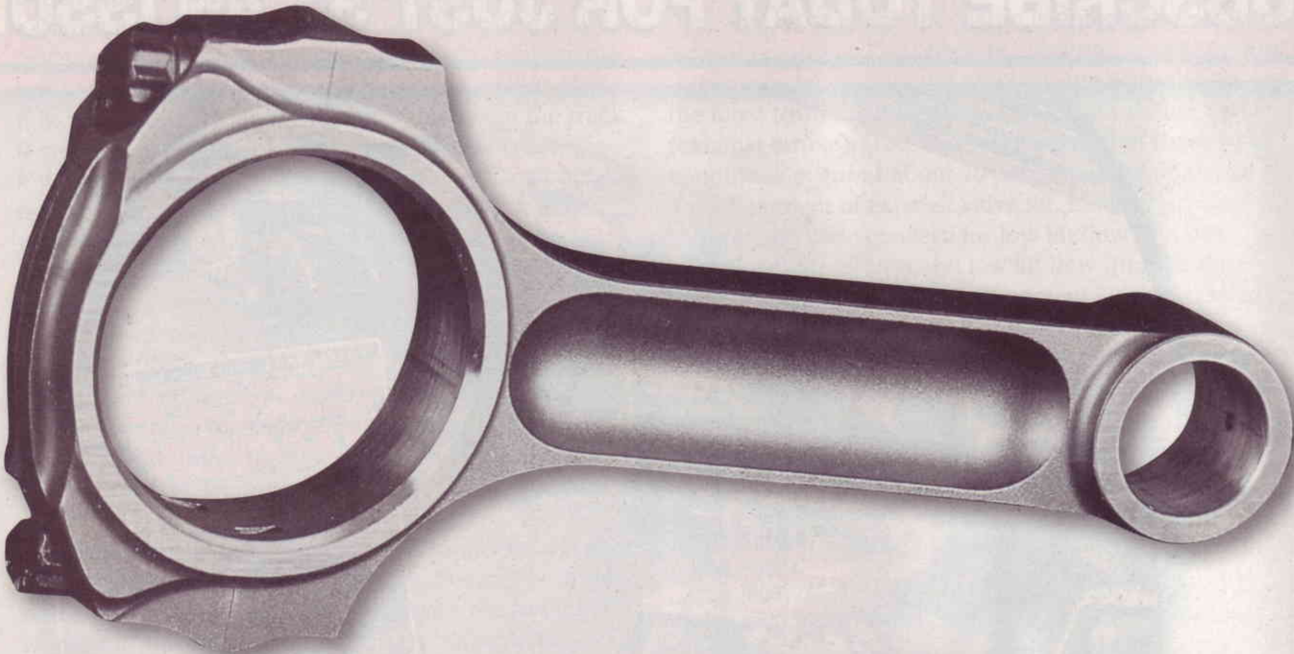

IT'S ON THE ROD AGAIN...

INNOCENT IN APPEARANCE, THIS GEOMETRICAL LINK PLAYS A GREATER POWER ROLE THAN YOU THINK

TEXT AND ILLUSTRATIONS BY
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This article is about the influence connecting rods have on the ability of an engine to make power, specifically at certain points in its rpm range. It does not contemplate materials, strengths, weaknesses, elasticity properties, or other topics typical of many editorials about rods. Instead, we'll look into the essential relationships of how piston motion, as affected by connecting rod length, relates to valve timing, spark timing, intake and exhaust port sizing, and other elements pertinent to optimizing volumetric efficiency (VE) or torque.

THE "SLIDER-CRANK" MECHANISM

In the study of mechanisms and their dynamics, an assembly common to the internal combustion engine is the slider-crank mechanism. It consists of a rotating crank, a

WHAT YOU'LL LEARN FROM THIS STORY

Since piston motion is affected by the relationship of the connecting rod length to the crankshaft stroke, you will discover that changing the rod length can have a material effect on ignition spark requirements, cylinder pressure conditions, optimum valve timing, and net torque. There is little doubt and substantial documentation demonstrating the importance of matching primary engine components to the length of a connecting rod. The following is intended to provoke thought and considerations about the way connecting rods affect overall power output.

"link" or piston, and a rod connecting the two (see illustration). Since the crank's axis is fixed at one point, the piston can move along a path either on or near a line intersecting the crank's axis of rotation. If the piston's motion is limited to travel only along this axis, then one example of this movement is the traversing of an engine's pistons in its cylinders.

Several mathematical equations describe the motion of pistons as a function of the crankshaft angle. Obviously, since there is a change of piston direction at each end of its stroke, both velocity and acceleration will be zero at these points. However, we are concerned about piston velocity and acceleration between top dead center (TDC) and bottom dead center (BDC).

By one definition, average velocity is a measure of distance traveled in a period of time. Instantaneous velocity, on the other hand, is a measure of velocity at a particular location or point in time relative to that location. More important to our discussion is the definition of acceleration: the "rate of change in velocity" or, depending upon how quickly velocity is increasing or decreasing, how acceleration can be either positive or negative.

As the length of a rod is changed, so are the velocity and acceleration characteristics of its attached piston at locations other than TDC and BDC.

PISTON MOTION AND ITS EFFECTS ON VOLUMETRIC EFFICIENCY

Especially in the case of normally aspirated engines, piston velocity and acceleration impact the rate at which a difference is created between atmospheric and cylinder pressure. It is important to understand that a condition in which cylinder pressure is lower than atmospheric pressure does not cause an engine to suck air. Rather, atmospheric pressure pushes air into the engine. The faster a piston moves downward, the more rapid this pressure difference is created and the quicker atmospheric force can fill the void. That's fundamental.

More to the point, since a piston's motion is a combination of acceleration, deceleration, and two changes of direction (TDC and BDC), it becomes crucial to determine its position in the cylinder bore when the highest rate of pressure drop is being created. Since the piston position in a bore can be related to the crankshaft angle, a fairly straightforward mathematical analysis provides this information.

Now, to the VE issue. Critical to optimizing volumetric efficiency is the timing of valve action to piston motion. Valve timing and piston motion are inexorably tied together and should be considered as such—especially when selecting camshafts and matching them to connecting rod lengths ("short" versus "long").

HOW ROD LENGTH AFFECTS PISTON MOTION

Since pistons momentarily stop at TDC and BDC, any change to rod length affects acceleration and velocity between these two end points. Right here, it may be helpful to make a general statement about how changes in rod length affect piston motion.

As a rule, lengthening a rod tends to cause a piston to remain longer (increased crankshaft angle) around TDC and BDC than with rods of shorter length. Let's assume an example in which the stroke distance is the same for two different lengths of connecting rods. In this case, we know each piston will travel the same TDC-to-BDC distance, and the longer rod will cause increased piston dwell time at these two end points.

Let's examine what goes on in between TDC and BDC by cutting right to the heart of the issue. We know the piston for each rod length will achieve maximum velocity and acceleration somewhere during the stroke. What's important is that this point (crankshaft angle) will be different for each rod length. As a piston approaches or departs TDC or BDC, the longer the rod, the slower this motion will be. As you would expect, the corollary is true for rods of shorter length.

In general, peak torque is largely influenced by the tuning characteristics (particularly dimensions) of the intake and exhaust system. Changes in connecting rod length tend to shift peak power rpm closer to or further from peak torque rpm. For example, as the connecting rod length is

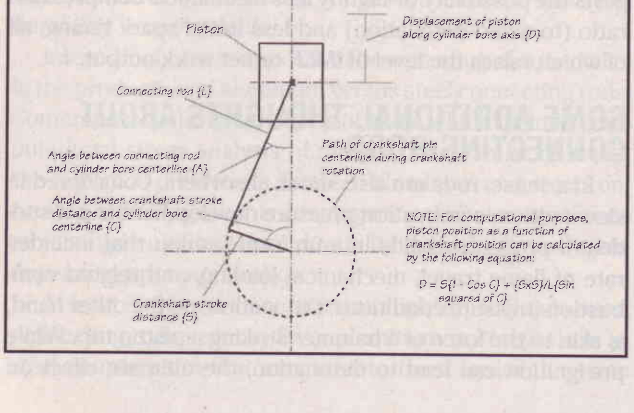


Illustration of Basic "Slider-Crank" Mechanism Characterizing Piston, Connecting Rod and Crankshaft Dimensional Relationships & Positions

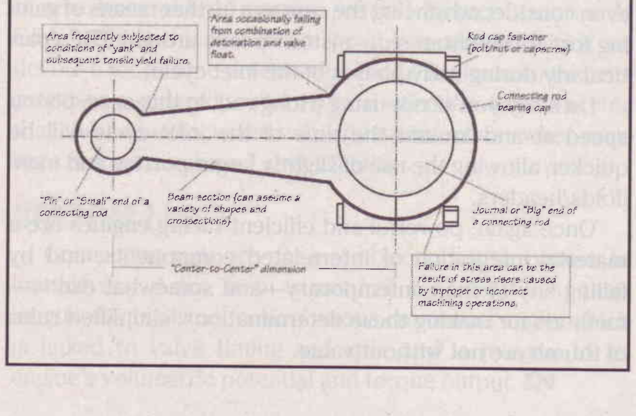


Illustration Showing Basic Connecting Rod Terminology and Areas Frequently Associated With Mechanical Failure increased, the peak horsepower rpm will move toward the peak torque rpm.

PISTON MOTION AND VALVE TIMING

Let's start this off with an example. Suppose we do the math for a slider-crank mechanism dimensioned with the stroke and rod length we'll use and attempt to select a matching camshaft. The numbers tell us the piston is moving at maximum velocity at 75 crankshaft degrees past TDC on the intake stroke. From another perspective, this tells us we have the potential for the highest VE (as affected by piston motion) at this crank angle. If the intake valve opening at this same crank angle is insufficient (or excessive) to maximize inlet flow, we've lost some advantage to optimize VE and torque (recall that an engine's volumetric efficiency and torque potential are virtually synonymous).

Some dyed-in-the-wool engine builders will make graphical plots (on an X-Y coordinate system) that show piston position as a function of crankshaft angle. Then they will superimpose a similar plot of valve-opening/closing dimensions onto the piston position graph. By comparing the two, a graphical representation of how the piston position compares to the valve opening reveals this relationship and what must be done to valve timing for proper matching of the two.

Other engine builders blessed with engine cycle analysis capability will make real-time cylinder pressure versus crankshaft angle traces and do a dynamic analysis of what is required for optimum valve motion to match existing piston motion. Still others will use computer software to perform iterative changes to valve timing and arrive at the same or similar conclusions. By whichever method you choose, integrating valve motion with piston motion is a contemporary must.

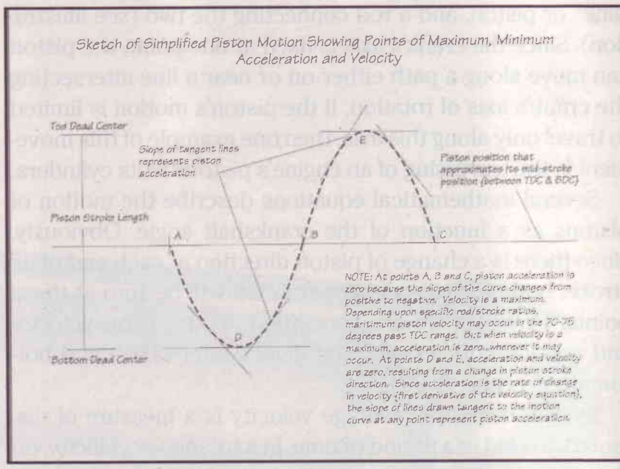
PISTON MOTION AND PORT FLOW RATES

Simply stated, if the piston isn't moving very quickly during the inlet cycle, something else must be added that will increase port flow rate. Although this condition should not exist, it often does if proper matching is not accomplished between piston motion and valve timing.

One of these is the use of an intake manifold with small runners (in terms of cross-section area). Small-diameter headers tend to "crutch" in the same fashion. You might even consider advancing the cam as a further means of gaining lost torque from slow piston speeds around TDC (particularly during early phases of the inlet cycle).

Let's say you're not using a long rod. In this case, piston speed at and around the time of the inlet cycle will be quicker, allowing the use of slightly larger porting and manifolds/headers.

Once again, powerful and efficient racing engines are a material integration of interrelated components, and by failing any of the contemporary—and somewhat exotic—methods for making these determinations, simplified rules of thumb are not without value.



PISTON MOTION, CYLINDER PRESSURE, AND IGNITION SPARK TIMING

If you are doubtful that these are related, consider this. If a piston stays around TDC longer, it'll do more work on the crank, perhaps, but let's consider something that goes along with this.

There's a term in the study of internal combustion engines called *constant volume combustion*. This amounts to a set of conditions that unravels rapidly throughout the burn while the piston is changing direction (stopped) at TDC. At this point, cylinder pressure and temperature rise suddenly and to high levels, sometimes tending to cause detonation or uncontrolled combustion.

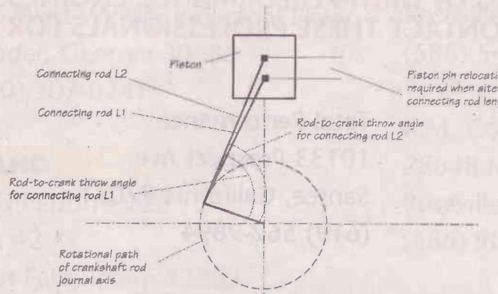
As connecting rod length is increased, instantaneous cylinder pressure becomes higher (all else being equal) approaching and at TDC than with a shorter rod. As a result, it is often necessary to run less initial spark timing with increased connecting rod length.

If we consider the amount of work done on a piston prior to TDC (negative) and after TDC (positive), it helps net power to reduce the amount of negative work. Net work (the difference between positive and negative) is called Indicated Mean Effective Pressure (IMEP). You could also say this is what we're calling "net work." While maintaining piston residence in the vicinity of TDC, the idea is to increase the dwell time for pressure on the piston, just past TDC. This increased pressure (from a longer rod), which also increases pre-TDC mixture density and flame rate, suggests the possibility of slightly less mechanical compression ratio (to avoid detonation) and less initial spark timing, all of which raises the level of IMEP or net work output.

SOME ADDITIONAL THOUGHTS ABOUT CONNECTING RODS

In a sense, rods are also shock absorbers. Considered in slow motion, combustion pressure development is not sudden. If proper, it builds in a uniform fashion that includes rate of flame travel, mechanical loading, and related combustion-pressure conditions. Detonation, on the other hand, is akin to the force of a hammer striking a piston top. While pre-ignition can lead to detonation, the ultimate effect on

Illustration Showing Some of the Effects From Changing Connecting Rod Length



NOTE: Several observations can be made by studying this illustration. In particular, note the apparent mechanical advantage afforded by the longer rod {L2} in applying combustion pressure forces onto the crankshaft journal {as compared to rod L1}. Additionally, "dwell time" of the longer rod in approaching and departing TDC is increased, allowing an extended time for torque application and faster burn rate from increased effective mixture density. Of the results this creates {longer rod}, peak horsepower is developed sooner in relation to peak torque rpm, causing less rpm to separate peak power and peak torque...ideal for engines operated in a relatively narrow span of rpm {superspeedway, etc.}.

connecting rods is the same. All these forces are ultimately transferred into the connecting rod, comprising multidirectional stress loads, many of which lie outside the geometrical axis of the rod. Part of this is caused by asymmetrical forces applied to the tops of pistons, the other part by dynamic action of the rods as connected to a crankshaft. Add to this the fact that "load sharing" is occurring among connecting rod sets, and it's possible for detonation in one cylinder to cause damage to a rod not associated with the problem cylinder.

It's possible to design a connecting rod that is too stiff. This can allow combustion pressure to transfer too rapidly to bearings (rod and crank) and an inability to absorb unavoidable pressure spikes associated with abnormal combustion. Furthermore, connecting rod stiffness comes into play when it's necessary to absorb torsional loads caused by rotary vibrations in a piston—somewhat like wringing out a wet rag.

MATERIAL SELECTION

Important to this decision is the ultimate use. Of the typical materials used, the following are common: cast iron, steel, titanium, aluminum, and powdered metal. Produced by methods that include casting, forging, or high-pressure die techniques, end use is the primary consideration for manufacturing choice—excluding economic factors. As is the case of virtually any engine component, especially for high performance or racing, a trade-off between cost and durability is unavoidable.

Interestingly, there appears to be a merging of economics in the production of aluminum versus steel connecting rods. Contemporary design methods of each, which include computational stress analysis of designs, seem to be reducing the historical differences between aluminum and steel connecting rods. Despite this convergence of choice, steel rods remain higher in long-term durability than aluminum, again depending upon application.

At least in theory, if not practice, high-impact loads upon connecting rods seem to favor aluminum in comparison to steel counterparts that may tend to burst under the same type of loads. What must also be considered is that the most damaging loads on a connecting rod do not occur during the pure compression of combustion. The oscillatory vibration of a crankshaft causes connecting rods to experience compression and tensile loads, alternatively, during every rotation of the crank. Essentially, they become rubber bands that must withstand these cyclical load patterns while maintaining sufficient dimensional integrity to not fail or cause piston/head contact or bearing damage, which brings us to a final area of importance.

CAUSES OF FREQUENT ROD FAILURE OR DAMAGE

Consider the comments of Rocky Childs (Childs&Albert): "There is a consistent opinion among many of the engine builders who are our customers that rod failure is most often caused by excessive combustion or detonation pressure. This simply isn't so. Now, that statement doesn't mean connecting rods won't fail during these times, but it's not the predominant period. In our experience, and I'd estimate about 90 percent of the cases we've specifically evaluated, rods don't fail during compressive loads. Actually, our data strongly indicates it's during the exhaust stroke that a connecting rod gets yanked apart as it departs from TDC.

"This isn't our imagination. If you look closely at the appearance of material along the parting surfaces between the failed pieces, you can visually note how the material has failed under a tensile load. This, of course, assumes damage to the parts that followed; the failure doesn't mask these areas and cause them to be unreadable. Furthermore, failures of this type usually occur just below the pin area."

Two other areas are commonly associated with rod failure. "Valve float, sometimes not even recognizable by a driver or engine builder because it's not always audible, takes away the cushion provided by combustion pressure as the pistons approach TDC. As a result, there's nothing to soften their approach to cylinder head surfaces, and pistons get thrown against the heads. It doesn't take much imagination to visualize the forces present when a high-revving piston passes through TDC with little or no resistance. It's not just about valvespring damage. Other factors come immediately into play, too."

Finally, there is another area of concern regarding rod failure. "Right where a connecting rod's beam section changes in area from wide to narrow, we find frequent failures. At C&A, we call this the 'hinge point,' an area to which we devote a lot of time determining the best dimensional compromises compared to rod material selection. It's something that should be discussed with any manufacturer when making a rod set purchase," says Childs.

BOTTOM LINE?

Connecting rods are not just objects that tie pistons to crankshafts. Aside from structural considerations, their length affects piston motion versus crankshaft angle, which is linked to valve timing and rpm and is integral to an engine's volumetric potential and torque output. **EM**