Systems Analysis of Technical Advancement in Earthmoving Equipment

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Abstract: The technical advancement of earthmoving equipment during the 20th century includes many improvements in key parts of machines. This paper uses five systems that make up earthmoving equipment (implement, traction, structure, power train, and control and information) to analyze this technical advancement. The analysis of each system includes its purpose and operation, technical limitations and key technologies, and a chronology of major advancements. The findings are the benefits of using the five systems for analysis of technical change, the sequence and timing of key technical advances in each system, the fundamental technologies that fostered these advances, and the integration of systems into balanced equipment designs. This increased understanding from this analysis results in significant implications and relevance for civil designers working on integrated teams, contractors selecting methods and planning operations, equipment suppliers developing new machines, construction educators teaching the technical basics of equipment, and researchers developing advanced modeling and simulation tools.

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Introduction

To many, equipment is construction. "Bulldozers" symbolize all types of civil construction while large cranes identify industrial and building projects, whether on remote sites or in congested urban settings. Although sometimes not apparent at first glance, all types of earthmoving equipment have advanced in many ways since their introduction. Large and highly competitive markets for infrastructure projects demand continued improvement in the performance of earthmoving equipment. Rapidly developing new technologies should allow this, but a better understanding of prior technical advancements at a systems level can help increase the rate and benefits from future new technology.

The purpose of this paper is to expand an earlier overview of innovation in construction equipment (Tatum 1989) by analyzing the technical advancement of earthmoving equipment in terms of five major systems that make up these machines. This leads to a better understanding of the changes that increased equipment capability and performance and to implications for practice, education, and research. The paper does not specifically address changes in the form and size of construction equipment. One view of these important advancements is that they were the synthesis or final expression of fundamental developments that occurred at a system level.

The paper begins with a brief review of relevant background concerning technical advancement and the technical basics of earthmoving. The major sections then analyze advances in each of the five equipment systems and the technologies that fostered these advances. The next section highlights conclusions regarding technical advancement in the systems and their integration for effective equipment and productive earthmoving operations tailored to project and site requirements. The final section describes implications and relevance for practice, education, and research. It recommends that designers consider equipment capabilities in earthwork designs, contractors more explicitly consider systems in their equipment selection and use, equipment suppliers further analyze the role and advancement of systems, educators address technical aspects of equipment performance, and researchers increase understanding of equipment development and provide tools for further integration of construction equipment.

Background of Technological Advancement

The background for this study of technical advances in earthmoving equipment includes prior research concerning mechanisms of technical advancement in multiple industries and histories of construction equipment.

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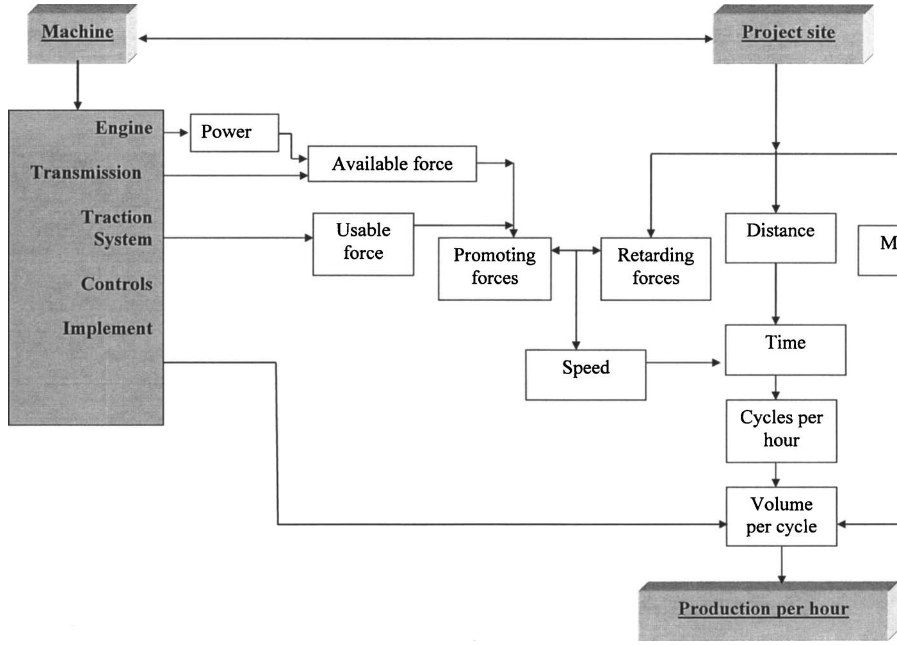

Fig. 1. Relationship between machine systems, site conditions, and production rate

Mechanisms of Technical Advancement

Focusing on manufactured products, prior investigations of processes for technological advancement provided useful insights to structure analysis of advances in earthmoving equipment. These include revolutionary new products followed by incremental improvement and the role of enabling technologies. In many industries, technology initially advances in highly visible revolutionary ways with the introduction of an entirely new product or process. Despite clear potential benefits, these new products or processes often do not initially perform much better than the ones they seek to replace. A series of incremental improvements of the new product or process then follows, often resulting in much more significant advances than the revolutionary first step (Rosenberg 1982). Investigators of technical progress for ships (Gillfillan 1935), railroads (Fishlow 1966), chemical fibers (Hollander 1965), and petroleum refining (Enos 1959) each identified major benefits from a series of incremental improvements. Many types of technical advancements build on new or improved fundamental technologies (Rosenberg 1982). Utterback (1994) uses the term enabling technologies to describe refinements in production processes that allowed subsequent product and process innovations. His examples included elements of production processes for rayon and ammonia compression refrigeration for icemaking.

Technical Advancement of Earthmoving Equipment

The earliest earthmoving equipment had important links to agriculture, especially in the development of tractors (Dane Lowry, personal communication, February 6, 2004; Leffingwell 1994). Haycraft (2000) identified the major technological advancements in earthmoving equipment from the beginning of the agricultural implement industry to the present. His excellent summary of product developments during six periods includes a description of fundamental new types of equipment along with increased size and horsepower of machines within each type. Cohrs (1995) described specific technical advances in each type of equipment from the very early use of machines for earthmoving. Nolde (1999) summarized 75 years of Caterpillar history, including products, manufacturing and facilities, and a timeline covering 1925–1999. Orlemann (2003) described the growth of the company during the 20th century, including new products and increasing size and capability within each product line. Leffingwell (1994) identified specific new features and capabilities that increased the performance of Caterpillar tractors. This background described the advancement of earthmoving equipment, including new forms and specific new technical features. However, it did not consider systems as a means to gain further understanding of how equipment capability increased.

Technical Basics of Earthmoving

Earthmoving equipment is a key construction-applied resource for heavy civil and infrastructure work. A brief technical overview of earthmoving operations, site characteristics, and principles of mechanics applied to earthmoving equipment provides necessary background for analyzing technological advancement in the systems that make up earthmoving equipment.

Mechanics of Earthmoving and Materials

In simplest form, earthmoving operations require cutting, moving, and processing material. Cutting is limited by the force available to shear the soil or rock. Moving is limited by the power available to move materials at speed while overcoming several types of resistance. The amount of force available from a machine and the speed at which it can provide this force determine its capacity. As shown in Fig. 1, estimating production rates of equipment in specific applications requires considering machine capability (as determined by the systems described in this paper) and site conditions.

Principles of mechanics govern the operation of earthmoving equipment. Force is the ability to cause displacement against resistance. It is measured in Newtons or pounds. Earthmoving ma-

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chines apply force either through drawbar pull or by the action of implements; both are further described below. Crawler or wheel tractors and several types of earthmoving equipment are rated in terms of force available to the traction system, termed supplied drawbar pull, in each gear of the machine. Usable drawbar pull, also termed traction, is the amount of force that the machine can transmit to the surface on which it is working. It is determined by the normal or vertical component of the machine weight times the coefficient of traction (a dimensionless ratio). On various types of soil surfaces, the coefficient of traction ranges from 0.2 to 0.7 for rubber tires and from 0.3 to 0.9 for crawler tracks (Peurifoy and Schexnayder 2002).

Work is the application of force through a distance, typically expressed as Newton meters or foot-pounds. Velocity is the rate of movement through a distance, expressed as feet/second or meters/second. Power is the rate of doing work, or force times velocity. Watts and horsepower are the typical measures. One watt is required to perform 1 N of work in 1 s; 1 hp is required to perform 550 ft-lb of work in 1 s. Power ratings vary across a wide range for different sizes and types of equipment and are quoted by manufacturers using several different standards which may or may not allow for the power consumption of auxiliaries such as fans and cooling pumps.

Several site characteristics, design requirements, project objectives, operator skills, and total cost govern the suitability of a machine to perform a desired earthmoving operation. These include characteristics of the soil or rock, quantities of material involved, tolerances for lines and grades, and schedule for the work. Important material characteristics related to earthmoving production include weight or density in various states (bank or natural, loose, or compacted), digging resistance, rippability, trafficability (ability to support load under repeated traffic), loadibility (ease of excavation and loading), cohesion, and moisture content and drainage characteristics (Nunnally 2002).

Key Systems for Earthmoving Equipment

The capability of a piece of earthmoving equipment to perform operations and its production rate are determined by five systems; they are the technological "genes" of the machine. The following list identifies these systems and the next sections describe each of them and its technical advancement. The systems are as follows:

1. The implements. This system applies the force and performs the actual earthmoving operation. Using an animal analogy, implements are the teeth or the paws and claws of the machine. Examples of implements include rippers to fracture material; dozer or grader blades to move material; excavator or loader booms, and buckets to separate and lift material; and truck or scraper bodies to carry material. Implements typically use force from hydraulic cylinders to raise, lower, and rotate relative to the machine itself.
2. The traction system. This system comes in contact with the ground and allows the equipment to apply force and move. It is the feet of the equipment; typically large for slow and powerful machines and small for fast and nimble machines. The major types of traction systems are steel or rubber tracks and small or large rubber tires.
3. The structure and suspension. This system connects components, transmits loads, provides attachment points for implements, and allows the machine to travel over uneven ground. It corresponds to an animal's skeleton. The machine's frame, articulation, and steering for wheeled equipment are the major parts of this system.
4. The power train. The power train delivers the power needed to move the machine and the implements, articulate, and stop. It is the muscles of the machine. The major elements are the engine, transmission, steering for tracked equipment, and brakes. Design of the power train typically emphasizes either speed or force.
5. The control and information systems. These systems enable the operator to direct and control all the other systems and provide information to guide operations or to monitor the performance and health of the equipment. They are the brains and nerves of the machine.

The following five sections analyze each of these systems. This includes purpose and operation, technical limitations of performance, key enabling technologies, and a chronology of major technical advances.

Technical Advancement of Implements

Function and Design

Implements apply force to cut and carry material to complete earthmoving operations. They include the component that contacts the soil and performs the desired operation, a container for the material if required, mechanical linkages that attach the implement to the structure, and positioning and forcing devices that raise, lower, rotate, or angle the implement as needed to perform the operation. Ripper teeth, bucket teeth, and cutting edges for dozer or grader blades illustrate the cutting component of implements. Excavator or loader booms and lift arms are examples of positioning and forcing devices. Buckets, truck bodies, and scraper bowls illustrate container types of implements.

Cutting force, wear resistance, volume and load carrying capacity, operational flexibility and control are key design parameters for implements. The weight and horsepower of the machine limit the force that the implement can apply. Major types of technical advancements for implements include new types and their integration and the transition from cable to hydraulic operation.

New Types of Implements and Integration with Machines

Completely new types of implements, some of which were pushed rather than towed, greatly increased the capability of several equipment types. LaPlat-Choate offered the first generally available dozer blade in 1923 (Cohrs 1995). LeTourneau developed the ripper (then called a rooter) as an implement towed behind a track-type tractor in 1926 (Haycraft 2000). These implements have since developed into several configurations and much larger sizes to increase capability and operational flexibility. Drott introduced the "4 in l" bucket in the late 1960s. It could load, level, scrape, grab, and backfill to grade (Cohrs 1995). Recent examples of continuing improvement include increased strength and hardness of materials used in implements and introduction of vibratory rippers (Dane Lowry, personal communication, February 6, 2004).

Early suppliers of earthmoving equipment relied on other manufacturers to provide the implements needed by the purchaser and user of the equipment. The industry then moved from relying on the aftermarket to integrated supply of basic implements with the machine. The Russell Grader Company offered a successful line of towed graders in 1921 (Leffingwell 1994). Caterpillar introduced the integral motor grader, the No. 10 Auto Patrol,

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including all implements and the engine, in 1931. The 1938 Tournapull integrated the tractor and the scraper and used an apron to retain material and a sliding plate to positively eject material (Haycraft 2000). The Model 583 Pipelayer, introduced by Caterpillar in 1955, was the first integrated design of the attachments for this operation (Nolde 1999). Case introduced its Model 320 in 1957 as the first loader–backhoe that was factory assembled and fully warranted by one manufacturer. During the 1980s Volvo offered a wide variety of front-end attachments using a quick coupler design for its front end loaders. Machines with this flexibility became known as tool carriers (Haycraft 2000).

Hydraulic Systems

Hydraulic systems greatly increased the capability of earthmoving equipment in many ways, including operating implements. Hydraulic systems supply high pressure oil to piston or rotary actuators to produce a force and a displacement. The major components are hydraulic pumps (typically driven by the engine in earthmoving equipment), control valves, high pressure hoses, and hydraulic cylinders or motors. Advances in each of these components contributed to the greatly increased capability of hydraulic systems for earthmoving equipment. Pump design progressed from gear pumps to vane pumps to the current axial piston pumps with a wide range of operational flexibility.

Maximum hydraulic pressures for drive systems progressed from 8,300 kPa (1,200 psi) in the 1950s, to 17,000 kPa (2,500 psi) in the 1960s, to 28,000–41,000 kPa (4,000–6,000 psi) in the 1980s. Improved filters and designs to maintain system cleanliness during operation and maintenance greatly increased reliability (Dale Ronsin, personal communication, April 16, 2004). Nitrogen accumulators have given hydraulic systems greatly increased capability to withstand shocks from hitting rocks and other frequent operating conditions (Dane Lowry, personal communication, February 6, 2004). Control of hydraulic systems, a further major advancement, is discussed below in the section on control and information systems.

Transition from Cable to Hydraulic Operation

Implements require force for positioning and cutting. Booms and lift arms provide the leverage; chains, cables, and hydraulic systems provide the force. The evolution of implements moved through these three methods of operation along with increased integration of the control systems with the machine. In 1900, W. A. Robinson designed the first excavator controlled by cables rather than chains. LeTourneau developed the design for a cable-controlled blade in 1927 (Cohrs 1995). He offered a cable-operated scraper with control unit in 1932 (Haycraft 2000).

Sir W. G. Armstrong developed very early hydraulic excavators for canal building in 1882 (Cohrs 1995). These machines used hydraulic cylinders to operate the bucket and the slewing gear. LaPlat-Choate offered a hydraulically powered dozer blade on a large scale by 1925. Russell, Galion, Austin-Westin, Champion, and Caterpillar all offered graders with hydraulic blade operation in the early 1930s. The inability of hydraulic systems offered at this time to produce downforce limited their effectiveness (Cohrs 1995).

Warner and Swasey offered the Gradall excavator with a telescoping boom and raking capability in 1945. Carl and Mario Bruneri patented an excavator with fully hydraulic operation in 1948. Their patent became the basis for excavators offered by SICAM, Drott, and Mitsubishi (Cohrs 1995). The Demag B-504, introduced in 1954, was the first excavator with fully hydraulic operation and offered the major advantage of 360° rotation. Caterpillar introduced the Model 225 hydraulic excavator in 1972, featuring a high-pressure variable-flow hydraulic system with pilot-operated controls. Komatsu's Explorer series of excavators, first offered in 1989, included advanced applications of hydraulic systems as used by all major manufacturers today (Haycraft 2000).

By 1975 the advantages of hydraulic systems had essentially eliminated the use of cable control (Haycraft 2000). Increases in the size and operating pressures of hydraulic motors and in the size of actuators increased the available force, design, and manufacturing technology improved the reliability, and advanced hydraulic and electro-hydraulic control systems increased both flexibility and precision of movement. These advances allowed positive downforce (up to the weight of the machine rather than the weight of the implement), greater degrees of freedom (to increase operational flexibility and force), precise positioning, and reduced cycle times.

In summary, implements have illustrated revolutionary advancements through complete new types such as rippers and various types of buckets. Implements also illustrated significant incremental improvement to increase functionality and productivity. Major technical advances in hydraulic systems, a key enabling technology for implements, fostered many of these incremental improvements. Advancements in control systems, further described below, greatly leveraged this increased capability.

Technical Advancement of Traction Systems

Function and Design

The traction system, typically steel tracks or rubber tires, forms the interface between the machine and the ground or other surface and governs grip and motion. This system provides mobility and allows the machine to develop the correct combination of force and speed needed to perform the earthmoving operation. Usable force is limited by the weight of the machine and the coefficient of friction of the traction system. Traction systems also limit ground pressure to that allowed by the underfoot condition and resist abrasion and wear.

Major options for traction systems include steel or rubber tracks and small or large rubber tires, with or without steel or other reinforced wearing surfaces. Track-type traction systems include a linked and pinned steel track with grouser bars to grip the soil, a track beam, and idler pulleys. These tracks pass over undercarriage rollers that are part of the suspension system. Drive sprockets, the interface with the final drive, apply force to the track pins to move the tracks and the machine over the soil.

Rubber tires are inflatable structures that carry the load from the mass of the machine and its payload. The weight on the driven wheels and the coefficient of friction between the tire and the ground provide the horizontal force needed to move the machine. The major parts of tires are the rim or ring for attachment to the wheel, the casing with internal reinforcement, and the tread. The capability of tires is a major design constraint for wheeled equipment. Heat buildup from high frequency flexing of tires limits the combination of load and speed, typically expressed as ton kilometer/hour or ton mile per hour. Wheeled equipment other than trucks requires single, large low pressure tires. Off-highway trucks require high-pressure, dual type tires (Haycraft 2000). Current haul machines typically use radial tires with the

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minimum number of plys to increase heat dissipation (Dane Lowry, personal communication, February 6, 2004).

Advancements in Track Systems and Equipment Using Tires

Technical advances in traction systems included increased speed and durability of track systems and increased capacity and operational flexibility of tires. Steam-powered agricultural tractors, offered by the Holt Brother Company in 1890 and the C. L. Best Company in 1904, used steel wheels (Leffingwell 1994). Ben Holt developed the first track-type tractor in 1904 (Cohrs 1995). C. L. Best offered his first crawler in 1912 (Leffingwell 1994). The Allis-Chalmers HD-14 tractor, introduced in 1939, included the "Positive Seal" track roller, the first sealed unit that extended the duration between lubrications (Haycraft 2000). Extensive use of sealed and lubricated track chain, beginning in the late 1970s to the mid 1980s, resulted in a major improvement in service life, maintenance cost, speed, and durability.

Universal Crane Company introduced wheeled excavators in 1920, followed by Bay City in 1922. The 1932 LeTourneau Carryall towed scraper was the first heavy earthmoving equipment to use pneumatic tires (Cohrs 1995). LeTourneau introduced the first integral rubber-tired earthmover, a motor scraper named the Tournapull, in 1938 (Haycraft 2000). The Tournadozer, offered in 1946, was the first dozer using tires (Cohrs 1995). Caterpillar introduced its first rubber-tired front end loader, the Model 944, in 1959 (Nolde 1999).

Tire Advancements

The increasing capacity and capability of wheeled earthmoving equipment demanded major advances in tires. LeTrourneau designed and fabricated the tire molds used by Firestone to produce tires for the 1932 Carryall. Firestone introduced prototype tires for off road service in 1934. Tire suppliers began offering wider tires that operated at lower pressures in the early 1950s. Problems with sudden failures from rock cuts and punctures led to a squarer profile and increased tread rubber. This in turn created difficulties with increased sidewall flexing and heat buildup. Tubeless tires gained general use in earthmoving equipment during the 1950s (Haycraft 2000). Use of nylon cord in tires for earthmoving equipment allowed significant increases in size, capacity, and heat resistance. Tires with the same strength required 30% less plies using nylon (Klump 1975; Schexnayder and David 2002).

The growth in truck sizes demanded larger high-pressure tires that the manufacturers began supplying during the 1950s. Caterpillar introduced the beadless tire in 1970. The design allowed mounting a replacement tread belt to the basic carcass (Haycraft 2000). The demands of haul trucks and loaders drove advances in tires. Michelin (2004) identified the following milestones in its development of tires for earthmoving equipment: first radial truck tire in 1946, first radial earthmover tire for dump trucks in 1959, all radial line of earthmoving tires in 1980, first radial earthmoving tire designed specifically for loaders (XMINE D2) in 1982, first 1.44 m (57 in.) tire designed for loaders (55/80R57 XMINED2) in 1992, low-pressure technology for large haul trucks in 1998, and new tire for rigid dump trucks in 2000. Goodyear recently announced a new design for large mining tires termed a two part assembly (Moore 2003a). The separate parts are a casing with circumferential grooves and a replaceable tread belt that surrounds the casing and locks into the grooves. This design lessens heat transfer from the casing to the tread to increase durability and allows replacement of either part separately if damaged.

In summary, both track systems and pneumatic tires were revolutionary advancements in traction systems for earthmoving equipment when introduced. Tires are a key enabling technology for this equipment and remain a limiting factor in machine capability. In response to the demands of equipment manufacturers and users, suppliers have made substantial incremental improvements in the capability and durability of tires.

Technical Advancement of Structure and Suspension Systems

Function and Design

The many components of the structure and suspension systems connect the major elements of the machine, attach the implements, transmit loads, and allow the traction system (tracks or tires) to respond to changes in ground conditions. The structure also defines the overall form of the machine. The design criteria for the structure system are determined by the weight of the machine, the horsepower and torque of the engine, and the load from operation of the machine and the implements. The structure generally consists of a welded steel frame, often made of custom-formed members, with bolted attachments and pinned joints for transmission of loads and repositioning of working configurations to increase machine flexibility.

Advanced Design Capabilities

Advanced design using computer-based tools served as an enabling technology for multiple systems of earthmoving equipment. Computer-based modeling and simulation software applications, along with proprietary processes that yield design solutions, made it possible to model the entire machine and balance the systems without extensive iteration in their design. These tools allowed simulation of the complete machine mission over operational cycles and provided loads and other criteria for the balanced design of all systems. Computer-aided techniques for analyzing forces and stresses, and designing components for automated manufacturing have also brought major improvements in the design of many components. Finite element modeling of design alternatives for all load-carrying elements of earthmoving equipment has produced more efficient and reliable designs despite increasing forces and demands of operational conditions.

Advanced Materials and Manufacturing Processes

Improved control, of the chemical composition of steel materials, along with new types of steel, increased strength, fatigue life, and wear resistance. As an example of strength changes, structures for earthmoving equipment manufactured until after World War II typically used steels with yield strength of 210,000–240,000 kPa (30,000–35,000 psi). This increased to 280,000–310,000 kPa (40,000–45,000 psi) after the war. The increased strength allowed significant weight reduction, such as from 11,360 to 7,270 kg (25,000–16,000 lbs) for the body of a 36,300 kg (40 t) off-highway truck (Klump 1975; Schexnayder and David 2002).

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Purpose-Built Structures

Machine frames and other structural elements that were custom designed and fabricated for a specific type of earthmoving equipment handled greater loads and provided special capabilities for greatly increased mobility. Advanced capabilities for analysis allowed identifying the different types of loading resulting from the many operating conditions of earthmoving equipment and designing joints for low stress (Dale Ronsin, personal communication, April 16, 2004). Examples of early purpose-built structures are the 1932 LeTourneau Model B Carryall scraper that used all welded construction and the 1958 LeTourneau–Westinghouse Haulpak truck that featuring a V-shaped body and variable-section main frame (Haycraft 2000). Custom designed frames using all welded construction are current standard practice (Dane Lowry, personal communication, February 6, 2004).

Articulation and Steering

Wheeled vehicles steer by varying the angle of the wheels with respect to the centerline of the machine. Frame articulation provided a new means of accomplishing this. Articulated systems added a hinge that allows horizontal or horizontal and vertical displacement of one section of the structure with respect to the other for decreased turning radius and increased ability to handle rough ground conditions. The 1937 Tournapull was the first integral, articulated wheel tractor–scraper earthmover. The Scoopmobile LD series wheeled loaders, offered in 1952, were the first machines of this type to use articulated frame steering (Cohrs 1995). Euclid introduced the first commercially successfully articulated wheel loaders, the L-20 and L-30 models, in 1962. Caterpillar followed with the 966B in 1963 as its first articulated wheel loaders. (Haycraft 2000). In 1966, Volvo offered the DR631 articulated hauler. This first commercially successful machine of this type had a capacity of 10 t. Deere introduced the first all hydraulic motor grader with frame articulation, its Model JD570, in 1967. The Caterpillar G series of motor graders, introduced in 1973, used frame articulation and front wheel steering for tight turning circles (Haycraft 2000).

New Types of Suspension

The design of the suspension system varies with the type of traction system. Track systems generally use equalizer bars, pinned rigid members, to connect the base frame with the upper body and provide three-point suspension that allows movement of the traction system with respect to the structure system. Tire systems generally use damped springs or air struts located at each wheel. Advanced suspension systems allowed greater equipment speeds over rough travel paths.

In 1925 Cleveland Tractor offered a machine with a special axle to support the crawler frames and free the drive sprocket from pushing and pulling forces. In 1926 Mead–Morrison offered the Model 55 tractor with oscillating crawler frames and a new roller suspension system. The Caterpillar D10 model, introduced in 1978, used a suspension design that located the track rollers in a flexibly-mounted bogie to improve ground contact and ride. These soft undercarriages increased the ability of machines to operate in rough ground conditions (a function of operator comfort and ability to control), increased operating speed, and lessened wear (Haycraft 2000).

For wheel vehicles, the suspension system uses springs or pneumatic devices between the axles and the frame to allow movement of the axles or independent wheels. The 1958 Haulpak truck featured a hydro-pneumatic suspension system. Michigan offered a suspension system for scraper drive axles in the 1970s (Cohrs 1995). Recent advances in suspension design include systems that use nitrogen over hydraulic oil to increase load transfer and shock absorption (Dane Lowry, personal communication, February 6, 2004).

Other Elements of Structure

Related to the structure, new design features have greatly improved the operator safety and working environment of earthmoving equipment. These include rollover protection structures (ROPS) and environmentally controlled cabs. ROPS were a feature of the Deere products dating from the mid-1960s.

In summary, the structure and suspension systems for earthmoving equipment are fundamental but not especially visible. Purpose built structures and frame articulation were revolutionary innovations for this system. Advanced materials, design tools and processes, and manufacturing techniques, each of which is a key enabling technology for these systems, brought incremental improvements in the structure. Suspension systems for track type and wheeled equipment also illustrated incremental improvements to increase productivity and operator comfort.

Technical Advancement of Power Train Systems

Two major components provide the force needed to move earthmoving equipment and to operate the implements. Engines develop the necessary power and transmissions and final drives deliver it in the many combinations of torque and speed needed to complete earthmoving operations. Power trains for earthmoving equipment also include steering to move track-type machines in the right direction and brakes to safely stop.

Diesel Engines

Engines use a combustion process to convert the chemical energy in fuel to the mechanical energy needed to produce force and velocity and perform earthmoving operations. Horsepower, speed (rpm), and torque are the key performance criteria of engines. Engines for earthmoving equipment must satisfy many types of criteria, such as reliability under field conditions, flexibility to operate over a wide range of speed and torque, and limitation of noise and emissions. Because of their superior performance regarding these criteria, diesel engines are a key enabling technology for earthmoving equipment.

Rudolph Diesel invented the diesel engine in 1892. Technical advancements have improved performance related to each of their design criteria. Examples of technologies that have supported these advancements include materials with increased strength and temperature resistance, fuel injection, turbocharging, improved oils and lubrication systems, and electronic engine controls. Other engine configurations developed during the 1960s and 1970s to increase power density included 60° vee engines with 8, 12, or 16 cylinders, dual gear-driven overhead camshafts, and four valves per cylinder. Further development of diesel engines during the 1980s and 1990s included direct injection combustion systems, electronically controlled unit injectors and additional engine configurations to lower emissions, improve engine life, and decrease fuel consumption (Connor et al. 1996).

Caterpillar first diesel engine (for the Diesel 60 tractor de-

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scribed below) used a four-cylinder configuration with displacement of 17.9 L (1,090 in.^{3}) to produce 64.6 kW (86.6 hp) at 700 rpm. It weighed approximately 3,180 kg (7,000 lb) and used a gasoline "pony" engine for starting. A current truck engine (Caterpillar Model 3176B) produces 272 kW (365 hp), and weighs 884 kg (1945 lb) (Connor et al. 1996).

Recent trends in diesel engines include lighter weight and increasing design for replacement rather than rebuilding. Many users now typically replace engines up to 200 hp, evaluate replacement for rebuilding for 200–400 hp engines, and rebuild engines above 400 hp (Dane Lowry, personal communication, February 6, 2004). Increased complexity of emissions controls is increasing maintenance effort and cost.

Engines and Power Systems for Earthmoving Equipment

In 1912 the Bucyrus Company offered a rail-mounted excavator that used an early engine powered by gasoline rather than steam. Menck offered an all-purpose excavator powered by a diesel engine in 1924 (Cohrs 1995). Holt, one of Caterpillar's predecessor firms, introduced the track-type tractor power with a gasoline engine in 1908. The 1931 Caterpillar Diesel 60 was the first use of a diesel engine in a track-type tractor (Haycraft 2000). The 1955 D9 tractor featured the first turbocharged diesel engine for earthmoving equipment; it increased engine output 45% (Connor et al. 1996). Subsequent milestones as these machines increased in horsepower included the Caterpillar D8 1 H (82 kW, 110 hp) in 1935, the Allis Chalmers HD-19 (144 kW, 193 hp) in 1947, the Caterpillar D9 18 A (214 kW, 286 hp) in 1955, the Euclid TC-12 (272 kW, 365 hp) in 1955, the Caterpillar D10 84 W (388 kW, 520 hp) in 1978, the Komatsu D575A-2 (783 kW, 1,050 hp) in 1991, and the Caterpillar D11 N 74Z (574 kW, 770 hp) in 1985 (Haycraft 2000; Caterpillar 2004).

Power Transmission Systems

These systems transmit the power generated by the engine to the final drive and the traction system of the machine. They provide multiple gear ratios to allow operating at the combination of speed and torque required by the desired load and speed of the machine. The major design criteria for power transmission systems are maximum allowable horsepower and torque, reliability, operational flexibility, efficiency, and limited maintenance requirements.

The transitions from manual to automatic and then to hydrostatic drive systems brought major advances in the performance of power transmission systems. Manual drive systems require a clutch to disengage from the engine and shift to another gear ratio. Powershift transmissions often use torque converters or fluid couplings to allow changes in gear ratios with minimal disruption to torque flow. These transmissions evolved into autoshift configurations, usually powershift as well, that shift according to predetermined logic without operator intervention. In addition, some types of torque converter transmissions use neither powershift nor autoshift. Automatic transmissions further improve operating efficiency and allow the operator to concentrate on the work tools. For haul units, downhill grades presented major challenges. Dual path transmissions and retarders increased ability to handle this mode (Dale Ronsin, personal communication, April 16, 2004).

Hydrostatic drives use hydraulic pumps and motors to transmit power at infinitely variable combinations of speed and torque. This permits a completely seamless flow of torque under all load conditions. This system also allows maintaining high pressure and flow of hydraulic fluid to operate the implements even when the tractor is operating at low speed.

Power Transmission Systems for Earthmoving Equipment

The 1946 Tournadozer featured a torque converter and powershift transmission (Cohrs 1995). In 1947 Allis-Chalmers introduced the HD-19 track-type tractor with the first torque converter in the drive train. In 1949 Euclid introduced the first wheel tractor-scraper with a separate engine powering the scraper wheels, made possible by the first successful use of a semiautomatic transmission in hauling equipment. Clark offered its Michigan line, featuring semi-automatic transmissions, in 1954. Caterpillar introduced the D8 H in 1958 with the company's first semiautomatic powershift transmission (Haycraft 2000).

The Demag 1954 B-504 hydraulic excavator used separate oil circuits for implements and final drive. Liebherr introduced the PR741, the first hydrostatically powered bulldozer, in 1968. The JCB 110 crawler loader, offered in 1971, featured a rear-mounted engine and hydrostatic drive (Cohrs 1995). Caterpillar introduced the Model 225 as its first fully hydraulic excavator in 1972 (Nolde 1999). Deere made a major commitment to hydrostatic drive in 1975. The firm introduced the JD750 hydrostatic bulldozer and matching 755 track loader, both of which used Sundstrand components, and also offered hydrostatic front-wheel assist on motor graders. In 1980, Caterpillar introduced four new track-type loaders with rear-mounted engines and more sophisticated hydraulic drive systems (Haycraft 2000). Liebherr, Zettlemeyer, Atlas, and others introduced rubber tired 4WD hydrostatic loaders primarily in Europe.

Final Drive

The final drive converts the power output from the power transmission system to the location, configuration, and relationship between torque and speed required by the traction system. Final drives typically include shafts, planetary reduction gears, and a sprocket for connection to a track or a hub for connection to a wheel. The key design criteria for final drives are ability to transmit the required horsepower and torque and the durability of the components.

Austin introduced a grader with rear tandem drive in 1928. The 1947 Hough Model HM featured the first all wheel drive for a loader. The 1948 Euclid scraper used a separate engine to drive each of the two axles (Cohrs 1995). Caterpillar first offered the oil-type clutch in the final drive of its D6, D7, and D8 tractors in 1953. These clutches reduced wear and eliminated the frequent adjustments required for dry clutches. In a different concept for final drive, LeTrouneau announced the electric drive system in 1950. This design used an electric motor and gearing installed in the hub of a wheel (Haycraft 2000). Component efficiencies and cost effectiveness of electric drive and now rapidly improving.

Steering and Brakes

The typical approach for steering a track-type machine is to change the speed of one track relative to the other by disengaging the final drive or varying the drive speed. The key design criteria for steering and brakes are the ability to maintain safe control of the machine in varying operating conditions.

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Holt patented steering clutches for steam tractors in 1893 (Leffingwell 1994). The 1921 Best Model 30 tractor featured differential steering and track brakes (Leffingwell 1994). The Euclid Cleartrac tractor, offered in the early 1930s, used double differential steering to avoid braking in turns (Cohrs 1995). International Harvester's TD-24 track-type tractor, introduced in 1947, offered the first two-speed planetary power steering (Haycraft 2000). This innovation allowed turns with power to both tracks. The 1954 Liebherr Model 90 was perhaps the first skid-steer wheeled loader (Cohrs 1995).

In summary, diesel engines and automatic transmissions were revolutionary innovations for power train systems in earthmoving equipment. They both also served as enabling technologies. Incremental improvements have steadily advanced all elements of power trains. These improvements have greatly increased output, reliability, operational flexibility, and environmental acceptability of many types of earthmoving equipment.

Technical Advancement of Control and Information Systems

Control systems make earthmoving equipment smart. They are the newest types of system and the most likely area of future advancement. They control the operation of other systems in the machine, provide design information, determine and communicate position, and monitor machine performance and health.

Technical Basis of Control Systems

Feedback control systems, typically combining electronic and hydraulic elements, greatly increase the ability of the equipment operator to position the machine and the implements as required to maximize productivity and the quality of the final product. These systems control the response of other systems, such as providing additional oil pressure to move a hydraulic cylinder as required by operator input to position an implement. Operating in automatic mode, they can monitor output parameters such as blade position, compare the actual with planned values, and send signals to actuators to make required corrections.

The increased capability and performance of each component in a control system indicates the steady pace of advancement for this key enabling technology. Sensors are now much more responsive, accurate, and rugged. Controllers now use chips to capture logic and greatly increase flexibility and accuracy of operation. Electric and hydraulic actuators now provide greater force, movement, response, and accuracy.

Early Control Systems for Construction Equipment

As an early example of partial machine control, the 1944 Hough Payloader included an automatic return-to-dig capability. The 1956 Preco grader featured an electronic control system for blade angle that corrected each 0.10 s (Cohrs 1995). In the late 1980s Liebherr developed its "Litronic" management system to sense load and control excavator functions. Equipment manufacturers experimented with electronic control systems beginning in the mid 1980s and made a full commitment to these systems for monitoring and control systems after 1995 (Haycraft 2000).

Hydraulic Control Systems for Construction Equipment

Current equipment models include several examples of specific advancements in the control portion of information and control systems. Advanced operator interfaces, such as the single lever or joystick to control multiple functions, now increase productivity and provide ergonomic working conditions. Engine control units monitor and control critical systems and functions, such as fuel injection and maximum revolutions. Electro-hydraulic control systems for machines and implements allow precise positioning and control of high force levels. Increased controllability of earthmoving equipment produces major benefits. Machines of the same weight and engine power today can deliver up to twice the implement power of 20 years ago. Advances in controls and operator ergonomics have allowed the operator to effectively control much more speed in operation to deliver dramatically increased productivity.

Hydraulic control systems progressed through three main types. The first, open center systems, operated constantly at full flow, with recirculation through the open center of the valve when not required by the actuators. Closed circuit systems, the second type, stopped flow when not needed by the actuators but continued to operate at high pressure. The current pressure compensated systems control pump output to satisfy demands for pressure and flow. The operation of control valves for hydraulic systems progressed from manual to solenoid-operated cartridge valves, to pneumatic pilot valves, to the current integrated electro-hydraulic valves (Dale Ronsin, personal communication, April 16, 2004).

Increases in the corner kilowatts or horsepower (the product of maximum pressure and maximum flow in hydraulic systems) of control systems indicate advances in their capability. During the 1960s a 16,360 kg (36,000 lb) machine used a 6.56 L (400 $in.^3$) engine to develop about 67 corner kW (90 hp). A current 16,360 kg (36,000 lb) excavator will use a 4.9 L (300 $in.^3$) engine to develop over 149 corner kW (200 hp).

Information Systems for Earthmoving Equipment

Microelectronic circuits and associated peripheral equipment, operating much like familiar microcomputers, store and provide information for all types of earthmoving equipment. This key enabling technology has advanced dramatically in the recent past, following major increases in computer processing speed, storage capacity, and data transfer rates. Major types of information that are becoming more available onboard equipment include configuration of the earthwork design for the specific project, real time position of the machine, and operating condition and health of each system.

Positioning systems have progressed from prior laser technology that provided only elevation (Tatum and Funke 1988) to rapidly advancing geographic positioning satellite (GPS) systems (Moore 2003b). These systems process signals from satellites and a base station to determine and display the machine's location. Onboard design information is an essential part of fully or partly automated systems for grading. The digital terrain models identify original ground contours and define the required lines and grades of the completed cut or fill. Combined with the required lines and grades at that location from the digital terrain model, this forms the basis for advice to the operator or instructions to the machine regarding necessary cut and fill at each location. This technology is now in its infancy. Suppliers and users are only exploring the beginnings of what is possible and this will have enormous impact as systems become ubiquitous on smaller and less expensive equipment. GPS systems can also provide input to other onboard or remote systems that monitor and report the location and utili-

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zation of the machines. This is a key information input to equipment management systems and will become as pervasive as the dash clock on a car.

Other types of onboard information systems continuously monitor a set of parameters indicating the performance and state of key systems and components and report out-of-tolerance or fault conditions to provide advance warning of potential problems. With the advent of low cost, high bandwidth wireless communications, this information is now available not only to the operator, but to the equipment manager and service entity in real time. This allows alerting all to the need for fuel, lubricants, periodic maintenance, and unforeseen failures. Equipment is no longer remote and isolated, but part of an interconnected construction system.

In summary, advances in control and information systems are a key enabling technology for earthmoving equipment and foster incremental improvement in each of the other systems. Control and information systems have recently advanced at a rapid pace and offer significant opportunities for further improvement in the performance of each system as well as the complete machine operating as a part of an overall site system. Smarter equipment will increase its own performance and life as well as the ability to work without support from other types of machines.

Conclusions

Findings from the above analysis of technological progress in the systems that make up earthmoving equipment leads to the conclusions highlighted in this section. These concern how the systems advanced, their usefulness in understanding technical change, and their integration to design balanced machines. The findings and conclusions lead to implications that are highly relevant for practice, education, and research. They are presented in the final section.

Technical Advancement of Systems

Implement systems advanced greatly by adding new types, integrating implements with earthmoving equipment, and using hydraulic operation. Key technical advances in traction systems included new track and tire designs. Structure and suspension systems advanced by using new materials, tailored designs such as articulation, and new manufacturing techniques. Key advances in power train systems included improved diesel engines and new types of power transmission systems. Applications of advanced control and information systems to earthmoving equipment provided major advantages in machine control and monitoring and improved the performance of other systems. The advances in each of the systems led to increased capacity, reliability, operational flexibility, safety, maintainability, longevity, and environmental friendliness of earthmoving equipment.

Importance of Systems and Enabling Technologies

The five systems proved a useful tool to analyze technical advancement of earthmoving equipment. They provide a structure to identify specific changes that increased the performance of different types of equipment. The five systems also highlighted the important role of a few key technologies in overall equipment advancement. We think of these as the technological "genes" of earthmoving equipment. Specific enabling technologies fostered technological advancement in single or multiple systems: hydraulics (implement and power train systems), tires (traction system), advanced computer techniques for analysis and design (implement, structure, and power train systems), advanced materials and manufacturing techniques (implement and structure systems), diesel engines and automatic transmissions (power train system), and microprocessors and electronics and information technology (all systems). Of the enabling technologies, electronics and information technology are poised for the highest rate of continued technical advance. Fortunately, these technologies influence the capability and performance of all the systems that comprise earthmoving equipment.

Systems and Machine Integration

Although the five systems proved very useful in analyzing technical advancements in earthmoving equipment, complete focus at the system level of analysis brings a risk of missing the critical need and importance of integrating these systems in the design of balanced machines that best meet the users' performance requirements. This requires recognizing that the systems are highly interdependent and that the best overall machine design may not allow the best design of each individual system. For example, hydrostatic drive systems may not provide the highest efficiency in transferring power to the traction system, but can provide the higher hydraulic pressures and flows needed for fast and precise operation of the implements. Also, modular components that bring significant for maintenance may include parts of multiple systems.

Looking another level higher, the systems and the earthmoving machines that they comprise perform as part of a larger system of earthmoving operations to meet project and design requirements on a specific site. A fully integrated view would therefore include four key elements: the priorities set by the project objectives, the design requirements, the equipment spread selected, and the capabilities of the individual pieces of equipment as determined by their systems. Optimal overall performance would require that each element in this larger system consider the capabilities and limitations of the other elements. Looking at the extremes for increased performance, the owners and designers that define the required results of the project could consider the systems that determine the capabilities of the equipment producing the constructed product to satisfy these requirements. Other factors to consider include site conditions, operators' capabilities, available equipment fleets, and other factors influencing the contractors' costs. This expanded view takes integration to the full extent and highlights the role of each element in the overall production system.

Relevance and Applications for Industry Practitioners, Educators, and Researchers

Facility Designers

The trend of increasing integration in project teams, using the design build contracting with single responsibility for design and construction or other approaches, suggests possible actions by designers to help realize the potential benefits of advanced earthmoving equipment. The increasing capability and use of GPS systems for all types of machines will require full definition of design requirements in digital terrain models. This different approach will also allow construction input, based on the capabilities of earthmoving equipment, regarding grade configurations

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and other features that will allow meeting the design requirements at the lowest possible cost. The capability of a design firm to provide integrated designs that are tailored to machine performance and productive operations can provide a substantial competitive advantage and opportunity to continue improving performance.

General and Grading Contractors

Contractors could apply the five systems to analyze different types of earthmoving equipment and select the most appropriate items for project objectives and site conditions. An integrated view of capabilities in multiple systems could also improve the effectiveness of equipment use. Going one step further, the capabilities and limitations of machines, as determined by their individual systems, are essential considerations in systems views of all site resources and operations needed to plan and efficiently complete a project. This broad perspective can assist in selecting methods and resources for challenging projects, providing input to the design if the project organization allows, and decision making regarding equipment fleets.

Equipment Designers and Suppliers

The construction equipment industry could guide development and hasten the adoption of useful enabling technologies to further increase the rate of improving equipment performance. Simulation and other modeling software to synthesize systems into a balanced machine present major potential for overall improvement. Although there is always opportunity to improve, implement, traction, and structure and suspension are currently the most mature systems for earthmoving equipment. Power train and control and information systems appear likely to continue developing. Future developments may also include electric drives as evolutionary replacements for hydrostatic traction systems.

Further improvements in modeling and simulation software will allow continued improvements in the efficiency balancing of systems, and refinements in controls software algorithms. Wireless communications of monitoring and diagnostics information to contractor and service centers, on-board position reference systems (not just GPS based), and on-board project design comparison to reference positions all in real time provide major potential for innovation in fleet management and construction project optimization and flexibility.

Rapid advancements in information and control technologies provide the same potential improvements in machine performance as the historical example of integrating implements with machine design. Envisioning information, including position, as a utility available to all field persons has significant potential implications for future design and use of equipment. The police car and the Abrams tank provide current examples of much greater onboard information availability for operations. Advanced information technologies could also create new requirements for operator qualifications and training, and even possibly help attract high-potential operators. Another major opportunity in improving the productivity of the machine in the context of the work site is continued advances in ergonomics and other design features that increase the productivity of the operator over the entire course of the work day.

Construction Educators

Analyzing the technical basics and fundamental limitations of earthmoving equipment and systems could assist in structuring the technical portion of construction equipment courses. Construction faculty can use the systems to break construction equipment into more easily understood parts to explain the technical basics of performance. The five systems also provide a helpful way to identify and learn about the differences in the equipment capability and effective use in different situations. This technical foundation can also help increase the students' understanding of underlying factors governing equipment selection and economics.

Construction Researchers

This analysis of technical changes in the five systems that make up earthmoving equipment highlighted what advanced and how each system changed. This understanding of technical progress at the system level will assist in future investigations of drivers and influences for the process of advancement. Haycraft (2000) described several periods of market demand that accompanied the advancements. Using the systems as a part of the analysis in further investigations of these drivers will assist in highlighting the mechanisms of advancement. Further research regarding the details of technological evolution for the most important enabling technologies identified in this paper would also provide useful input to equipment manufacturers and contractors seeking to improve specific aspects of machine performance.

Identifying the types of information and knowledge needed by equipment operators and the control and information systems that support them could foster further advances in information and control systems for earthmoving equipment. This could include an historical analysis of equipment cabs and their displays. Future research could also include field tests of historical and current machines of the same type to assess the changes in performance that have resulted from technological advancement.

Researchers can make a major difference in the effectiveness of earthmoving by increased understanding of the construction knowledge (including systems, machines, and field operations) that designers can consider in selecting lines and grades that most economically meet the requirements of the project. Future researchers can also continue to develop tools to simulate and model the interaction of multiple machines working simultaneously at a site to complete many different types of earthmoving operations.

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