DIESEL ENGINE RIGHT-SIZING

Selecting the Appropriate Engine for an Application

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INTRODUCTION

HORSEPOWER & WORK

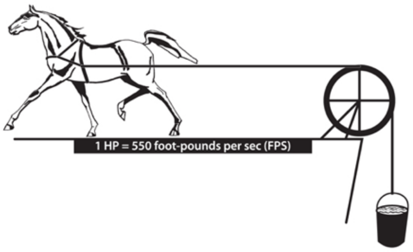

Figure 1. Stringham, Blair (August 2013). Understanding Horsepower & Water Horsepower. Retrieved from website: https://aces.nmsu.edu/pubs/_m/M227/welcome.html

In physics, power is defined as the rate of doing work or the amount of energy transferred per unit time. $P = W/t$.

In the United States, most of us relate to power generally as horsepower. James Watt, a Scottish engineer from the late 1700s, is credited with adopting the term "horsepower" by comparing the output of steam engines to that of horses. Watt determined that a horse could pull roughly at the rate of 550 pounds over a distance of one foot in one second. But most of us just refer to it as hp. From an automotive consumer or performance enthusiast perspective, the theory is that more hp is associated with a better overall experience. However, in practice, this is not necessarily accurate. There are many factors to consider such as the weight of the more powerful engine needed to create that additional hp; the impact on the overall vehicle weight, engine and transmission efficiencies; engine torque and torque rise; and more. A similar applications engineering approach also applies to diesel engines in nonroad applications.

WHAT ABOUT TORQUE?

When selecting an engine for a specific need, one cannot make the best choice based solely on power. Another critical performance parameter must be considered. So, if power is the rate of doing work, then what is torque and its relevance to diesel engines and right-sizing? You never hear someone say, “I need a 400 ft-lb engine,” but maybe you should. Torque is the force applied over a specific distance, hence the common imperial units of ft-lb. In the context of an engine, you can imagine the torque as the force applied through combustion to the crankshaft via the piston/connecting rod. Torque is not time-dependent like power. Remember: Power is the rate of doing work. It is dependent upon time and torque, as it is the force applied over a certain distance per a unit of time (unit of ft-lb per second). Or, really, when you think about it, power is the rate of applying torque. Typically, a diesel engine will exhibit peak torque near the middle-to-low end of the engine’s speed range. For example, the KOHLER® KDI 3404 TCR engine with a rated speed of 2200 rpm makes peak torque at 1400 rpm. The percentage increase in torque from rated speed down to the peak torque speed is referred to as torque rise and is also important for performance. It is basically the lugging capability of the engine when it is hit with a big load. KOHLER KDI TCR engines feature electronically controlled high- pressure common rail direct injection, which allows for very quick engine response in this torque rise region.

$$\text{TORQUE RISE} = \frac{\text{Peak torque} - \text{torque @ rated speed}}{\text{Torque @ rated speed}}$$

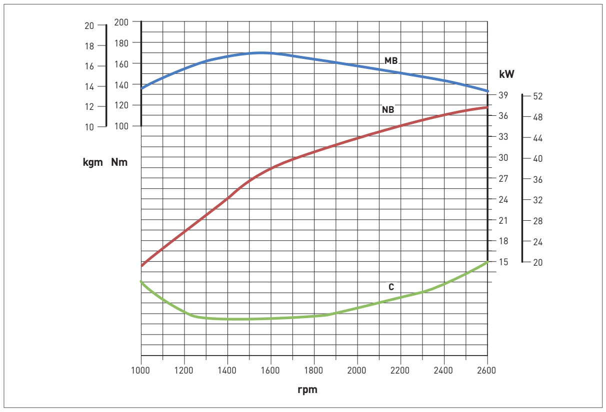

Figure 2. Torque rise equation and example

EMISSIONS AND DIESEL ENGINE TECHNOLOGY

In today’s world of ever-changing emissions standards, OEMs are perpetually faced with making decisions as to what diesel engine is best-suited to power a specific application (e.g., skid-steer loader, excavator, forklift, telehandler, generator, dewatering pump, compressor, etc.). In North America, we have seen nonroad diesel engine emission standards progress from unregulated Tier 0 up to Tier 4 Final, requiring up to 90 percent reduction in emissions of particulate matter, hydrocarbon and oxides of nitrogen. These reductions, in turn, have fueled the progression of the nonroad diesel engine design toward technologies such as electronically controlled high-pressure common rail direct injection, turbocharging, charge air cooling and cooled exhaust gas recirculation, These technologies commonly require the use of exhaust aftertreatment such as diesel oxidation catalysts, selective catalytic reduction (SCR) and diesel particulate filters (DPF), depending on the engine power category. So, essentially, the modern nonroad diesel engine is quite like the modern automotive diesel engine in terms of the incorporated technologies. One could argue that the emission test cycle for Tier 4 Final is also quite severe compared to the equivalent onroad or automotive test cycles. The Tier 4 Final test cycle is representative of a multitude of nonroad machine-duty cycles. The days of mechanically driven fuel-injection equipment, manual throttle cables/levers and manual stop levers (when is the last time you saw one of those?) are nearly a distant memory apart from diesel engines < 25 hp (19 kW). As the modern engine design has grown in complexity, so has the importance in engine right-sizing.

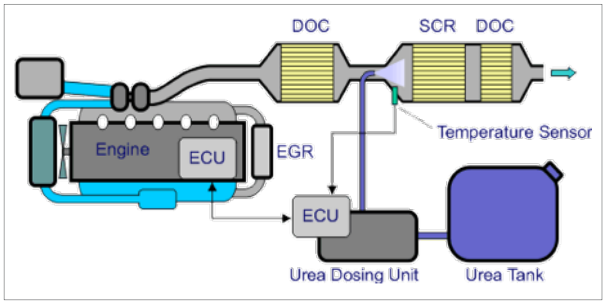

Figure 3. Urea-SCR system schematic
Retrieved from website: https://www.dieselnet.com/tech-cat_scr_mobile.php

RIGHT-SIZING CONCEPT FROM AUTOMOTIVE MARKET

Right-sizing in the context of the automotive industry is the practice of designing engines for optimal performance and operating characteristics to fit an intended vehicle. Or, in other words, it's the practice of matching the cylinder capacity of a drive unit to the size of a vehicle. Oh, and let's not forget to consider the intended market for the product. Years ago, in the United States, when fuel was much lower in cost, it was more common to find large-displacement naturally aspirated engines powering most vehicles on the roads. Performance and durability were great, but fuel consumption was high. Still, these products were well-accepted in the United States and continue to be popular to some degree. However, in Europe, fuel cost is nearly three times higher than in the United States. As such, these larger vehicles with high-displacement engines are not as common there.

In effect, right-sizing, led by automotive manufacturers such as Mazda, Audi and Fiat Chrysler Automobiles (FCA), is a response to engine downsizing. Much like the nonroad diesel engine market, the automotive industry has also faced—and is currently facing—stringent emissions and fuel economy requirements. As the engine technologies advance, engines are becoming more efficient with higher power densities. You can imagine how the trend of downsizing caught on in the automotive world by utilizing smaller-displacement engines, turbocharging, lighter materials, direct injection, etc. It's an easy solution to the rising pressures of meeting reduced emissions and fuel economy targets. Reduce engine displacement and match a turbocharger. But we cannot forget that this downsized engine design must meet the customer expectations over a specific duty cycle throughout its useful life and beyond. For example, if the customer holds onto his/her vehicle longer than the designed useful life of the engine, he/she may begin to feel the financial implications of the components/materials used in a certain downsized engine, as maintenance costs increase. This ultimately is misapplication of a downsized engine. Mazda observed this potential problem with engine downsizing in the marketplace, and this led them to a renewed focus on engine right-sizing. It was this focus that spawned Mazda's SKYACTIV engine technology that continues to push engineering boundaries with its high compression ratio. This is not to say that all downsized automotive engines are evil, as downsizing and right-sizing can coexist. The concept is simple: you need the right engine for the right application to sell into a specific, known market.

NONROAD DIESEL ENGINE RIGHT-SIZING

Engine right-sizing is nothing new to us in the realm of nonroad diesel engine application engineering. One always aims to apply the appropriate engine for a specific application considering a multitude of factors such as ambient operating temperature range (min to max), maximum operating altitude, machine duty cycle, drive type, etc. This is regardless of the emissions level of the engine. With that said, as described above, today's nonroad diesel engines are more complex in design with electronically controlled injection and in some cases sophisticated exhaust aftertreatment systems. Therefore, more higher-cost components are at risk if engine right-sizing practices are not followed.

As OEMs are transitioning into using Tier 4 Final or European Stage V nonroad diesel engines in their equipment, the tendency is to request a specific engine power output (e.g., 74 hp, 100 hp, 134 hp, etc.) from the engine manufacturers. However, at times, you may find that the actual average load on the engine in a particular application is much lower. For example, OEM X has requested a 100-hp engine, but you determine that the average load is only 20 hp. In this simplistic case, one could deduce that most likely the 100-hp engine is not a good match.

However, a structured approach such as a 9-block analysis should be taken to thoroughly evaluate engine performance criteria in the application and mitigate risks. In addition to average load, some other factors to analyze include minimum and maximum engine load, engine performance metrics in the application, temperatures, vibration, noise, etc. Ambient operating conditions also play an important role in right-sizing. Much like sizing an engine considering the duty cycle and loads, you must also consider minimum, average and maximum ambient temperature conditions. An application designed to run only in freezing conditions especially needs close attention, as diesel engines are much more combustion-efficient when they are warm.

WET STACKING

A diesel engine craves load and thrives under such conditions due to the nature of the compression ignition (CI) combustion process. I’m referring, of course, to the high temperature and pressure needed in the combustion chamber for fuel atomization without the presence of a spark. A diesel engine is accustomed to that high temperature and pressure. In fact, it is most efficient under high load. The piston rings seat more effectively providing appropriate cylinder compression. As such, blow-by (soot, water vapor and unburned fuel that can blow by the piston rings and contaminate crankcase oil) is reduced. Conversely, low combustion and, thus, exhaust temperatures are detrimental to diesel engine life. When a diesel engine operates at exhaust temperatures less than 200°C, one can expect several afflictions including soot accumulation at the piston rings and exhaust valves as well as in exhaust manifolds. Light loads can also cause “wet stacking,” which is the collection of unburned fuel in the engine exhaust system and turbocharger. This degrades engine performance over time and can also lead to engine failure.

Since light loading results in a less effective seal between the piston and cylinder wall, blow-by is increased. When an engine is produced, its cylinders feature a nice cross-hatch pattern on them to help retain a small amount of oil in them for lubrication and piston ring sealing. During light-load operation, this cylinder crosshatch pattern is eventually worn away resulting in cylinder glazing. Over time, the increased blow-by contaminates the engine oil in the crankcase and can eventually break down the oil. Finally, what started as lubricating oil may become more of a sludge, which isn’t exactly the best lubricant for components like precision engine bearings. So, essentially, wet stacking creates one giant snowball effect on the destruction of a diesel engine.

CONCLUSION

The core of the diesel engine has not changed much since Mr. Rudolf Diesel patented his namesake design in 1893. Performance is still generated via the compression-ignition process. Efficiency improvements have been realized over time, and the diesel engine is still rather efficient considering a well-to-wheels approach. Nonroad diesel engine right-sizing is paramount now more than ever given the sophisticated technologies and costs at stake. Engine manufacturers and construction equipment OEMs must collaborate to thoroughly evaluate an application profile and ultimately select the right-sized engine to do the job considering a multitude of engine performance and application operation criteria. I challenge industry professionals to refocus their mindsets around this concept and embrace the use of right-sized engines and/or hybrid solutions.

ABOUT THE AUTHOR

Patrick Exley is manager, Diesel Engines Americas for Kohler Engines. He has extensive applications engineering experience and works closely with leading equipment manufacturers to maximize engine performance.

Kohler Engines manufactures diesel engines ranging between 9.1 and 134 hp. The company's KOHLER® Direct Injection (KDI) diesel engines meet Tier 4 Final emissions standards without a diesel particulate filter. The KDI line has been well-received by global manufacturers of skid steers, forklifts, light towers, compact excavators and more. For additional details, visit KohlerEngines.com.

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