Engine Rebuilding Project

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Abstract

This report documents the comprehensive breakdown and rebuilding of a Honda GCV190 engine, obtained from a Honda HRX 217 lawnmower. The focus of the report is on the engine and its critical components. As such, accessory mechanisms specific to operations of the lawnmower will only be lightly discussed or excluded entirely. All abnormalities within the breakdown and rebuild process are discussed. Measurements on crucial components were obtained when the engine was in its most disassembled state and the information was imported into various engine simulation calculations using MATLAB. The MATLAB code used is available for viewing in Appendix A. This report also includes a comparison of simulation results to the metrics published by the manufacturer. Key features specific to the engine's application are highlighted and explained in detail. Overall the Honda GCV190 engine is a robust, well-designed engine that has proven useful in many small engine applications.

Procedure

The Honda GCV190 engine this report is focused on was obtained from a Honda HRX 217 lawnmower. Both the gasoline and oil were drained from the machine prior to any disassembly, and the fuel cutoff valve was set to "off." The blade was removed by removing two #14 bolts. The engine was removed from the chassis of the lawnmower by removing four #14 bolts. There is also a ring that holds the pull starter cable in a convenient location and a steel throttle cable that is used to hold the flywheel brake pad open that were removed as well. Finally, an adjustable wrench was used to loosen the tension in the belt of the self-propelled transmission box. With the tension relaxed from the drive pulley, the engine was lifted entirely from the lawnmower and will henceforth be treated as a separate entity.

With the engine separated from the lawnmower, various external accessories were easily removable. All external accessories used a #10 bolt, each bolt varying in length for the purpose required. The accessories, include the carburetor, the air-box, the pull-starter assembly, the muffler and heat guard, sparkplug, and the top cover and fuel tank. The linkages between the carburetor and the governor were removed, and will be discussed in further detail later in the report. External accessories, such as those listed above, were treated as piece parts, and were not disassembled individually due to their complexity or fragility.

With the external accessories removed, the main focus shifted the internal components. Because of the difficulty involved in applying enough torque to both ends of the crankshaft to remove both the flywheel and load accessories, an electric impact wrench was used to remove the nuts on either end. The blade attachment and self-propeller puller were removed with light blows from a rubber mallet. The flywheel was not as easily removable. After a tiring combination of pry-bars and mallets, I learned that the flywheel was designed to be removed using a jaw puller. AutoZone provided a free rental of the device, shown in Figure 1, and the flywheel was easily removed by placing each of the three hooks in the locations marked in the service manual.

Figure 1-Free Rental Flywheel Puller Made Removal of Flywheel Much Easier

After all obstructions were removed, the crankcase bolts could be removed and the crankcase could be separated. There were eight #10 bolts used, positioned as shown in Figure 2, to hold the crankcase to the block. With these bolts removed, the crankcase can be separated using a pry-bar, destroying the existing silicon seal. A razor was used to scrape the surface clean in preparation for a new silicon seal. Remaining oil in the crankcase was soaked up using paper towels, and the crankcase was set aside. The lower half of the journal bearing holding the connecting rod to the crankshaft was removed by removing the two #10 bolts as shown in Figure 3.

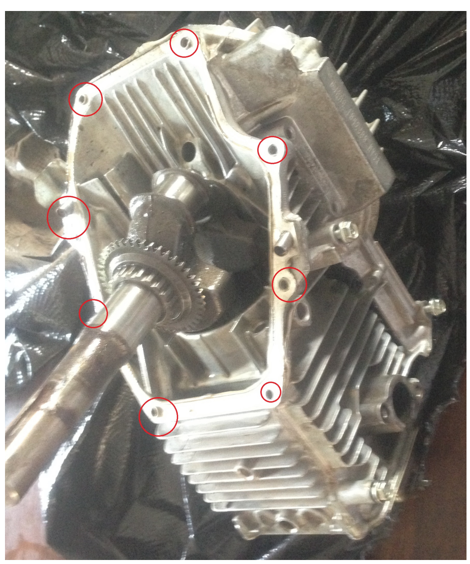

Figure 2- Locations of 8 #10 bolts used to secure crankcase to block

Figure 3-Piston journal bearing with bolts

The valve cover was removed via removing the four #10 bolts on the front of the engine. Like the crankcase, when the valve cover is removed, a silicon seal is destroyed and a razor was used to clean the surface. A screwdriver and a mallet were used to displace the end of the shaft for the cam gear enough to use pliers to pull the shaft out completely. With the shaft removed, the cam gear can float freely. The timing belt was loosened from the crankshaft and the camshaft could be completely removed. Both the crankshaft and cam gear were set aside. The shafts for the rocker arms were removed using a screwdriver, mallet, and pliers and both the shafts and rocker arms were set aside. The valve springs were depressed by hand, and the locking plates for each valve were removed, freeing the springs and plates, and allowing for the valves to move freely. The conditions of the valve guides were checked, and because they were still in excellent condition, they were left alone.

With all obstructions removed, the piston was removed from the cylinder. Because the valves were already loose, they were removed completely through the cylinder. The compression and oil rings were removed from the piston. With all major components removed from the engine, all parts were cleaned and measurements began.

Digital calipers were used to measure various features of various parts. Namely, the bore diameter, valve dimensions, cam gear lobe dimensions, crankshaft dimensions, piston and ring dimensions were measured, and an attempt to measure the deepest point of the clearance volume was made. The complex nature of the shape of the clearance volume made measuring it difficult, so the bore volume and the compression ratio will be used to calculate the clearance volume in the simulation. Also, due to the geometry of the cylinder, obtaining valve-opening dimensions was not possible. The valves created a very good seal, so the external dimensions of the valve will be used as approximate valve opening dimensions. These measurements are used in the Analysis portion of this report to detail operating characteristics and allow for more accurate simulation results.

After measurements were made, reassembly began. The valves were placed back into their respective ports, and the springs and locking plates locked their movement. The cam gear was reinstalled, followed by the rocker arms. With the valve train reinstalled the piston rings were re-grooved and compressed while the piston was slid back into the cylinder. Pictures taken during the breakdown process were consulted to ensure the correct direction of the non-symmetrical piston. Next the timing belt was installed, with the plastic markings shown in Figure 4 horizontal as instructed in the manual to ensure correct timing. With the valve train complete, a new silicon seal was applied, as shown in Figure 5, and the valve cover was reinstalled using a torque wrench to 8 Nm as per the manual. The bottom of the piston journal bearing was replaced using a torque wrench with 10 Nm as per the manual. A new layer of silicon was applied to the mounting surface of the crankcase, and the case was bolted to the block replacing the eight bolts, torqued to 8 Nm.

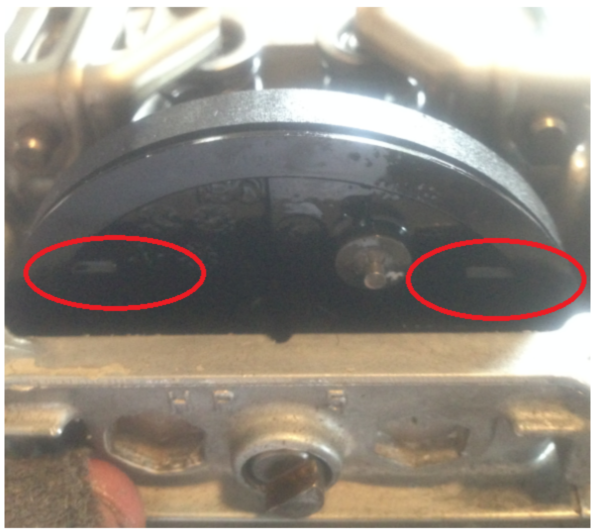

Figure 4- Cam gear markings ensure correct timing

Figure 5- Silicon gasket maker was used to seal valve cover and crankcase

The flywheel was reattached to the top of the crankshaft using an impact wrench. The drive pulley and blade attachment block were reattached to the bottom of the crankshaft, using an impact wrench, however too much torque was applied and the drive pulley was cracked. The drive pulley does not affect the engine performance so a new pulley was ordered and the process continued.

The carburetor and choke/governor assembly were removed weeks prior to the engine breakdown, and unfortunately the pictures that were taken to reference during reassembly were not very helpful weeks after being taken. CTE Small Engines of Auburn provided assistance with the order of the parts that make up the intake/carburetor tract. The pull starter assembly was mounted above the flywheel, and the engine was reinstalled on the chassis of the lawnmower to make troubleshooting and starting the engine easier.

The manual calls for .4L of 10W-30 engine oil to be poured directly through the dipstick access port, so the oil was added and measured to the correct level using the procedure outlined in the manual. The manual suggests applying 1-2 teaspoons of oil on top of the cylinder through the spark plug hole, and pulling the starter cable multiple times to distribute it. A measuring cup was not immediately available, so the amount was estimated as it was poured through a funnel into the spark plug hole. The starter cable was pulled several times as instructed and the spark plug was reinstalled.

When trying to start the engine, with the sparkplug reinstalled and the cylinder sealed, the starter cable was very hard to pull. Not knowing what hydro-locking an engine was at the time, I assumed more oil was needed, and added more oil onto the top of the piston. When the spark plug was reinstalled, the pull start cable would not even turn the crank a full rotation anymore. Online resources were referenced, and I learned that a highly resistive pull start cable is often the result of hydro-locking, so I followed procedures to fix the issue. After most the oil had been ejected from the cylinder, the spark plug was reinstalled and the engine started on the first pull, immediately ejecting oil through the muffler, and blowing thick white smoke, so the engine was stopped after 5 seconds of running. After further consultation with a peer, I was informed that it would be ok to simply let the oil in the cylinder burn off, so the engine was started again, and allowed to run for approximately 5 minutes, when white smoke was no longer being produced.

Having completely removed the governor assembly and not having a portable tachometer immediately available, the engine revolutions were adjusted by ear, to a speed that was sufficient enough for smooth running, but likely less than optimal RPM. CTE Small Engines again assisted in setting the RPM of the engine to the correct speed.

Part Analysis
Autochoke System
A feature included in the design of the engine is the Honda Autochoke System. In older small carbureted Honda engines, the cold start air fuel ratio problem was solved by using either a lever that directly allows for the user to adjust the choke throttle plate, or a primer bulb that would allow for additional fuel to be manually injected before starting. Many users reportedly did not understand the purpose of the choke or primer bulb however, leading to hard or no-start conditions. Honda solved this issue by bypassing the user, adding complexity to the design, but allowing for inexperienced users to intuitively start the engine.

As shown in Figure 6, when the engine is cold, the wax cylinder is in it's smallest length, and the spring force on the choke control arm holds the choke plate it the fully choked position. As the engine warms up, the wax cylinder expands, driving the piston forward, overcoming the spring force and opening the choke plate. Figure 7 shows the choke plate in the fully closed, partially open, and fully open positions by moving the choke control arm. The piston can be seen installed in Figure 8.

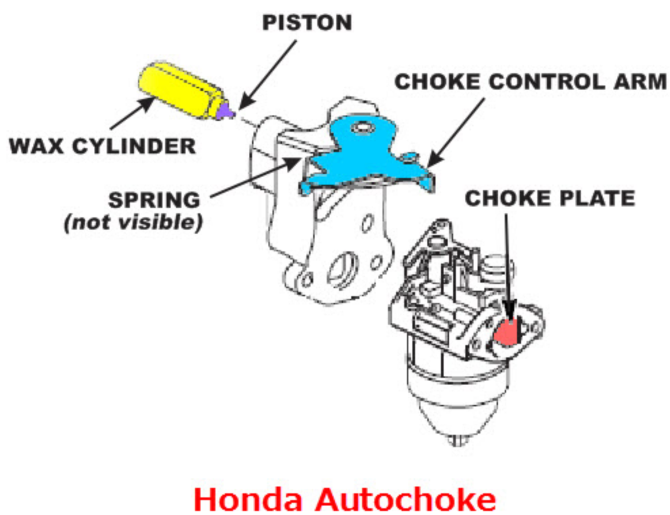

Figure 6- Exploded view of parts in Honda Autochoke System

Figure 7- Left to Right, choke plate positions are actuated from fully closed to fully open via the choke control arm

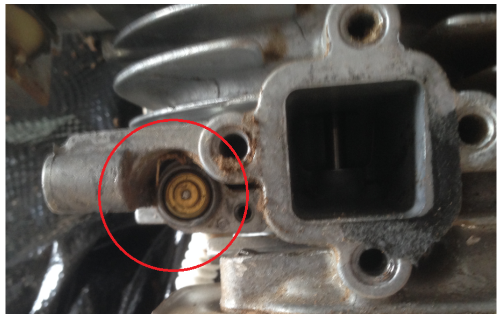

Figure 8- Piston installed in block is moved laterally using thermal expansion of a wax cylinder, and actuates the choke control arm.

Pressure Relief Lobe

Another design feature specific to this engine is the pressure relief cam lobe present on the cam gear. The engine is a pull start, 4-stroke engine, and as such, the compression and expansion strokes are fairly hard to overcome the internal pressure gradients via pulling of the starter cable. Honda engineers solved this issue by adding an additional, spring actuated cam lobe 180° from the intake lobe position, that opens the exhaust valve slightly during compression and expansion strokes when the crankshaft is turning at very low RPM (such as a startup condition).

When the crankshaft is rotating at very low RPM, the spring force on the arm holds the arm in the low speed position, allowing the lobe to protrude at measured height of 4 mm. As the engine RPM reaches full operation speed, the centrifugal force on the arm overcomes the spring force and moves the arm to the full speed position, rotating the lobe 180°, leaving a flat surface, allowing for the cylinder to remain closed during normal operation compression and expansion strokes. The maximum measured valve lift of the exhaust valve when opened by the pressure relief lobe was only slightly more than 1mm. The cam gear is shown in Figure 9, and the lobe can be seen in low speed, and full speed configurations.

Figure 9- Cam gear in low RPM mode has lobe present (left), at high RPM the lobe is rotated to a flat shape (right)

Airflow/Valvetrain
This engine has a carbureted intake that feeds from an air box containing a paper air filter, shown in Figure 10. The charge flows through a passage cast directly into the block (Figure 11), and the overhead intake valve allows for the charge to enter the cylinder. There was no direct way to measure the valve port diameters, so the valve dimensions will be treated as the port diameter openings.

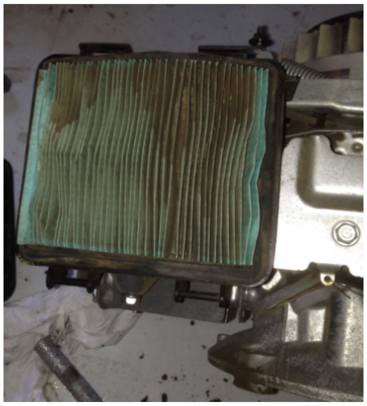

Figure 10- Air enters engine through a paper filter in the air box

Figure 11-Intake path is cast directly into block. Circled in red is intake valve port.

The valvetrain is operated by a single cam gear, using an internal timing belt driven directly from a gear pressed onto the crankshaft. The cam gear has a single operating lobe used for both the intake and exhaust valves. The lobe actuates a rocker arm shown in Figure 12, which opens the respective valve. Maximum valve lift was measured by rotating the crankshaft by hand, and measuring the displacement of the top of each valve. Maximum valve lift for each the exhaust valve and intake valve is slightly more than 5 mm.

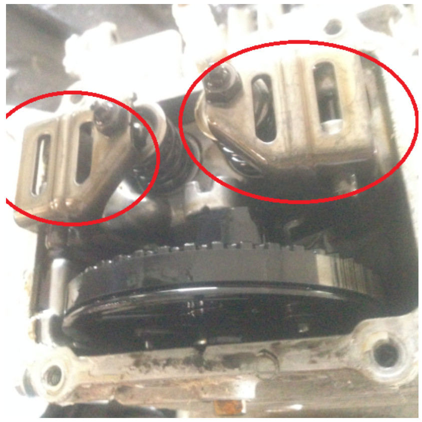

Figure 12-Assembled Valvetrain

Burned gas leaves via the exhaust port, and again travels through a passage cast directly into the block. The burned gas leaves the block through a hole in the block, which has a muffler, mounted directly onto the hole. The muffler is shown in Figure 14, and is covered by a heat guard in typical operation. The intake and exhaust valves were measured and dimensions are available in Table 1.

Figure 13- Exhaust path is cast directly into block. Circled in red is exhaust valve port.

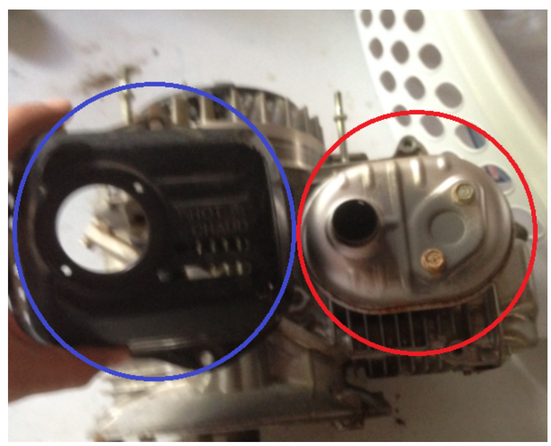

Figure 14-Heat guard (blue) covers muffler (red) during normal operation

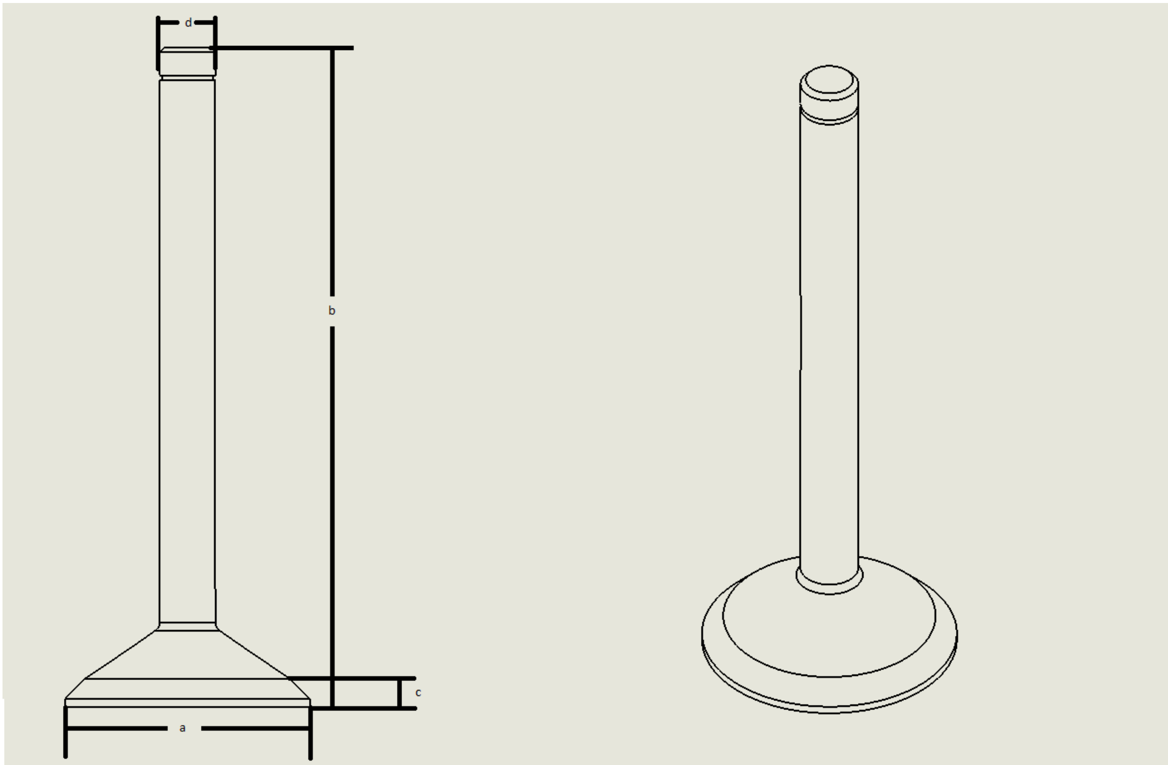

Figure 15-Solid model of valve for dimensions. Groove along top holds spring retaining plate.

Table 1- Recorded Intake and Exhaust Valve Measurements

	Intake	Exhaust
a	25 mm	24 mm
b	64.5 mm	64.5 mm
c	2.75 mm	2.75 mm
d	5.45 mm	5.45 mm
Max Lift	5 mm	5 mm

Using these face diameters, and Equation 1, the maximum curtain area of each valve can be calculated.

$$A_{curtain,max} = \pi * D_{valve} * l_{max} \quad (1)$$

$$A_{intake\ curtain,max} = \pi * .025\text{m} * .005\text{m} = 3.93 * 10^{-4}\text{m}^2$$

$$A_{exhaust\ curtain,max} = \pi * .024\text{m} * .005\text{m} = 3.77 * 10^{-4}\text{m}^2$$

The port limit is calculated using Equation 2,

$$A_{port\ limit} = \frac{\pi}{4}(D_{port}^2 - D_{stem}^2) \quad (2)$$

$$A_{intake\ port\ limit} = \frac{\pi}{4}(.025^2\text{m} - .00545^2\text{m}) = 4.68 * 10^{-4}\text{m}^2$$

$$A_{exhaust\ port\ limit} = \frac{\pi}{4}(.024^2\text{m} - .00545^2\text{m}) = 4.29 * 10^{-4}\text{m}^2$$

The port limit is greater than the max curtain area of each valve, so the flow is not limited by the valve stem diameter.

Fuel Flow

The fuel reservoir is combined with the flywheel cover in one large injection molded cover shown in Figure 16. The fuel uses gravity as the method of transport to the carburetor, and has a manual shutoff valve located midway along the fuel line. The published specifications mention a fuel capacity of .93L and specify unleaded 86 octane or higher as the fuel type.

Figure 16-Fuel tank (blue) is molded into flywheel cover, and gravity feeds through a shutoff valve (red) to the carbuerator

Cooling

The engine is an air cooled engine, and the block has fins across the entire outside to assist in cooling. In addition, the flywheel has fins shaped into it, allowing for much more effective, forced convection cooling. The splash lubrication system allows for cooling of internal parts, including the piston. Figure 17 shows the fins surrounding the block.

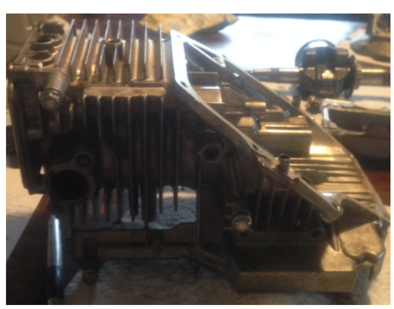

Figure 17- The entire exterior of the engine block is covered in fins, allowing for natural convection cooling of the block.

Ignition

This engine is commonly used as portable, power generation in small machines such as lawnmowers and pressure washers, so the addition of a battery would likely be counterproductive. Instead, this engine makes use of a transistorized magneto ignition system. A pair of magnets is embedded in the flywheel as shown in Figure 18, which rotates via the crankshaft. Mounted on the top of the engine block is the pickup/ignition coil, as shown in Figure 19, and is subject to the magnetic field created by the rotating magnets.

Figure 18- A shaft key being used to demonstrate the magnetic sections embedded in the flywheel.

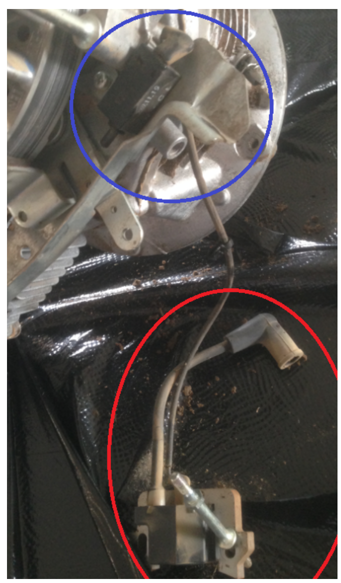

Figure 19- The pickup coil (blue) is sensitive to the EMF created by the rotating magnets. The voltage is amplified and sent to the sparkplug via the transformer coil (red).

The ignition system is transistorized, thus having a solid-state design rather than non-solid state designs that use a cam to actuate a switch that produces the voltage drop across the plug. As the first magnet approaches the pickup coil, the magnetic flux of the magnet flows through the coil. As the second magnet approaches the coil, the first magnet is moving away from the coil, and the combined magnetic flux creates an electromagnetic field that can be amplified through the use of a small transformer. This voltage produced is used to create the spark required for ignition. As the second magnet passes over the coil, the flux is gradually decreased and diminished until the flywheel returns to the same angular position to create another spark.

Piston and Rings

The piston was measured to have an outer diameter of 68.75mm. The piston had two compression rings and an oil ring with two spacers. The rings and piston are shown in Figure 20. The piston and connecting rod have non-symmetrical designs to aid in balancing of the skirt force on the piston, and the piston can only be installed in the correct orientation. If the piston is installed in the incorrect orientation, the “arm” visible on the journal bearing in Figure 3 makes contact with the side of the crankcase, prohibiting the crankshaft from rotating. This is a clever method used to prevent the piston from being installed incorrectly resulting in unbalanced operation and possible component failure.

The piston rings were measured while they were uninstalled, and were found to have an OD of 72 mm, and ID of 67 mm, and a gap of 1 mm. The thickness was measured to be .95 mm.

Figure 20- Piston with rings installed

MATLAB Simulation

This engine has published torque and power ratings, for a range of speeds, shown in Figure 21. Other engine metrics such as bmep and bsfc are not published, but using the MATLAB code in Appendix A, along with published engine parameters such as cylinder size and compression ratio, relatively accurate estimates can be made for these metrics. The simulation power and torque ratings are calculated in the same simulation, and can be used as a reference for how reliable the estimated metrics are by comparing published torque and power ratings to simulated ratings. The simulation code is based off of a thermodynamic calculation of the engine cycle, accounting for species change, combustion rate, and using various efficiency estimates.

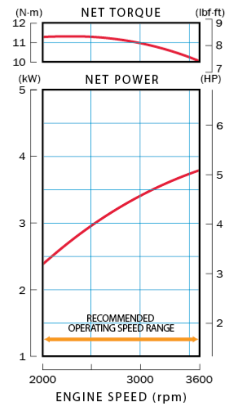

Figure 21- Honda Published Performance Curves vs Engine Speed

The simulation uses a Weibe function to calculate the heat release rate, which is directly related to cylinder pressure, which in turn is directly proportional to power and torque output of the engine. The Weibe function is a mathematical function that models the actual heat release rates in an engine due to combustion of a fuel. This function, shown in Equation 3, uses two parameters, obtained through experimental data, to fit the curve to the specific engine. Due to the lack of resources, obtaining these values to this engine specifically was not realistic, so a value of 5 was used as the function efficiency factor, a, and a value of 3 was used as the function form factor, n. These values can change drastically due to the nature of curve fitting. Although these values can very possibly be very inaccurate for this specific engine, using the Weibe function to model the heat release of the fuel is much more accurate than assuming that combustion is instantaneous.

$$x_{bg} = 1 - \exp\,[-a\left(\frac{\theta - \theta_s}{\theta_d}\right)^n \tag{3}$$

Where θ is the independent variable, a is the efficiency factor, n is the function form factor, θ_s is the start of combustion, θ_d is the duration of the burn, and $x_{bg}$is the fraction of burned gas to total volume of working fluid in the cylinder.

The Weibe function relates the burned gas fraction directly to crank angle, and again, due to lack of published documentation and resources, various properties of angular position vs engine events was simply not available. A start of combustion angle of 40° BTC, and a burn duration of 40° seem to be reasonable estimates, and leaves the species mixture at the beginning of expansion entirely burned gas. The plot of this function is shown in Figure 22.

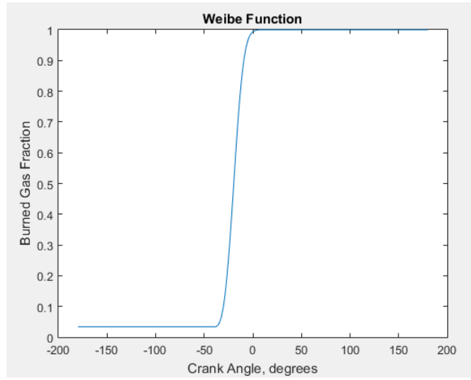

Figure 22- MATLAB plot of the Weibe curve used to model burned gas fraction vs crank angle during simulation

Additional estimates that affect the calculations include the fuel air equivalency ratio, which was estimated to be 1.077, a slightly lean condition that is a fair estimate for optimal running conditions, but would not be as accurate for conditions such as start-up (choked flow), or in situations where ambient temperature extremes are of concern. Finally, volumetric efficiency and mechanical efficiency were estimated to be .80 and .75 respectively, and various complexities, such as heat loss and advanced fluid flow are neglected from the simulation for sake of simplicity of calculation, all of which affect the calculations to various degrees. Nonetheless, the simulation is still a fairly accurate estimate of engine performance, and simulation results vs. published results are available in Table 2.

Table 2- Published Results vs Simulated Results

	Published English	**Published SI**	**Simulated English**	**Simulated SI**
Brake Power	5.1 HP	3.8 kW	6.70 HP	4.99 kW
Brake Torque	7 ft.lb	10 N.m	9.77 ft.lb	13.25 N.m
Bmep	N/A	N/A	129.1 psi	8.90 bar
Bsfc	N/A	N/A	.4415 lbm/hp.hr	268.6 g/kW.hr
Exhaust Temp	N/A	N/A	1936° F	1057.7° C
Peak Pressure	N/A	N/A	1006.0 psi	69.37 bar
Peak Temp	N/A	N/A	5053° F	2795° C

Simulation Analysis

The simulation results are close to the published results, but are slightly higher. The volumetric efficiency and mechanical efficiency play a large role in the resulting calculations, and the efficiencies used were entirely estimated. Still, the results are close enough to be useful in rough estimations of metrics such as bmep and bsfc. The calculated bmep is 8.90 bar, which is around what is expected. Assuming a ground vehicle engine bmep is around 10 bar, 8.90 bar is slightly less, resulting in less power output, but longer life of the parts. The application of this engine is power generation for light power tools such as a lawnmower, generator, or pressure washer, where long life is of higher priority than high power output.

The calculated bsfc is 268.6 g/kW.hr, which results in about 1.34 kg/hr of fuel usage. Using a fuel density of 737 kg/m^3 and other conversion factors, evaluated at $3/gal, the cost of operation is around $1.44/hr. Again, this is as expected, where the cost of operation of the tools this engine is used in, is expected to be very low.

Conclusion

The Honda GCV190 engine is a small, one cylinder, 4-stroke engine designed for use in light to medium sized power tools like lawnmowers, generators, and pressure washers. Comparing published metrics to simulation metrics, it can be concluded that cost of operation is very low, as expected, and the engine bmep is on the lighter side, favoring longer life over power output. Honda engineers have made operation very simple for the end user, by including features such as the Autochoke System, which allows for anyone to easily start the engine without needing to know about what a choke does, and the mechanical automatic depressurization by use of a variable lobe on the cam gear to make pull starting the engine easier. The use of a transistorized magneto ignition provides a robust, self-contained ignition system that does not require an external power source. Overall, the Honda GCV190 engine is a well-designed engine, with focus on its specific application and emphasis of ease of use for the end user.

Appendix A

The MATLAB code used in this simulation was developed by Dr. Peter Jones of Auburn University. The code, including variable values used, is available below:

```
clear all
 global statements
 global Ru fuel phi
 global Bore Stroke Rod VTC
 global thstartr thdurr aWeibe nWeibe xr
% set constants
Ru              = 8314.4;    % universal gas constant in J/kg.K
n               = 2;         % relative rotative efficiency: 2-stroke=1; 4-stroke=2
Ncyl            = 1;         % number of cylinders
Bore            = 69.0e-03;  % cylinder bore diameter in meters
Stroke          = 50.0e-03;  % piston stroke in meters
Rod             = 60.0e-03;  % connecting rod length in meters
compress        = 8.5;      % compression ratio
Nrpm            = 3600;      % engine speed in rpm
Pref            = 101325;  % intake reference pressure in Pa
Tref            = 298;       % intake reference temperature in K
Rref            = 287.1;     % intake reference temperature in J/kg.K
Tim             = 360;       % intake manifold temperature in K
Pex             = 108.0e+03;% exhaust manifold pressure in Pa
etav            = 0.80;      % volumetric efficiency
etam            = 0.75;      % mechanical efficiency (exclusive of gas pumping)
phi             = 1.077;     % fuel air equivalency ratio
fuel            = 2;         % fuel type (1-CH4; 2-C7H17; 3-C14.4H24.9; 4-CH3OH; 5-CH3NO2)
HV              = 43.2e+06;  % fuel heating value in J/kg
thstartd        =-30;        % crank angle at start of combustion in degrees
thdurd          = 40;        % combustion duration in crank angle degrees
aWeibe          = 5;         % Weibe heat release function efficiency factor
nWeibe          = 3;         % Weibe heat release function form factor
tol             = 1e-04;     % conversion relative tolerance
% conversions
Vdcyl           = pi/4*Bore^2*Stroke;
Vdeng           = Vdcyl*Ncyl;
VTC             = Vdcyl/(compress-1);
VBC             = compress*VTC;
Nrps            = Nrpm/60;
crank           = Stroke/2;
thstartr        = thstartd*pi/180;
thdurr          = thdurd*pi/180;
rhoref          = Pref/Rref/Tref;
mair            = etav*rhoref*Vdcyl;
[FA,Mch,cvch,cPch,uch,hch,soch,dsodTch]=gasprops(fuel,phi,0,Tim);
mfuel           = FA*mair;
fuelrate        = Ncyl*mfuel*Nrps/n;
mch             = mfuel+mair;
Rch             = Ru/Mch;
% iteration for exhaust temperature
Texguess        = 1200;
eTex            = 1;

while eTex>tol
% residual mass
    [FA,Mr,cvr,cPr,ur,hr,sor,dsodTr]=gasprops(fuel,phi,1,Texguess);
    Rr              = Ru/Mr;
    rhor            = Pex/Rr/Texguess;
    mr              = rhor*VTC;
    xr              = mr/(mr+mch);
% isenthalpic intake
% initial conditions for Tendin loop
    Hendin          = mr*hr+mch*hch;
    hendin          = Hendin/(mch+mr);
    Tendinguess     = (mch*cPch*Tim+mr*cPr*Texguess)/(mch*cPch+mr*cPr);
    eTendin         = 1;
    xbendin         = xr;
% iterate to find Tendin
    while eTendin>tol
```

```matlab
[FA,Mendin,cvendinguess,cPendinguess,uendinguess,hendinguess,soendinguess,dsodTendinguess
]...
            =gasprops(fuel,phi,xbendin,Tendinguess);
        Tendin      = Tendinguess+(hendin-hendinguess)/cPendinguess;
        eTendin     = abs(Tendin-Tendinguess)/Tendin;
        Tendinguess = Tendin;
    end

[FA,Mendin,cvendin,cPendin,uendin,hendin,soendin,dsodTendin]=gasprops(fuel,phi,xbendin,Te
ndin);
    mendin        = mr+mch;
    Vendin        = VBC;
    Rendin        = Ru/Mendin;
    Pendin        = mendin*Rendin*Tendin/Vendin;
% solve compression/combustion/expansion temperature
    options       = odeset('MaxStep',0.01); % cycle temperature solution options
    [thetar,T]    = ode23(@dTdtheta,[-pi pi],Tendin,options);
% end of expansion properties
    np            = length(T);
    Tendexp       = T(np);

[FA,Mendexp,cvendexp,cPendexp,uendexp,hendexp,soendexp,dsodTendexp]=gasprops(fuel,phi,1,T
endexp);
    mendexp       = mendin;
    Vendexp       = VBC;
    Rendexp       = Ru/Mendexp;
    Pendexp       = mendexp*Rendexp*Tendexp/Vendexp;
% isentropic blowdown
% initial conditions for TendBD loop
    soendBD       = soendexp-Rendexp*log(Pendexp/Pex);
    k             = cPendexp/cvendexp;
    TendBDguess   = Tendexp*(Pex/Pendexp)^((k-1)/k);
    eTendBD       = 1;
    xbendBD       = 1;
% iterate to find TendBD
    while eTendBD>tol

[FA,MendBD,cvendBDguess,cPendBDguess,uendBDguess,hendBDguess,soendBDguess,dsodTendBDguess
]...
            =gasprops(fuel,phi,xbendBD,TendBDguess);
        TendBD     = TendBDguess+(soendBD-soendBDguess)/dsodTendBDguess;
        eTendBD    = abs(TendBD-TendBDguess)/TendBD;
        TendBDguess= TendBD;
    end

[FA,MendBD,cvendBD,cPendBD,uendBD,hendBD,soendBD,dsodTendBD]=gasprops(fuel,phi,xbendBD,Te
ndBD);
    VendBD        = VBC;
    RendBD        = Ru/MendBD;
    PendBD        = Pex;
    mendBD        = PendBD*VendBD/RendBD/TendBD;
% exhaust temperature estimate check & update
    Tex           = TendBD;
    eTex          = abs(Tex-Texguess)/Tex;
    Texguess      = Tex;
end
% indicated work in one cylinder
[V,dVdth]      = Volume(thetar);
[xbf,dxbfdth] = Weibe(thetar);
M              = 1./((1-xbf)/Mch+xbf/Mr);
R              = Ru./M;
P              = mendin.*R.*T./V;
dWi            = P.*dVdth;
Wi             = trapz(thetar,dWi);
etat           = Wi/mfuel/HV;
% performance parameters
Wb             = Wi*etam;
taub           = Wb*Ncyl/n/2/pi;
Wdotb          = Wb*Ncyl/n*Nrps;
bmep           = Wb/Vdcyl;
```

```
bsfc          = fuelrate/Wdotb;
[Pmax,iPmax]  = max(P);
thPmax        = thetar(iPmax);
Tmax          = max(T);
% unit conversions
WdotbkW       = Wdotb/1000;
Wdotbhp       = WdotbkW*1.341;
taubftlb      = taub*3.281*0.2248;
bmepbar       = bmep/100000;
bmeppsi       = bmep*0.2248/3.281^2/12^2;
bsfcgkwhr     = bsfc*1000*1000*3600;
bsfclbmhphr   = bsfc*2.2048*745.7*3600;
TexC          = TendBD-273.15;
TexF          = TexC*9/5+32;
thetad        = thetar/pi*180;
thPmax        = thPmax/pi*180;
Vcc           = V*1000000;
Pbar          = P/100000;
Pmaxbar       = Pmax/100000;
Pmaxpsi       = Pmax*0.2248/3.281^2/12^2;
TmaxC         = Tmax-273.15;
TmaxF         = TmaxC*9/5+32;
% output
fprintf('\n')
fprintf('Brake power                        %6.2f kW \n',WdotbkW)
fprintf('Brake torque                       %6.2f N.m \n',taub)
fprintf('Brake mean effective pressure      %6.2f bar \n',bmepbar)
fprintf('Brake specific fuel consumption %6.1f g/kW.hr \n',bsfcgkwhr)
fprintf('Exhaust temperature                %6.1f C \n',TexC)
fprintf('Peak pressure                      %6.2f bar \n',Pmaxbar)
fprintf('Peak temperature                   %6.0f C \n',TmaxC)
fprintf('\n')
fprintf('Brake power                        %6.2f hp \n',Wdotbhp)
fprintf('Brake torque                       %6.2f ft.lb \n',taubftlb)
fprintf('Brake mean effective pressure      %6.1f psi \n',bmeppsi)
fprintf('Brake specific fuel consumption %6.4f lbm/hp.hr \n',bsfclbmhphr)
fprintf('Exhaust temperature                %6.0f F \n',TexF)
fprintf('Peak pressure                      %6.1f psi \n',Pmaxpsi)
fprintf('Peak temperature                   %6.0f F \n',TmaxF)
fprintf('\n')
fprintf('thermal efficiency                 %6.4f \n',etat)
fprintf('Location of peak pressure          %6.3f degrees \n',thPmax)
figure(1)
plot(thetad,Vcc)
xlabel('Crank Angle, degrees')
ylabel('Volume, cubic centimeters')
figure(2)
plot(thetad,xbf)
xlabel('Crank Angle, degrees')
ylabel('Burned Gas Fraction')
title('Weibe Function')
figure(3)
plot(thetad,R)
xlabel('Crank Angle, degrees')
ylabel('Gas Constant, J/kg.K')
figure(4)
plot(thetad,Pbar)
xlabel('Crank Angle, degrees')
ylabel('Pressure, bar')
figure(5)
plot(thetad,T)
xlabel('Crank Angle, degrees')
ylabel('Temperature, K')
figure(6)
plot(Vcc,Pbar)
xlabel('Volume, cubic centimeters')
ylabel('Pressure, bar')
```

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