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# Keynote: Off-Road Mobile Machinery Fuel Efficiency: A Total Systems Perspective

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## ABSTRACT

Increasing the work per unit of fuel burned of mobile off-road equipment has positive economic and environmental implications through reduced owning and operating costs and lower greenhouse gas emissions. To realize and drive these benefits, the enormous diversity of the types and applications of off-road machines and the functions they perform must be considered. The optimization of fuel efficiency, productivity, and cost, while meeting emissions requirements for off-road equipment, can be best achieved by taking a total systems perspective, considering applications, and appropriately tailoring technologies. This paper will illustrate the benefits of systems optimization using detailed examples of a hybrid hydraulic excavator and medium wheel loader and examine the benefit of technologies at the component, engine, machine system, and worksite levels.

## INTRODUCTION

Off-road heavy equipment is central to many industries that drive economic growth and sustained progress around the globe. This equipment is put to work building roads, moving goods and products on rail and ships, mining natural resources, delivering oil and gas, creating infrastructure, building homes, harvesting crops, providing emergency power, and supporting public safety and homeland security. The businesses and agencies that utilize this equipment have strong business drivers to improve productivity and reduce fuel consumption, and, thus, lower greenhouse gas emissions. Industries that rely on off-road equipment—such as agriculture, forestry, general construction, road construction, mining, rail, marine freight transport, public safety and homeland security, military, and airport operations—add significant value to economies around the world. Competitive pressures, environmental and social sustainability, and strong customer desire to reduce owning and operating costs, are drivers for these industries to continuously increase productivity, improve fuel efficiency, and reduce greenhouse gases. The investments in research and development financed by heavy equipment producers have the greatest potential impact on fuel efficiency and greenhouse gas reduction when they can be focused on the most optimized and highest impact technologies, products, and services.

Off-road heavy equipment in fleets and the fuel burned by this equipment can be a significant portion of the operating cost in the industries where they are used, providing a strong business driver to continuously reduce fuel usage in operations. To illustrate this, the typical owning and operating costs of construction equipment are shown in Figure 1. In Europe and the United States, fuel costs are around 20-25% of the operating cost. In China and India, fuel costs can be as high as 60% of operating costs. The prevalence of fuel as a portion of the cost drives owners to find the most fuel-efficient solutions to improve their operating efficiencies. This, in turn, drives heavy equipment manufacturers to innovate around ways to continuously improve productivity and efficiency to serve their customers better and to gain competitive advantage.

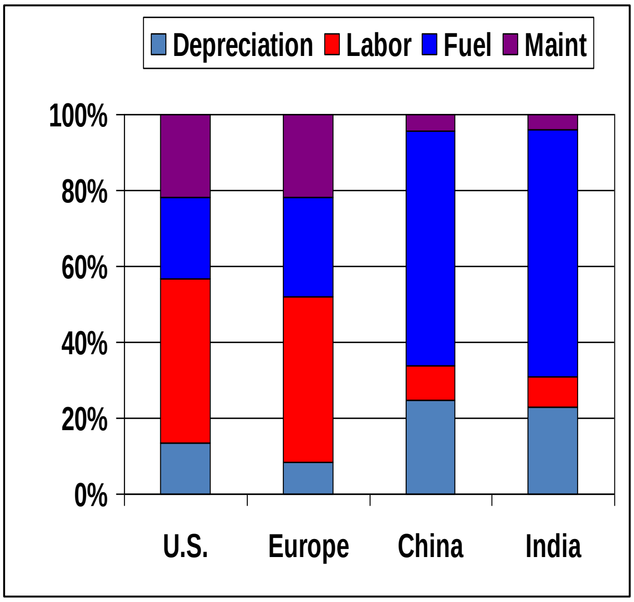


Figure 1 Owning and Operating Cost by Location

Diesel engines are at the heart of, and a mainstay in, the industry sectors that use off-road equipment. The diesel engine provides performance and economic advantage through durability, energy efficiency, and low-speed torque offered in comparison with other forms of power. Nearly 100% of construction equipment, 90% of the freight tonnage, over 70% of power used in mining, and two-thirds of agricultural equipment are powered by diesel engines **[1]**. Diesel engines serve a range of applications with power requirements from 10 horsepower for lawn and garden equipment to 100,000 horsepower for engines used in ocean-going ships.

Diesel engines have been on a steady march of improving fuel efficiency over the more than 120 years since their invention by Rudolph Diesel in 1892. The first engine operated with 26.2% brake thermal efficiency, despite diesel engines having a theoretical efficiency of 64% **[2, 3]**. Now, the diesel engine has improved to as high as 54% thermal efficiency for low speed, large engine applications, such as large ships, where engine weight is relatively insignificant. In higher speed applications such as trucks, buses, newer diesel cars, and off-road equipment, today's diesel engines have a peak brake thermal efficiency of around 45% **[4]**. However, the average efficiency over the course of a cycle is lower than the peak efficiency and is closer to 37% **[5]**. While technologies continue to evolve that will further improve the thermal efficiency of the engine, the most aggressive estimates of potential improvements, while meeting U.S. and European criteria pollutant emissions targets, are in the range of an additional 10-15% or a maximum peak efficiency near 55% **[6]**.

There is a large diversity of applications, mechanical demands, and duty cycles for off-road equipment. Within the off-road mobile diesel equipment category alone, applications include, but are not limited to, off-highway mining trucks, excavators, wheel loaders, compactors, motor graders, track loaders, landfill compactors, bulldozers, backhoes, agriculture tractors, skid steer loaders, pipe-layers, material handlers, asphalt pavers, and telehandlers. Most of these off-road vehicles require the power source to not only propel the vehicle but operate attachments, such as buckets, blades, grapples, and shovels. Further, engine-driven hydraulic pumps are frequently used to power attachments. With a high variety of applications and application profiles, engine duty cycles can vary greatly. Despite this variability of application, there is one thing in common with all off-road equipment: it is used to do work. The output measures are varied by job and can be tons of material moved, asphalt laid, or soil compacted. Likewise, the input measures—such as fuel used, labor, and maintenance costs—can vary. Optimizing productivity, or the ratio of outputs to inputs, is critical wherever the work is done.

Insight to optimizing the useful work and reducing the fuel consumed by off-road machinery can be obtained through a machine energy audit in a given application. Previously published audits of a Cat® wheel loader, Cat hydraulic excavator, and Cat articulated truck are shown in **Figure 2**.

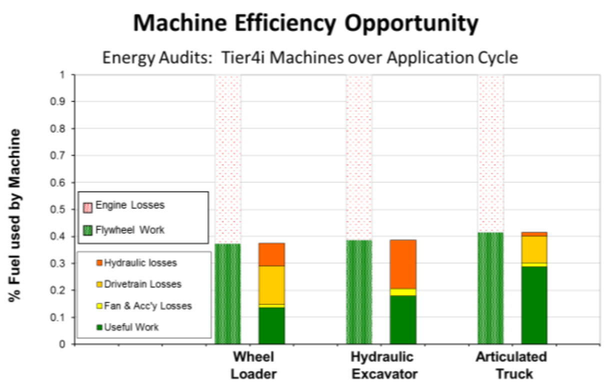


Figure 2 Energy Audit by Cat® Product

These audits show there is opportunity for improving fuel efficiency through an approach that takes into account the application of the equipment and using a systems integration approach to the engine, drivetrain, hydraulics, and cooling systems.

This paper reviews the range of efficiency gains that can be achieved through new technology and optimization of the diesel engine and compares this to the fuel efficiency that can be gained through consideration of application and taking a total systems integration approach on the machine and the job site. Detailed examples of gains in efficiency and productivity through system integration on a hydraulic excavator and a wheel loader will be shown.

## POTENTIAL FOR FUEL EFFICIENCY IMPROVEMENTS FROM A DIESEL ENGINE

Diesel engines in off-road applications have evolved to achieve fuel efficiencies in the range of 40% to 43%. For the construction equipment shown in **Figure 2**, the peak brake thermal efficiency is typically 41% to 42% **[7]**. Gains in diesel engine fuel efficiency have been achieved and continue to progress through advances in fuel systems, turbocharging, materials advancements, and electronic controls, among others. Further opportunities for improvements in diesel engine efficiency could be realized through component optimization on engines, and through the recovery of lost exhaust energy. More specifically, there are a number of technologies under development such as waste heat recovery through organic Rankine cycle, optimized valve events, reduced exhaust backpressure, engine down-speeding, improved turbocharger efficiency, and increased peak cylinder pressure that will contribute to advancements in fuel consumption. An illustration of a partial list of technologies with the potential to improve engine fuel consumption is shown in **Figure 3**. While this comparison is provided for technologies under development at Caterpillar, there are similar assessments available from other diesel engine manufacturers **[8]**.

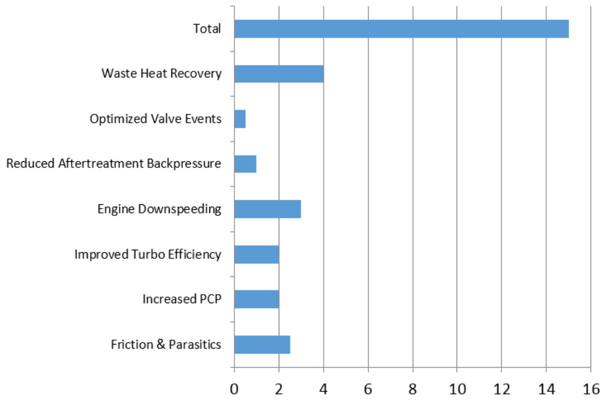


Figure 3 Fuel Efficiency Improvement by Technology

Application of these technologies and others can potentially raise brake thermal efficiency to around 50%. However, the estimates shown in Figure 3 are for a steady-state like operating mode. These technologies will have varying impact on efficiency improvement throughout the load and speed range of the engine. The successful commercialization of these technologies in a broad application will only be achieved if the value-to-cost ratio meets market requirements and performance, space claim, and emissions targets are simultaneously met. Many of the technologies currently under development have a cost-to-fuel-efficiency ratio that is too high to perpetuate broad application.

Some of the engine technologies in Figure 3 are challenged in mobile equipment where the space for installation is limited and added weight can negatively impact efficiency. One such an example is the waste heat recovery using a Rankine cycle to heat a fluid and then expand it across a turbine to extract useful work. This is a good method of improving efficiency and, as shown in Figure 3, results in the largest improvement. However, to achieve these improvements, large heat exchangers must be added to the engine package, as well as an expander, fluid lines, and a method to return power to the drivetrain. These components can add 15% to 25% to the cost of the basic engine to achieve this 4% efficiency improvement, as well as significant increases in weight and package size.

While significant improvements are still possible through engine improvements alone, there are significantly larger engine efficiency improvements available through optimization of the engine operation considering the application. An engine operating significantly below its full power capability has reduced efficiency, as the friction and pumping work consume a higher percentage of the fuel energy. As the engine's operating speed is decreased and the torque increases to deliver the same power, the efficiency increases due to friction and pumping becoming a smaller percentage of the total power. Therefore, optimization of operating speed and load has become a common approach to improving efficiency.

A typical engine efficiency map is shown in **Figure 4**. Efficiency islands are plotted versus torque and speed. In general, as speed decreases and load increases, the efficiency increases. This does not continue indefinitely as turbomachinery efficiency decreases after a certain point, decreasing the engine efficiency.

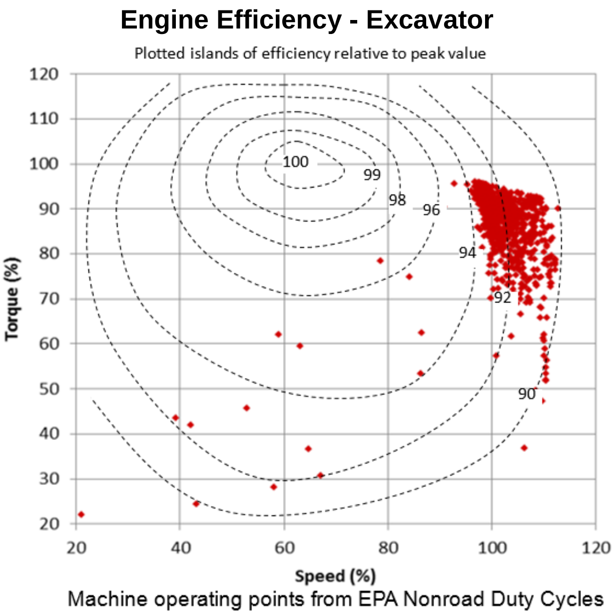


Figure 4 Engine Efficiency Map

Different machine applications operate on different portions of the engine load and speed range. As an example, operating points for four off-road applications from the EPA Off-Road Transient Cycle are plotted on the efficiency map as shown in **Figure 5 [9]**.

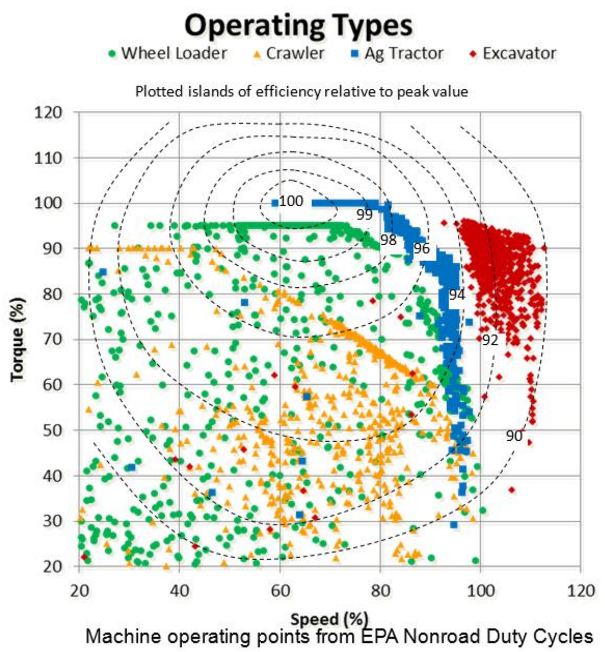


Figure 5 EPA Off-Road Transient Cycle Operation Points for Various Operating Types

The efficiency varies significantly between applications and operating conditions. Also, note the range of operation variability between applications.

An excavator or agricultural tractor operates over a relatively narrow range compared to a wheel loader or a crawler (also known as a bulldozer).

To illustrate how efficiency can be improved by decreasing the speed and increasing the torque, the excavator operation cycle alone is plotted in Figure 6 below.

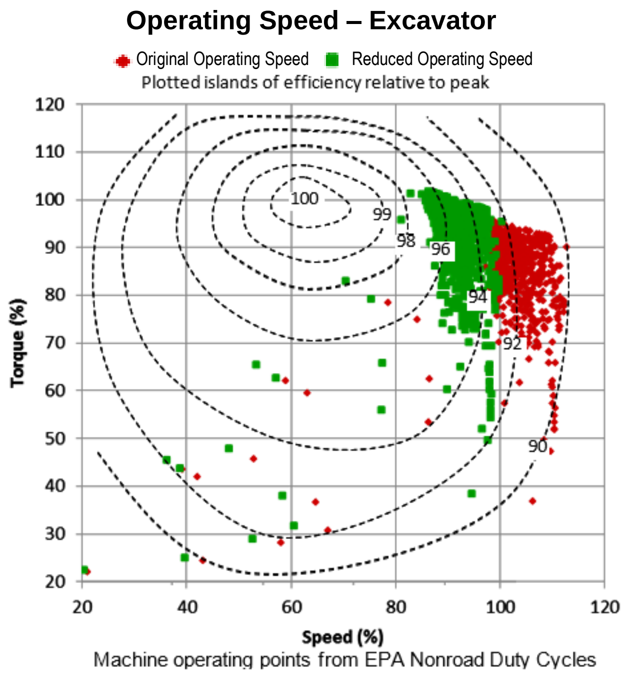


Figure 6 EPA Off-Road Transient Cycle Operation Points for Excavators

**Figure 6** shows that when operating at high load, the efficiency is about 92% of the maximum possible. If the speed is decreased and the torque increased to maintain the same power, the efficiency increases. At the lower speed, the high load efficiency increases to 95% of the maximum possible.

As the torque increases, the ability of an engine to respond to transient loads decreases. For applications that have a steady load, this is not a significant problem. However, many machines are highly cyclical and the requirements for transient response capability are extremely high. The engine speed can be decreased only so far while maintaining the necessary response without adding transient capability. Engine response can be improved through a variety of methods including turbochargers with variable geometry turbines, variable valve timing, and supercharging. A typical trend of engine speed and torque during a rapid load increase is shown in **Figure 7**. This is sometimes referred to as speed recovery from block loading, which is typical of hydraulic excavator operation.

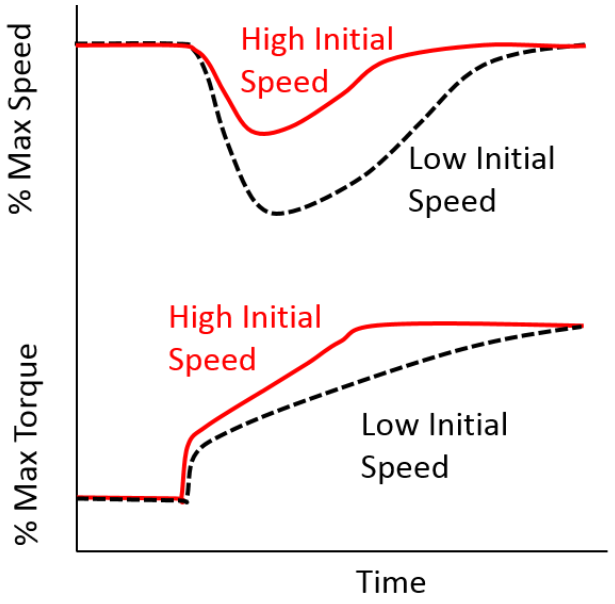


Figure 7 Hydraulic Excavator Block Loading

Another approach to maintaining sufficient transient response is to optimize the machine and engine systems, not just the engine. By close coupling of controls between the machine and the engine, command delays can be eliminated. Other methods, such as a short burst of energy from an auxiliary source, can allow the engine or air system to accelerate and deliver more torque quickly.

## FUEL EFFICIENCY GAINS WITH APPLICATION CONSIDERATION AND SYSTEM INTEGRATION

### Hydraulic Excavator

The potential for fuel efficiency improvement and subsequent greenhouse gas reduction becomes significantly larger when the application of off-road machines and the functions they perform are considered along with a total systems integration approach of the engine, controls, hydraulics, cooling systems, and other major systems. A large tracked hydraulic excavator will perform a variety of earthmoving jobs, including mass excavation, trenching, shaping, truck loading, lifting, and many others. In almost all applications, the excavator operates in a very cyclical mode. For example, in a truck loading application cycle, shown in **Figure 8**, the excavator will fill the bucket, lift, swing, and dump repetitively. One of these cycles is typically 16-20 seconds with the upper structure accelerating and braking twice during one cycle. As the energy audit for a hydraulic excavator in Figure 2 shows, typically only 15-20% of the fuel input energy is actually used to perform useful work. In consideration of the machine application profile, and through deep system integration to eliminate losses and maximize performance, Caterpillar has recently introduced an excavator that reduces fuel per ton of material moved by up to 50% and commensurately uses 33% less fuel per hour than the previous, non-hybrid model.

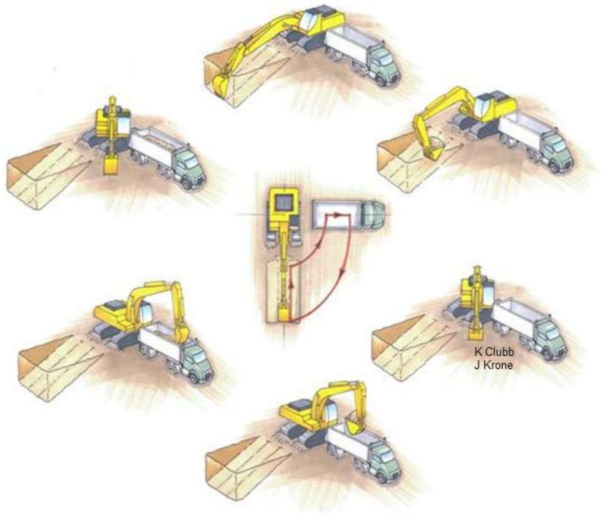



Figure 8 Cyclical Hydraulic Excavator Process

The Cat® 336E H hybrid excavator was introduced in 2013 and has demonstrated up to 50% greater fuel efficiency than previous models. This machine provides an example of the benefits of deep system integration in providing fuel efficiency gains that could not have been realized if all the on-board systems and components were not carefully integrated. The simple and straightforward design of the 336E H hybrid excavator utilizes three building block technologies that led to increased fuel efficiency. First, the hybrid excavator conserves fuel with engine power management via the Cat Electronic Standardized Programmable (ESP) pump. Second, performance is optimized using restriction management via the patented Cat Adaptive Control System (ACS) valve. Last, the hybrid excavator reuses energy via the hydraulic hybrid swing, which captures the excavator's upper structure swing brake energy in accumulators and then releases the energy during swing acceleration.

The Electronic Standardized Programmable (ESP) pump is electronically controlled to up-stroke and de-stroke to save fuel and ensure smooth transitions between the 336E H hybrid power sources, which are the engine and accumulator. Engine and pump power are synchronized by integrated electronic controls that manage the overall hydraulic hybrid system to minimize restrictions and maximize efficiency and productivity. With the hydraulic hybrid technology, pump displacement with the ESP pump increased from 160 cc/rev per pump on the standard 336E to 184 cc/rev per pump for the 336E H. This increase translates to improved implement flow/velocity for faster cycle times at lower engine speeds that also results in improved fuel efficiency in all applications, and lower owning and operating costs.

The ESP pump high responsiveness, coupled with advanced and integrated engine controls, enables the engine to operate at lower engine speed. The 336E H has 1500 rpm isochronous engine speed, versus 1800 rpm on the standard 336E. The reduced engine speed on the 336E H not only improves fuel efficiency but offers other benefits, including quieter operation.

**Wheel Loader**

The wheel loader has a much wider engine operating range as compared to the excavator (Figure 5). In this case, again, application consideration and a total machine system integration approach can reap larger fuel efficiency benefits than engine optimization alone. The requirements of the application drive unique technology implementation compared to the excavator. In this case, the Cat 966K XE wheel loader will be used to illustrate the technologies and benefits of systems integration.

For the 966K XE wheel loader, systems integration and power balance of engine, advanced powertrain, and implement systems were used to achieve significant fuel efficiency improvements with quick response, acceleration, and power. Field measurement of machines showed a 24% reduction in fuel burned per unit of work (liters/ton).

The improvements were achieved by understanding the customer applications and machine utilization across a wide range of machines, and then implementing and integrating new component and system technologies. **Figure 9** shows that an advanced, integrated Caterpillar continuously variable transmission was matched to the machine to make it well balanced and easy to operate at extremely low engine speeds. CVT match with corresponding hydraulic pump sizing is used to enable the engine to run at a more efficient operating range independent of machine ground speed resulting in 1250-1600 rpm for the XE versus 1500-2100 rpm for the conventional powershift transmission machine. The continuously variable transmission eliminates the need for the torque converter, thus improving powertrain efficiency and greatly reducing the heat generation under severe rim pull load. While aggressively digging, the continuously variable transmission consumes roughly half the energy of a conventional transmission. Additional fuel consumption benefits are achieved when energy is recovered during machine retarding. During deceleration, machine momentum is recovered as free energy to power implements or the cooling fan. As a result of the lower speed operation, reductions in heat rejection and sound levels are also realized on this machine.

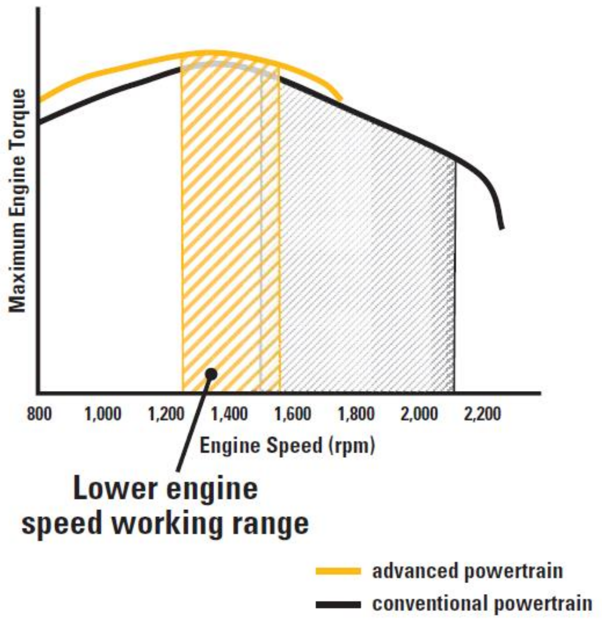


Figure 9 Continuously Variable Transmission Effect on Torque and RPM

**Operator and Site-Level Impact to Fuel Efficiency and Greenhouse Gas Reduction**

The potential for fuel efficiency improvement and subsequent greenhouse gas reduction is further increased beyond the machine when operator efficiencies and job site solutions are considered. Caterpillar has a number of technologies, products, and services in the market today that have measured and proven benefits in operator and job site productivity. While it is not within the scope of this paper to review the details of these technologies and solutions, some examples and the commensurate benefits will be outlined.

The overall performance, including fuel efficiency and productivity, of a machine can vary greatly, (>10%)

depending on the operator. Training, tools, and technologies, both on-board and off-board, are available for both new and experienced operators to provide know-how on the operation of Cat machines in efficient and productive ways, to improve operator performance. These tools measure the operator performance and provide feedback, coaching, and semi-automated or automated features to improve performance in situ. These features are extensive and include a wide breadth of the product lines. For example, earth moving solutions such as Cat Grade Control take advantage of many components already built into today's Cat equipment, including sensors, displays, and on-board data processing. Both new and experienced machine operators of select Cat track-type tractors, pavers, mills, motor graders, excavators, and wheel tractor scrapers can realize improvements in efficiency over a wide range of applications to generate the correct depth, grade, slope, and cross slope **[10]**. This type of technology provides the capability to combine digital design data, in-cab operator guidance features, and automatic controls to improve performance **[11]**.

Using the track-type tractor as an example, there are additional automation features that can improve performance, including AutoCarry™ that automates blade lift to maintain desired blade load, improves load consistency, and reduces track slip; Auto Blade Assist that automates blade pitch and lift during load/carry/spread cycle based on operator preferences; and Automatic Ripper Control that automates ripper height, limits track slip, and reduces wear during heavy ripping applications **[12]**.

Cat Machine Drive Power (MDP) for compactors can also improve efficiency by providing the operator with real-time feedback. MDP is a machine-integrated soil compaction measurement technology that evaluates rolling resistance. That resistance provides an indication of soil stiffness and load-bearing strength, as well as whether compaction is adequate to hold the road, parking lot, building, or other structures planned for the site. MDP can eliminate the need for multiple passes of a compactor. Operators inside the MDP-equipped soil compactor can view real-time results on a monitor in the cab. A green area on the display means the area was covered and targets were met. A red area indicates trouble spots and alerts the operator to make adjustments **[13]**.

For wheel loaders, Cat Aggregate Autodig automates the loading process. Aggregate Autodig provides smoother loading cycles and consistently full payloads, and eliminates tire spin—all without touching the controls **[14]**. Cat Production Measurement is a Cat® Connect Payload technology that improves loading and hauling productivity in wheel loader applications where customers require precision weighing and accurate loads. This on-the-go payload system weighs loads as the bucket is being loaded—with no interruption in the loading cycle. Advanced weighing features enable the operator to make quick load adjustments before leaving the stockpile. Payload data can be viewed at a glance to assist operators with fast, efficient loading to exact specification, eliminating the costly guesswork that results in under and overloading. Cat Production Measurement benefits include reduced cycle times, higher productivity, and lower fuel and operating costs **[15]**.

There are multiple examples of operator assistance on Cat machines. Sequence Assist, Load Assist, and Cat Grade Control features on a Wheel Tractor Scraper automate features such as loading, hauling, and dumping to improve productivity and allow operators to focus on guiding the machine **[16]**.

Job site solutions can take a number of forms and can be broadly described as the implementation and integration of on-board machines and off-board technologies and business support elements to optimize the productivity, safety, and equipment management at a given job site. Earle et al. showed that in a back-to-back comparison of an identical road construction project, implementation of technology for site productivity improvement resulted in a 43% fuel savings, 95% lower surveying costs, and 52% less time to complete [16]. Technologies used in this study included machine control and guidance on tractors and excavators.

Current product offerings for mine sites, such as Cat MineStar™, offer integrated technologies and services that help mines deliver the lowest cost per ton through productivity, equipment management, safety, and sustainability. Likewise, Cat Connect is a framework of technologies and services that help monitor, manage, and enhance operations for positive results, including improved productivity in industries other than mining, such as construction and quarry industries. Cat Connect uses data from technology-equipped machines to obtain a clear view of various vitals, such as location and service intervals, for a fleet on a job site regardless of the brand or type of machine. This includes a variety of information, such as productivity, fuel consumption, and maintenance. Equipment management increases uptime and reduces operating costs by monitoring fuel burn, location, and utilization of machines, as well as health and maintenance issues, like hours and fluid contamination. Technologies are used to measure payloads and cycle times to optimize production and reduce loading and hauling costs. Grade and compaction control technologies assist in completing operations in a shorter time frame with more accuracy and less rework.

The fleet efficiency and productivity benefits of site-specific fleet and management services have been demonstrated in a limestone quarry. The site used nearly 8% less equipment while operating at a significantly higher level of productivity. In addition to meeting Tier 4 emissions standards, site equipment improved fuel efficiency by more than 20%. The solution also helped the quarry reduce its dust emissions considerably. Finally, less traffic, more reliable equipment, ergonomic and safety features, and better operator training contributed to overall safety improvements **[17]**.

## CONCLUSION

The potential for fuel efficiency improvement and subsequent greenhouse gas reduction becomes significantly larger when the application of non-road machines and the functions they perform are considered and a total systems integration approach of the engine, controls, hydraulics, cooling systems, and other major systems on the machine is taken into account. Furthermore, substantial gains can be achieved by looking beyond the machine, considering human factors, operator efficiencies, and the total job site. This paper gives detailed examples of engine, machine, and site level productivity and fuel efficiency gains that can be achieved by taking a systems and site integration approach.

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