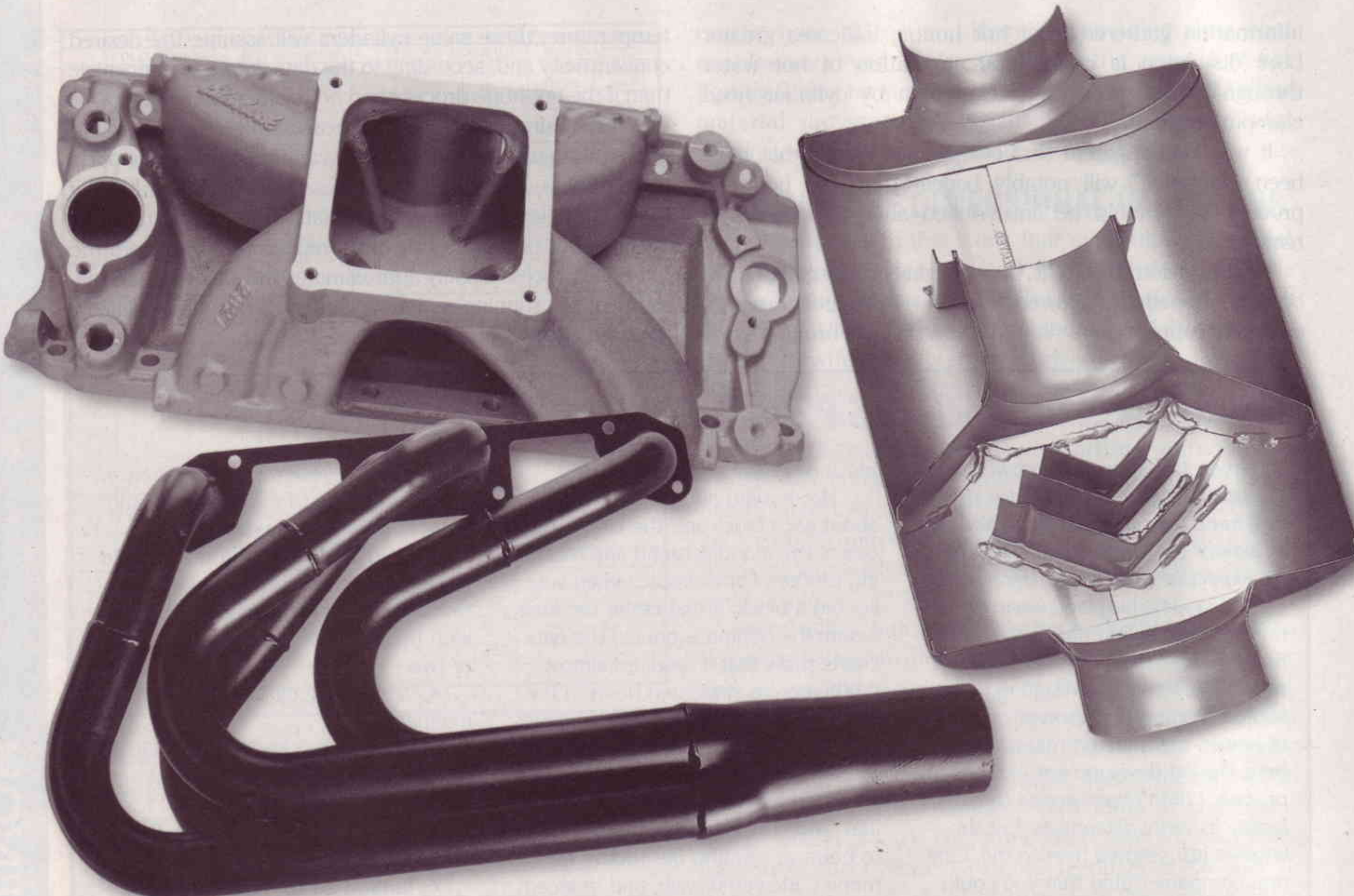


MAKE EVERY CYLINDER COUNT

ENGINES MAKE THE MOST POWER WHEN EVERY CYLINDER IS INDIVIDUALLY TUNED. HERE'S WHERE THE SATURDAY NIGHT RACER CAN BEGIN

BY JIM MCFARLAND

Let's get right to the heart of this matter. Visualize a single-cylinder, four-stroke engine. It has an intake manifold, a carburetor, an exhaust pipe, a camshaft, and an intake and exhaust valve. Simple enough, right? We know it's possible to manipulate this little engine's torque curve over a range of rpm by adjusting the flow path diameter and length in combination with valve timing. That's a given. But first, we need to discuss some background information before diving into procedures that optimize individual cylinder power.

THE BACKGROUND

We know that the net torque curve produced by our engine is a combination of an induction system curve and an exhaust system curve. We can tune these two curves separately and combine them to locate overall torque precisely where we want it to be.

While flow activity in an intake or exhaust system is unsteady (neither constant nor linear), a mean flow velocity (MFV) can be determined at any particular rpm. Factors that influence MFV are piston displacement, compression ratio, valve timing, and rod-to-stroke geometry. At peak torque, there is an MFV that's basically identical for all engines. It lies in the range of 240-260 feet/second.

Of the factors that impact MFV, the cross-section area of the flow path is critical. All else being equal, change this area, and the MFV changes correspondingly. At any given rpm, an increase in the cross-section area will result in a decrease in flow rate. Decrease this area, and the flow rate increases.

Based on these relationships, the design or selection of intake and exhaust components can materially affect where an engine produces its torque, relative to rpm. We know that an MFV of 240-260 feet/second occurs at peak torque, so we can use this information as a tool in the sizing (or choice) of intake manifolds and headers. We'll get more into that a bit later.

So far, we've discussed the characteristics of a single-cylinder engine. Now let's see what happens if we add cylinders. Two factors immediately become apparent. One is the influence on piston movement and torque transfer when two or more cylinders are connected to the same crankshaft. One cylinder's power strokes can be felt among cylinders that are not on their own power strokes. Crankshafts tend to wrap up during this process and experience oscillations throughout their length. This disturbs piston strokes in adjoining cylinders and affects their volumetric efficiency.

Simply stated, a spark-timing figure that may be correct for a cylinder at the front of an engine may need to be retarded for cylinders toward the rear. This torsional deflection of the crank requires individual cylinder spark timing if power is to be optimized. Valve-timing accuracy also is upset, according to the amount of crankshaft (and camshaft) wrapup.

Another significant factor is the so-called "cross-talk" (pressure excursions and disturbances) that occurs in the intake and exhaust systems of joined cylinders. Visualize a single-plane intake manifold where all port runners connect to a common plenum chamber. Pressure pulses traverse the chamber throughout the engine's rpm and load range and tend to influence pure inlet flow among the cylinders. Depending on the amount of cylinder pressure at each intake valve opening, these disturbances can reduce each cylinder's ability to optimize power.

They also can contaminate fresh air/fuel mixtures and disrupt each cylinder's ability to achieve its highest level of volumetric efficiency. Inspection of piston tops and combustion chambers can reveal specific burn patterns as well as the power produced by individual cylinders. More uniformly distributed burn patterns are characterized by a lack of light and dark combustion residue on pistons and chambers. Concentrations of dark patterns suggest overly

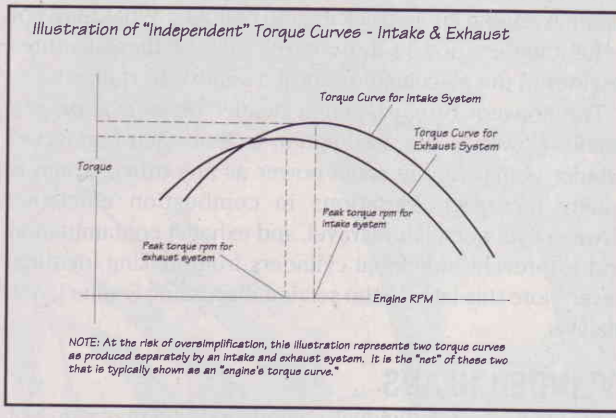
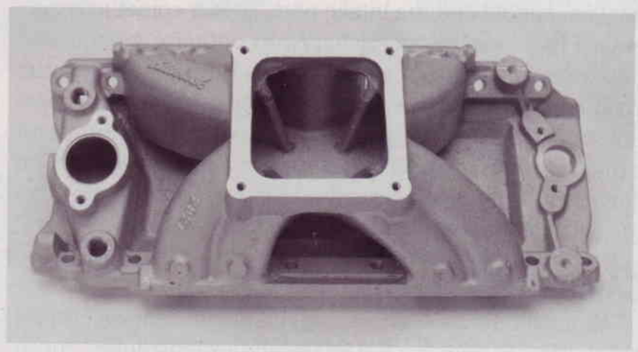


Illustration 1: Intake and exhaust systems make separate contributions to overall torque output. Therefore, each is a candidate for independent tuning. The wider apart each is tuned, the flatter the net torque curve. The closer each is tuned, the more the aggregate torque curve peaks.



This single-plane Edelbrock manifold is typical of designs incorporating runners of different length. It offers an opportunity to tune other components of the engine to vary the point at which peak individual cylinder torque is produced.

rich burns and lost power, especially at higher rpm.

Clearly then, net power is produced by the combination of an engine's components, so it is important to recognize the relationships among them. Understanding their integrated working is vital to selecting and matching parts intelligently. Let's look at some of these pieces.

INTAKE MANIFOLDS

Manifold runner lengths are typically unequal, particularly for carbureted engines. As with unequal header primary pipe lengths, this inequality affects the relationship between torque output and rpm. Since Edelbrock introduced its single-plane, V-8–type manifold in the early '70s, tens of thousands of similar design concepts have proliferated in the circle track community. Yet the camshafts most often used with these manifolds do not compensate the short runners for the inner four cylinders and long runners for the outer four. Some Nextel Cup teams have discovered the benefit of such camshafts; the Saturday night contingent has yet to catch on.

EXHAUST HEADERS

The use of equal (or unequal) length primary pipes and the incorporation of one or more stepped sizes of pipe are common among circle track engine builders. What may not be fully understood is the control each of these features provides in the placement of torque relative to rpm.

The concept of equal-length header pipes is a proven benefit. However, the assumption is that each connected cylinder is making the same power as any other, which is usually incorrect. Variations in combustion efficiency between cylinders, flame travel, and exhaust contamination tend to prevent individual cylinders from making identical power. Note this later in the section discussing Engine Cycle Analysis.

CYLINDER HEADS

In most cases, individual combustion chambers do not produce identical burn patterns or pressure. Variation in chamber shape is one cause, but the most frequent culprit is an inequality of air delivered by individual manifold runners.

Remember, the total inlet path is comprised of both the intake manifold and the intake port. So it is sometimes necessary to adjust the port shapes to optimize combustion pressures in each combustion space. Burn patterns in the chambers or on the piston tops will enable you to achieve this, or it can be done by measuring in-cylinder combustion dynamics via Engine Cycle Analysis or similar methods. The limited budget of most Saturday night racers confines them to visual inspection of components.

CAMSHAFTS

Manufacturers are increasingly happy to provide custom grinds, so consider having intake and exhaust lobes cut to match the rpm ranges of different inlet paths. For example, the two-length intake manifold design previously described can produce a broader torque band by incorporating an intake and exhaust lobe for the long (or bottom-end torque) length and another intake and exhaust lobe for the short (or higher rpm) length. It doesn't require much imagination to see how this works; in fact, the practice could be incorporated into header-pipe sizing that matches the intake paths to which each pipe is attached (Illustration 3).

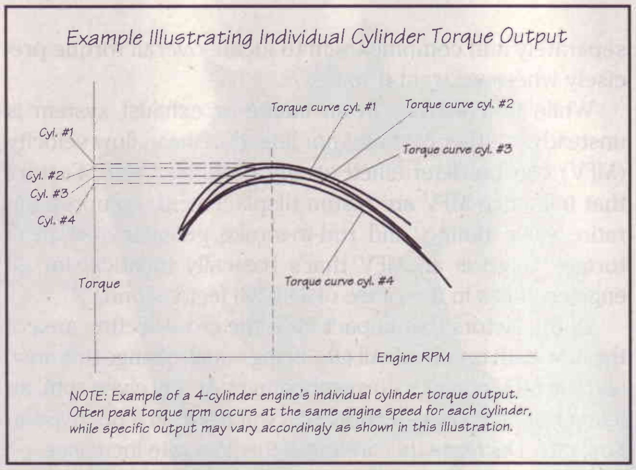
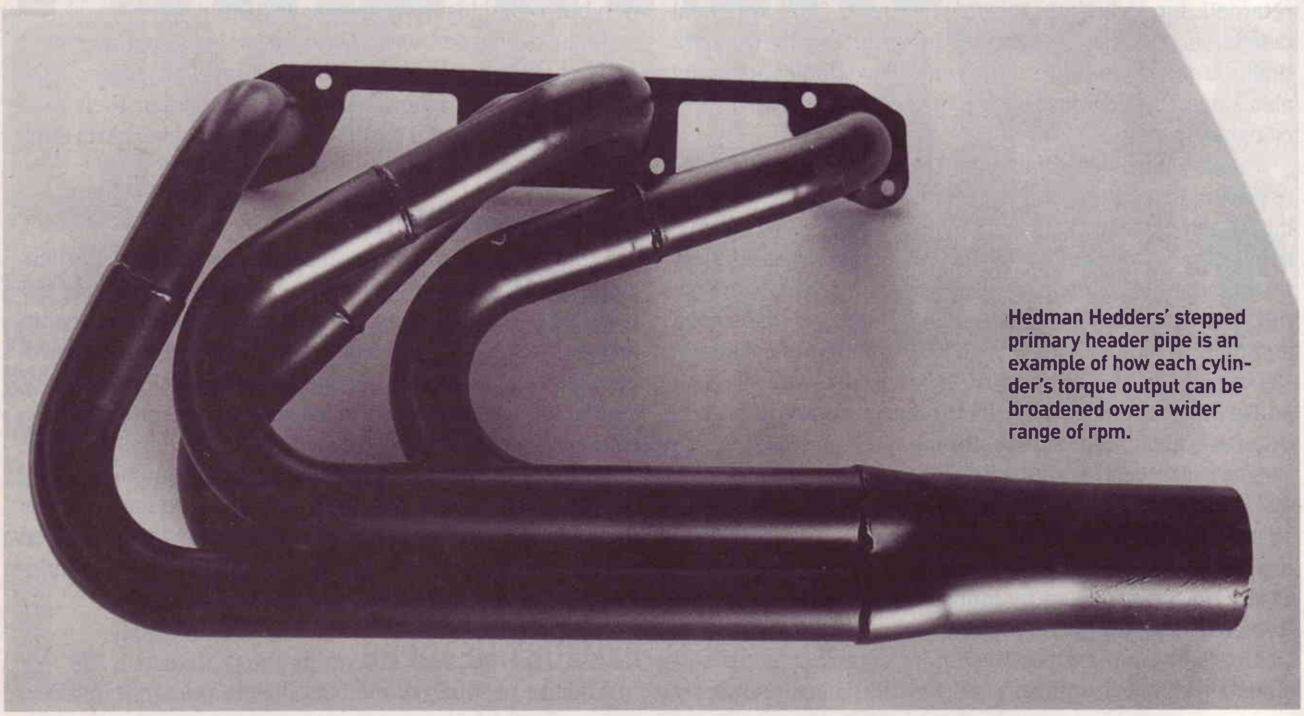


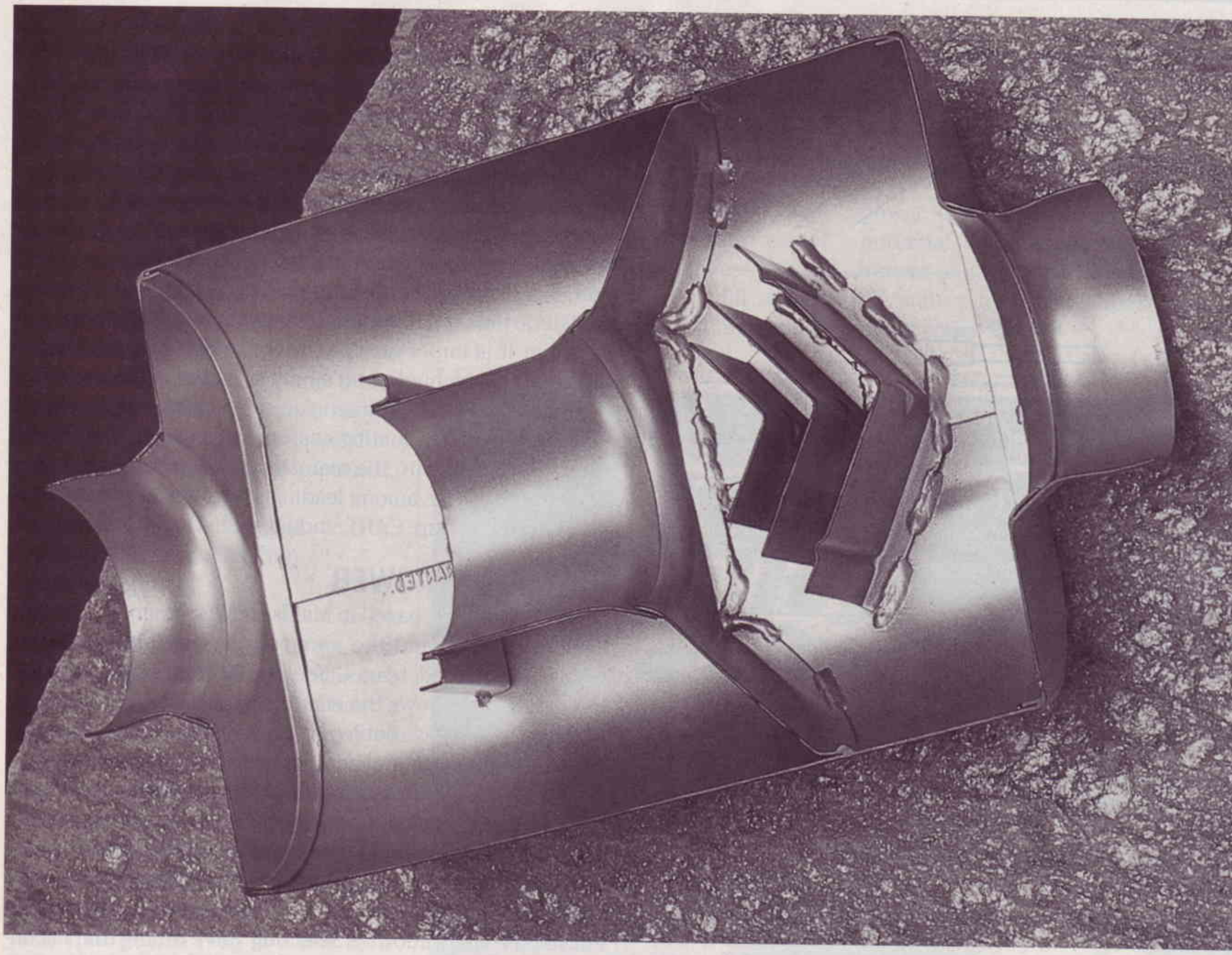
Illustration 2: This series of plots shows how torque output and peak torque rpm points can vary among an engine's cylinders. The peaks may not occur at the same rpm, which creates a further broadening of the net torque curve.

IGNITION SYSTEMS

Several manufacturers, including MSD, offer systems that permit individual cylinder-spark timing. Settings can be determined by combustion-process feedback that keys off ignition spark ionization at the plug's gap. Cylinder-to-cylinder air/fuel ratios vary as a function of rpm, load, and mixture-motion characteristics, so the ability to optimize spark timing for each cylinder is an additional tool for maximizing total power. We've even seen electronic ignition systems



Hedman Hedders' stepped primary header pipe is an example of how each cylinder's torque output can be broadened over a wider range of rpm.



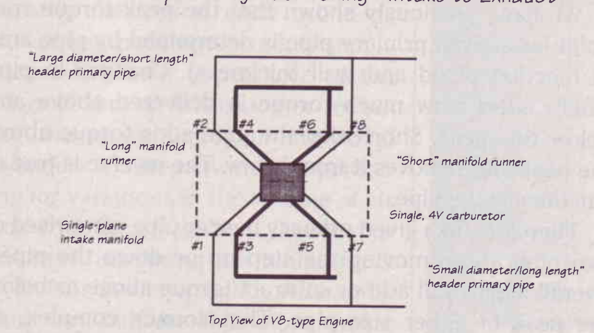
Backpressure reductions also allow individual cylinder tuning to be optimized. This Flowmaster "Delta Flow" concept is reported to provide low-pressure conditions for additional cylinder evacuation and increased power.

with trigger wheels (reluctors) of uneven tooth spacing that vary the amount of spark advance from cylinder to cylinder. All these techniques address the specific spark-timing requirements of cylinders displaying different pre-combustion patterns.

ENGINE CYCLE ANALYSIS (ECA)

ECA is a form of high-speed information gathering, which is useful largely because of the speed at which the internal combustion process takes place. The process measures the

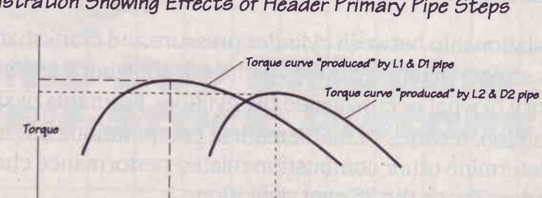
Illustration of Specific Cylinder Tuning - Intake to Exhaust



NOTE: Study this illustration. It represents one method for optimizing individual cylinder power, and it focuses on the benefits of "tuning" short /long intake manifold runners with short/long and large/small diameter primary header pipes, joined in a common collector. See accompanying caption for further discussion about the benefits of this concept.

Illustration 3: Matching intake and exhaust path lengths (including cylinder-specific valve tuning) is particularly effective when attempting to optimize short- and long-track torque requirements.

Illustration Showing Effects of Header Primary Pipe Steps



NOTE: First of all, this illustration is conceptual in nature. It is not based on specific data. However, it does show how small diameter primary pipe tends to produce a torque peak lower than that of a larger diameter pipe. When each pipe "sees" a mean flow velocity of 240-260 ft./sec., a torque "peak" results. The larger pipe requires more rpm than the small to reach this flow rate. Changes in pipe length do not affect peak torque rpm, only the amount of torque produced above or below each pipe's respective torque peak.

Illustration 4: Stepped headers produce a broader and flatter torque curve. Make certain to match the rpm and torque requirements with the proper primary pipe size and step location.

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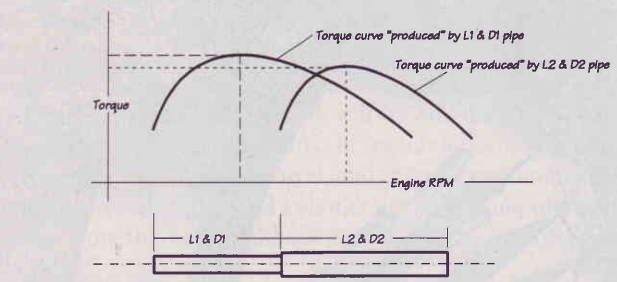

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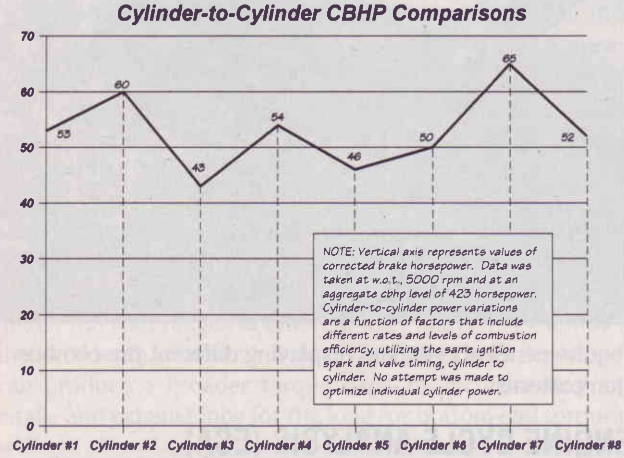
Illustration 5: It's not just about stagger-jetting a carburetor. Variations in cylinder-to-cylinder airflow, combustion space (chamber and piston top), mixture motion, and spark timing can all influence individual cylinder-combustion efficiency.

Cylinder-to-Cylinder CBHP Comparisons



Information Courtesy of Hi-Techniques, Inc.

Illustration 6: These traces represent the in-cylinder pressure histories of a four-cylinder engine. Variations in peak pressure (vertical axis) and the different crankshaft angles at which these peaks occur (horizontal axis) are further evidence of cylinder-to-cylinder power differences, as measured by Engine Cycle Analysis.

relationship between cylinder pressure and crankshaft angle. A stream of information is gathered, showing a pressure history of what occurs inside the cylinder. From this basic information, a series of mathematical computations are made to determine other combustion-related performance characteristics. That's the 25-cent definition.

Specifically, an encoder is fitted to an engine's crankshaft snout and is electronically linked to one or more pressure-sensing devices exposed to the combustion pressure in a single cylinder. That was a decade ago. Today, all of an engine's cylinders may be analyzed simultaneously and are sometimes coupled with pressure sensors in the intake and exhaust tracks of each cylinder.

ECA studies power levels produced by each cylinder over a range of engine speeds and loads. Data acquisition can occur at a rate of one million samples per second and crank angles down to one tenth of a degree, producing almost real-time information. Components such as manifolds, ports, combustion spaces (chambers and piston tops), valve timing, and spark timing can be matched to make all cylinders produce identical power. The process is especially useful in determining the best compromises for power in circumstances when cylinders "talk" to one other through common areas such as intake manifold plenums and exhaust header collectors.

This article is not intended to take you into the bowels of ECA, but it is important for the Saturday night racer to be aware of this technology. It's only a matter of time before it becomes affordable from engine dyno operators as a cost-effective way of evaluating customers' engines. Then it will then find its way into the mainstream of circle track racing. It is already in use among leading professional teams, especially in Nextel Cup, CART, and Formula One.

OPTIMIZING POWER

Hi-Techniques, based in Madison, Wisconsin, is a leading source for ECA, and the company has enlightened some widely recognized teams. See the accompanying engine-dyno data that shows the effects of optimizing spark timing and other engine variables on an individual cylinder basis (especially valve timing and compression ratio).

One of the best approaches to optimizing individual cylinder power is to consider certain physical aspects of your components and tune them accordingly. For example, connecting short and long intake runners to large and smaller primary header pipes helps broaden the torque curve (see Illustration 3). Selecting valve timing that is consistent with these two ranges of torque output can further enhance a broader, flatter torque curve. The use of stepped headers also helps to extend torque curves, aiding off-the-corner torque while still retaining straightaway speed. How this works is shown in Illustration 4. Of course, the selection of pipe size and step location will affect where and how much torque is shifted between the two peaks derived from the pipe outside-diameter (od) selection. Here's how that works.

We have previously shown that the peak torque rpm point for a given primary pipe is determined by pipe area (a function of od and wall thickness). Changes in pipe length affect how much torque is delivered above and below this peak. Shortening the pipe adds torque above the peak and removes it from below. The reverse is true of lengthening the pipe.

Therefore, in a given primary header pipe comprised of two pipe areas, moving the step up or down the pipe's overall length will add or subtract torque above or below the peak of either size pipe. That sounds complex, so examine Illustration 4. The caption and footnote should clear up any confusion about the effects of adjusting primary pipe step location.

According to Hedman Hedders President Ron Funfar, "We've found particular benefit in the 'stepped header' concept. Race headers, as well as those for light- and mediumduty trucks used for towing, show torque gains in the low- and mid-range rpm when built with properly sized primary tubing."

Using the rule that 240-260 feet/second of flow velocity in an exhaust or intake path equates to peak torque rpm, the following equation is useful in selecting these passages' sizes. There are fundamental differences between intake and exhaust flow (including gas/mixture temperatures and piston position at peak-flow velocity), but you can still arrive at workable dimensions by using this mathematical approach:

Peak torque rpm = (Passage cross-section area x 88,200) ÷ cylinder volume

By transposing these terms, you can determine the rpm at which a given cross section will produce a torque peak (intake or exhaust) or what cross-section area is required to produce peak torque at a desired rpm. The equation is a tool that can be used to evaluate existing cross sections or determine cross sections required to produce specific torque peak rpm points. Plug in a few numbers—you'll quickly see the value of this equation.

So, what about spark timing? Cross-jetting carburetors to compensate for poor cylinder-to-cylinder air, fuel, or air/fuel distribution is a time-honored method of tuning for best power. But even when plug readings begin to equalize, that does not necessarily mean that each cylinder's power has been optimized; it simply means the burn appearance of the plugs is similar. Advancing or retarding the spark timing of individual cylinders is a step toward compensating for variations in the volume of air and fuel in any given cylinder. For example, advancing the timing for a cylinder showing a slightly rich condition may indicate that more timing would help burn the fuel that's already present, resulting in a power increase for that particular cylinder.

IS IT WORTH THE TROUBLE?

That depends upon how many ways you'd like to split the hairs. Hi-Technique's example engine—a 350ci small-block Chevy—produces a corrected 826 bhp. Optimizing individual spark timing increased this number to 836.5. Further manipulation of valve timing and compression ratio raised this to 848.5 hp. For engines built to rules that allow limited modifications, "power by the cylinder" may make more sense than if the rules are more lenient. Then again, ultra-competitive teams may wish to optimize parts functions regardless of what the rules allow. In any event, maximum engine power is not obtainable unless the potential combustion efficiency and output of each cylinder is addressed, no matter how you choose to take those steps. **EM**