TRANSPORTATION IN THE TWENTY-FIRST CENTURY: TECHNOLOGICAL INNOVATION

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Contents

Summary

Change in transportation systems arises not only from technical change in vehicles and physical infrastructure, but also via the evolution of nonmaterial infrastructure and information capital. This paper reviews literature on the innovation process and applies it to the case of transportation. Particular emphasis is placed on the evolving role of transportation in the knowledge economy. An historical perspective is taken on the evolution of the systems since 1950 as a prologue to considering how likely trends in the economy and in transportation technology will transform the systems between the present and 2025. From both a technological and an institutional perspective, many of the innovations that are to occur in the near future will address problems that have arisen because of the proliferation of transportation activities, including congestion and pollution. Given the limited scope for the expansion of conventional infrastructure, the application of information technology to transportation infrastructure will be needed to increase capacity without expanding the physical dimensions of the system. Commercialization of household personal transportation is presented as a likely novel arena for innovation in transportation service provision.

1. Introduction and Overview

The history of transportation is one of an ever-rising volume of travel, of greater speed and reliability, of increasing comfort and safety, together with sharply decreasing travel costs. The long-standing trend of declining costs is illustrated by Figures 1 and 2, which provide evidence of falling freight rates over multiple decades in the nineteenth and twentieth centuries. Progress toward ever-greater speed of travel is illustrated by Figure 3, which shows how successive technological advances have created an envelope of exponentially increasing speed through time.

The explanation for this historical progress lies in technological change, whose function in transportation—as in other economic sectors—is to expand the arena of practical human possibility. The traditional view ties transportation progress to innovations or novel physical objects embodied in the two most visible components of the transportation system—vehicles and physical infrastructure. Indeed, the pace of technological advances in these two areas has quickened in recent times, as successive waves of innovations—the steamship, the locomotive, the electric streetcar or trolley-bus, the internal combustion engine, the jet aircraft, containers, the "megaship," and so on—improved the quality and sharply lowered the costs of transportation. There have been parallel advances in the physical infrastructure—tunnels, suspension bridges, railroads over all kinds of terrain, the US interstate highway system, modern airports, and new marine terminals.

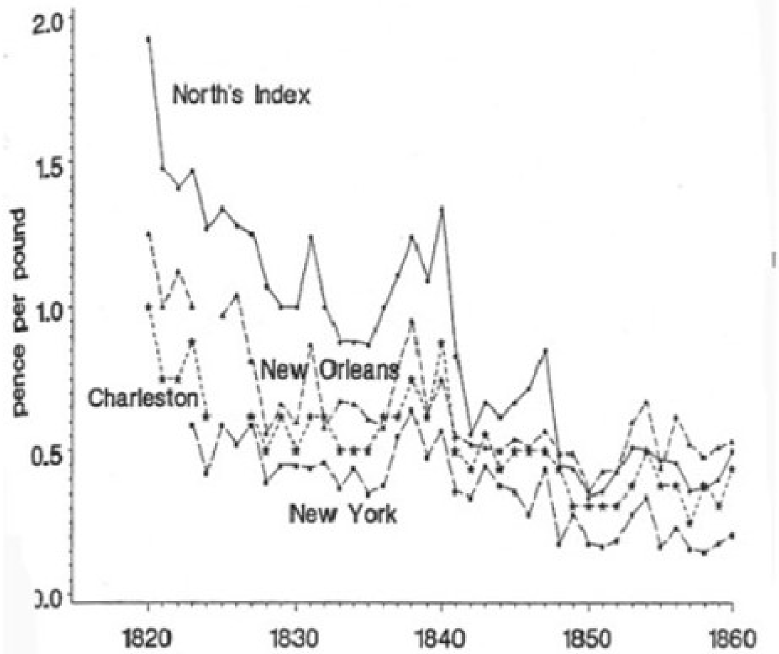

Figure 1. Cotton freight rates and North's *Index*, 1820–1860. Source: Knick Harley C. (1988). Ocean freight rates and productivity, 1740–1913: the primacy of mechanical invention reaffirmed. *Journal of Economic History* **48**, 851–876.

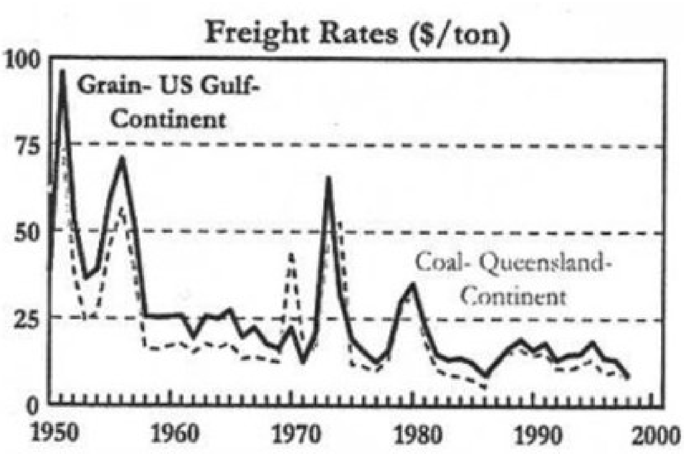

Figure 2. Freight rates, 1950–2000. Source: Special feature: Commodities in the 20th century. *Global Commodity Markets*, January 2000.

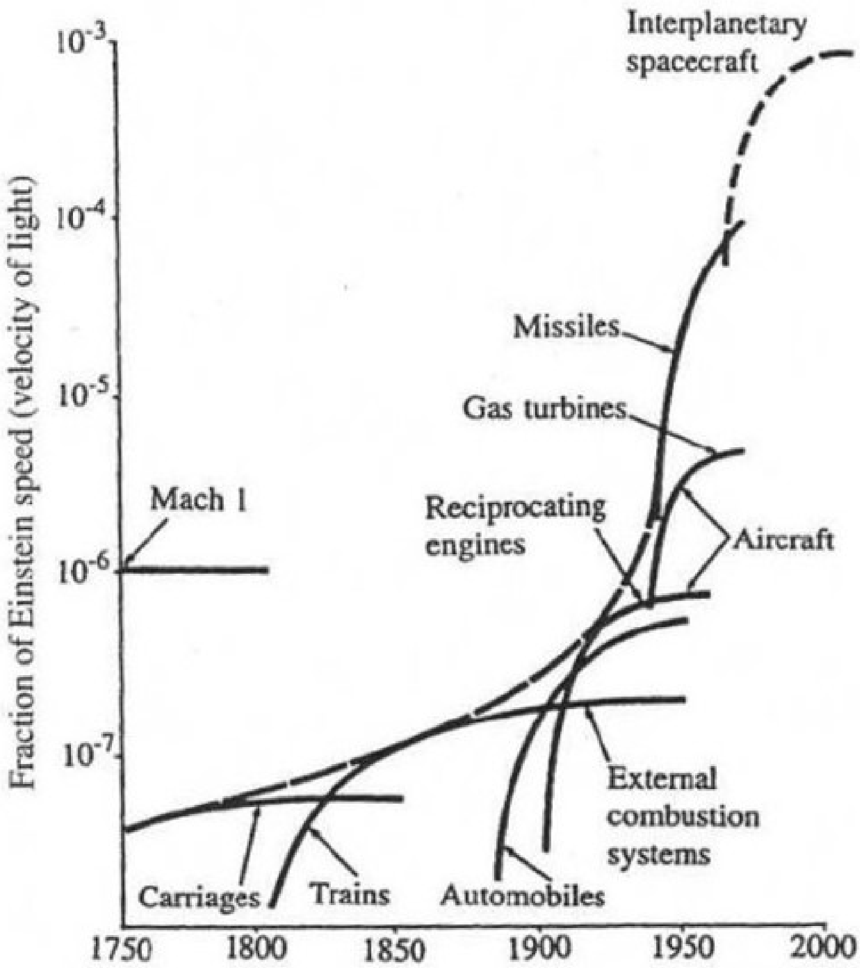

Figure 3. Speed trend curves for powered vehicles. Source: Suarez-Villa L. (2000). *Invention and the Rise of Technocapitalism*. Lanham: Rowman and Littlefield.

The traditional attribution of technical change in vehicles and physical infrastructure as the sources of the secular transportation improvements is only part of the story. What has not been generally recognized about transportation progress is the role played by two other components—the nonmaterial infrastructure of the transport system, and the complementary information capital and infrastructure of the transportation system. Far less visible than its physical counterpart, nonmaterial infrastructure—comprising economic institutions, regulations, policies, logistical systems, the knowledge base for transport governance, and so on—facilitates the efficient, coordinated use of vehicles and physical infrastructure. Then there is the role of the final component, namely the information technologies (IT) in increasing the capacity and functionality of transport operations, transport equipment, and transport infrastructure. IT, comprising a broad range of devices, functions, and supporting tools used in sensing, generating, processing, transmitting, and communicating information, offers vital information to transport operators and travelers, enhancing their responsiveness and efficiency, and making possible other transport innovations. Such knowledge-providing and enabling functions of IT in transport services have historical antecedents in the sextant and chronometer, which enabled more precise global navigation in the eighteenth century; in the telegraph, which promoted transcontinental rail operations in the nineteenth century; and in the radio and radar, which were so critical to navigation in the twentieth century. The current efflorescence of new information technologies at the cusp of the twenty-first century is massively transforming transportation industries and the scope of their services.

Thus the quantity, variety, and quality of transportation services at a point of time are jointly determined by the technologies embodied in the four system components—vehicles, physical infrastructure, nonmaterial infrastructure, and information infrastructure—and the interactions among them (see Figure 4).

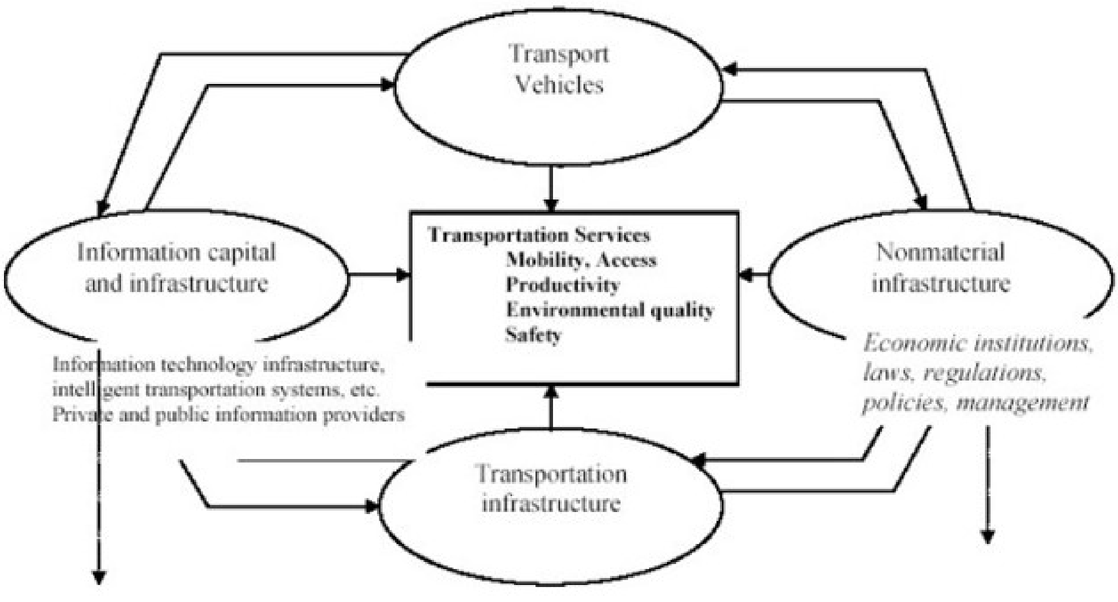

Figure 4. Components of a transportation system

Transport, as with any other form of technology, comprises not only physical artifacts but also the public knowledge that underlies the artifacts, and the way they are used in a society. An institutional innovation that offers strong incentives for transport actors to engage in productivity-enhancing activities, or a new transport management and governance system, is therefore just as much a technological innovation as any novel vehicle.

Indeed, the success of an innovation process, by which transport technology is conceived, developed, and deployed on a large scale, depends on social-supporting systems, which evolve with the introduction, elaboration, and diffusion of any technology. As elaborated in the body of this article, the advent of specific transport-related technological opportunities in society creates interests that affect the behavior and evolution of the social-supporting mechanisms, which in turn powerfully affect the transport technology options that are selected in the economy for further development and diffusion. Over time, the evolution of transport system technologies is a consequence of several factors: the internal logic of the technologies, the evolution of other transport system component technologies, the evolving logic of the social-supporting systems that undergird the transport system, and all this evolution occurs in the context of the broader demographic, economic, technological, and societal forces that govern the demand for transport services.

The last quarter of the twentieth century has witnessed vast changes in transport technologies as conceived here—introducing novel physical technologies, generating new markets, developing innovative organizational structures, reinventing old services, and introducing novel transport services—all the while precipitously dropping costs of passenger and freight movement, and increasing efficiency, speed, and reliability of transport services. Such transport developments have been among the major drivers of the globalization of economic activity, which represents a high degree of functional integration between globally dispersed economic activities. In turn, globalization, which is emerging as the norm in an increasing set of economic activities, generates new opportunities for transport innovations in the context of the ongoing restructuring and spatial reorganization of worldwide production, distribution, trade, and consumption. In this context, the transport operators have begun to offer intermodal, seamless transport services and a variety of new supply chain services in and between countries that strengthen exporters' competitiveness in the global economy in a virtuous cycle of growth and development.

This article surveys and interprets these transport sector developments at the cusp of the twenty-first century, in the context of powerful forces of social, economic, technological, and institutional change, which shaped the scope and content of transportation activities in the latter half of the twentieth century—first in the United States and other affluent, industrialized economies, and then in the industrializing, low-income economies. Since these "drivers" of transportation have observable effects in both affluent and low-income countries, and these forces of change show no sign of slackening, this chapter visualizes transportation in the first quarter of the twenty-first century in terms of reasonable implications of what has taken place already.

Section 2 of the article reviews the key change process of transport innovation, delineating it as a sociotechnical rather than as a technical process. As the transport (physical) innovations are reproduced, transferred, and diffused widely in society, institutional, managerial, and policy innovations in the transport sector appear, so that a transport innovation consists of the creation of a sociotechnical transport system, which in turn serves as a source of economic growth and development.

Section 3, in the spirit of "past as prologue," scans the cumulative transportation changes over the second half of the twentieth century in the context of major technological, economic, demographic, and institutional factors. The aim is to begin to comprehend the nature of the factors that underlie the discontinuities and transformations that have occurred in that period in transportation and society—thereby gaining some idea of the directions ahead.

Section 4 attempts to visualize transportation in the first quarter of the twenty-first century in terms of reasonable extensions of powerful trends observed today. Since transportation represents a derived demand, this section begins with the year 2025, when the transition to the information age is advanced, with fast-evolving knowledge work and workers, organizational innovations, and highly "transparent" governance systems. It proceeds to a discussion of how all the above changes in knowledge society influence the evolution of technologies and the institutions governing transport, and thereby the nature and quality of transportation services in major parts of the world. The remarkable aspect of transportation 2025 may not be its size or technical sophistication; indeed, it may be the novel forms that transportation services acquire. An example of a novel form of provision of household travel concludes the discussion.

2. Transport Innovation Process

No thing is created suddenly, any more than a bunch of grapes or a fig. If you tell me that you desire a fig, I answer that there must be time. Let it first blossom, then bear fruit, then ripen.

Epictetus, first century AD

Transport innovation is the process where intelligence and effort are applied to conceive, develop, and implement an artifact, such as a novel transport vehicle or infrastructure, on a large scale in society. Innovation is different from research and development (R&D) or invention, though the latter two are key components of the innovation process. The innovation process covers a variety of inventive efforts, stretching from initial conceptualization to establishment of technical feasibility (invention), to commercial feasibility, and finally to subsequent wide diffusion of the transport artifact in the larger society.

Theoretical inquiry into the innovation process takes two major approaches. First, technical change may be viewed as a rational choice of the best innovation among a set of feasible changes. A second approach is to view technical change as a process of trial and error, as the accumulation of small, individually minor, improvements of the production or the transport enterprise. Marxist and neoclassical theories of technical change at the level of the firm adopt the rational actor approach, although they impute different goals to the innovator—profit maximization in neoclassical theory, and innovation as power in the class struggle according to Marxists. Schumpteter is perhaps the single most influential writer in this grand tradition of explaining technical change and its consequences. Rather than using the straitjacket of profit maximization, he focused on creativity and disequilibrium, and the dynamic character of capitalism. All these theories focus on the earlier part of the technical change process—from the conceptualization of the idea to the invention, and then to the initial innovation.

On the other hand, the second approach to the analysis of technical innovation is the cumulative change process, which is evident in the work of economic historians and "evolutionary" theories of technical change. This approach conceptualizes the technology-diffusion process historically, and focuses on the factors that affect the pattern and spread of diffusion of innovation into the larger economy. What circumstances promote successful accumulation of knowledge? What conditions promote rapid diffusion? The relevant literature on technology diffusion and technology trajectories has implications for the way we have conceptualized in this article the role of transport-innovation process in shaping transportation in the twenty-first century.

The earlier literature on technical change emphasized the role of demand-side considerations on the rate and directions of technological advances Schmookler, Rosenberg and others, while conceding the power of demand forces, have pointed out the importance of supply-side considerations as well. Even big technological breakthrough inventions have much more gently declining slopes of cost reduction than is indicated in many studies, and thus longer gestation periods for innovations to be generally adopted.

If a technology innovation is to be diffused widely, several contributory factors must operate. First, there is a period of critical "secondary inventions" and design modifications that improve the quality and efficiency, and thus the artifact's adoption chances. Since artifacts in their early forms are highly imperfect and offer moderate improvements over earlier artifacts, the pace at which subsequent improvements arrive will greatly determine the rate of the new artifact diffusion. As Rosenberg notes, while the introduction of the steamboat (1815–1820) led to a significant fall in real freight costs, the absolute and relative decline in real freight rates was greatest in the period of improvements (1820–1860).

Second, there is the role of development of human skills and capital-goods capacity, on which the rise of the new technique depends in order to be exploited effectively. In the earlier stages, IBM and other high-technology firms had not only to develop the sophisticated machinery and the trained labor they needed to produce and sell, but also to educate the consumers. At a later stage of development of this technology, however, there are a significantly larger level of appropriate resources in the market at large and for further human skill development.

Third, in the case of a major technology such as the motor car, the improvements necessary to support its broad acceptance take time. This is particularly true when the source of change is not only the "producer" (i.e., the inventor, engineer, and manufacturer), but also the user or consumer of the artifact. Such users—in particular rural households—who "learn by using" helped shape in the first two decades of the twentieth century the artifact of the motor car and indeed the motor car system itself. Kline and Finch show that farm households, while initially opposing the car ("the rich man's plaything"), were soon won over. Many farm men, who had previously operated steam engines and stationary gasoline engines, found new uses for the car as they used it—the buggy car, whose high wheels cleared the hump in the country roads; the touring car with a removable back seat, which could be converted into a small truck; the use of auto power for grinding their grain, plowing their fields, and so on. Rural households used the car more as its advantages became clear—increased accessibility to farm inputs, to markets, and to consumer goods of the modern era. Manufacturers, in response to the farm households' novel interpretations of the car as a new artifact, developed and added new versions of the artifact (e.g., tractors and pickup trucks) to the car family. By 1920, the US Census reported that a larger percentage of farm households owned a motorcar than nonfarm households.

Fourth, the diffusion of an innovation is facilitated by complementarity in productive activity between different techniques. The growing productivity of an economy is the complex outcome of large numbers of interlocking, mutually reinforcing technologies, the individual components of which may not be that significant. Thus, an interrelated clustering of innovations will stimulate rapid diffusion. Nelson and Winter developed the concept of technological trajectories or directions of advance common to a wide range of technologies. They propose the concept of a "selection environment" that influences the development path of a technology. In this biological evolution metaphor, the role of genetic inheritance may be viewed as played by the inherent logic of technological development, while natural selection by the environment is carried out by the social mechanisms, including the market (millions of decentralized and uncoordinated decisions). Other social decisions involved in technology selection include regulations of environmental quality and those pertaining to occupational health and safety.

The innovation process thus comprises an evolution of an entire technological system. Such a technological innovation system, as noted earlier, stretches all the way from research through artifact invention, to developing procedures for fabricating and marketing the artifact on a large scale, and promoting ancillary technologies and service activities that support and increase the functionality of the original transport artifact. Consider, for example, the evolution of the motor car. The innovation process created around this artifact is a large, complex, technological system of transportation that includes many subsystems—consisting not only of the car producers, dealers, and distributors, but also of the system of service stations and repair shops, of the motor car credit and insurance systems, of highway construction and maintenance, of driver licensing, traffic controls, and law enforcement. In addition, over time as car use widens, it pulls along a variety of ancillary technologies, which range from gas pumps and speed radar devices to car electronics. The creation of these many subsystems forms a part of the innovation process in which the car is the core artifact. These physical and social innovations surrounding the motor car are not visualized and generated all at once, but rather evolve over time in close interaction with one another.

2.1. Institutional Innovations in Technology Evolution

In order that institutions can perform their role of guiding reasonable expectations in interpersonal and group dealings, the stability of those institutions is vital and this is valued. However, institutions change over time in order to realize latent gains by overcoming disequilibria caused by changes in product demand, resource endowments, and technical change. The notion that when the economic base of a society is changed, innovations are induced in the institutional structure, is subscribed to by a variety of scholars—Marxist ("with the change in the economic foundations the entire immense superstructure is more or less rapidly transformed"), structural–functional (sociology and anthropology), and neoclassical economics.

The neoclassical theory of induced innovation suggests that organizational innovations occur when economic agents, confronted by new transaction costs, economies of scale, the need for the internalization of externalities, and for redistribution of income, attempt to lower costs and realize economic gains. In the course of technical change specialization and division of labor increase, and so do a variety of transaction costs. These costs include:

- transportation and communication costs;
- measurement costs (to determine the quality, quantity, and dimensions of the service exchanged);
- insurance costs (hedge against unforeseen circumstances); and
- enforcement costs.

Corresponding to each type of transaction cost, a producer service activity develops to lower such costs. Over time, specialization in that producer service leads to changes in industrial organization (e.g., externalization of such services). Such developments in turn, through cost reductions, lead to growing demand for such services. The government also provides some of the producer-service-like functions (e.g., those designed to regulate competition, and protect employees' working conditions and the environment).

A recent example of such organizational artifact development in transportation is the emergence of transport logistics and supply chain services, which have evolved in response to a host of new transaction costs and the economies of scale involved in the process of globalization. These logistical and supply-chain services have, in the last two decades, created on a national and worldwide scale, organizational innovations that:

- represent a reform of the governance regime for cross-border movement of cargo—deregulation, privatization, reinvention of the customs function, and so on, thereby lowering the costs of global freight flow;
- promote financial coordination among internationally trading units through new risk reduction mechanisms;
- have created efficient business logistical systems; and
- developed a better governance of cross-border freight flows through harmonization of physical standards of cross-border vehicles.

The upshot of these related organizational innovations has been the growth and development of seamless intermodal freight flow.

2.2. The Interplay of Technical and Institutional Innovations in Transport Evolution

In reality, technical and organizational innovations reinforce one another and accelerate the process of technology diffusion. The evolution of urban infrastructure services (transportation, water supply, and sewer system) in the United States in the 19th century illustrates this interplay very well. The patterns and pace of development of infrastructure reflect the interplay of mutually reinforcing organizational innovations in the private, voluntary, and public sectors, and technical developments in materials, and in the metallurgical and chemical industries. The earlier innovations were by the public sector, to reduce risk and provide investment and an institutional framework for promoting further private investment. The later organizational innovations consisted of structural changes in city government in the form of new charters or authorized revisions of old charters.

The rapid development of urban infrastructure systems in the United States in the late nineteenth century depended on the growth of investment banking, which provided the vast amounts of infrastructure capital through a national bond market. Voluntary associations, such as professional organizations (e.g., American Water Works Organization, American Pubic Health Association, American Society of Civil Engineers) provided a venue both for lobbying for infrastructure investments and for increasing the knowledge and supply of skilled personnel. On the urban political side, the replacement of commercial and upper-class groups by the emerging localized and patronage-spoils–equity-oriented machine politics greatly increased infrastructure services. Other innovations included special districts for the construction and management of infrastructure.

Parallel to these organizational innovations there were significant complementary technical innovations (e.g., improved methods of manufacturing cast-iron pipe and of coating interiors for pressure maintenance, and newer paving and construction materials). Once these technical innovations were adopted in a few places, their diffusion throughout the urban network was made possible by the next round of private organizational innovations—packaging and franchising these water-supply technologies by the early innovators. Figure 5 provides a view of the development and diffusion of urban infrastructure services.

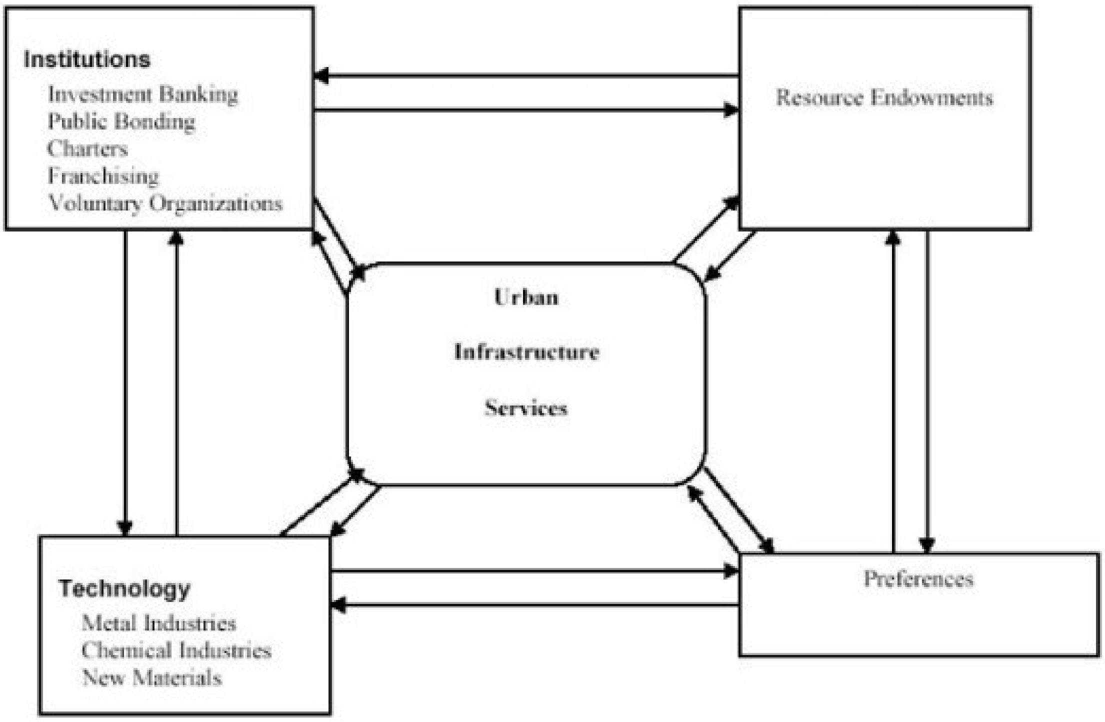

Figure 5. Development and diffusion of nineteenth-century US urban infrastructure

It is clear from the discussion in this section that transport technology is not autonomous, but evolves in response to the structures and purposes of the social milieus in which the transport system operates. The analysis of the transport innovation process requires models of change that describe the evolution of an entire transport technological system, and that are consistent with the special characteristics of the transport sector. Again, since transport artifacts include not only smart vehicles and freeways, but also financial and logistical innovations, the reform of economic and cross-border regulations, and technical and organizational changes have to be viewed together in a dynamic, interactive manner. Furthermore, the evolution of transportation services, which represent a derived demand, has also to be considered in the context of powerful economic, institutional, and societal forces of change that shape the scope and content of transportation.

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Biographical Sketches

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