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Policy recommendations for a transition to sustainable mobility based on historical diffusion dynamics of transport systems

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ABSTRACT

Emerging transportation technologies have the potential to surmount carbon lock-in and enable a transition to environmentally sustainable mobility. Promising options include biofuels; hybrid, plug-in hybrid, and battery electric vehicles; hydrogen fuel cell vehicles; maglev trains; and the Hyperloop. To varying degrees, widespread adoption of these technologies is complicated by the chicken-and-egg problem of infrastructure provision. Consumers are unlikely to adopt a technology in the absence of supporting infrastructure, but infrastructure provision is unprofitable without a critical mass of adopters. To derive policy recommendations for overcoming this problem, this study analyzes historical data on the diffusion dynamics of transport systems in the United States. The methodology systematically compares the relative timing of diffusion processes for infrastructure, vehicles, and travel. A striking regularity observed across transport systems is that the diffusion of infrastructure precedes the adoption of vehicles, which precedes the expansion of travel. On the chicken-and-egg conundrum, findings thus support the view that infrastructure comes first. The analysis leads to three salient policy recommendations: support adequate infrastructure provision early in the technology life cycle, target suitable niche markets to maximize the impact of infrastructure investment, and leverage distributed technologies to reduce overall infrastructure requirements.

1. Introduction

Technological changes in transportation since the onset of the Industrial Revolution have fundamentally reshaped human societies. By increasing travel speeds, successive transport systems including canals, railroads, motor vehicles, and airplanes have significantly expanded the spatial ranges of human activities. These systems have had profound impacts on virtually all sectors of the economy and facets of our daily lives (Grubler, 1998). Settlement patterns, diets, social networks, industrial organization, leisure pursuits, and warfare have all evolved to reflect the latest advances in transportation technology.

While modern transportation technologies provide tremendous benefits to society, there is a growing awareness that the current system, dominated by internal combustion engine vehicles (ICEVs) and airplanes consuming petroleum products, is environmentally unsustainable. Fossil fuel combustion for transportation is a major source of air pollution, which causes more than two million premature deaths each year (WHO, 2006). Poor air quality is a particularly severe health hazard in developing world cities, where 98% of residents are exposed to unhealthy levels of air pollution, and pollutant concentrations in some locales exceed WHO guidelines by more than an order of magnitude. The transportation sector is a leading producer of greenhouse gas (GHG) emissions that contribute to climate change, and transportation emissions are growing faster than any other energy end-use sector (Sims et al., 2014). Transportation accounted for 14% of global GHG emissions in 2010 (IPCC, 2014) and 27% of U.S. GHG emissions in 2015 (EPA, 2017). The present motor vehicle system is plagued by a host of other deficiencies including traffic congestion (which exacerbates environmental impacts), security risks related to oil supply, and accidents.

Growing awareness of the negative environmental impacts of fossil-fuel-based transport has deepened policy interest in enabling a transition to sustainable mobility. There are a number of promising, emerging technologies that offer different visions of what a future sustainable mobility system might look like. These alternatives include biofuels, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), maglev trains, and the Hyperloop. While each of these technologies has certain advantages compared to the present fossil-fuel-based transport system, achieving a technology transition in transportation will be difficult. The current system is positively reinforced by existing infrastructures, related technologies and industries,

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dedicated human capital, behaviors, and lifestyles. Overcoming these barriers will likely require substantial policy support to encourage infrastructure investment, technology adoption, and environmentally friendly lifestyle choices.

This study derives insights and policy recommendations for a transition to sustainable mobility by analyzing historical data on the diffusion dynamics of transport systems in the United States. A systematic methodology is applied to each historical system to elucidate important regularities in the relative timing of infrastructure, vehicle, and travel diffusion processes across systems. The remainder of this article is structured as follows. Section 2 reviews the most relevant literature on technological lock-in, techno-institutional complexes, technology transitions, barriers to adoption, and the historical diffusion of transport systems. The data analysis methodology is described in Section 3, which also delineates the data sources. Section 4 presents data on the historical diffusion of transport systems as well as numerical results. The article concludes in Section 5 with three policy recommendations that follow from the results, and a few final thoughts about the future of transportation.

2. Literature review

2.1. Technological lock-in

The dominance of certain technologies tends to persist even as inherently superior new competitors arise. This phenomenon, known as *technological lock-in*, stems from increasing returns to technology adoption that positively reinforce the dominant alternative (Arthur, 1989). Lock-in is thus a special case of *path dependency* featuring *positive feedback loops*. Arthur (1994) identifies four primary classes of increasing returns that sustain lock-in: scale economies, learning economies, adaptive expectations, and network economies.

Scale economies reduce the costs of technologies with large market shares, and are particularly important drivers of lock-in to technologies for which the high fixed costs of required infrastructure have already been sunk. Learning economies make costs decline with cumulative production experience, and they widen the cost advantage of technologies that achieve substantial early adoption relative to less mature competitors. Adaptive expectations of potential adopters tend to assume that the most promising technology at present will remain dominant in the future, which can make continued adoption of that technology a self-fulfilling prophecy. Network economies make adopting a technology more valuable as the number of other adopters increases. Network effects are major sources of increasing returns where adoption by multiple users is complementary (e.g., a telephone is more valuable if there are more telephone users to call) or related industries are stimulated by greater adoption (e.g., wider use of a hardware system leads to greater availability of software for it).

Convergence on a dominant technology has some advantages in that it aligns expectations, enables standardization and cost reductions, and creates market stability that encourages investment. However, lock-in can be detrimental when it prevents superior technological alternatives from supplanting established, inferior ones. Several prominent examples of lock-in have been analyzed and discussed in the literature. David (1985) recounts how the QWERTY keyboard layout remains entrenched even though many other keyboard layouts allow for significantly faster typing. In fact, the dominant QWERTY design was developed in the late nineteenth century to slow down typing in order to avoid jamming early typewriters. While modern computer keyboards cannot be jammed by fast typing, we have inherited the QWERTY layout.[1] Cowan (1990) argues that the light water reactor became locked-in as the dominant nuclear power technology due to early adoption on U.S. Navy submarines that carried over to civilian electricity generation. Technologically promising alternatives such as heavy water and gas graphite reactors have not been able to penetrate the market. Other cases of lock-in highlighted in the literature include alternating current for electricity transmission, and ICEVs, which were in competition with steam-powered and electric cars during their formative phase (Arthur, 1989; Cowan, 1990).

Scholars use the term *carbon lock-in* to describe the collective inertia of energy systems based on fossil fuels, including electricity and transport systems (Seto et al., 2016; Unruh, 2000, 2002). Lock-in is particularly strong for these systems because they are subject to all four classes of increasing returns identified by Arthur (1994). The current global energy system is the largest infrastructure network ever built, comprising tens of trillions of dollars of assets that span two centuries of technological evolution. Measured by the carbon price required to induce an immediate transition to low-carbon alternatives, fossil-fuel-based transportation technologies are the most firmly entrenched components of the energy system (Seto et al., 2016).

2.2. Techno-institutional complex

Lock-in to individual technologies can be difficult to escape, but the phenomenon intensifies when the dominant technology forms the basis of a broader *techno-institutional complex (TIC)*. A TIC arises when related technologies, infrastructures, institutions, organizations, and behaviors co-evolve with the core technology to create a comprehensive complex spanning technological and social systems (Unruh, 2000, 2002). The elements of a TIC positively reinforce one another and collectively develop considerable inertia. TICs are roughly equivalent to *socio-technical systems* (Nykvist and Whitmarsh, 2008) and *infrasystems* (Loorbach et al., 2010), terms which are also employed in the literature.

ICEV transport is a quintessential TIC that frequently serves as an example of the concept (van Bree et al., 2010). Adoption of ICEVs drove the continued expansion of road networks and petroleum product pipelines. Use of gasoline taxes to fund road networks, which in turn stimulate additional vehicle ownership and driving, institutionalized mutual, positive reinforcement. Gas stations proliferated to sell fuel to ICEV drivers, and generations of mechanics acquired the skills to repair vehicles. As the motor vehicle industry grew, related industries such as oil and synthetic rubber grew as well. The built environment evolved toward suburban settlement patterns that are entirely dependent on the automobile. Institutions were created to educate new drivers, administer registrations and licenses, enforce safety standards, and offer vehicle insurance. Car ownership came to be seen as a symbol of socioeconomic success and leisure activities based on vehicle travel (e.g., road trips) ascended in popularity. Escaping lock-in to ICEVs as the dominant transport technology would require a competitor to overcome the entire TIC that developed around them, which makes a transition to sustainable mobility particularly daunting.

2.3. Technology transitions

Technology transitions are "major, long-term technological changes in the way societal functions are fulfilled" (Geels, 2002). For a technology transition to occur, lock-in to an existing technology or TIC must often be escaped. A conceptual framework for understanding how lock-in can give way to a technology transition is provided by the multi-level perspective advanced by Geels (2002). The perspective distinguishes three levels: *landscape*, *regime*, and *niche*. A dominant TIC exists at the meso-level of the regime. Therefore, a technology transition is the

[1] While most economists accept the QWERTY keyboard as a canonical example of lock-in to an inferior technology, Liebowitz and Margolis (1990) challenge this view. They question the evidence establishing the superiority of the alternative Dvorak design, and (*footnote continued*) argue that the persistence of QWERTY is more a coordination failure than a pure externality issue.