Understanding Exhaust:

The How & Why

No exhaust system is ideal for all applications. Depending on their design and purpose, all exhaust systems compromise something to achieve something else. Before performing exhaust changes or modifications to increase performance, it is critical to determine what kind of performance you want.

- Do you want the best possible low-end and mid-range power or maximum top-end power?
- Will you be using an aftermarket cam with different lift, duration, timing and overlap?
- Have you investigated the relationship between torque (force) and horsepower (amount of work within time)?
- Do you want a cosmetic exhaust system or a performance exhaust system?

Without careful thought about these variables, an exhaust system can yield very disappointing results. On the other hand, a properly designed and tuned exhaust system that is well-matched to the engine can provide outstanding power gains.

The distinction between "maximum power" and "maximum performance" is significant beyond general discussion. Realistically, one exhaust system may not produce both maximum power and maximum performance. For a car to cover "X" distance as quickly as possible, it is not the highest peak power generated by the engine that is most critical. It is the highest average power generated across the distance that typically produces the quickest time. When comparing two horsepower curves on a dynamometer chart (assuming other factors remain constant), the curve containing the greatest average power is the one that will typically cover the distance in the least time and that curve may, or may not, contain the highest possible peak power.

In the strictest technical sense, an exhaust system cannot produce more power on its own. The potential power of an engine is determined by the proper amount of fuel available for combustion. However, the efficiency of combustion and engine pumping processes is profoundly influenced by the exhaust system. A properly designed exhaust system can reduce engine pumping losses. Therefore, the design objective for a high performance exhaust is (or should be) to reduce engine-pumping losses, and by so doing, increase volumetric efficiency. The net result of reduced pumping losses is more power available to move the motorcycle. As volumetric efficiency increases, potential fuel mileage also increases because less throttle opening is required to move the motorcycle at the same velocity.

Much controversy (and apparent confusion) surrounds the issue of exhaust "back-pressure". Many performance-minded people who are otherwise knowledgeable still cling tenaciously to the old school concept.... "You need more back-pressure for better performance."

For virtually all high performance purposes, backpressure in an exhaust system increases engine-pumping losses and decreases available engine power. It is true that some engines are mechanically tuned to "X" amount of backpressure and can show a loss of low-end torque when that backpressure is reduced. It is also true that the same engine that lost low-end torque with reduced back-pressure can be mechanically re-tuned to show an increase of low-end torque with the same reduction of back-pressure. More importantly, maximum mid-to-high RPM power will be achieved with the lowest possible backpressure. Period!

The objective of most engine modifications is to maximize the proper air and fuel flow into, and exhaust flow out of the engine. The inflow of an air/fuel mixture is a separate issue, but it is directly influenced by exhaust flow, particularly during valve overlap (when both valves are open for "X" degrees of crankshaft rotation). Gasoline requires oxygen to burn. By volume, dry, ambient air at sea level contains about 21% oxygen, 78% Nitrogen and trace amounts of Argon, CO2 and other gases. Since oxygen is only about 1/5 of airs volume, an engine must intake 5 times more air than oxygen to get the oxygen it needs to support the combustion of fuel. If we introduce an oxygen-bearing additive such as nitrous oxide, or use an oxygen-bearing fuel such as nitromethane, we can make much more power from the same displacement because both additives bring more oxygen to the combustion chamber to support the combustion of more fuel. If we add a supercharger or turbocharger, we get more power for the same reason, more oxygen is forced into the combustion chamber.

Theoretically, in a normally aspirated state of tune without fuel or oxygen-rich additives, an engines maximum power potential is directly proportional with the volume of air it flows. This means that an engine of 80 cubic inches has the same maximum power potential as an engine of 100 cubic inches, if they both flow the same volume of air. In this example, the powerband characteristics of the two engines will be quite different but the peak attainable power is essentially the same.

Flow Volume & Flow Velocity
One of the biggest issues with exhaust systems, is the relationship between gas flow volume and gas flow velocity (which also applies to the intake track). An engine needs the highest flow velocity possible for quick throttle response and torque throughout the low-to-mid range portion of the power band. The same engine also needs the highest flow volume possible throughout the mid-to-high range portion of the powerband for maximum performance. This is where a fundamental conflict arises. For "X" amount of exhaust pressure at an exhaust valve, a smaller diameter exhaust pipe will provide higher flow velocity than a larger diameter pipe. Unfortunately, the laws of physics will not allow that same small diameter pipe to flow sufficient volume to realize maximum possible power at higher RPM. If we install a larger diameter pipe, we will have enough flow volume for maximum power at mid-to-high RPM, but the flow velocity will decrease and low-to-mid range throttle response and torque will suffer. This is the primary paradox of exhaust flow dynamics and the solution is usually a design compromise that produces an acceptable amount of throttle response, torque and horsepower across the entire powerband.

A very common mistake made by some performance people is the selection of an exhaust system with pipes that are too large in diameter for their engine's state of tune. ***Bigger is not necessarily better and is often worse.***

Equal Length Exhaust

The effectiveness of equal length exhaust is widely debated. Assuming that an exhaust system is otherwise properly designed, equal length pipes offer some benefits that are not present with unequal length pipes. These benefits are smoother engine operation, tuning simplicity and increased low-to-mid range torque.

If the pipes are not equal length, both inertial scavenging and wave scavenging will vary among engine cylinders, often dramatically. This, in turn, causes different tuning requirements for different cylinders. These variations affect air/fuel mixtures and timing requirements, and can make it very difficult to achieve optimal tuning. Equal length pipes eliminate these exhaust-induced difficulties. "Tuning", in the context used here, does not mean installing new sparkplugs and an air filter. It means configuring a combination of mechanical components to maximum efficiency for a specific purpose and it can not be overemphasized that such tuning is the path to superior performance with a combination of parts that must work together in a complimentary manner.

In an exhaust system that is properly designed for its application, equal length pipes are generally more efficient. The lengths of both the primary and main section of pipes strongly influence the location of the torque peak(s) within the powerband. In street and track performance engines with longer pipes typically produce more low-to-mid range torque than shorter pipes and it is torque that moves a motorcycle. The question is... Where in the powerband do you want to maximize the torque?

- Longer pipes tend to increase power below the engine’s torque peak and shorter pipes tend to increase power above the torque peak.
- Large diameter pipes tend to limit low-range power and increase high range power.
- Small diameter pipes tend to increase low-range power and to some degree limit high-range power.
- "Balance" or "equalizer" chambers between the exhaust pipes tend to flatten the torque peak(s) and widen the powerband.

Among the more astute and responsible exhaust builders, it is more-or-less understood that pipe length variations should not exceed 1" to be considered equal. Even this standard can result in a 2" difference if one pipe is an inch short and another pipe is an inch long.

Exhaust Scavenging and Energy Waves

Inertial scavenging and wave scavenging are different phenomena but both impact exhaust system efficiency and affect one another. Scavenging is simply gas extraction. These two scavenging effects are directly influenced by pipe diameter, length, shape and the thermal properties of the pipe material (stainless, mild steel, thermal coatings, etc.). When the exhaust valve opens, two things immediately happen. An energy wave, or pulse, is created from the rapidly expanding combustion gases. The wave enters the exhaust pipe traveling outward at a nominal speed of 1,300 - 1,700 feet per second (this speed varies depending on engine design, modifications, etc., and is therefore stated as a "nominal" velocity). This wave is pure energy, similar to a shock wave from an explosion. Simultaneous with the energy wave, the spent combustion gases also enter the exhaust pipe and travel outward more slowly at 150 - 300 feet per second nominal (maximum power is usually made with gas velocities between 240 and 300 feet per second). Since the energy wave is moving about 5 times faster than the exhaust gases, it will get where it is going faster than the gases. When the outbound energy wave encounters a lower pressure area such as a second or larger diameter section of pipe, the muffler or the ambient atmosphere, a reversion wave (a reversed or mirrored wave) is reflected back toward the exhaust valve without significant loss of velocity.

The reversion wave moves back toward the exhaust valve on a collision course with the exiting gases whereupon they pass through one another, with some energy loss and turbulence, and continue in their respective directions. What happens when that reversion wave arrives at the exhaust valve depends on whether the valve is still open or closed. This is a critical moment in the exhaust cycle because the reversion wave can be beneficial or detrimental to exhaust flow, depending upon its arrival time at the exhaust valve. If the exhaust valve is closed when the reversion wave arrives, the wave is again reflected toward the exhaust outlet and eventually dissipates its energy in this back and forth motion. If the exhaust valve is open when the wave arrives, its effect upon exhaust gas flow depends on which part of the wave is hitting the open exhaust valve.

A wave is comprised of two alternating and opposing pressures. In one part of the wave cycle, the gas molecules are compressed. In the other part of the wave, the gas molecules are rarefied. Therefore, each wave contains a compression area (node) of higher pressure and a rarefaction area (anti-node) of lower pressure. An exhaust pipe of the proper length (for a specific RPM range) will place the wave’s anti-node at the exhaust valve at the proper time for its lower pressure to help fill the combustion chamber with fresh incoming charge and to extract spent gases from the chamber. This is wave scavenging or "wave tuning".

From these cyclical engine events, one can deduce that the beneficial part of a rapidly traveling reversion wave can only be present at an exhaust port during portions of the powerband since it's relative arrival time changes with RPM. This makes it difficult to tune an exhaust system to take advantage of reversion waves which is why there are various anti-reversion devices designed to improve performance. These anti-reversion devices are designed to weaken and disrupt the detrimental reversion waves (when the wave's higher-pressure node impedes scavenging and intake draw-through). Specifically designed performance baffles can be extremely effective, as well as heads with D shaped ports. Unlike reversion waves that have no mass, exhaust gases do have mass. Since they are in motion, they also have inertia (or "momentum") as they travel outward at their comparatively slow velocity of 150 - 300 feet per second. When the gases move outward as a gas column through the exhaust pipe, a decreasing pressure area is created in the pipe behind them. It may help to think of this lower pressure area as a partial vacuum and one can visualize the vacuous lower pressure "pulling" residual exhaust gases from the combustion chamber and exhaust port. It can also help pull fresh air/fuel charge into the combustion chamber. This is inertial scavenging and it has a major effect upon engine power at low-to-mid range RPM.

There are other factors that further complicate the behavior of exhaust gases. Wave harmonics, wave amplification and wave cancellation effects also play into the scheme of exhaust events. The interaction of all these variables is so abstractly complex that it is difficult to fully grasp. There does not appear to be any absolute formula that will produce the perfect exhaust design. Even super-computer designed exhaust systems must undergo dyno, track, and street testing to determine the necessary configuration for the desired results. Last but not least, the correct choices and combinations of carburetor, air cleaner, cam shaft, ignition, and exhaust used in the proper relationship to each other for the intended riding application will always produce the finest quality results. Most important of all, is to do your research prior to purchasing the combination of products and equipment best suited to your individual needs