# Innovations in Earthmoving Equipment: New Forms and Their Evolution

C. B. Tatum, F.ASCE[1]; Michael Vorster, M.ASCE[2]; and Mac Klingler[3]

**Abstract:** The technological advancement of earthmoving equipment during the 20th century includes the introduction of at least seven completely new forms. The purpose of this paper is to analyze the introduction of five new forms (track-type tractor, off-highway truck, wheel tractor scraper, hydraulic excavator, and loader-backhoe) and their subsequent incremental improvement. The description of innovation for each machine includes markets and the state of technology at introduction, differences of the new form, and changes during subsequent development. The major findings from this analysis are the key role of new technology for machine systems in the development of the new forms, the continued importance of each form in earthmoving markets, and the significant continued advancement of the equipment through incremental improvements. These findings are relevant for practice to assist in identifying possible improvements in equipment capability and work procedures. The results will also assist educators in courses concerning equipment capability and technical advancement and researchers in considering new equipment forms and capabilities as a part of developing new tools to model and improve equipment-intensive construction operations.

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## Introduction

Manufacturers now provide a wide range of machine forms for earthmoving equipment. Current product lines include equipment types that evolved from agricultural tractors in the early 1900s along with entire new machine forms introduced and further developed since then. The purpose of this paper is to analyze innovative new forms of earthmoving equipment by identifying the technical advancements that they included and the key steps in the subsequent evolution of each machine form.

The paper begins with a review of background regarding product innovation, including earthmoving equipment. The next sections then analyze five major new forms of earthmoving equipment introduced from 1931 to 1957, including market conditions and state of technology at introduction, technical differences of the new form, and subsequent development for improved performance. The next section describes analysis across the examples, including conditions in markets and firms, advancements made by the new forms, how they evolved, and a vision of emerging new species. The final sections highlight conclusions from this analysis relating to the existing innovation background and describe relevance for practice, education, and research.

[1]Professor, Dept. of Civil and Environmental Engineering, Stanford Univ., Stanford, CA 94305-4020 (corresponding author). E-mail: tatum@stanford.edu

[2]Professor, Dept. of Civil and Environmental Engineering, Virginia Polytechnic Institute and State Univ., Blacksburg, VA 24061-0105. E-mail: mikev@vt.edu

[3]Retired, Advanced Research and Development, John Deere Construction Equipment Division, 33 Spring Creek Lane, Galena, IL 61036; formerly, Manager. E-mail: klinglers47@msn.com

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## Background of Technological Advancement

Prior findings regarding technical advancement in other industries suggest possible mechanisms to consider in analyzing earthmoving equipment. This background review also identifies key sources describing the advancement of earthmoving equipment.

### *Technical Advancement in Other Industries*

A combination of market forces (pull) and technological availability (push) appears to prompt innovation in many markets (Rosenberg 1982). Market forces are critical for the diffusion of new technologies that offer prospects for profits for both manufacturer and user. However, the focus of inventive activity and the availability of improved technology is also a significant factor in the technological progress within a market. Thus the two drivers are highly related.

In many industries, technology initially advances in highly visible revolutionary ways with the introduction of an entirely new product or process. Foster (1986) found that revolutionary advances create a new "S" curve of potential gains in product performance and incremental improvements realize this potential. Despite clear potential benefits, many new products or processes do not initially perform much better than the ones they seek to replace. A series of incremental improvements of the new product or process follows introduction, often resulting in much more significant advances than the revolutionary first step (Rosenberg 1982; Christensen 1997). Investigators of technical progress for ships (Gillfillan 1935), railroads (Fishlow 1966), chemical fibers (Hollander 1965), and petroleum refining (Enos 1958) each identified major benefits from a series of incremental improvements.

Abernathy and Utterback (1978) found that suppliers offer many types of products until a dominant product design gains market acceptance. This design synthesizes technological innovations introduced independently in prior products and offers a new combination of desired performance characteristics. It also often results in standardization with limited product improvement as manufacturers shift their focus to process innovation and increased production efficiency. Examples of dominant product designs include the Model T Ford and the IBM personal computer.

### Market Conditions for Earthmoving Equipment

Haycraft (2000) identified major types of projects and periods in which they created major markets for construction equipment. These included: canals building in America from the 1780s until 1860, at Suez in the 1860s, and in Panama from 1904 to 1914; railroads in America from the 1840s to 1900; highways in America from the National Road completed in 1818 to the Interstate Highway system in the 1960s; water projects from the early 1900s to the 1950s; and mining projects from the 1850s to the 1990s. He highlighted the Interstate decade (1956–1965) as a period of intense highway construction and demand for earthmoving equipment.

The reconstruction of Europe and Japan following World War II created a demand for construction equipment to work in confined urban spaces with high population densities. The high average rainfall in many European countries also encouraged development of equipment that could work in difficult underfoot conditions.

### Technical Advancement of Earthmoving Equipment

Haddock (2002) described the history of product development for 16 types of earthmoving equipment. For each type, he used many examples of machines offered by leading firms to illustrate the increased sizes and new features offered. Cohrs (1995) reviewed specific technical advances in each type of equipment from the very early use of machines for earthmoving. He provided an especially useful part of the background for identifying the first machine of a new type, such as excavators, and the technical differences in subsequent models. Haycraft (2000) identified the major technological advancements in earthmoving equipment from the beginning of the agricultural implement industry to the present. This included the major new forms of equipment analyzed in this paper. Caterpillar's *Earthmoving handbook* (Caterpillar 2004) also includes a useful chapter summarizing design characteristics and performance of historical models.

Christensen (1997) contrasts sustaining and disruptive technologies and uses the transition from cable shovels to hydraulic excavators as one example. The dominant suppliers of large cable shovels (the sustaining technology) did not transition to hydraulic excavators (the disruptive technology) because excavators did not offer advantages to the large excavation contractors who were the major purchasers of shovels. Other firms developed the hydraulic excavator for the smaller markets of utility and residential contractors. As the hydraulics technology improved, it met the needs of all types of potential users and took over the market.

Several researchers have developed measures of performance improvement in construction equipment as a part of analyzing changes in construction productivity and costs. These factors are useful to highlight the specific changes of an innovation. Rossow (1977) identified technology packages for 1920, 1950, and 1970; these considered changes in size, power, and operator skill levels. Goodrum and Haas (2004) used five technology factors to develop an index of changes in construction tools and equipment in his investigation of technology and construction productivity: level of control (ranging from hand tools fully controlled by humans to cognitive devices that fully control equipment operation), amplification of human energy (ranging from full to no human energy required), information processing (ranging from none to self control of equipment), functional range (degree of enhancing an operator's ability to complete a task), and ergonomics to increase safety, efficiency, and comfort.

## Key Systems and New Machine Forms for Earthmoving Equipment

Changes in the key systems that make up each type of earthmoving equipment are the major metrics for the innovations that produce new machine forms. This section describes these systems and identifies the new machine forms that we will analyze using these systems.

### Machine Systems

The capability of a piece of earthmoving equipment to perform operations under differing conditions and its production rate are determined by five systems. The implements apply force to move earth and rock. 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 raise, lower, angle or rotate relative to the machine itself. The forces required to do this are provided by cables or hydraulic cylinders. Several of the new machine forms included new combinations of implements.

The traction system contacts the ground, applies force, and creates movement. 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 pneumatic tires. New machine forms provided new combinations of traction systems and implements or structures. The structure and suspension connect components, transmit loads, provide attachment points for implements, and allow the machine to travel over uneven ground. This system corresponds to an animal's skeleton. The machine's frame, articulation, springs or struts at wheels, and steering for wheeled equipment are the major parts of this system. New machine forms resulted from new design of structures, such as articulation.

The machine's power train delivers the power needed to move, turn, 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. Major innovations in the drive train, such as hydrostatic systems, resulted in new machine forms. The control and information systems enable the operator to direct and control all the other systems and provide information about the performance and health of the equipment. They are the brains and nerves of the machine. Advances to these systems have not yet produced new machine forms, but they are critical elements of improved capability for all of the systems. They offer significant potential for job site innovation, improved coordination, work process simplification, and project cost reduction.



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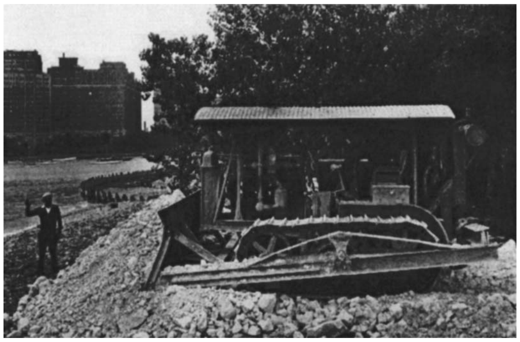

**Fig. 1.** 1931 Caterpillar Model sixty tractor (Haddock 2002, used with permission)


**Fig. 2.** 2004 Caterpillar D5G tractor (used with permission from Craig Vorster)

### *Major New Forms of Earthmoving Machines*

The following sections analyze five major new forms of earthmoving equipment introduced from 1931 to 1957. Table 1 gives a summary comparison of the states of the systems for the new form and an example of a current version of the equipment.

Haycraft (2000) identified seven new equipment forms as key milestones in the technical advancement of earthmoving equipment. The 1931 Caterpillar Model Sixty tractor, with a diesel engine producing 63 drawbar hp (47 kW) was the first commercial use of a diesel engine in earthmoving equipment. The 1931 Caterpillar Model 10 Auto Patrol combined the power train and implements as the first self propelled motor grader. It used pneumatic tires and a drive system with the engine mounted over the rear drive wheels. It also integrated the grader blade and scarifier, implements previously supplied by others. The 1936 Euclid Model R-15 was the first truck designed for off-road service. The 1938 LeTourneau Tournapull was the first self-propelled, self loading, pneumatic-tired, tractor–scraper.

The 1947 Hough Model HF was the first pneumatic-tired wheel loader with hydraulic actuation and the engine in the rear. The 1954 Demag Model B-504 was the first fully hydraulic excavator, including machine drive and bucket positioning. The 1957 Case Model 320 was the first complete factory packaging of the loader–backhoe. Space limitations forced the writers to exclude the motor grader and the wheel loader from the following analysis of new forms.

## Diesel-Powered Track-Type Tractor, 1931

The track-type tractor shown in Figs. 1 and 2 is a highly versatile equipment form, used primarily for loosening and breaking material, transporting material short distances, and leveling. The bulldozer blade to dig and push material and the track-type traction system are its distinguishing features. Applications range from residential lot preparation using the smallest machines to overburden removal in mining operations using the largest machines.

### *Market Conditions and Technology at Introduction*

Agricultural development of the California delta in the early 20th century required powerful machines able to operate in poor soil conditions (Haddock 2002). The Holt and Best companies, predecessors of Caterpillar, offered agricultural draft tractors with early track-type traction systems to increase flotation. Gasoline engines were the major power source. In 1931, the United States was in the midst of the great depression. Federal programs prompted labor-intensive construction to increase employment. The track-type tractor contributed to the mechanization of road building and to canal and flood control projects (Haycraft 2000).

Caterpillar's 1931 Diesel Sixty tractor (Fig. 1) was the first commercially successful machine of its type. It followed the 1919 Best Sixty tractor. The major new feature of the model was its diesel engine, which had seen only limited prior use in earthmoving equipment (Haycraft 2000). The basic tractor did not include implements in conformance with practice at the time.

### *Machine Development and Current Models*

Comparing Figs. 1 and 2 indicates little change in overall machine form for track-type tractors since introduction. However, Table 1 indicates significant advancements in each machine system, following the increased capability of enabling technologies such as hydraulic systems, diesel engines, hydrostatic transmissions, and control and information systems. By 1933 Caterpillar diesel tractors, offered in three models, outsold gasoline-powered models (Nolde 1999). Several other models of track-type tractors illustrate incremental improvements since introduction of the machine form. The 1947 Allis-Chalmers HD-14C was the first use of a torque converter. The 1955 Caterpillar D9D used the first turbocharged engine. Caterpillar offered sealed and lubricated tracks in 1963. The 1974 Liebherr PR731 featured hydrostatic drive and control by a single joystick.

Several firms began supplying separate implements as early as the late 1920s, including dozer blades and rippers for use with track-type tractors. Some experimented with hydraulic operation of implements at that time but the inability to produce down force limited applications. Later development of capable hydraulic pumps and actuators, hydrostatic drive systems, and advanced control systems allowed application of ever larger track-type tractors to precise grading work around building sites. This extension of the application scope prolonged the life cycle of a machine form that was in serious decline. Sealed and lubricated tracks also extended the life cycle of tractors by increasing the service interval and decreasing operating cost.

The Caterpillar D5G (Fig. 2) is an example of a current smaller track-type tractor (Caterpillar 2004). As shown in Table 1, all of the systems have advanced significantly from the Diesel Sixty, resulting in major differences in the capability and performance of even a machine of roughly the same size. D5's integrated and hydraulically controlled implements greatly increase



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**Fig. 3.** 1936 Euclid R15 truck (Haddock 2002, used with permission)

the flexibility and productivity of the machine. Dual path hydrostatic transmissions provide uninterrupted power flow and precise machine positioning. Advanced control and information systems available for current tractors include precise control of the engine, transmission, and implements, along with monitoring equipment health. Global positioning systems (GPS) allow automatic grade control.

## Off-Highway Truck, 1936

The off-highway truck shown in Figs. 3 and 4 and ranging from small capacity to the very largest earthmoving machines featured on book covers, transports earth, and rock over intermediate to long haul distances. The very large body and tires are the major features. Applications include all types of construction projects requiring hauling and surface mining.

### *Market Conditions and Technology at Introduction*

The U.S. economy was still struggling to begin growth in 1936. Demands for hauling in mining operations were satisfied by rail until truck capacities increased. The demands of the Hoover dam project prompted Mack Truck to redesign trucks for this special application in 1931 and then offer off-road models (Haddock 2002). Major expansion of mining operations created a demand for larger capacity trucks in the 1950s and 1960s (Haycraft 2000).

The 1936 Euclid Model R-15 (Fig. 3) was the first truck designed specifically for off-highway use in earthmoving operations (Haddock 2002; Haycraft 2000). The heavy duty structure and suspension system allowed hauling its 15 t (13.5 metric t) load over surfaces not passable by conventional trucks. Its pneumatic tires, driveshaft rather than chains in the power train, heavy frame, one-piece welded body, and suspension were major differences that set the standard design for this equipment.

**Fig. 4.** 2004 Volvo A25D articulated hauler (used with permission from Volvo)

**Fig. 5.** 1938 LeTourneau tournapull (Haddock 2002, used with permission)

### *Machine Development and Current Models*

Several other models of off-highway trucks illustrate incremental improvements since introduction. The 1915 Mack Model AC and 1931 Model AP used welded steel bodies designed for off-highway use. The 1934 Euclid Trac-truck was the firm's first off-road product. Northfield of England designed the first integrated hauler in 1957. The 1965 Dart D-2771 was the first mechanical-drive, two-axle truck with greater than 100 t (91 metric t) capacity (Haddock 2002). The 1965 Volvo DR631 was the firm's first articulated truck and used four-wheel drive. Caterpillar introduced its Model 785 off-highway truck in 1985, followed by Model 789 in 1986 (Nolde 1999). Caterpillar acquired design rights from ADT and offered the Model D400D as its first articulated truck in 1986. The 1996 D400E model included an ejector to allow dumping and uniform spreading without raising the bed (Haddock 2002).

Articulated trucks developed as a significant new machine form. The combination of frame articulation, all-wheel drive, and locking differentials allows articulated trucks to work in conditions that would prevent use of rigid-frame trucks. This versatility provides major advantages under certain site conditions despite the increased complexity and cost of this machine form. The higher rainfall in many parts of Europe favors the articulated truck.

The Volvo 25D Articulated hauler (Fig. 4) is an example of a current product with a size and application roughly equivalent to the Euclid R-15. The engine, automatic transmission, all-wheel drive, and lockable differentials are major differences in the power train system. The articulated frame and strut-type suspension also indicate significant advancements in the structure system. Applications of new technology allow the information and control systems to monitor and assist in operating the other systems.

## Wheel Tractor Scraper, 1938

The wheel tractor scraper shown in Figs. 5 and 6 excavates and loads material and transports it over intermediate haul distances. The bowl, or transport container, and its associated gate and ejector are the major components. Contractors use scrapers of various



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**Fig. 6.** 2004 Caterpillar 621E wheel tractor-scraper (photograph by Michael Vorster)

sizes on projects requiring extensive excavation and intermediate hauling, such as highways, airports, and shopping centers.

### Market Conditions and Technology at Introduction

By 1938 United States economic activity was beginning to increase. Transportation and water projects were increasing in volume. Water resource and flood control projects required large earthwork quantities and haul distances that increased demand for scrapers (Haycraft 2000). Interstate highway construction in the 1950s and 1960s created strong demand for even larger scrapers. The availability of this large fleet at the end of the primary interstate projects provided an amortized asset searching for dirt moving work. This gave rise to many projects that, on their own, could not support the manufacture of large scrapers.

The 1932 LeTourneau Carryall scraper was the first to combine cable control, positive ejection, an apron to retain material, pneumatic tires, and all-welded construction. Towed by a crawler tractor, it allowed one-person operation. The 1938 Tournapull (Fig. 5) added a front engine and single-axle drive unit to allow much higher operating speeds and set the pattern for future integrated and articulated tractor-scrapers (Haycraft 2000).

### Machine Development and Current Models

Comparing Figs. 5 and 6 indicates little change in form of motor scrapers since introduction. Specialized design and articulation of the structure provided much greater operational flexibility. Several other models of the motor scraper illustrate incremental improvements in this equipment form. The 1938 LeToruneau A Tournapull was the first high-speed earthmover and included a unique hitch allowing 180° swings. The 1961 Clark 290M developed for military applications included a four-wheel drive tractor with dozer blade and a 25 $Yd^3$ (18.3 $m^3$) Euclid 58SH scraper. The 1970 Komatsu WS-23 added suspension to scrapers. The 2000 Terex THS-15 featured four-wheel hydrostatic drive and an advanced cutting edge (Haddock 2002). The 1941 Caterpillar DW-10 was the firm's first self-propelled scraper. Caterpillar introduced its first hydraulic scraper and first dual-engine scraper in 1962 (Nolde 1999). The firm added elevating scrapers to its product line in 1964.

Incremental improvements of motor scrapers addressed several problem areas. Early unsuspended two-axle scrapers were not stable on long and fast hauls. Traction and loadability limited performance. Significant evolution to solve these problems included improved hydraulic control, two axle articulated configuration, dual engines, all wheel drive, and elevators for self loading. These technical advancements allowed the machines to operate independently and in lower traction conditions. Despite these improvements, the scraper has been in decline as a viable machine form for over 2 decades, replaced primarily by articulated haul trucks that are more flexible and capital efficient.

The current state of design for motor scrapers is illustrated by the Caterpillar 621G (Fig. 6). Its design retains the same basic configuration of implements, but with hydraulic operation. As shown in Table 1, each of the other systems has changed significantly. The integral power train includes a 330 hp (246 kW) diesel engine and an 8-speed automatic power shift transmission. The articulated structure supports the tractor and scraper portions of the machine, connected by a complex neck joint. Information and control systems assist the operator for greater productivity and monitor all parts of the machine.

## Hydraulic Excavator, 1954

The hydraulic excavator shown in Figs. 7 and 8 and offered in a wide range of sizes, digs material, and loads it into trucks or stockpiles. The bucket and its two-part boom are the primary features. Excavators are used on most types of construction projects, particularly for utility placement and site development.

### Market Conditions and Technology at Introduction

The major reconstruction of Europe and Japan following World War II created a need for small and flexible construction equipment. This led to a substantial effort to develop the excavator based on WWII aircraft hydraulics technology and use it for clearing, demolition, and infrastructure renewal. Commitment to major expansion of infrastructure created growth in trenching and excavating in the United States during the mid 1950s. Substantial completion of the interstate highway program in the late 1970s prompted a shift to reconstruction and improvement projects that required less bulk earthmoving but more flexible equipment (Haycraft 2000). Christensen (1997) identified mining operations and large grading projects as the major market segment for large cable shovels prior to hydraulic excavators. Utility and residential contractors working with small excavation quantities and in constrained spaces created a new market for the hydraulic machines.

The 1954 Demag Model B504 (Fig. 7) was the first hydrostatically driven, track mounted, fully hydraulically controlled and fully-revolving excavator (Haycraft 2000). Prior equipment had used hydraulic operation of implements only.

### Machine Development and Current Models

Comparing Figs. 7 and 8 indicates few changes in basic machine form between the initial and current hydraulic excavators. Hydraulic excavators initially served a niche market segment but also took over the larger market previously served by cable shovels as the hydraulic technology improved to allow greater capacity and reliability (Christensen 1997).

Several other models of excavators illustrate incremental improvements since introduction. Liebherr offered a wheeled model, the L300, in 1955 and expended its product line to include very large mining excavators. Poclain offered successful line of machines using piston hydraulic pumps to supply fluid at 4,500 psi (31,000 kPa) compared with the average of 2,500 psi



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**Table 1.** Systems Comparison for New Equipment Forms and Current State of Development

| New equipment form | New machine | State of systems in machine that introduced new form | Example of current form, size | Current state of systems |
|---|---|---|---|---|
| **Track-type tractor** | **1931 Caterpillar Model Diesel Sixty Tractor**, 60 hp (45 kW); first commercial model with diesel engine | **Implement**: supplied by independent firm, cable operated, single motion<br>**Traction**: steel track, rigidly mounted rollers<br>**Power train**: 4 cylinder engine, manual clutch<br>**Structure**: frame using standard structural shapes<br>**Control/information**: manual, mechanical | **Caterpillar D5G**, 90 hp (67 kW), 19, 630 lb (8920 kg) operating weight ⟨www.cat.com⟩ | **Implement**: variable pitch, power angle, and tilt blade<br>**Traction**: sealed and lubricated track, solid mounted undercarriage<br>**Power train**: 5 L, 6 cylinder engine, dual path hydrostatic drive<br>**Structure**: one-piece custom mainframe, robotically welded<br>**Control/information**: joystick electro/hydraulic and GPS blade control, equipment monitoring |
| **Motor grader** | **1931 Caterpillar Model No. 10 Auto Patrol**; first integral motor grader | **Implement**: integrated blade with powered controls<br>**Traction**: four pneumatic tires<br>**Power train**: integrated gasoline engine in rear<br>**Structure**: rigid frame using standard shapes<br>**Control/information**: manually operated mechanical controls for blade positioned by shafts and gears | **John Deere Model 670C-II Motor Grader**, 140 hp (104 kW), 36,000 lb (16,360 kg) operating weight ⟨www.deere.com⟩ | **Implement**: grader blade, ripper, scarifier, all hydraulic controls<br>**Traction**: six pneumatic tires<br>**Power train**: 6-cylinder turbocharged engine; power shift transmission, 8 speeds each direction; all wheel drive; multidisc brakes<br>**Structure**: articulated frame<br>**Control/information**: electro/hydraulic and GPS blade control, equipment monitoring |
| **Off-highway trucks** | **1936 Euclid Model R15**, 15 t (13.4 metric t) capacity; first truck designed for off-road service | **Implement**: hydraulic dump body<br>**Traction**: pneumatic tires<br>**Power train**: diesel engine, planetary final drive<br>**Structure**: heavy duty, off-highway, rear dump<br>**Control/information**: manual, mechanical | **Volvo Model A25D Articulated Hauler**, 310 hp (228 kW), 47,430 lb (21,560 kg) operating weight, 11 cy (8.3 $m^3$) capacity ⟨www.volvoce.com⟩ | **Implement**: hydraulic dump body<br>**Traction**: six radial earthmover tires<br>**Power-train**: 6 cylinder, turbocharged diesel engine; torque converter, planetary-shift, 6-speed transmission; transfer case, 3 transverse and one longitudinal lockable differentials for 6-wheel drive; air-hydraulic disc brakes<br>**Structure**: articulated frame, 3-point suspension per axle<br>**Control/information**: information display, load-sensing hydraulics, diagnostics |
| **Wheel tractor–scraper** | **1938 LeTourneau Tournapull**; first tractor–scraper; incorporated scraper and control innovations from 1932 Carryall | **Implement**: bowl, apron, rear wall for positive ejection, cable control<br>**Traction**: four pneumatic tires<br>**Power train**: integrated, wheeled, tractor with single axle drive<br>**Structure**: custom fabricated beams for movable components; all welded construction; hitch for 180° swing<br>**Control/information**: manual operation of cable control | **Caterpillar 621G**, 330 hp (246 kW), 124,590 lb (56,510 kg) operating weight, 22 cy (16.3 $m^3$) heaped capacity ⟨www.cat.com⟩ | **Implement**: bowl, apron, rear wall for positive ejection, double-acting hydraulic control<br>**Traction**: four pneumatic tires<br>**Power train**: emission compliant engine; power shift transmission with 8 forward speeds and electronic control; 2 wheel drive<br>**Structure**: custom frame with articulated neck joint<br>**Control/information**: electronic control module for engine and machine; diagnostic capability |



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**Table 1.** (*Continued.*)

| New equipment form | New machine | State of systems in machine that introduced new form | Example of current form, size | Current state of systems |
|---|---|---|---|---|
| **Wheel loader** | **1947 Hough Model HA**, 1 cy (0.74 $m^3$) bucket; first loader with engine in rear | **Implement**: bucket, hydraulic actuation<br>**Traction**: four pneumatic tires<br>**Power train**: engine in rear, all-wheel drive<br>**Structure**: solid frame, rear wheel steer<br>**Control/information**: return-to-dig positioning | **Komatsu WA180-3 wheel loader**, 120 hp (90 kW); 2.1–2.9 cy (1.6–2.1 $m^3$) bucket: 20,780 lb (9,445 kg) operating weight ⟨www.komatsu america.com⟩ | **Implement**: bucket, hydraulic control<br>**Traction**: four pneumatic tires<br>**Power train**: 6-cylinder turbocharged diesel engine; 4-speed full power shift transmission; all-wheel drive; hydraulic, wet disc brakes<br>**Structure**: custom steel frame<br>**Control/information**: hydraulic, four positions for boom and three for bucket |
| **Hydraulic excavator** | **1954 Demag Model B-504,** 41 hp (30 kW), 10 t (9 metric t) weight, 0.6 cy (0.5 $m^3$) bucket; first fully hydraulic and full revolving | **Implement**: backhoe bucket, hydraulic operation<br>**Traction**: tracks<br>**Power train**: hydrostatic drive and controls<br>**Structure**: steel frame<br>**Control/information**: full hydraulic | **Volvo EC160B hydraulic excavator**, 109 hp (81 kW) engine; 0.72 cy (0.55 $m^3$) bucket; 39,930 lb (17,204 kg) operating weight ⟨www.volvoce.com⟩ | **Implement**: range of bucket sizes<br>**Traction**: tracks with 7 top and 7 bottom rollers, hydraulic adjusters<br>**Power train**: 6-cylinder diesel engine; two-speed travel motors<br>**Structure**: X-shaped frame<br>**Control/information**: hydraulic, priority for boom, arm, or swing |
| **Loader–backhoe** | **1957 Case Model 320;** first complete factory packaging of backhoe and loader | **Implement**: front loader bucket, rear backhoe; hydraulically operated<br>**Traction**: four pneumatic tires<br>**Power train**: 2 wheel drive<br>**Structure**: farm tractor derivative, lower to ground<br>**Control/information**: manual | **John Deere Model 310G**, 70 hp (52 kW), 15,540 lb (7,060 kg) operating weight ⟨www.deere.com⟩ | **Implement**: front loader with range of buckets, rear backhoe; hydraulic hammer, vibratory plate compactor, ripper; hydraulically operated<br>**Traction**: four pneumatic tires<br>**Power train**: 4.5 L, 4 cylinder diesel engine; power shuttle transmission with 4 speeds forward and reverse; all wheel drive, wet multiple-disc brakes<br>**Structure**: custom frame<br>**Control/information**: load-sensing hydraulic |

(17,200 kPa) on machines using gear pumps. Komatsu introduced its PC-5 line of excavators that included four working modes in 1988. Caterpillar's introduction of its Model 225 hydraulic excavator in 1972 affirmed the validity and worldwide importance of the machine form. The firm expanded the 200 series product line to include the Model 235 in the 40-t (36 metric t) class in 1973, the 245 in the 70-t (65 metric t) class in 1974, and the 19-t (17 metric t) 215 in 1975 (Haddock 2002).

The hydraulic excavator benefited tremendously from steady evolution in the delivered power and controllability of the hydraulic function. This resulted in nearly doubling of the applied power over the last 30 years, allowing installed engine power to remain relatively constant for a given machine weight and limiting the escalation of fuel consumption with capacity. The versatility of this form has also increased greatly through a wide range of attachments, along with ability to operate in confined spaces because of models with zero tail swing.

The Volvo EC 160B, an example of current excavators, uses approximately the same size bucket as the B504 (see Fig. 8). It also shares the same basic configuration of the boom and stick and the hydraulic actuations. Table 1 indicates that both machines

**Fig. 7.** 1954 Demag B504 excavator (Haddock 2002, used with permission)



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**Fig. 8.** 2004 Volvo EC160B hydraulic excavator (used with permission from Volvo)

use hydrostatic drive. The most significant evolution for this machine is information and control. These systems provide major improvements in reliability and controllability.

## Loader-Backhoe, 1957

The loader-backhoe shown in Figs. 9 and 10 uses separate buckets attached to its front and rear to dig and load material. The two buckets are the distinguishing feature. Contractors use these highly versatile machines for small foundation and utility work.

### *Market Conditions and Technology at Introduction*

The expansion of infrastructure construction in the United States continued through the late 1950s. A boom in housing construction created a demand for smaller and more flexible equipment for this work. The 1957 Case 320 loader–backhoe (Fig. 9) was the first example of this product that offered all implements fully factory assembled and warranted. Before this machine was available, purchasers mounted similar implements on farm tractor derivatives (Haycraft 2000).

### *Machine Development and Current Models*

Comparing Figs. 9 and 10 indicates a consistent form of these versatile machines. Several other models of loader–backhoes illustrate incremental improvements since introduction (Haddock 2002). The 1963 Case 580B included hydrostatic steering and an extendible dipperstick or boom. During the 1980s mechanical front wheel drive became a high demand option, first in Europe then spreading to North America, to extend the utility of the machine in poor weather conditions. Caterpillar offered the 416 as its first loader–backhoe in 1985. The firm extended this line to six models by 1989, signaling the market importance of this form worldwide. The 1991 JCB 214e featured the combined use of four-wheel drive and four-wheel steer.

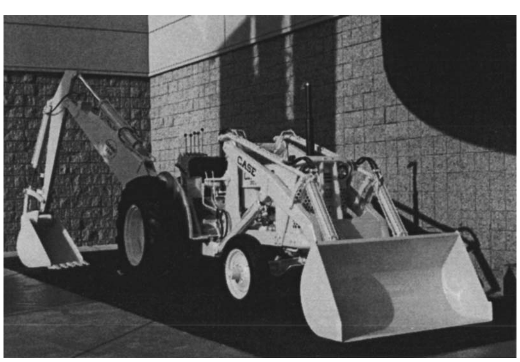


**Fig. 9.** 1957 Case 320 loader backhoe, (Haddock 2002, used with permission)


**Fig. 10.** 2004 Deere 310SG loader-backhoe (used with permission)

The loader-backhoe is probably the most entrepreneurial of the machine forms. As the market demand developed, local contractors and welding shops began to adapt agricultural loaders and tractors. The European market continued to prompt experimentation regarding this machine form, including use of higher pressure hydraulics to increase loader capacity combined with the transport and digging capability of a backhoe. Various combinations of articulation, hydrostatic transmissions, and four-wheel steer continue to appear in Europe but none has captured the universal market acceptance on the original form.

The Deere Model 310G loader–backhoe (Fig. 10) illustrates current designs for loader backhoes. Table 1 identifies differences in the types of implements available, all wheel drive, purpose built frame, and open center hydraulic system characterize a simple, flexible, rugged, and reliable utility machine.

## Analysis of Innovation in Machine Forms

The five examples if new machine forms for earthmoving equipment described above leads to the following findings regarding how they developed and evolved. This includes conditions in markets and advanced system technology, drivers and processes for evolution of the new forms, and vision of emerging new species.

### *Conditions in Markets and Advanced Systems Technology*

The introduction of the seven new forms of equipment corresponded to the major trends in construction markets identified by Haycraft (2000). Increased farm to market road building corresponded to the introduction of the track-type tractor and the motor grader in 1931. National highway, water resource, and mining projects required major earthmoving during the period of introducing the off-highway truck in 1936 and the wheel tractor scraper in 1938. Early signs of a transition to smaller and renovation projects with more challenging spatial constraints corresponded to the introduction of the wheel loader in 1947, and the



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loader backhoe in 1957. The scale of postwar reconstruction and the physical constraints of job location in Europe and Japan also provided strong incentives for the hydraulic excavator introduced in 1954 and subsequently accepted in the United States. The cost and limited availability of manual laborers in most economically developed countries has created markets for smaller models of loaders, excavators, and backhoes.

### Drivers and Processes for Evolution of New Machine Forms

Suppliers and users persistently pursued incremental improvements of the new machine forms. They sought to make the earthmoving equipment more productive, versatile, simple, and reliable. Many of the incremental improvements extended the usable "range" of operation for the equipment, either in poor ground or weather conditions or to peripheral jobs. These needed capabilities and functions prompted further evolution. The goal was to improve the economic viability of the new machine forms to provide the greatest flexibility of use and the lowest cost construction operations. This increased return on the investment in the equipment and extended its lifecycle.

One technical driver appears especially significant in the systematic evolution of the new machine forms: improved deployment and control of power. Many of the incremental improvements increased the amount of power available or the controllability of its deployment to move the machine or precisely position the implements. These improvements increased the capability of the machines to perform challenging construction operations under a much wider range of conditions. Analysis of equipment improvement also highlights the importance of integration within and between systems.

### Systematic Evolution of Form and Size

Small and young U.S. firms supplying earthmoving equipment appeared to focus on experimentation and spasmodic invention, such as the elevating scraper. Inventors in small firms produced the majority of the revolutionary innovations that became the new machine forms. For example, Best created the track-type tractor initially to solve the problem of agricultural draft tractors working in soils with low bearing pressures. LeTourneau envisioned the motor scraper along with the wheel bulldozer and loader and offered these new machine forms.

Larger firms subsequently used their engineering and marketing resources to develop and offer improved versions of the new types of equipment. Their entry into the new market segments effectively validated or legitimized the innovation of the new machine form. Once the form reached consensus, competition shifted to production cost and reliability, favoring the largest competitors. The increased reliability and performance of subsequent products offered by larger firms resulted primarily from evolutionary or incremental improvements. This product strategy characterizes financially managed businesses.

Table 1 summarizes many other highly significant advances in earthmoving equipment during evolution of the new machine forms. Implements changed significantly for two types of equipment (track-type tractor and wheel tractor–scraper) because of hydraulic operation. Advances in traction systems included sealed and lubricated tracks and major increases in tire size and durability. Articulated frames resulted in a significant advance in the machine structure for four of the current models of the equipment types (motor grader, wheel tractor–scraper, off-highway truck, and wheel loader). The power train for current models of these equipment types includes the key advancement of hydrostatic drive for the track-type tractor and the wheel loader. All-wheel drive and locking differentials also increased the capability of the backhoe-loader and established the utility of the off-highway truck. The current version of each equipment type includes significant advances in control (especially for hydraulic systems) and information systems. Perhaps even more significantly, these advances appear to be only the first steps in realizing the potential of these systems.

Increases in machine weight and horsepower are easily measured parameters of continued development to improve capability and performance. This development has taken interesting paths. Market demand for increased machine capability combined with increased availability of the technologies needed for each machine system resulted in consistent increases in machine size and power until the early 1990s. The mining industry continues to create a market for even larger and more powerful machines.

More recently several factors have increased the market for smaller machines. Limitations in truck and even rail transport began to greatly increase the cost of mobilization for very large equipment. The size and specialization of these machines also limited their flexibility and application to multiple types of projects. Firms also began to develop smaller equipment for demolition and redevelopment, building foundations and utility systems, infrastructure repair and replacement, and urban redevelopment. The lack of availability and high cost of manual labor has also driven a proliferation of "mini" equipment to replace the worker with a shovel.

Despite these divergent trends, a significant market remains for what we will call "anchor" machines, sizes that remain industry standards due to their relationship to certain work tasks that have remained relatively constant. Four-wheel drive loader buckets that fill trucks in three passes, excavators with weight and lift capacity to handle and place certain sewer and manhole pieces, and backhoes with particular digging depth capacity are all examples of "anchor" machines. Certain sizes have maintained significant volumes regardless of other trends noted above.

### Vision of Technologies Allowing New Equipment Forms

What new types of machine forms are likely to come next? Schexnayder and David (2002) envisioned the evolution of earthmoving machines into mobile counterweights serving as work platforms for an array of tools. Control and information systems are currently improving at the greatest rate and providing a basis for improvements in the other systems. Recent advances in onboard positioning reference (GPS and other) and off-board communications foreshadow tremendous potential for improvement by integrating the machine with the civil design for the project and with other machines to improve overall site operations.

Advances in hydraulic manipulators operating with multiple degrees of freedom and increasing capability for computer control will allow new forms of machines with radical new capabilities. Researchers are currently investigating further integration of these technologies and adaptation to the special demands of earthmoving equipment (Cho et al. 2004; LeBlond et al. 1998). The analysis of new equipment forms and the systems technologies that allowed these advancements in this paper suggests a trajectory of future advancement. Many of the new forms synthesized advanced technologies in new ways to provide special machine capabilities that met growing market needs. Major markets for



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massive infrastructure expansion in developing countries and infrastructure renovation in developed countries will prompt further advancement of earthmoving equipment. Facilitated by greatly enhanced capability for information processing and even reasoning about conditions and equipment performance, these machines will provide both the increased production and the more precise control demanded by these two types of infrastructure projects.

## Conclusions Regarding Innovation

Technological advancement of earthmoving equipment is consistent with many elements of the background regarding conditions and processes of innovation. Introduction of the new machine forms described in this paper illustrated significant elements of the combined forces of market pull and technology push previously identified by Rosenberg (1982) and others. The seven machines fall into three major phases of market emphasis: secondary road construction before World War II, major grading projects for interstate roads and water projects after World War II, and smaller projects in more constrained environments since the early 1950s. The overall market expanded and contracted with economic conditions and contained both traditional elements and new segments. Despite these dynamics, two of the new machine forms each fell into the three market periods mentioned above. The seventh new type, the wheel loader introduced in 1947, spanned the last two market phases and developed in both large and small sizes to contribute to both.

Each of the seven new forms of earthmoving equipment was a revolutionary innovation. As detailed in Table 1, these occurred either through a new synthesis of available technologies, such as implements or hydraulic drives, or a new technology for a system, such as diesel engines or heavy-duty pneumatic tires. Following the background from other industries (Foster 1986), these new machines often did not initially satisfy performance requirements but experienced significant incremental improvement.

Remarkably, each of the seven new types of equipment was also a dominant product design (Abernathy and Utterback 1978) that is still used today. The basic form of the machines, as indicated by the elements and configuration of each of the systems, continues to characterize the state-of-the art. However, each type of equipment has shown significant incremental improvement since introduction. Each of the machine systems increased in capability and operational flexibility. For each new machine form, one or more incremental improvements have extended both the range and the lifecycle. These examples of technological evolution allowed the functions of each form to adapt to changes in the work scope and environment, to improve performance, and to remain economically viable.

## Relevance for Practice, Education, and Research

Contractors can use the background of equipment advancement described in this paper to help identify beneficial capabilities of new equipment to meet new types of project requirements and prompt further new forms and improvements. The analysis approach described in this paper can help anticipate the trajectory of increased equipment capability and performance. Considering both revolutionary and incremental improvements can prompt foster increased planning and development of additional options for increased performance in meeting new types of requirements. Sustainable construction operations are one example. Designers can add greater value to earthwork projects by considering changing and potential new equipment capability in their designs for earthwork and building substructures. Advanced modeling tools will allow detailed consideration of site conditions, special project requirements, and advanced equipment capability in developing alternatives for construction methods and operations as part of an integrated design process.

Educators can use this background regarding new forms of earthmoving equipment to structure course materials and increase students' understanding of equipment capabilities and improvement. Understanding this background of revolutionary advances and incremental improvements will assist in grasping the capability and limitations of current equipment. These examples of innovation will also spur ingenuity in developing new methods and selecting resources for specific projects. Construction researchers can use the process of improvement described in this paper to continue developing earthmoving equipment as an example of conditions and processes for innovation in design and construction. They can also experiment with new forms and technologies for systems that follow a likely trajectory for future equipment advancement while developing new tools to model earthmoving equipment as part of a total construction system that improves performance of site operations.

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