RAILROAD TRANSPORTATION

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Summary

The introduction of railways revolutionized transportation and changed the economic geography of the world. Higher speeds, greater comfort, and lower costs allowed the railroads to dominate transportation for more than a century. However, the railways lost much of their allure with the introduction of automobiles, trucks, and air transportation. The inevitable shrinkage of rail markets left many rail networks in poor condition, both financially and physically, necessitating government ownership in most countries. Public support of railroads has been justified for various reasons, including support of local industry, promotion of energy conservation, and as an alternative to congested highway-based systems.

This article provides an overview of the engineering, operating, and competitive issues facing railroads. Understanding both the potential for and the limits of rail service is necessary in considering the role for rail in achieving mobility and sustainability goals.

Although rail is no longer dominant, there are clearly markets where rail can still be very successful. High-speed passenger services can, for some corridors, compete effectively with both airlines and autos, while modern, heavy-haul freight services are well suited for long distance, high volume shipments. Intermodal services are attractive both for freight and for passenger services, especially if there are efficient terminals for transferring between rail and other modes of transportation.

1. Introduction

Railroads transformed the world in the nineteenth century and supported the industrial expansion of the early twentieth century, then declined in the face of airline and highway competition. To survive, railroads were forced to rationalize their systems, develop more efficient operations, and introduce new services. At the turn of the twenty-first century, railroads remain dominant for bulk transportation, provide the backbone of rapidly growing intermodal freight services, and compete successfully with airlines in medium distance markets. Highway congestion, limited airport capacity, and environmental concerns guarantee a continued role for rail systems in the twenty-first century.

The introduction of railways reduced transportation costs and travel times by an order of magnitude, changing the economic geography of the world forever. Railways integrated continents, escaping geographic constraints dictated so long by the location of ports and inland waterways. Cheaper transportation meant remote sources for raw materials and broader markets for products, enabling economies of scale by consolidating production. Railways favored the development of cities that were larger or better located in relation to railroad development and diminished the fortunes of those that were bypassed. In North America, railways enabled rapid development of the Midwest and West. Chicago became the "Metropolis of the American West" and the largest rail hub in North America, quickly surpassing St. Louis and the other cities along the Mississippi River. In South America and Africa, railways opened up the interiors of the countries, often enabling the export of coal, ore, or agricultural products. In China and India, railroads provided the transportation links necessary to connect large national economies.

Railroads required vast amounts of capital. The possibilities and opportunities were evident to investors, despite a suspicion that profits were in construction rather than in operation of lines. While many companies failed in the recessions and panics of the nineteenth century, the best of the survivors were highly profitable. Railroads became the first industrial superpowers, inventing management structures as they expanded, establishing vast communication networks, and using military discipline to control operations over thousands of route-miles.

Railway expansion continued worldwide into the twentieth century. The expansion of the railways was finally slowed or stopped by international turbulence and violence. The railways, like the countries they served, suffered from the devastations of two world wars, the resulting shrinkage of world trade, and the financial and social disruptions of the Great Depression. By the end of World War II, railways were at best worn out and at worst destroyed. Massive investment was needed to revitalize the systems; where such investment was unavailable, the systems were destined to a slow, but certain decline.

The turmoil of war and depression masked the emergence of new modes of transportation. Military logistics dominated freight transport, and military needs suppressed the growth of highway transportation. With peace came the realization that railways were too slow and unreliable to withstand the appeal of automobiles, the speed of airplanes, and the flexibility of trucks. The strategic question was how best to respond: whether to hang on to the old systems, try new approaches, or simply abandon the field. The struggle was difficult for railroads, their customers, and towns that were dependent upon rail. The loss of markets, price competition, and decaying infrastructure frequently led to bankruptcy.

By the end of the twentieth century, railway networks were no longer ubiquitous. Where road networks developed, automobiles and trucks carried most of the regional passengers and tonnage. For longer trips, trucks captured some of the high value freight and airlines most of the passengers. In most countries, the loss of traffic resulted in railroad bankruptcies, line abandonment, and government ownership. In North America and Australia, where distance favors rail, the railroads survived, but primarily for freight; more tonnage was handled, but route-miles and market share declined. In India and China, which still lacked modern highway networks and where air transportation was expensive, railroads remained dominant and rail capacity was a major concern. In Europe, the major concern was for passenger service, although there were hopes for freight. In Europe and in Japan, high-speed passenger services connected major cities, offering medium distance service superior to airlines.

Despite competition from other modes and the financial collapse of so many railroad companies over the second half of the twentieth century, rail remains the mode of choice for several important markets: bulk commodities like coal, ores, sand and gravel, and grain; long-distance movements of containerizable freight; and medium distance, high-density passenger services. Since railroads are generally more energy efficient than highway or air transportation, expanded use of rail will reduce both energy consumption and emissions of greenhouse gases. As railroads are flexible in their energy choice, especially for electrified lines, they are not as oil-dependent as other transport modes. Railroads also require less land than highways for rights-of-way, which is important in urban and also in environmentally sensitive regions. In undeveloped areas, for instance interior regions of South America or Africa, railroads are less intrusive than roads because access can be controlled, whereas new roads generally entice new settlement. Thus, railways are generally viewed as a key element for sustainable freight and passenger mobility in the twenty-first century.

2. Railroad Technology

The basic elements of the railway system are the track structure, locomotives, rolling stock, terminals, and the control system. The essence of the railway system is the “steel wheel on the steel rail,” implying both low rolling resistance and guided transport. With a durable, level surface, it is possible to pull a car or, better, a “train of cars” (which is how the concept of a train was originally phrased) with a minimum expenditure of energy, thereby maximizing the load pulled for a given source of power.

2.1. Route and Track Structure

Route choice is important for engineering and marketing reasons. Engineers balance the costs related to distance, curvature, grades, tunnels, and bridges. Marketing concerns include the ability to serve current and potential markets, as well as location relative to competing lines and modes.

Route selection is dominated by the need for a nearly level route. If grades are too steep, tremendous energy will be expended, and the benefits of low rolling resistance will be lost. Railroads can operate with grades of 4% (a rise of 4 feet in a distance of 100 feet, or 40 m over 1 km), but only with difficulty; normally, the maximum grade is 1–2%. Railroad routes therefore tend to follow the natural features of the landscape, using cut and fill, tunnels, and bridges as necessary to maintain a nearly level route. Operating savings over the life of these circuitous routes justifies the added construction expense.

Train size and speed are limited by engineering factors related to safety and cost. The main consideration is that the train stays on the track, despite dynamic interaction between the train and the track. Rail and wheels are designed to minimize energy dissipation at the wheel/rail interface and to provide strength to resist the forces of the operating environment. For any curve, lateral forces are a function of wheel and rail profiles, car weight, center of gravity, and train speed. Since the running surface of a wheel is conical, the rolling radius increases as lateral forces shift cars toward the outside of the curve. This difference in rolling radius allows cars to navigate modest curves without initiating flange contact. For sharper curves, the flange comes into contact with the rail; at a sufficiently high speed, the lateral forces will cause the wheel to climb up and over the top of the rail, causing a derailment. This destructive possibility limits train speeds and curvature.

To allow higher speeds, the outside rail can be superelevated, which allows gravity to offset some of the lateral forces. The maximum superelevation is determined by the requirement that equipment with the highest center of gravity must be able to stop safely on the curve, meaning that the gravitational force acting on the center of gravity of the car must fall between the rails. Superelevation is problematic in locations where several kinds of trains operate at different speeds, such as curves located close to passing sidings. Passenger trains may run along such curves at high speeds, whereas low-priority freight trains will frequently be stopping at the siding. If superelevation is maximized for passenger trains, then freight trains will tend to crush the low rail. If superelevation is designed to accommodate the low speed freight trains, then the passenger trains may have to slow down to negotiate the curves.

Variations in track geometry and stiffness will stimulate dynamic activity and increase the probability of a derailment unless speed is reduced. Issues of track/train dynamics therefore underlie railway or regulatory standards for track geometry and track strength. Track geometry standards define limits for such measures as variation in track gauge (distance between the rails), crosslevel (relative height of rails), and vertical or horizontal alignment (variation between the center of the track and the design location). Track stiffness is a measure of the deflection of the track structure under load. As a train moves along the track, there will be a slight deflection of the rail under each wheel; the greater the deflection, the greater the interaction between the equipment and the track structure and the more rapid the deterioration of the track geometry and the track components. To minimize the risk of derailment, train speeds must be reduced where there are significant variations in track geometry or where the track structure is weak. Or, from a track standards perspective, the track geometry needs to be better and the track structure stronger to support higher speed operation.

Economic considerations may further limit train speeds and track quality. For low-density lines, minimizing maintenance cost is much more critical than train speed. For major freight lines, speeds of 40–70 miles hr^{-1} (64–112 km hr^{-1}) are almost always deemed sufficient, and lower speeds are often acceptable. Higher speeds are desirable for intercity passenger operations, requiring better track geometry for passenger than for freight operations.

Engineering departments ensure that track geometry and strength are adequate by selecting, installing, inspecting, maintaining, and eventually replacing track components. A basic challenge is that the “steel wheel on the steel rail” concentrates loads in a contact patch that is smaller than 1.5 cm^2, creating pressures greater than 50 000 Mg/m^2. The track structure must spread these loads over a wide enough area that they will not deform the natural subgrade, which commonly supports only 10–20 lb/sq.in. While many different approaches have been tried, the typical track structure has rail installed on steel tie plates that are attached to wooden or concrete ties (sleepers) that are embedded in ballast that may be sitting on a layer of sub-ballast that is sitting on the natural sub-grade. The larger the cross-section of the rail head, the better it is able to withstand the extreme stress; the larger the tie plates and the better the fastening system, the lower the pressure on the ties; the larger and more closely spaced the ties, the lower the pressure transmitted to the ballast; and the deeper the ballast and sub-ballast, the lower the pressure transmitted to the subgrade. The choice of components determines how the pressure is distributed and the maximum loads that can be safely transported over the route.

Economic limits will be tighter than safety limits for axle loads in mainline operations, because heavier loads increase deterioration rates of some track components. Although operating expenses generally decline for heavier loads, these savings may be offset by higher expenditures for inspection, maintenance, and replacement of track components. Higher quality materials can be used to reduce deterioration, and research has helped the industry introduce more durable steel, premium fastenings, concrete ties, premium turnouts, and other improvements in track components. For example, concrete ties are more costly than wood ties, but they are frequently used in passenger routes and on curves in high tonnage freight routes because they are more durable, hold gauge better, and provide stiffer support.

Route and track characteristics also determine the size of equipment that can be carried. Clearances limit the width, height, and shape of equipment. Sharp curves limit the length of vehicles, as very long vehicles may derail. Bridge characteristics limit the maximum loading density, in other words the gross weight of a car divided by the length of a car. Clearances, maximum axle loads, and maximum loading density are therefore key design parameters for rail equipment.

2.2. Locomotives

Locomotives provide or apply the power required to move the trains. The basic engineering concerns are maximum power, tractive effort, adhesion, and sustainable operation on grades at low speeds. Energy is needed to overcome rolling, curve, and wind resistance; to climb grades; and to operate lighting, air conditioning, and other external loads. For high-speed operations, maximum power requirements are critical, as it is the power that allows operation at high speeds up the ruling grades. Power is generally not critical for freight trains, which simply slow down when going up grades. For heavy freight, the main concern is that the tractive effort is sufficient to start a heavy train up a grade. Tractive effort is the product of the mass of the locomotive and the coefficient of friction at the wheel/rail interface (adhesion). Tractive effort therefore represents the force that can be applied to overcome initial rolling resistance and gravity. Heavy, six-axle locomotives with high adhesion are preferred for heavy freight trains.

The typical freight locomotive has a diesel engine that produces electricity to drive traction motors that are mounted on and actually turn the axles. The ability of the traction motors to sustain maximum loads without overheating provides a lower limit on the speed of operation up grades, which thereby provides an equivalent limit for the minimum power requirements for the locomotive. Diesel-electric units can be coupled together and operated by a single crew, and heavy trains may be pulled by three, four, or more units.

Steam locomotives have largely been replaced, because of major disadvantages relative to diesel-electric locomotives. First, they required a separate crew for each unit. Second, they operated with a driving action that imparted extreme forces to the track structure, resulting in faster track deterioration and a need for stronger bridges. Third, they belched vast quantities of smoke and soot compared to diesel-electric locomotives. Steam locomotives are highly romantic in dreams, but an environmental nightmare in reality.

Electrified railways are common, especially for passenger systems. In an electrified railway, the power is produced off-line and delivered to the locomotive through the overhead catenary. With this system, the maximum power is no longer limited to what the locomotive itself can produce, so that peak power can be provided to operate up grades at high speed. Because of the high cost of the catenary, electrified operations are generally found to be too expensive for freight operations.

2.3. Freight Equipment and Commodities

A freight car (wagon) is a platform or box designed to carry certain commodities and equipped with couplers to allow assembly into a train. The classic boxcar is just that: a box with one or two doors mounted over two trucks (bogeys). A covered hopper car, which is loaded through hatches at the top and unloaded through hoppers at the bottom, is commonly used for grain, fertilizer, plastic pellets, or other bulk commodities that need to be protected during the trip. An open hopper, commonly used for coal, has no top, so it can be loaded more easily. Gondola cars are open, without hoppers, and must be unloaded from the top. For coal, gondola cars are equipped with rotary couplers so that the whole car can be grasped, twisted, and unloaded by a rotary dumper at a port or power plant.

For these cars, key design issues relate to tare weight, dimensions, payload, and loading density. Since cost per unit capacity declines as cars get larger, there is an incentive to make larger cars with lighter tare weights, subject to the size and weight limits defined by the operating environment. In North America, the standard coal car in the 1960s had a carrying capacity of 70 tons and a tare weight of 30 tons; the standard in the 1980s was a similar, but larger steel car with a carrying capacity of 100 tons and a tare weight of 31.5 tons; in 2000, the standard is an aluminum car with a carrying capacity of nearly 120 tons and a tare weight of 22 tons. Thus the ratio of net load to tare weight has increased from 2.5 to more than 5 over a 30-year period for heavy haul operations.

Other cars are designed for efficient loading and unloading for special commodities. Flatcars can be used to transport loads that are too big or too heavy to fit easily into one of the other kinds of cars. Heavy duty flats with three-axle trucks can carry very heavy loads. Auto racks can be attached to a basic flat car to create a multilevel car that provides one or two additional levels for carrying automobiles. After a number of multilevels are placed at an assembly plant for loading, a ramp is moved to the front of the first car and raised to the proper height to reach the first, second, or third level of the auto rack. Steel panels bridge the gap between the rail cars, so that automobiles can be driven from the first rail car through to the following cars, allowing rapid loading and loading. Auto racks today are generally closed to prevent damage from weather or falling or thrown debris.

A variety of innovative equipment types have been developed to facilitate intermodal transportation: the movement of trailers or containers using a combination of rail, highway, and waterway operations. At first, standard flat cars were used to carry trailers or containers and portable steel panels could be used to bridge the gap between cars so that trailers (or containers on chassis) could be loaded by backing them up a ramp and along several flatcars. A standard 89-foot (27.1 m) flat car could handle two trailers (40 or 45 feet long; 12.2 or 13.7 m) or four 20-foot (6.1 m) containers. This process required a very heavy flat car to act as a bridge handling the full weight of a trailer.

If trailers or containers are loaded and unloaded using cranes, then lighter designs are feasible. The flat car can become a "spine car" that only has a small landing area for the wheels of a trailer or the corners of a container. To save more weight, multiple cars can be permanently coupled, creating an articulated set of platforms with just one truck under each articulated joint. Containers handled with cranes do not have to be on a chassis, so the vertical clearance required is less than what is needed for a trailer. In fact, if clearances permit, it is possible to stack containers two high on flat cars. The double stack car has a well for the first container (or two 20-foot, 6.1-m, containers). The second container is held in place, in one design, by bulkheads at the end of the flat cars. In another design, the second container is attached using interbox connectors at the corner posts (the corners of intermodal containers have steel columns to make them strong enough to be stacked in terminals or on container ships; the interbox connectors lock into the hollow columns and hold the containers in place).

The need for expensive lift equipment to load and unload trains tends to limit intermodal operations to high-density corridors. Other types of equipment allow efficient intermodal operations with cheaper terminal operations. One approach is a modern version of the original flatcar that, in North America, is called the “Iron Highway.” This equipment is a long, articulated platform designed to handle a dozen or more trucks or containers; the ends of each unit drop down to serve as ramps, allowing truck drivers to load the train in the old-fashioned way. Since the platform is continuous, it is possible to handle any length container or trailer or truck-trailer combination. This type of equipment is used in Europe to shuttle trucks through tunnels in the Alps rather than allowing them to drive over the congested, environmentally sensitive passes. In North America, this equipment has been tested but is not in widespread use.

Another low-cost approach is the “roadrailer.” The original concept was to add a rail axle to a highway trailer, so that the same trailer could move as part of a train or on the highway. To operate on the railway, the highway axles would be raised and the rail axle would be lowered (using a hydraulic or pneumatic system); trailers could be coupled to one another with a slackless coupling system that provided a very smooth ride. There were two problems with this system: the trailer was expensive and the weight of the axle limited the loads that could be carried on highways. The solution was to create a special rail car that consisted merely of a truck (bogey) with a small shelf designed to support the roadrailer trailer and facilitate connections for the train’s electrical and braking systems. A train could be assembled by first using a small forklift to position the bogeys along a track at appropriate intervals; drivers could then position each roadrailer for coupling and raise the wheels. This system provides the low cost of a double stack system by reducing the cost of the rail equipment, improving fuel efficiency, and eliminating the need for complex terminals. This system is used in North America on routes that do not justify double stack; it is operated as a separate intermodal system, imitating a service-conscious trucking operation.

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Bibliography

Ambrose S.E. (2000). *Nothing Like it in the World—the Men Who Built the Transcontinental Railroad 1863–1869*, 431 pp. New York: Simon and Schuster. [This book is an interesting account of the financial, political, and engineering efforts required to build a railroad across vast distances in the nineteenth century.]

American Railway Engineering and Maintenance-of-Way Association. *Manual of Railway Engineering*. Washington, DC: American Railway Engineering and Maintenance-of-Way Association. [This set of volumes are the basic North American reference for engineering standards for railway track and structures, and are updated annually.]

Car and Locomotive Cyclopedia of American Practice. New York: Simmons-Boardman Publication Corp. [This series of books are excellent references for details on rail equipment.]

Chandler A.D. Jr. (1962). *Strategy and Structure: Chapters in the History of the American Industrial Enterprise*, 457 pp. Cambridge, Massachusetts: MIT Press. [This book highlights the role played by railroads in inventing the communications and organizational tools required for modern corporations.]

Cronon W. (1991). *Nature's Metropolis: Chicago and the Great West*, 530 pp. New York and London: W.W. Norton and Co. [This thorough history examines the way in which rail transportation changed the size, location, and functions of cities in the American west.]

Hay W.W. (1982). *Railroad Engineering*, second edition, 758 pp. New York: John Wiley and Sons. [Although technologically outdated, this text still provides an eminently readable summary of railroad engineering issues and concepts.]

Jane's Intermodal Transportation. Coulsdon, Surrey, UK: Jane's Information Group. [This book is an excellent reference for basic information on equipment and routes.]

Locklin D.P. (1966). *Economics of Transportation*, sixth edition, 882 pp. Homewood, Illinois: Richard D. Irwin, Inc. [This is the classic text for understanding the economics and the history of railroad regulation.]

Muller G. (1995). *Intermodal Freight Transportation*, third edition, 287 pp. Lansdowne, Virginia: Eno Transportation Foundation and Intermodal Association of North America. [This book is a useful introduction to all aspects of intermodal freight transportation in North America.]

Vance J.E. Jr. (1986). *Capturing the Horizon: The Historical Geography of Transportation since the Sixteenth Century*, 660 pp. Baltimore and London: The Johns Hopkins University Press. [This is a very thorough study of the development of transportation systems over the past 400 years, with examples primarily from Europe and the US. The main theme is that improving transport capabilities were harnessed to overcome geographical barriers, thereby changing the economic geography of the world.]

Biographical Sketch

Carl D. Martland graduated from MIT with a BS in Mathematics in 1968 and an MS in Civil Engineering and the Civil Engineer degree in 1972. He has been on the research staff at MIT since 1972, and served as the program manager of the Association of American Railroad's Affiliated Research Laboratory at MIT from 1983 to 2001. His 30 years of experience at MIT have included research on railroad reliability, applications of new technology to railroad operations, rail freight terminal productivity, track maintenance planning and costing, strategic planning for intermodal freight transportation systems, and metropolitan transportation planning. Mr. Martland teaches Project Evaluation and Transportation Demand and Economics. He has consulted with all of the major North American Railroads and with many public agencies concerning railroad operations and economics and, more broadly, freight systems. Mr. Martland has published more than 120 papers and research reports, including many award-winning papers. Mr. Martland served as president of the Transportation Research Forum in 1986 and chair of the Rail Applications Special Interest Group of INFORMS in 1998. In 1997, the Transportation Research Forum selected Mr. Martland as the recipient of the Distinguished Transportation Researcher Award, recognizing his lifetime achievements in rail freight systems research.