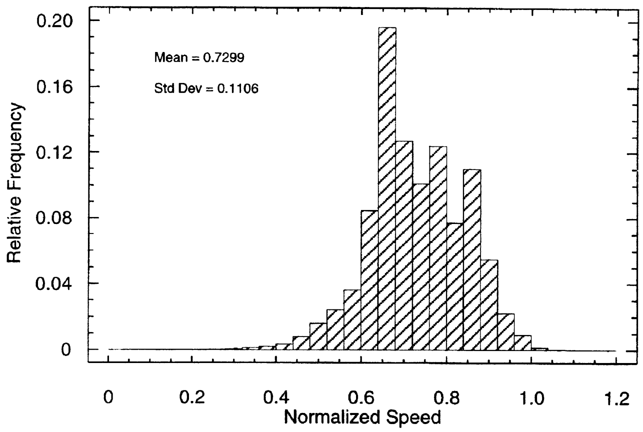

Figure 3. Relative Frequency Histogram for Normalized Speed - Moderate Driving

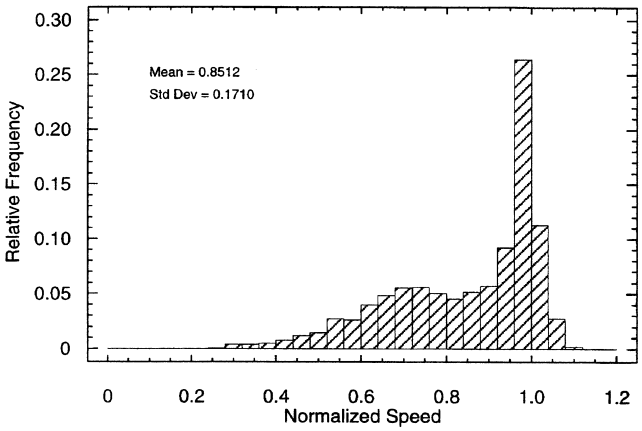

Figure 4. Relative Frequency Histogram for Normalized Speed - Freestyle Driving

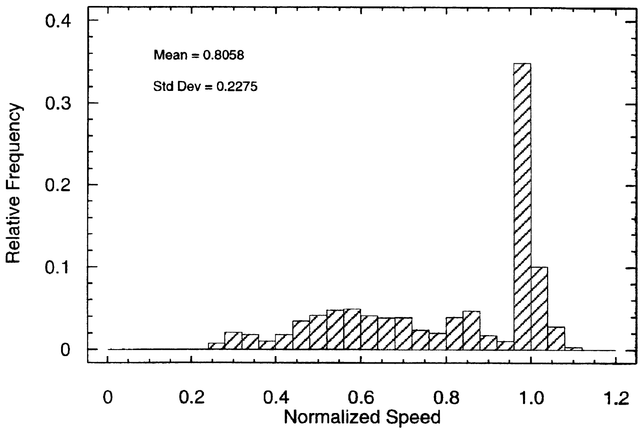

Figure 5. Relative Frequency Histogram for Normalized Speed - Lake Driving

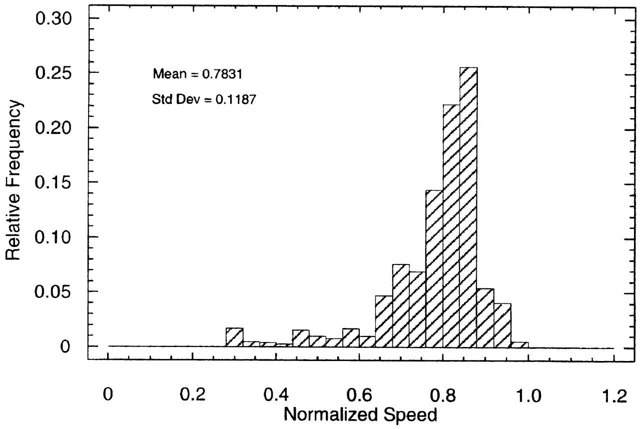

Figure 6. Relative Frequency Histogram for Normalized Speed - Double Driving

Normalized power histograms are illustrated in Figures 7 through 12, with the composite across all driving styles shown in Figure 7. Again, freestyle and lake driving revealed similar distributional shapes with two areas of grouping; one near 0 and one near 100 percent. Moderate driving clustered around 20 percent, as shown in Figure 12.

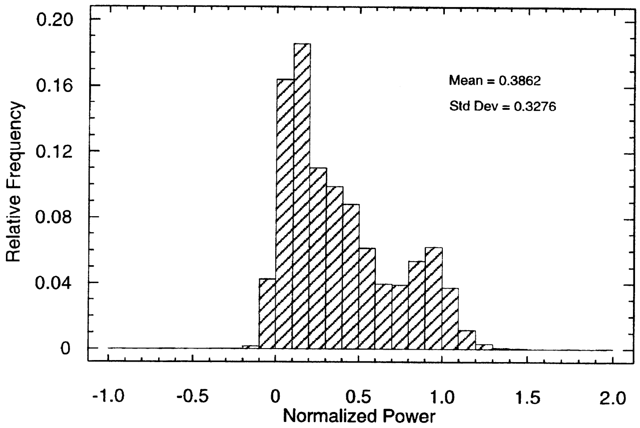

Figure 7. Relative Frequency Histogram for Normalized Power - All Data

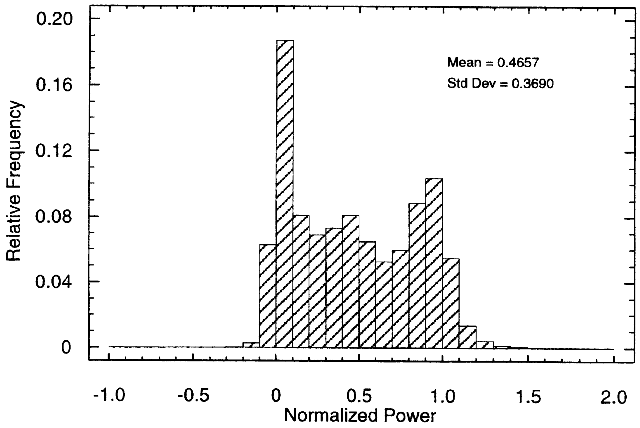

Figure 8. Relative Frequency Histogram for Normalized Power - Aggressive Driving

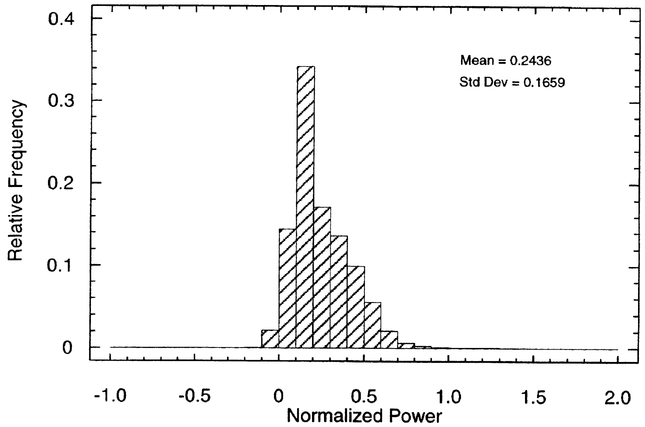

Figure 9. Relative Frequency Histogram for Normalized Power - Moderate Driving

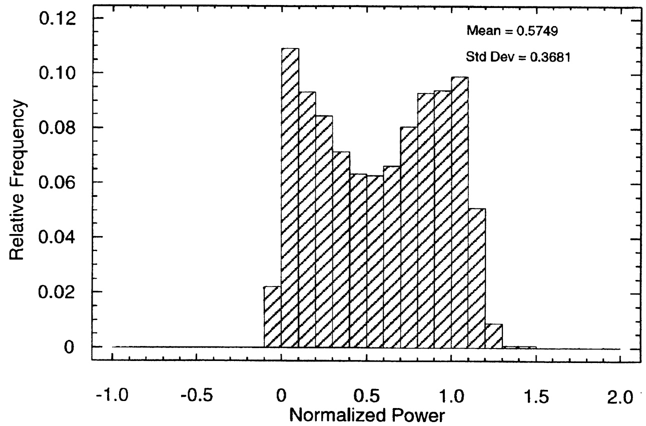

Figure 10. Relative Frequency Histogram for Normalized Power - Freestyle Driving

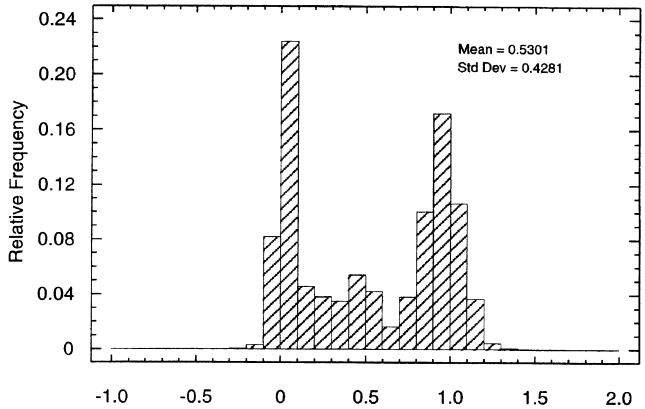

Figure 11. Relative Frequency Histogram for Normalized Power - Lake Driving

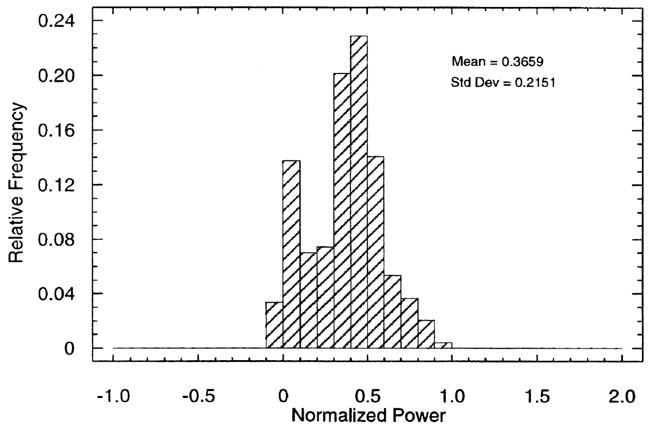

Figure 12. Relative Frequency Histogram for Normalized Power - Double Driving

Table 2. Description of CARB J1088 Test Cycle

J1088 Mode	**1**	**2**	**3**	**4**	**5**	**6**
Speed, % of Rated	85	85	85	85	85	Idle
Load, % of Max.	100	75	50	25	10	0
Weight Factor	9%	20%	29%	30%	7%	5%

Because the times actually spent in the field study operating the sleds in the defined driving styles did not represent the snowmobiling population, correction factors were applied to the field data to properly weight each style's contribution to the database. Ideally, population driving style percentages would be derived from a study of actual snowmobile usage, however, such data were not available. Thus, target driving style percentages were based on industry experience.

COMPARISON WITH J1088 TEST CYCLE – The J1088 test cycle (Table 2) has been used in the past for measuring snowmobile emissions. To determine whether this cycle is appropriate for snowmobiles, composite snowmobile operating data (weighted and smoothed) were compared with the CARB J1088 test cycle and mode weight factors. Table 3 lists the frequency counts and percentages of the total for normalized speed and normalized torque values, segregated into speed and torque intervals similar to the J1088 test cycle.

Data grouped in the normalized speed range of 0.75-0.95 are comparable to the 85 percent of rated speed setpoint in the J1088 test cycle. The normalized torque intervals were also chosen to reflect modes 1 through 5 of the J1088 test cycle. Using these subdivisions, only 41.1 percent of the operating data fall in the 85 percent (0.75-0.95) rated speed range, and over 46 percent of the data occur at normalized speeds less than 0.75. This clearly indicates that a multiple speed scenario is needed to accurately classify the snowmobile data. Additionally, if we consider only the data in the 85 percent rated speed range, the percentages of operating time spent at the various torque conditions strongly disagree with the J1088 mode weight factors as shown in Table 4. A chi-square goodness-of-fit test was performed to determine whether the collected operating data percentages in the 85 percent rated speed range are similar to the J1088 test weight factors. At the 5 percent level of significance, the chi-square goodness-of-fit test rejects the hypothesis that the collected data have mode percentages statistically similar to the J1088 weight factors.

RECOMMENDED SNOWMOBILE ENGINE TEST CYCLE – In order to determine which normalized speed (nspeed) and torque (ntorque) combinations would be appropriate for a steady-state test cycle, smoothed nspeed and ntorque were divided into 0.05 (5%) intervals to provide a detailed view of operating modes. The frequency counts were determined and plotted as a three-dimensional histogram as shown in Figure 13. Note the multiple peaks at high torque and high speed conditions, medium torque and medium-high speed conditions, and low torque and medium speed conditions. A frequency table of this data was analyzed, and five areas of peak operating mode frequencies were identified.

Test cycle setpoints were determined as the mean values for the smoothed nspeed ranges, and the weighted mean values for smoothed ntorque ranges. Mode weight factors were determined by dividing total frequency counts in each of the five clusters by the sum of all frequency counts, and proportionately increasing each factor to provide a total weight factor of 100 percent.

Table 3. Frequency Counts and Percent of Total for Smoothed Normalized Speed and Smoothed Normalized Torque Ranges

Normalized Speed	**Frequency Counts and (Percent of Total) for Normalized Torque Ranges**						
	0-0.05	**0.051-0.175**	**0.1751-0.375**	**0.3751-0.625**	**0.6251-0.875**	**> 0.875**	**Total**
< 0.75	7469.8 (7.79)	10737 (11.19)	24638 (25.69)	1572.2 (1.64)	86.88 (0.09)	209.27 (0.22)	44713 (46.62)
*0.75-0.95	149.22 (0.16)	484.02 (0.50)	8303.7 (8.66)	24432 (25.47)	5368.7 (5.60)	693.73 (0.72)	39431 (41.11)
> 0.95	0 (0)	0 (0)	11.86 (0.01)	450.52 (0.47)	3177.2 (3.31)	8125.8 (8.47)	8125.8 (8.47)
Total	7619.05 (7.94)	11220.7 (11.70)	32953.3 (34.36)	26454.8 (27.58)	8632.72 (9.00)	9028.78 (9.41)	95909.4 (100)
* Represents J1088 speed							

Table 4. Frequency Counts and Percentages of J1088 Torque Levels at 85 Percent of Rated Speed

J1088 Mode	1	2	3	4	5	6
Torque, %	100	75	50	25	10	0
Normalized Speed, 0.75-0.95	693.73 1.8%	5368.7 13.6%	24432 62.0%	8303.7 21.1%	484.02 1.2%	149.2 0.3%
J1088 Weight, %	9.0	20.0	29.0	30.0	7.0	5.0%

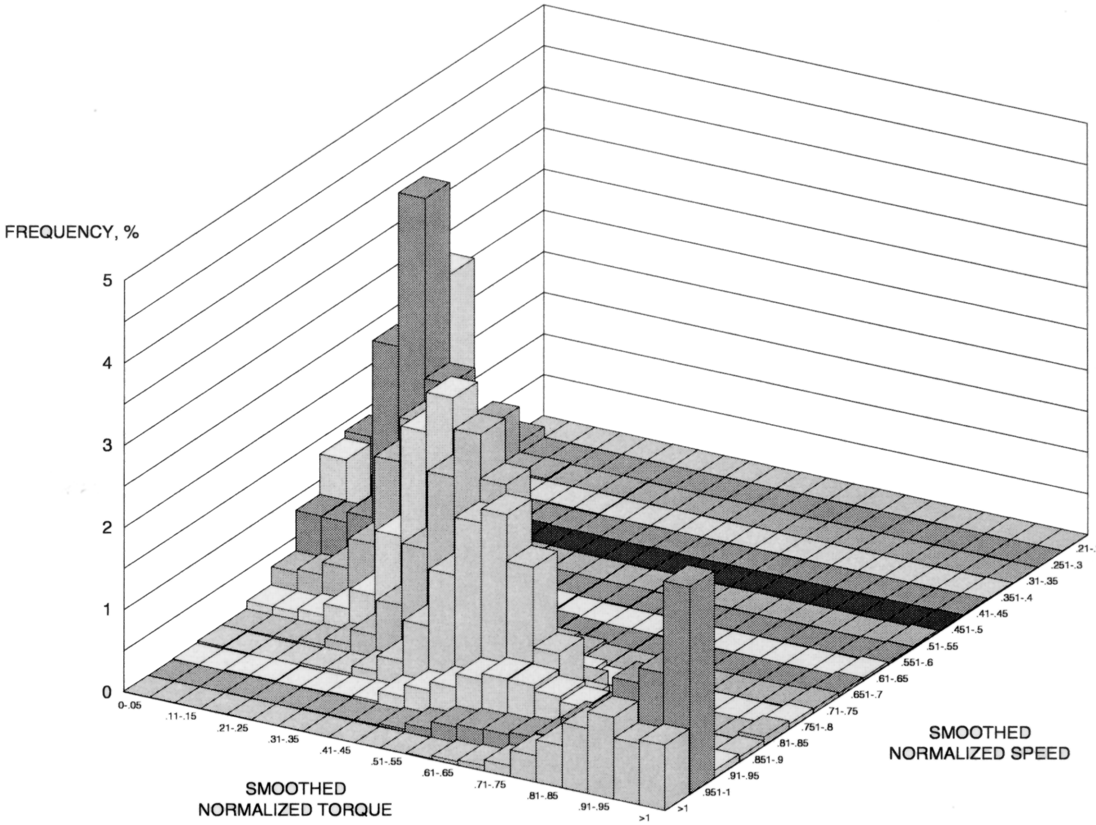

Figure 13. Three-Dimensional Histogram of Smoothed Normalized Speed by Smoothed Normalized Torque

The matter of an idle mode had to be addressed separately because there was very little idle operation in the field data. This is consistent with most user practice where the snowmobile is started when the operator is ready to go, and shut off for anything other than a brief stop. For reference, the idle speeds of the four snowmobiles in the field study are given in Table 5.

It was decided to incorporate idle in the test cycle by combining idle with other lower speed operation in mode 5. To allow for the normal variation between different engine makes and models, it was decided to define mode 5 as a no-load, idle speed mode, rather than to arbitrarily specify a higher speed. A five percent weight factor was assigned for this mode. The recommended snowmobile test cycle, incorporating these adjustments, is shown in Table 6.

Table 5. Snowmobile Idle Speeds

Snowmobile	Idle Speed	
	rpm	Nspeed
Arctic Cat	2100	0.31
Polaris	2400	0.29
Ski-Doo	2200	0.32
Yamaha	2300	0.30

Table 6. Recommended Snowmobile Engine Test Cycle

Mode	1	2	3	4	5
Nspeed	1.0	0.85	0.75	0.65	Idle
Ntorque	1.0	0.51	0.33	0.19	0
Weight, %	12	27	25	31	5

Test modes are to be run in order, from highest to lowest speed. In this study, 1.0 nspeed was defined as the maximum steady engine speed in snowmobile operation. Since this value cannot be determined in an engine test (without the snowmobile drivetrain), this value will have to be specified by the snowmobile manufacturer. Ntorque values are then determined as a fraction of maximum (WOT) torque observed at 1.0 nspeed.

DEVELOPMENT OF SNOWMOBILE ENGINE TEST PROCEDURE

INCORPORATION OF THE MARINE EMISSIONS MEASUREMENT PROCEDURE – A number of emissions measurement procedures have already been developed that could be appropriate for snowmobiles, provided the correct test cycle were used. These include the International Standards Organization (ISO) 8178 Test Procedure(2), ICOMIA Standard No. 34-88 for marine engines(3), and the EPA test procedures established for small utility engines(4), and for spark-ignited marine engines.(1) It was decided to incorporate one of these existing procedures into the snowmobile engine emission test procedure. EPA's marine engine test procedure was of particular interest because it has been used for a number of years to test similar types of two-stroke engines, such as are used in personal watercraft. A number of changes are necessary to adjust the EPA marine procedure for use with snowmobile engines. Most importantly, the snowmobile test cycle must be substituted for the marine cycle.

ENGINE SET-UP – Snowmobiles are designed to run in cold weather with dense intake air. Inlet air conditions have an effect on both power and emissions. Most carbureted snowmobile engines require a main jet change with significant changes in ambient temperature and/or altitude. Improper jetting can result in poor performance, spark plug fouling, or engine seizure. Given a certain jetting, an increase in temperature will cause a reduction of power and an increase in CO and HC emissions.

To obtain repeatable test results, it is critical to use proper jetting and correct atmospheric conditions. Atmospheric conditions in a test cell are usually different than those found on the manufacturers' jet charts and conditions for which the engine was designed to operate. Extrapolation from the jet chart is necessary to adapt the engine for test cell operation, but extrapolation is valid for only for one or two jet sizes beyond the jet chart. Additionally, obtaining representative temperatures in an engine test cell can be very expensive, particularly in test laboratories not dedicated to snowmobile engine testing.

An inlet air temperature between 10°C and 20°C is recommended for snowmobile engine testing. The engine must be jetted for the temperature of the inlet air and the barometric pressure of the test cell. Extrapolation from the jet chart shall be performed (when necessary) by graphing jet size as a function of temperature, and passing a straight line through the two end points.

The tuning characteristic of the exhaust pipe is a function of exhaust temperature. These pipes are designed for peak performance with air blowing over them from vents in the snowmobile hood. It is recommended to use a fan or a blower to cool the pipe. Air stream velocity should be between 10 and 15 m/s, covering a majority of the projected area of the pipe(s). Air flow direction should be opposite to the direction of vehicle travel.

DYNAMOMETER REQUIREMENTS – Snowmobile engines can be difficult to run on a dynamometer because engine torque increases sharply as the speed of the engine approaches its power band. This may create an unstable condition for the dynamometer controller. Snowmobile engines tend to oscillate or behave erratically on certain types of dynamometers, such as most water-brake models.

Nearly all current production snowmobile engines produce between 20 and 130 kilowatts of power, with maximum speeds approaching 9000 rpm. A mid-sized (150 kW) high speed (10,000 rpm) eddy current dynamometer is recommended for snowmobile engine testing.

EMISSIONS SAMPLING PROCEDURE – The Code of Federal Regulations, 40 CFR 91 Subparts D and E, contains detailed equipment specifications and test procedures appropriate for use with snowmobile engines. The procedure is designed to maximize repeatability of results, which can be difficult to achieve with snowmobile engines. The following points are addressed to adapt the EPA marine procedure for use with snowmobiles.

The location of the sample probe is well addressed in the EPA marine procedure. Although water injection is not used in snowmobile exhaust systems, it can still be difficult to position a sample probe to obtain a well-mixed sample if the engine has multiple exhaust pipes. The tailpipe is not necessarily a good location because expansion waves in the exhaust can draw air up into the tail pipe and possibly into the sample probe. Sampling from the final chamber of the muffler, or sampling from each individual exhaust pipe and averaging, are two possible approaches.

The EPA marine procedure specifies the analytical system for raw gas emissions sampling in detail. A heated flame ionization detector (HFID) and a heated primary sample train are specified. It is important that these requirements are met because two-stroke engines emit hydrocarbons which may condense in an unheated system.

Intake air mass flow measurement is not recommended, because this can interfere with the tuning of the engine air intake system, which has a negative effect on performance and emissions of a two-stroke engine. Since air flow cannot be measured, the fuel flow must be measured so that emission rates can be calculated on a mass flow basis.

Emission results are to be reported in units of g/kW-hr, based on the snowmobile test cycle and mode weight factors. An alternative constant volume sampling procedure is also provided in the EPA marine procedure. This dilute exhaust version of the test procedure was used with the recommended snowmobile test cycle in a 1997 study of fuel and lubricant effects on snowmobile emissions performed for the State of Montana(5).

ROUND-ROBIN EMISSIONS TEST RESULTS

To validate and refine the test procedure, two round-robin engines were selected and circulated among the manufacturers for testing. Selection criteria were that the engines must be simple and dependable, and represent both liquid and fan cooling. Engines selected were an Arctic Cat (Suzuki) 440 cc twin cylinder, liquid-cooled engine with dual carburetors, and a Ski-Doo (Rotax) 503 cc twin cylinder, fan-cooled engine with dual carburetors. These engines were tested at Ski-Doo, Suzuki, Yamaha, Fuji, Polaris, and Arctic Cat facilities. It must be emphasized that a sample of two engines is not sufficient to characterize currently available snowmobile engines. Reported test results should not be interpreted as representative of snowmobile industry baseline emissions.

Tests were run using the EPA marine procedure with the recommended snowmobile test cycle. Carburetors were jetted for typical laboratory test conditions, and this jetting was maintained for all subsequent testing. Although the EPA procedure specifies making a lubricating oil flow measurement which is to be added to the fuel flow value used for emissions calculations, this oil flow measurement can be difficult to make, has a minimal effect on the final emissions results, and has no effect on the repeatability of results. Due to these facts, oil flow was not measured during round-robin testing.

Upon completion of the testing, results were exchanged between ISMA members and analyzed. Arctic Cat engine results are reported in Table 7, and Ski-Doo engine results are reported in Table 8. It was concluded that the level of hydrocarbon variation was larger than expected, and that additional work was needed to determine the cause of this variation.

Table 7. Arctic Cat 440 cc Engine Emission Results

Test Facility	HC, g/kW-hr	NO_x, g/kW-hr	CO, g/kW-hr
Ski-Doo	132.0	0.7	466.8
Suzuki (Arctic Cat)	196.3	0.2	499.4
Yamaha	144.0	0.7	521.0
Fuji (Polaris)	197.8	0.8	597.4
Polaris	171.8	0.5	487.5
Arctic Cat	170.0	0.4	495.0
Mean	**168.7**	**0.55**	**506.2**
COV	**15.9%**	**36.6%**	**6.9%**

Table 8. Ski-Doo 503 cc Engine Emission Results

Test Facility	HC, g/kW-hr	NO_x, g/kW-hr	CO, g/kW-hr
Ski-Doo	139.3	0.8	564.6
Suzuki (Arctic Cat)	153.1	0.8	509.1
Yamaha	149.0	0.9	567.0
Fuji (Polaris)	163.6	1.4	602.5
Polaris	122.6	1.0	496.5
Arctic Cat	119.0	0.9	431.0
Mean	**141.1**	**0.98**	**528.5**
COV	**12.5%**	**22.9%**	**11.7%**

Instrument calibration may explain some of the observed variation. For example, fuel flow rate during mode one (peak power speed at wide open throttle) should be the same at each test laboratory. The coefficient of variation (COV) of mode one fuel flow rate was about 2.5 percent with one laboratory as high as 4 percent above the average. As another example, emissions quality, based on total emissions, was calculated for each laboratory's emissions data whenever possible. This technique used calculated air-fuel ratio to estimate the concentrations of unmeasured exhaust gas components(6). The sum of all constituent concentrations should equal 100 percent. Most results from this work were between 98 percent and 102 percent. This indicates very good calibration, although one laboratory consistently produced results of 95 percent which indicates marginal calibration.

Analysis was also performed to determine the size of each measurement's contribution to the total variation. Final results, reported in grams per kilowatt-hour, are calculated from engine power, fuel flow, and raw exhaust emission concentrations. Coefficient of variation was determined for input data and is reported in Table 9. From this analysis, it appeared that variation in hydrocarbon and fuel flow measurements made the largest contributions to variation in brake-specific results.

To identify the source of this variability, it was necessary to determine test repeatability in a single laboratory. Ski-Doo ran emissions test on the Rotax 503 cc fan-cooled round-robin engine three times per day on three different days. Results are shown in Table 10, and indicate that excellent repeatability can be obtained in an individual laboratory.

Table 9. Coefficient of Variation of Input Data

Data	Arctic Cat 440	Ski-Doo 503
Fuel Flow	6.80%	5.62%
Power	2.79%	3.01%
HC	16.61%	7.31%
CO	2.55%	3.94%
Total Carbon ($HC+CO+CO_2$)	4.36%	1.48%

Table 10. Ski-Doo Laboratory Repeatability Study, Ski-Doo 503 cc Engine

Test Number	Intake Air Density, kg/m^3	Power, kW	HC, g/kW-hr	NO_x, G/kW-hr	CO, g/kW-hr
1	1.163	41.0	101.1	1.016	446.2
2	1.162	41.0	102.3	1.022	448.6
3	1.159	41.0	103.5	0.986	448.4
4	1.154	41.0	103.9	1.023	455.5
5	1.155	41.0	102.4	1.027	449.0
6	1.155	41.0	104.1	0.992	447.2
7	1.144	41.0	102.7	0.970	457.1
8	1.142	41.0	105.2	0.997	464.7
9	1.141	41.0	103.3	0.897	465.5
Mean	**1.153**	**41.0**	**103.2**	**0.992**	**453.6**
COV	**0.69%**	**0%**	**1.1%**	**3.9%**	**1.6%**

To confirm repeatability in the Arctic Cat laboratory, both round-robin engines were tested and compared to the original results. As shown in Table 11, results compared well with those previously obtained.

During original testing, inlet air density varied among test facilities. A relationship between air density and both power and CO was observed. To further study the effects of air density, additional testing was performed at Arctic Cat and Ski-Doo. Two consecutive emission tests were performed with low and high air densities. A seven percent decrease in air density was achieved by raising the intake air temperature by 20°C. Results are shown in Table 12.

Table 11. Arctic Cat Laboratory Repeatability Study

Engine	Test	Intake Air Density, kg/m^3	Power, kW	HC, g/kW-hr	NOx, g/kW-hr	CO, g/kW-hr
Ski-Doo 503	Original	1.12	39.7	119.0	0.9	431.0
	Retest	1.16	40.4	113.0	1.4	396.0
Arctic Cat 440	Original	1.10	43.0	170.0	0.4	495.0
	Retest	1.07	44.4	171.0	0.6	480.0

Table 12. Effects of Intake Air Density on Emission Results

Engine	Test Facility	Measured Variation with 7% Decreased Air Density						
		Fuel Flow	Power	HC, Wtd. Conc.	CO, Wtd. Conc.	Total Carbon	HC, g/kW-hr	CO, g/kW-hr
Arctic Cat 440	Arctic Cat	4.3%	-4.3%	5.4%	7.4%	2.0%	12.8%	14.9%
	Ski-Doo	12.2%	-6.5%	16.5%	21.6%	6.1%	33.7%	37.3%
Ski-Doo 503	Arctic Cat	1.0%	-3.1%	3.0%	8.2%	1.8%	5.4%	10.9%
	Ski-Doo	1.3%	-6.6%	6.1%	10.1%	2.6%	13.5%	17.7%

It was concluded that variation in intake air density has a compound effect on brake-specific emission rates. This occurs because the decrease of intake air density causes fuel flow rate and raw emission concentrations to increase (in the numerator), and power to decrease (in the denominator) in the brake-specific emission calculation. Only total carbon (in the denominator) offsets this compound effect, as it increases slightly with density.

It was observed that the Arctic Cat 440 engine was much more sensitive to changes in air density than the Ski-Doo engine. The Arctic Cat engine develops 102 kilowatts per liter, compared to the Ski-Doo engine which develops 75 kilowatts per liter. The wave pulse through the Arctic Cat engine is likely tuned more aggressively to achieve the higher power output. Generally, when a two-stroke engine is aggressively tuned for one speed, the tuning at other engine speeds tends to be poor. This can result in increased in-cylinder concentrations of residual exhaust, which degrades combustion quality, causing increased sensitivity to inlet air conditions. It was also observed that engine results were more sensitive to changes in inlet air density at the Ski-Doo laboratory. To date, no direct cause of this phenomenon has been identified.

SUMMARY

A five-mode test cycle was developed from analysis of real-time snowmobile operating data. This cycle was combined with the EPA marine emission measurement procedure to create a snowmobile emission test procedure. This procedure was optimized for use with snowmobiles after extensive round-robin testing of two engines. Issues addressed included dynamometer performance, sample probe location, carburetor adjustment, and intake air conditions.

Round-robin testing showed that snowmobile engine emissions are very sensitive to a number of factors, including inlet air conditions and the design and tuning of the snowmobile engine. Emission results repeated very well within two individual laboratories, and factors contributing to variation between laboratories have been explored. Even with strict adherence to the test procedure, a certain level of laboratory-to-laboratory variation can be expected because combustion in high-performance two-stroke engines can be unstable at part throttle modes.

Recommendations for future study include further investigation into parameters that affect snowmobile engine emissions test results.

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