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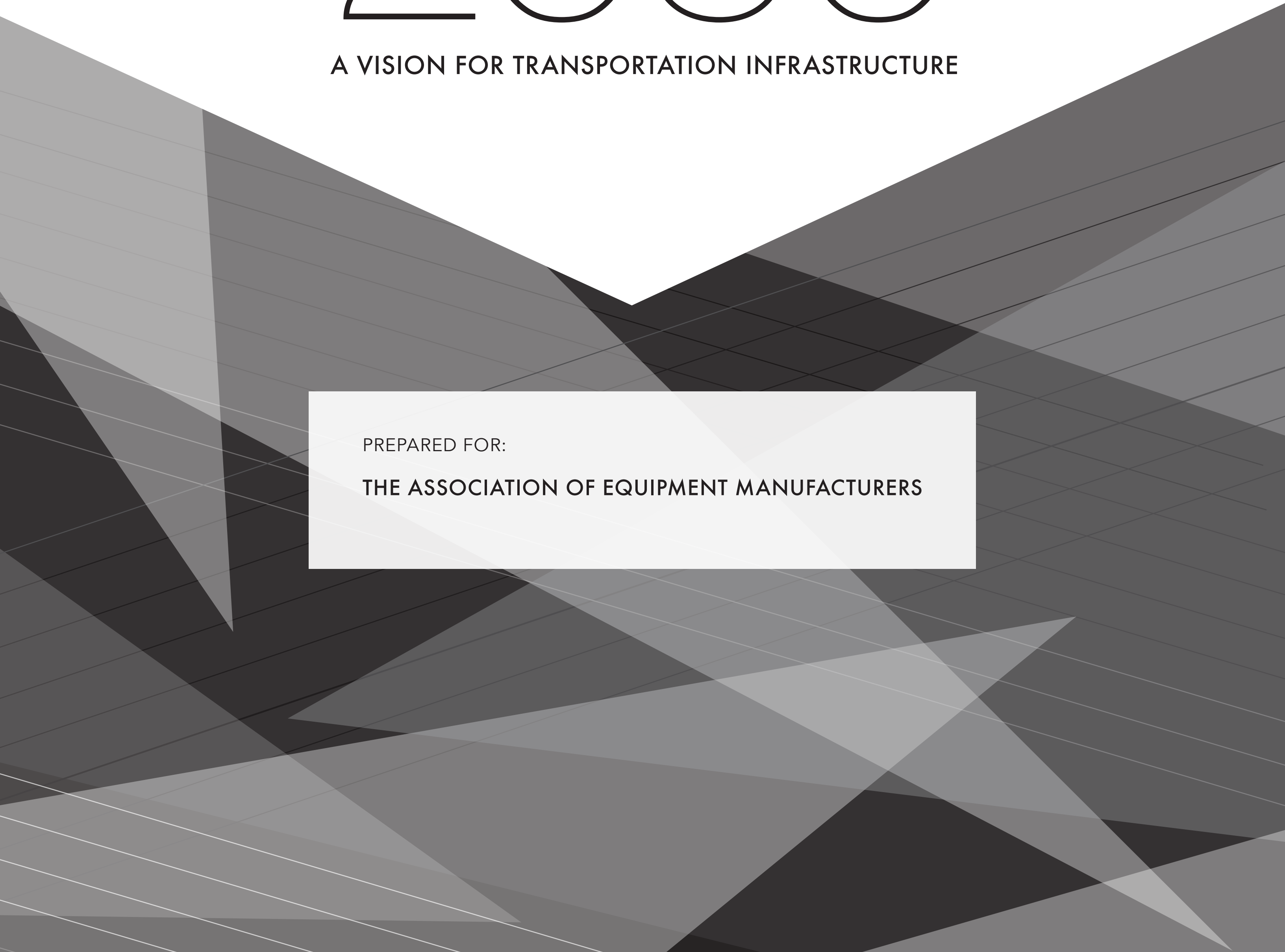
MOBILITY 2050

A VISION FOR TRANSPORTATION INFRASTRUCTURE



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MOBILITY 2050

A Vision for Transportation Infrastructure

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Prepared for

The Association of Equipment Manufacturers

By

The Transportation Center
Northwestern University
Evanston, Illinois

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Preface

To assure the future of our economy and society we must address how we move people and goods, not just for today, but by looking forward to the country of tomorrow. Our way of life depends on the choices we make moving forward. Today's U.S. transportation infrastructure system was built for a different time. But the global economy and emerging technology have changed everything, and tomorrow will be still different. Looking forward, we must accommodate a growing population, shifting demographics and a changing economy.

The Association of Equipment Manufacturers (AEM) and its Infrastructure Vision 2050 initiative is pleased to sponsor this exploration of the future needs of our transportation infrastructure. We believe there is a need to clearly articulate the motivating factors and trends that will help form a national, long term vision for U.S. infrastructure. There is much to discuss, debate and most importantly, to decide.

Two things are clear to those of us who worked on this project. We need funding and political courage. A properly planned infrastructure investment should pay for itself. This is a core belief for those of us who care about the long-term future of U.S. infrastructure.

We cannot rely on the public sector alone to solve this problem. As this study illustrates, what is needed is a strong partnership and deep collaboration between public and private sectors to make significant and valuable progress in determining how this country and its economy will move in the year 2050.

Quick and persistent work is needed to catch up to the accelerating rate at which technology is advancing. These advances provide major opportunities and meaningful solutions to some of the biggest transportation infrastructure problems we face. Each component of a long term vision must include the latest in technological innovations, but also what will be in the pipeline ten, twenty, and even thirty years from now. Relatedly, we must convert the excitement these innovations are generating into a widespread public commitment to reaching a cohesive vision that ensures shared prosperity among all communities and all industries. An effective and efficient infrastructure will bring our people together and further improve commerce.

I'd like to express sincere thanks to the team at the Northwestern University Transportation Center, the assembled experts who contributed to this study, as well as Dean Julio Ottino of the McCormick School of Engineering and Applied Science, for their openness and passion in assisting AEM with the Infrastructure Vision 2050 initiative.

As a longtime representative of the equipment manufacturing industry, I am proud to be a part of building quality infrastructure at home and abroad. This is an issue deeply rooted in this industry. However, most importantly, as a father and a grandfather, I am driven by a personal imperative to create a better future for the next generation – and that includes helping to create a first-class transportation infrastructure system in the United States. That reason alone is enough to pay attention and get involved in this important conversation. This study serves as a start.

Ronald M. De Feo
CEO, Kennametal
Chairman, AEM Infrastructure Vision 2050 Task Force
May 2016

EXECUTIVE SUMMARY

Mobility 2050 – A Vision for Transportation Infrastructure

Prepared for the Association of Equipment Manufacturers

By the Transportation Center, Northwestern University

Supported by a grant from the Association of Equipment Manufacturers, Northwestern University's Transportation Center undertook an exploration of the factors, needs, and opportunities facing U.S. transportation infrastructure in the next 35 years. The objective of the study was not to forecast the future, but to frame the possibilities and thus to inform the public and policy makers about future needs for transportation infrastructure.

The project began with an assessment of the condition, performance, and funding for the various modes based on publicly available data. Condition deficiencies of various degrees exist across all of the publicly supported modes – highways, public transit, inland waterways, and, to a lesser extent, airports and airways. While a general transportation infrastructure disaster is not imminent, and the condition of some elements is stable or slowly improving, the deteriorating condition of transportation infrastructure is degrading system performance – producing long travel times, reduced reliability, higher user costs, and larger externalities. Long term degradation of transportation system condition and performance is producing a subtle but important drag on the economy, and some critical bottlenecks are causing quite specific problems. Aging infrastructure is increasingly vulnerable to unexpected disruptions from natural phenomena and component failures.

These outcomes can largely be attributed to two factors: insufficient and unsustainable funding for public investment and reinvestment in transportation, and inefficient deployment of those funds that are available.

Modes operated by the private sector, notably railroads and pipelines, are generally in better condition than the public modes. In the private sector, the links between condition, performance, revenues, and profits are explicit and more closely managed than on the public side, where it is easier to ignore or defer needs because the impact on revenues and the economy is less apparent, though not less important.

The remainder of this study identified important, changing aspects of the economy, technology and society, considering the kinds of developments and trends likely to occur in the next 35 years and then assessing their likely impacts on the demand for and supply of transportation infrastructure.

The future is framed in terms of three overlapping scenarios: *business as usual*, particularly in terms of transportation infrastructure funding and investment policies; *sustainable and resilient cities*, a result of a concerted national effort combining public policies and market forces to reinvest in cities; and *competitive success*, a market-driven path that prioritizes economic gain over long term sustainability.

The chapter on transportation infrastructure and the economy addresses the effects of transportation technology and costs on the location and efficacy of economic activities and the structure of cities. Changing resource costs, innovative technologies such as vehicle automation, and new delivery mechanisms such as ride sharing, may be game changers that affect future settlement patterns and determine competitive advantage. Pricing the use of transportation infrastructure may become both a source of funds for renewal and a way to allocate scarce capacity. Both theory and history suggest that efficient transportation services, *ceteris paribus*, can drive economic development and global competitiveness, delivering some measure of success under any scenario.

Technological advances and value changes are creating a revolution in the way people travel, particularly in cities. The chapter on technologies for urban personal travel shows that information technology and market innovations are expanding the variety of options available to travelers, and young people are increasingly benefiting from that variety. The demand for variety includes preferences for non-motorized travel and increased density and diversity of cities. Planners and policy makers have new kinds and vast quantities of information with which to guide the future of transportation infrastructure and services. That future needs to include renewal and rebuilding of infrastructure to accommodate new ways of living and innovative mobility options. To respond to market opportunities, that infrastructure must be built on not only an understanding of the variety of mobility options, but also a strategy for designing smart cities and smart transportation services, sensor- and communications-based designs that will make cities and their transportation systems a central part of the Internet of Things, functioning seamlessly together.

Rapid changes in technologies and markets are already stretching the capacity of the public sector to respond, facilitate, and finance innovations, and it will be important to grow that capacity so that public policy is not a brake on system progress. In response, private businesses, which are showing increasing interest in transportation markets and innovation, are likely to take even stronger leadership roles in mobility services. The need for transportation infrastructure will change but it will not decrease, and the challenge will be to find ways to assure that infrastructure for the future.

Information and communications technologies (ICT) have become essential for managing, operating and using mobility services in both the freight and passenger sectors. While the promise of ICT sometimes gets ahead of the reality, as in the case of the substitution of communication for travel, history suggests that barriers related to the technologies themselves, skilled personnel, and attachment to old behaviors usually erode, and the benefits of ICT catch up – sometimes very quickly, as in the case of smart mobile devices.

The future is likely to be one of ubiquitous and high capacity broadband services, augmented reality tools that will affect work, shopping, system management and information dissemination, and cloud computing that will massively increase computing capacity using only modest mobile devices. That future is one in which almost everything and everybody will be connected, introducing a broader variety of integrated, coordinated service options and delivery mechanisms for passengers and freight, and very soon, high levels of automation in the transportation system.

The transformative power of ICT may, on one hand, relieve some of the capacity constraints on fixed networks, at least for personal travel, but will also demand investments in infrastructure renewal and updating to take advantage of new technologies for sensing, assessing, communicating and managing transportation systems. The risk of inaction is losing ground in the global movement to boost transportation performance using ICT as its nerve system.

The chapter on supply chain management and logistics describes the role of transportation infrastructure in the success of businesses, moving resources and components to manufacturing centers, products to markets, and recoverables to recycling facilities. This role is changing rapidly as eCommerce becomes the norm for both consumers and businesses. Network bottlenecks and reduced delivery reliability can affect entire production and distribution supply chains, often manifested in higher inventory costs to compensate for an under-performing transportation system, or relocation of manufacturing and logistics hubs to places where transportation, particularly intermodal service, is more efficient.

This is an issue for intercity freight, where easily accessible locations are attracting manufacturing and distribution centers from more congested places. It is also important for urban deliveries, the "last mile" challenge that can consume a large fraction of the transportation bill. That bill affects consumers, businesses, and the economic viability of places. Future freight mobility needs will focus on performance, which depends on sufficient capacity, flexibility to address costly disruptions, as well as environmental consequences of supply chain operations. Future infrastructure needs can be met in part by making more efficient use of existing capacity through operational changes, e.g., off-hour deliveries, pricing for access, new mobility models including ride sharing concepts for freight, and applications of ICT to manage supply chain operations.

The chapter on the evolution of omni-channel retailing describes the rapid changes occurring in retailing – the declining reliance on traditional retail stores, the burgeoning demand for direct delivery of goods – and the ways in which the increasing diversity of delivery channels places new and greater demands on transportation infrastructure. Online shopping with direct delivery has greatly expanded the demand for last-mile shipment. Today some products are marketed through face-to-face showrooms that carry no inventory, e.g., custom clothing or high-end automobiles may be shopped locally, manufactured in distant places, and delivered directly to customers. This drives the demand for both quick long distance freight movements and last mile deliveries. Increasingly in high density locations – central cities and large college campuses – deliveries go to one of a few central facilities, where customers themselves or volunteers pick up packages for home delivery. The particular modality depends on the product, its customization level, inventory costs, the ability to deliver multidimensional information about products (e.g., virtual reality technologies), and customer preferences for price and swift delivery.

This diversity places broad demands on the freight system as well as passenger travel to retail stores, showrooms, and pickup centers. Transportation cost will continue to be important, but in some cases it will be dominated by demand for efficiency and reliability. This balance can be expected to evolve as advances accelerate in experiential technology (e.g., for viewing, trying on or trying out products) and customized manufacturing (including 3D printing). As this balance changes, pressures on transportation infrastructure are likely to be felt across all elements of the supply chain.

The chapter on the challenges of infrastructure condition attributes infrastructure deterioration to aging, exposure to environmental forces, and the stresses of utilization. The consequences include delays and reduced reliability, leading to increased user costs, and in some cases facility failures and serious safety risks.

Rational, condition-based reinvestment and rehabilitation can extend facility life and performance in a cost-effective manner. Timely condition data, informing responsive decision processes, can interrupt this cycle. Increasingly, embedded sensors and wireless communications can provide those data, with more elements of transportation infrastructure monitored and connected in the future. Facilities will generate real-time information on which both users and managers can base intelligent use and investment choices. The ultimate challenge is to secure the resources and the commitment to invest them intelligently.

Transportation infrastructure and the future of cities describes cities as the economic engines that drive U.S. and global productivity. They are complex systems of flows and networks – of people, information, energy, goods, and waste materials. For the most part these interacting elements evolve independently without much planned coordination. In most U.S. cities, dependence on the automobile and low density land use, which are synergistic, extract a significant toll on the environment and sustainability. The future could bring a departure from the business as usual path toward more sustainable cities – higher densities, reduced dependence on the private auto, and more local sourcing of energy and treatment of waste products. Automobiles are not likely to go away, but their nature is likely to change radically – electrically-powered, smaller, increasingly automated, and perhaps in the long run collectively owned. Personal mobility may change so that it serves, rather defines, a new, sustainable urban lifestyle.

Moving cities on the path to sustainability will take a new level of integration and coordination, making use of emerging smart technologies, and amplified by the evolving values of younger generations. In the long term, the path to sustainability can bring competitive economic and social advantages likely to offset the costs of transition. Renewed infrastructure of all kinds will be the backbone of that path. This can happen gradually by taking advantage of opportunities to rehabilitate and restore transportation and other infrastructure components as they reach the end of their lives.

The chapter on paying the way for future transportation infrastructure addresses factors contributing to the long term underfunding of transportation infrastructure, reasons for resistance to increasing funding through user fees, and threats to the sustainability of the highway network from the uncertain future of the motor fuel taxes as a funding source. More direct use of user fees is offered as a sustainable strategy for funding publicly-supported transportation infrastructure. This mirrors the success that private, revenue-driven transportation services have had in the U.S. While existing and emerging technologies are changing the demand for transportation capacity, the need for fixed infrastructure will not fade in the future, and meeting that need is an essential investment in the economic and social vitality of the nation. It will be important to make the case to assure support for such investments; smart, data-driven decision must direct the funds to best uses; and a sustainable and equitable user fee system will serve to underwrite the future of a world-class transportation infrastructure for the United States.

CHAPTER ONE

Introduction and 2050 Framing Scenarios

By Joseph L. Schofer

Introduction: Scenarios and what can be learned from them

Transportation – the ability for people and goods to move about, and their ability to get to and from places – is an essential contributor to the economic and social well-being, and to the security, of people, things, and places. Limits to mobility and accessibility are barriers to success, satisfaction, and sometimes to health and safety. Transportation infrastructure is the foundation that assures the delivery of transportation services.

This study explores the possible states of the world in 2050 that will influence the characteristics of and demands on U.S. transportation infrastructure. How will different futures affect the need for connectivity, capacity, and quality of that infrastructure? How will external factors affect its condition and performance?

The objective of this exploration is to help citizens and their leaders decide what infrastructure investment and development strategies are needed to assure satisfactory transportation system performance that supports a productive, efficient, and sustainable economy and society between now and 2050. These strategies include sources and uses of funds for transportation infrastructure, as well as policies and incentives to assure the availability of efficient and effective transportation services in the future.

The work begins with an overview of the functions of the transportation system and discusses some of the major forces outside of transportation that affect the performance of that system. It then describes scenarios or visions of what the future might be as driven by those external forces. These scenarios are contexts within which the transportation system must function and policies and plans that support it must be formulated, tested, and implemented. To address future uncertainty, three scenarios are defined that span a range of reasonable possibilities. The work explores how these future scenarios make different demands on transportation infrastructure, and how outside forces and opportunities affect the system, influence those demands, and present new ways to deliver and assure transportation services. Subsequent chapters explore specific factors that, from the perspective of the several scenarios, define future transportation needs and opportunities for meeting those needs. The report concludes with an examination of current transportation infrastructure policies and funding patterns and offers some guidance for the path moving forward.

Functions of transportation systems

A transportation system is a collection of infrastructure components, vehicles, rules and procedures that produce the services of the system through the actions of people. Transportation creates value by facilitating the mobility of people and goods and the accessibility of places. The outputs of transportation infrastructure and system operations can be characterized by these attributes – what's important about transportation services to users and communities:

1. Connectivity – the places served and connected to other places by transportation networks and the modes that use them. While the highway network in the U.S. is virtually ubiquitous, there are important exceptions in the west and southwest parts of the nation where a disrupted link can lead to detours of hundreds of miles. In Canada and Mexico, there are major regions where mobility of people and goods depends on very sparse networks. All North American maritime ports are connected to the highway network, but some are not connected to high capacity highways and others are not directly linked to the rail network (for efficient on-dock rail).
2. Capacity – the throughput capability, people, tons, or containers moved per hour or day. Capacity and performance are tightly linked through demand for service, i.e., if the demand is high relative to capacity, facilities become congested and performance, in terms of travel times and reliability, will be degraded. Capacity also can mean load-carrying capability which, if restricted, limits the kinds of vehicles and cargoes that can be moved over a link, e.g., a bridge.
3. Performance – travel times, reliability (arrival time variability), safety and security, resilience against disruptions. These characteristics affect traveler and shipper costs, on time deliveries, inventory requirements, and risks to people and products.
4. Flexibility or adaptability – design features that enable transportation infrastructure to meet changes in demand or external forces and threats rapidly and cost-effectively.
5. Environmental effects – environmental and other externalities produced by the presence and operation of transportation systems. For example, values and policies increasingly requiring that transportation systems and services moderate or eliminate release of greenhouse gases or other noxious byproducts, including noise.

The relationships among condition (e.g., pavement roughness), performance, policies, investments, and outcomes are illustrated in Figure 1. Physical condition influences system performance, as does the demand on that system (e.g., congestion effects); context (state of the economy, individual values and preferences, global conditions, climate change); and, of course, investments made (or not made) to operate, preserve, and improve transportation infrastructure. The outcomes, the higher level results that are the motivation for managing and improving transportation, include economic efficiency and competitiveness, income, employment, quality of life, and satisfaction.

The right transportation infrastructure and operating strategies are necessary to assure these outcomes. To do this requires sufficient and carefully-directed resources; failing to provide and deploy the necessary resources leads to system performance gaps, the inability to deliver effective and efficient transportation services, and these gaps will constrain the outcomes that are so important to the nation and its people. The potential for such performance gaps, and actions to minimize them, are discussed throughout this report.

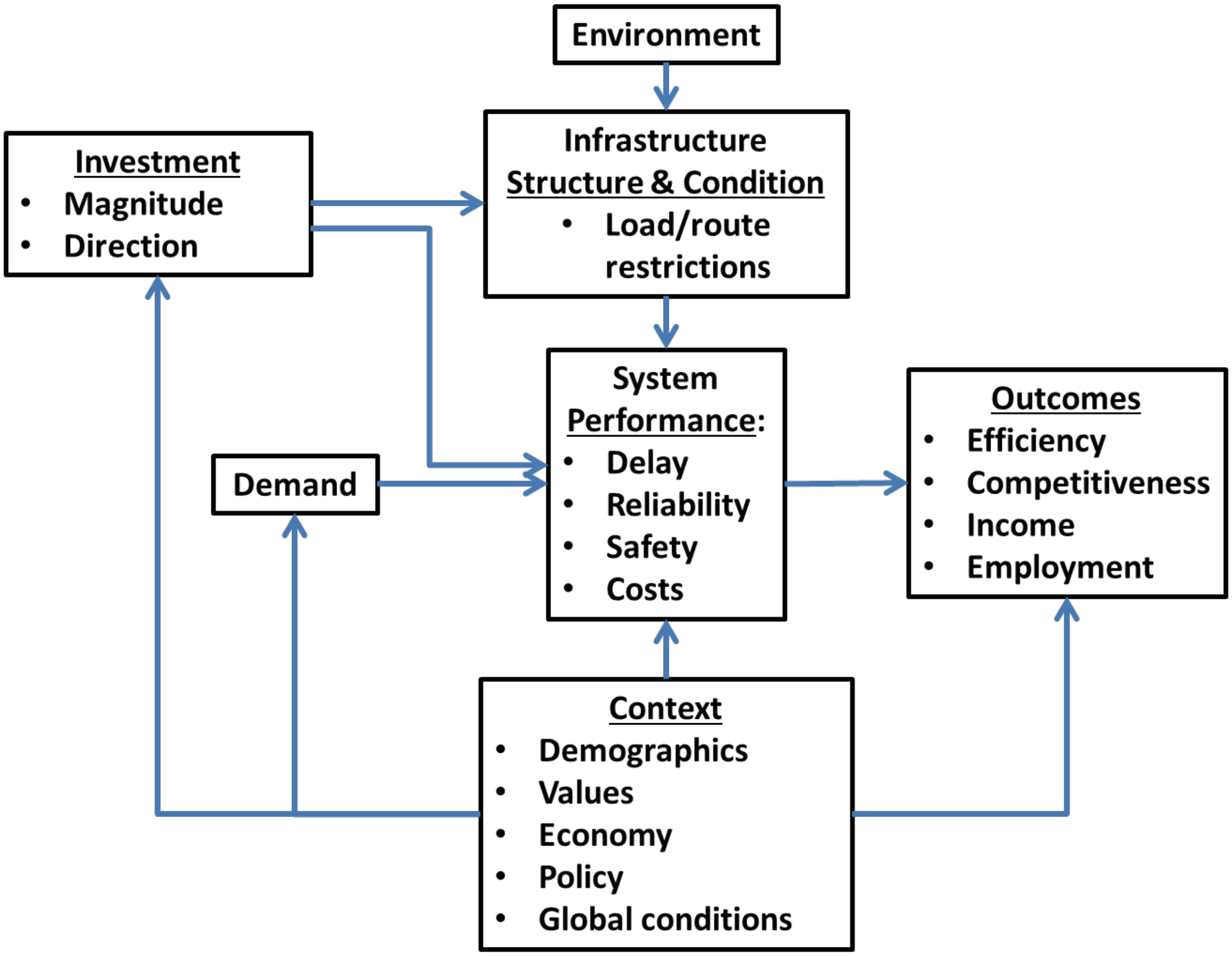

Figure 1: Factors Influencing Transportation System Performance

Driving forces – what will shape the future for transportation infrastructure?

The scenarios that frame this study are defined by the forces and factors that will influence transportation performance in the future. Among the major trends affecting future transportation performance – influencing each scenario but in different ways – are these:

- Shifting demographics. The demographic future will be one of increasing diversity, an aging but active population, people retiring at older ages, and increased income dispersion. The demand for passenger travel will change and diversify.

- <u>Locational trends</u>. Population is likely to continue shifting nationally (movement south, west, and northwest to high tech jobs and moderate climates), and regionally (growth in central cities, suburban fringes). Pressures on transportation services will shift in location.
- <u>Changes in values and behavioral patterns</u>. Younger people seem to hold different preferences and priorities, e.g., commitment to sustainability, the sharing economy, purchase of services vs. ownership of resources, and desire for higher density living. Will changes manifested today persist as the population matures?
- <u>Marketing, manufacturing, and logistics patterns</u>. Channels for retailing, locations for sourcing, manufacturing, and distribution centers are diversifying. Logistics modalities are evolving rapidly under competitive pressures and technological opportunities. How will these trends affect traffic flows and infrastructure requirements?
- <u>The global economy</u>. International trade is growing, new competitors are entering markets, and new consumption sites are emerging. Will the North American economy be more or less connected to the rest of the world? What does this mean for logistics and transportation infrastructure?
- <u>Accelerating technological change</u>. New information and computer technologies are affecting every element of the economy and society, importantly, the transportation sector. Connected and autonomous vehicles may revolutionize both freight and passenger transportation and bring fundamental changes to the motor vehicle industry. Wireless connectivity is affecting the demand for the movement of people and goods, and these impacts are likely to grow and become even more disruptive in the future. Technologies and analytics are enhancing infrastructure management and utilization. New materials and sensors are increasing infrastructure durability, extending structural life, and reducing surprise failures. How will infrastructure needs change?
- <u>Climate change</u>. In 2050 time frame, a serious increase in severe weather, driven by climate change, could threaten some coastal areas; the Mississippi Valley may be hit by floods and tornados, northeast cities by snowfall and storm surges, the west by drought-driven forest fires. Such disruptive events may interrupt logistics more frequently, damaging infrastructure, reducing economic efficiency, and boosting capital and operating costs. What does this mean for infrastructure resilience?
- <u>Public policy trends</u>. The role of governments in supporting and sustaining transportation infrastructure, economic and environmental regulation, taxation, and resource allocation has been changing, affecting the balance between federal and state, and public and private players in infrastructure investment and management. How will ideology and pragmatism be balanced?

Trends in these and other key factors will define the contexts within which transportation systems must function over the next three decades, presenting challenges, changing demands, and opportunities. In the next section, trends in these factors are used to define three scenarios representing possible 35-year futures.

Three scenarios to frame the future for transportation infrastructure

Scenario 1: Business as usual – static policies in a changing world

In this scenario, there is little change in the directions, policies, and priorities affecting the operation and development of transportation infrastructure. In particular, the engagement and effectiveness of government, particularly the federal government, in transportation funding and policy effectiveness erodes because of a combination of politics, ideology, and lack of consensus on the importance of transportation as the backbone of the economy and who should pay for it. Business as usual for transportation infrastructure has these characteristics:

- Absence of an effective national transportation policy framework will make it difficult to guide system evolution toward specific goals.
- Lack of a sustainable, long-term funding strategy, at least at the national level, for modes, infrastructure, and services that receive federal support in any form, i.e. highways, mass transit, inland waterways, and airport and airways facilities. Pipelines and most railroads in North America are privately owned and so investment is not a public responsibility. However, these modes are regulated by government, and matters of safety and service allocation are in the public purview. Railroads benefit from government grants and loans for projects that support economic development objectives, making public funding policy salient to them as well.
- Technological innovation will be largely unplanned and public policy response to changing technology will continue to be reactive and uncoordinated.
- Absent or weak public policy role in intermodal coordination and service planning will be a growing concern because most freight shipments, and many passenger trips, use multiple modes. This coordination gap is now partially filled by actions of private carriers, terminal operators, and some local governments.
- Gradual and unplanned devolution of federal roles and responsibilities to states willing and able to act to fill the policy and funding vacuum, particularly for the highway system.
- Inconsistent support for transportation infrastructure across states and provinces, especially highways and mass transit, but also for general aviation airports, will erode the “system” in transportation systems.
- Funding gaps result in continued deferred maintenance, degradation and abandonment of facilities; infrastructure renewal needs for mass transit will be large and growing.
- Conflicts in policies and actions at some state borders will complicate collaborations on projects to meet network capacity needs.
- Private sector infrastructure initiatives will grow modestly in return for toll revenues or availability payments from public agencies. Private investors seeking appropriate return on investments will “cherry pick” the most productive projects, skipping those that may have less revenue potential even if they have high social value. The least economically productive projects will be left to the public sector, or remain undone. Some private investments will fail to deliver sufficient return and will be devalued, sold, or thrown into bankruptcy.

Unsustainable public funding, infrastructure management and expansion driven by disparate state and local needs and goals, and a *laissez faire* approach to location planning at the regional and local levels define an uneven trajectory for transportation infrastructure and services, disconnected from strategic goals such as economic competitiveness or environmental sustainability. Disjointed, market-driven technological advances will keep the system moving but the absence of strong policies makes it difficult to achieve the full potential of new technologies for mobility management and substitution. Urban sprawl continues, accompanied by more congestion in cities and suburbs. North America becomes less competitive and energy costs grow because of both resource costs and inefficient utilization. Together, these factors lead to declining system resilience and thus increased losses due to natural and man-made disruptions. Variations in values and policies result in some states doing better than others.

Implications: Gradually increasing congestion and logistics costs; loss of competitiveness; unmet demand for transit facilities compounded by declining physical condition of existing systems; loss of services and connections to low volume places. Demand for capacity increases but funds for investing are limited.

Scenario 2: Resilient and sustainable communities

This future is driven by the confluence of changing values, dissatisfaction with the growing amount of time wasted in travel, rising energy and resource costs, severe weather disruptions, and aggressive national and local policies to limit greenhouse gases. Integrated policies and technology developments support compact settlement patterns and thus more efficiency living: live, work, shop, manufacture, and grow locally. Increased density boosts congestion, but also supports greater use of non-motorized travel, including biking and walking.

Additionally, local manufacturing reduces some long distance freight movements, boosting intra-urban freight flows and the use of non-motorized modes. The sharing economy becomes the norm, facilitated by higher density living. Vehicle automation leads to productive recovery of time spent traveling. Innovations in pricing lead to more efficient use of transportation infrastructure, thus reducing continuing pressures to expand the system, and produce a revenue stream that pays for operations and well-chosen capital investments. To take full advantage of these efficiencies, the infrastructure, indeed the structure of cities, must change. These investments can be integrated into rehabilitation and renewal programs in older cities. Places that adopt strong sustainability policies will grow in economic competitiveness because of efficiency, long-run cost reductions, and resilience advantages.

Implications: This scenario demands both commitment and investment by both public and private sectors to rebuild center cities and their transportation infrastructure, to provide more mass transit and facilities for non-motorized travel, and to accommodate efficient urban freight operations. The commitment to sustainability would eventually extend far beyond transportation systems, affecting housing characteristics and locations, management of water resources, and recycling and recovery of materials, water, and energy to reduce resource shortfalls. It is likely to lead to a reorientation of the motor vehicle industry to produce a smaller number of shared, automated vehicles. Such changes will require much time and money, and so, unlike the business as usual scenario, a resilient and sustainable future would evolve over many decades through a long series of individual and collective advances.

Scenario 3: Competitive success

This scenario is driven by money, markets, and dominating technologies, in contrast to the more altruistic Scenario 2, resilient and sustainable communities. Scenario 3 can be characterized as hedonistic because the underlying assumption is that economic incentives and tastes overtake (or overlook) limits on critical resources, for example, energy, water, and clean air. Technological breakthroughs, accelerated by market demand, a population increasingly facile with information technologies, and competitive pressures, make economic development and growth primary goals. Growing transportation needs are met with big infrastructure investments, funded with road pricing.

Trade grows, driving long distance freight flows as well as commuter traffic. Global economic integration intensifies, relying on both transportation and communications services. Much manufacturing, or at least assembly, returns to North America, while distribution aims are world-wide. Population is dispersed – live, work where you want, supported by ubiquitous wireless broadband and increased transportation capacity. Weather disruptions worsen but they are managed with large investments in hardened infrastructure, backed up by wireless connectivity, allowing much activity to go on despite transportation interruptions.

Implications: This scenario will require large infrastructure investments in both capacity expansion and shifts to new, faster technologies (e.g., high speed rail for freight as well as passengers) to support increased travel. Sustaining this scenario will be largely dependent on continued economic growth. Tensions may arise between environmental and economic interests; the winner may be decided based on external factors – resources availability and costs, and major climate events.

What will the future be and how can we influence it?

These three scenarios are drawn to represent realistic extremes; in these cases, either sustainability, economic success, or business as usual wins the day. The future is likely to be less distinctly drawn, mixing attributes of several scenarios. It is important to recognize that scenarios are not predictions, but are outlines of possibilities which may require particular actions or investments to achieve or avoid. Considering these extremes may clarify future needs, challenges, and opportunities for transportation and other infrastructure systems. Most likely the future as it will affect transportation infrastructure will mix some static policies and values with major efforts to achieve sustainability, both without sacrificing too much economic success.

While the transportation system alone, and investments in it, will not define the future, strategic infrastructure investments may be able to do more than simply support a particular future; they may be able to help achieve a better future. In fact, there are important historical examples of large scale transportation investments producing major positive economic and social changes.

- The U.S. transcontinental railroad opened up the West for massive population growth and made possible development of natural resources and agriculture in the middle of the continent.
- The Interstate Highway System radically changed the way freight and passengers make long distance trips, supported rapid suburbanization of large cities, and grew (and destroyed) towns across the nation.
- Midway airport made Chicago the air travel hub of the nation and the world, attracting business headquarters and assuring global connectivity for the Midwest.

On the other hand, the St. Lawrence Seaway, intended to open Midwestern Canada and the United States to massive growth in foreign trade, has not produced a sustained economic impact, in part because it has been dominated by efficiency improvements in competing, surface modes that have strengthened coastal ports as the gateways to global trade.

These are examples of investments in transportation infrastructure providing high quality accessibility that were expected to produce massive economic development and social change. The first three are success stories, the fourth, arguably, is not. While many factors contributed to these outcomes, accessibility was primary among them. Sometimes the right mix of factors can make a large difference, helping achieve economic, social or strategic goals. There are myriad smaller scale, and more recent examples of synergies between transportation and economic, social, or environmental development.

Thus, it may be possible to move among different future scenarios by the strategic application of policies and investments. Such a proactive approach requires an understanding of today's direction, a consensus on a preferred future or futures, policies and investment opportunities that have the power to make a difference, and the resources and will to act.

The next chapter provides a current snapshot of the condition, performance, and funding patterns for the primary modes of transportation in the United States. The chapters that follow explore the future for transportation infrastructure from seven different perspectives, representing key determinants of, and opportunities for, transportation in the future, and building on the scenarios presented here to outline the needs, barriers, and opportunities that frame the future of transportation infrastructure.

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CHAPTER TWO

Where We Stand: Transportation Infrastructure Today

By Lama Bou Mjahed
and
Joseph L. Schofer

Introduction: An overview of current infrastructure

Transportation infrastructure underpins the health of the domestic economy and the well-being of society. Flows of people and goods are dependent on a complex multimodal transportation system of highways, bridges, airports, waterways, mass transit systems and railroads. There is much discussion by experts and advocates about the deteriorating state of the American transportation infrastructure. Former U.S. Secretary of Transportation Ray LaHood described the systems as on “life support” in 2014.[1]

These statements are backed by studies that assess that infrastructure in terms of grades or global rankings. In 2014, U.S. infrastructure was ranked 12th globally by the World Economic Forum[2] (mainly for its shortcomings compared to countries in Northwest Europe and East Asia), and in 2013, the American Society of Civil Engineers[3] (ASCE) assigned it a grade of D+ (i.e., poor). This chapter provides a data-driven, multimodal profile and assessment of the state of U.S. transportation infrastructure. This serves to add nuance to the customary tale, to characterize the needs and challenges, and to highlight some of the implications for the economic efficiency and competitiveness, income, employment, and the quality of life. This profile is divided into four sections: 1. Condition of the infrastructure; 2. Performance of the transportation system; 3. Infrastructure funding and investment patterns; 4. Conclusions for the economy and society. A series of infographics illustrating this profile is included at the end of this chapter.

Infrastructure Condition

The condition of U.S. transportation infrastructure, manifested by insufficient capacity, load restrictions, slow zones, rough pavements, and, in the worst cases, by physical failures, presents travel and logistics challenges across almost all modes. Condition information is collected from inspection reports, age-based projections, reports of failures, and sometimes in the form of performance degradation (e.g., congestion due to limited capacity.)

Some indicators show improving conditions for Inland waterways, airports and freight rail. For example, lock availability is trending upward, but delays continue to mount because of limited capacity of aging locks. Overall, trend in highway pavement roughness measures, which characterize condition and ride quality, and affect operating costs and cargo damage, has been mixed Between 2000 and 2010, the percentage of rural vehicle miles traveled (VMT) on pavements having acceptable ride quality declined from 93.8 to 87.8 percent.[4] However, the percent of rural VMT on pavements with good ride quality (a subset of the acceptable ride quality classification) increased from 55.2 percent to 64.6 percent. The share of urban VMT on pavements with good ride quality rose from 35.0 percent in 2000 to 44.0 percent in 2010. The share of VMT on the National Highway System (NHS –Interstates plus major highways) operating on pavements with good ride quality rose from 48 percent in 2000 to 60 percent in 2010.[5] Smaller facilities, rural and urban, carrying the first/last mile movements that are critical to supporting economic activities and competitiveness, seem to be in the worst condition.

The number of derailments on freight railroads has been falling[6], but significant derailments involving release of hazardous materials still occur and receive considerable public attention.

Bridges, critical links that are often bottlenecks on the road network, show disparities in condition, with urban bridges in better condition than rural facilities, leading to uneven services that sometimes force long detours, particularly affecting heavy trucks. Still, the U.S. has fewer deficient (threatened or limited load carrying capacity) and functionally obsolete (restricted ability to meet functional requirements) bridges now than the past decade. There is little public knowledge of the condition of railroad bridges, but many, some in critical locations, are more than 100 years old.

Finally, it appears that no transportation mode in the U.S. is in more serious physical condition than mass transit where deferred maintenance has left 30 percent of the assets in "poor" to "marginal" condition,[7] with needs concentrated in guideways and control systems. The current national backlog exceeds $85 billion[8] and New York City's Metropolitan Transit Authority alone faces a $105.7 billion backlog over the next two decades.[9] The annual investment required to eliminate the existing system preservation backlog by 2030 is roughly $18.5 billion;[10] at present the U.S. is investing about $10 billion per year for rehabilitation and replacement.

Infrastructure Performance

The performance of transportation infrastructure is what users experience directly. Performance is described in terms of four characteristics: delay (travel times), reliability, safety and user costs. Performance is affected by several factors: 1. The capacity and condition of infrastructure; 2. The demand for services on these systems which is influenced by the economy and the price-performance competition among the modes; and 3. Investment made by owners – public or private – to sustain and improve the modes.

Air passenger and freight performance has been a bright spot in recent years, with the percentage of flights delayed decreasing slightly across the system as a whole. Weather is the overwhelming cause of delays (60 percent of delayed flights in 2014[11]). However, the resilience of air services to weather and congestion-related disruptions is undermined by the lack of reserve capacity in runways, gates, aircraft and air crews, making the airline system vulnerable even to small scale disruptions. Such disruptions cascade through the air network, causing system delays that can last for hours or even days. The choke points are at the busiest hubs in the nation – Chicago, Newark, San Francisco, Atlanta and Washington, D.C. Airline delays cost the economy $28.9 billion in 2007, $16.7 billion of which were borne directly by users. [12]

Capacity and throughput constraints at rail hubs have substantial performance impacts on the freight system, as well. These are interchange points where cargo is resorted and handed off among carriers or modes (e.g., rail-truck). As is the case for air services, delays at some major rail hubs can propagate through regional and national networks, disrupting supply chains, increasing costs, and sometimes forcing shifts in routes, modes or facility locations. Data on the performance of the freight rail system is hard to acquire because of proprietary interests or the railroads.

Highway congestion and delay have continued to increase; the gap between demand and capacity has led to a consistent increase in delay-hours per auto commuter in the past 15 years. Trucks experience serious congestion at many locations in the U.S., mainly in and around major cities but in some cases on truck-heavy rural Interstate highways, where tractor-semi-trailer combination trucks can represent 50 percent or more of the traffic flow. In 2015, the most congested locations for trucks were Atlanta's I-85-285 and Chicago's I-90-94,[13] which are among the several critical national hubs.

For urban travelers, the increase in average commute times on public transit has been substantial, reaching 53 minutes on average in 2009 from 42 minutes in 1995[14] indicating that, on average, transit is not gaining ground in its competition with the automobile, a necessary step in mitigating congestion and air quality problems in urban centers. This is despite substantial investment in fixed guideway transit – light rail transit route miles nearly doubled between 2002 and 2012;[15] from 2000 to 2010 a total of $84.7 billion was invested in transit improvements, of which $60.9 B was spent on fixed assets.[16]

Finally, ports and inland waterways have both seen performance deteriorate in recent years with increasing delays and queues at ports and locks. Forty-nine percent of commercial vessels on the inland waterways network were delayed in 2014[17] because of insufficient lock capacity. Delays at ocean ports have grown in part because import flows have increased substantially, while capacity in the ports and on ground access facilities has not kept pace. Virtually no port performance data are currently published, but the recently-passed surface transportation reauthorization bill, FAST - Fixing America's Surface Transportation - mandates development of port performance measures by the U.S. Bureau of Transportation Statistics. Labor conflicts have affected performance of the key national container ports of Los Angeles and Long Beach, California. This has shifted some flows to other ports, including Gulf coast facilities accessed through the Panama Canal. The opening of larger locks on the Canal in the spring of 2016 is putting pressure on Gulf and East coast ports to expand dock capacity and deepen channels to accommodate larger ships. Much of this work will not be completed when the new locks open.

Infrastructure Spending

The highway network is the most extensive publicly-owned transportation infrastructure component, and so it is not surprising that highways were the focus of 59 percent of public spending (i.e. federal, state and local), in 2014 amounting to $165 billion.[18] State and local governments, which own 97 percent of U.S. roads and highways,[19] contributed to 72 percent of this investment. Nonfederal spending on highways decreased 21 percent between 2003 ($140 billion) and 2011 ($110 billion), growing to $120 billion in 2014. Federal money for highways decreased 31 percent between 2001 and 2014, from $65 billion to $45 billion. Federal highway spending relies on the Highway Trust Fund (HTF), which has two main sources of revenue: the federal excise tax on motor fuels (MFT) that has been unchanged since 1993, and truck-related taxes. The MFT has not been adjusted to meet rising costs, among other factors. Instead it has been sustained by transfers of $55 billion from general funds in the past seven years[20]).

Fifty-six percent of public highway funds go for capital expenditures, and the remaining 44 percent is spent on operations and maintenance (O&M). The shortfall of the HTF, influenced by improving corporate average fuel economy (CAFÉ) standards, growing use of alternative energy sources, and less driving per capita, threatens the sustainability of current highway funding mechanisms.

In 2014, mass transit received $65 billion primarily from state and local governments (77 percent). The rest came from the federal budget, including 16 percent of HTF allocations. An estimated $50 billion of public money was spent on operating and maintenance (O&M) (62 percent), and $25 billion (37 percent) on capital expenditures. An estimated $15 billion in fare revenues helped support O&M costs in 2011); capital support was provided about equally by federal and local entities ($7 billion each in 2011)). Federal assistance for capital funding increased by 40 percent between 2005 and 2011 but these funds are still insufficient for eliminating the capital renewal backlog.

Inland waters received $10 billion in 2014, 57 percent of which came from state and local entities and 43 percent from federal funding, half of the latter coming from federal taxes of $0.20 per gallon on diesel fuels consumed by commercial vessels, which goes into the Inland Waterways Trust Fund (IWTF). The remaining federal support comes through Congressional appropriations from general revenues. There is 50-50 cost-share between appropriations and IWTF for new constructions and major rehabilitation projects. Sixty percent of public waterways spending goes into O&M and 40 percent into capital improvements.

Port and harbor maintenance is also supported by the Harbor Maintenance Trust Fund, with taxes on imports and domestically traded goods as its revenue source. The harbor maintenance tax is a

0.125 percent charge on the value of cargo shipped or cruise tickets sold.[21] It is generally levied at coastal and great lakes ports. The fund brought in around $1.8 billion in 2014 in taxes on cargo from importers and domestic shippers using coastal and Great Lakes ports. The money is used for port maintenance such as dredging to maintain channel depths, not for new construction, e.g., investments to serve larger vessels coming through the expanded Panama Canal.

Airports and airways received $36 billion in public money in 2014. Fifty-six percent came from state and local sources and the rest from the federal Airport and Airways Trust Fund, which is fed by a variety of taxes levied on passenger tickets (70 percent in 2014), use of international air facilities (22.8 percent), cargo (3 percent), and aircraft fuel (1.5 percent)[22]. Most large airports collect passenger facility charges (PFC) (limited to $4.50 for every enplaned passenger at commercial airports controlled by public agencies). A maximum of two PFCs per one-way trip is allowed, capping the total passenger PFC to $18 per roundtrip.[23] Airports use these fees to fund FAA-approved projects that enhance safety, security, or capacity, reduce noise or increase competitiveness. Airport and airway funding goes to facilities and equipment as well as research and development. In fact, FAA fiscal year's 2015 budget request of $15 billion allocates $300 million for badly needed maintenance of existing system and, $836 million in Nextgen base funding, most of which is directed to facilities and engineering investments.[24]

Railroads, since they are privately owned, profit-making enterprises, receive the lowest share of public money in the form of grants and loans (such as the Transportation Infrastructure Finance and Innovation act (TIFIA[25]), the Transportation Investment Generating Economic Recovery (TIGER[26]) program and American Recovery and Reinvestment Act funds[27]). Since the passage of the Staggers Act in 1980, which deregulated U.S. railroads, both the opportunity and the incentive to invest in infrastructure renewal increased substantially. The industry has invested $575 billion in infrastructure and equipment in the past 35 years.[28] Some public monies benefiting railroads flow through local agencies investing in economic development projects aimed at attracting or retaining jobs.

Finally, with the increasing difficulty of securing public funds, private money has been drawn into financing, but not funding, public infrastructure through public-private-partnerships or P3s. These typically involved private, up-front financing, designing, constructing and operating roads, bridges, airport projects, and transit facilities, in return for tolls, fare revenues, and/or availability payments from public agencies. Over the past 20 years, more than 80 transportation P3s have been completed in the U.S. involving $46 billion in investment.[29]

U.S. transportation infrastructure is large and aging. Much of it was built more than four decades ago, and is series need of repair and restoration. What monies are spent on this infrastructure go largely to maintenance and rehabilitation, rather than new construction. Where funds are limited, as they are today, it becomes difficult to find the resources to build new and better when the old is in dire need of repair. Where major new infrastructure facilities are built, it is sometimes done at the expense of aging facilities in serious need of rehabilitation.

Conclusion

Adequate funding to maintain, improve, and expand transportation is essential for the system and services it provides, and at the same time it is increasingly difficult to secure those funds in a sustainable way. The impacts of funding shortfalls on the conditions and performance of the infrastructure can be highly visible and broadly felt as capacity constraints, bottlenecks, accidents, delays, and in some cases total failure of facilities. Of course, the U.S. transportation system, its managers and customers, are highly resourceful and self-motivated, assurung that people and goods usually continue to move despite the obstacles presented by deficient infrastructure.

What is less obvious is slow increases in user costs – in time, money, and other resources – that raise the costs of virtually everything in the economy, discourage or block the growth of jobs and income, and reduce economic competitiveness.

It is estimated that Americans lost $160 billion in economic efficiency in 2014 due to poor roadway performance (congestion).[30] Public transit riders have experienced miles of slow zones, breakdowns, derailments, and fires that wasted their time, sometimes exposed them to the risk of injury and death, and discouraged them from traveling by transit. Congestion at interchange points for all modes, rail, highways, airports and airways, ports, and inland waterways, slows the movement of people and goods, increases costs for transportation and inventory, degrades the ability to compete in the global economy and depletes the economy.

ASCE's Failure to Act report estimates if further investment is not made in the system, the mounting cumulative economic (direct) and societal cost could be $651 billion in 2040 due to deficient bridge and pavement conditions and $1,049 billion due to deficient passenger bus and rail and inter-city rail infrastructure. Furthermore, this report estimates that an annual loss of $95 billion in GDP in 2020 and $255 billion in 2040[31] could be incurred if there is a shortage in funding of inland waterways and marine ports. Funding gaps for airports could lead to an annual loss of $47 billion in GDP in 2020 and $70 billion in 2040[32].

Finally, it is important to note that bringing together data on the condition and performance of U.S. transportation infrastructure is made more difficult because of fragmented ownership and responsibilities for facilities and services, the reluctance of private owners and operators to share their data and the long intervals between data collection efforts (which means that some data are years out of date). On the public side, it is even more difficult to secure funds for data collection and analysis than it is to find the resources to maintain transportation facilities.

Filling these data gaps is important to provide an informed basis for investment decision-making, to make the case for the necessary resources , and to track progress and build the knowledge base for smarter transportation infrastructure management decisions in the future.

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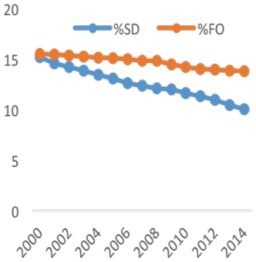
Highways and Bridges

Truck and auto congestion is increasing across all U.S. cities regardless of size

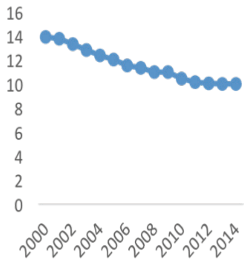
Small cities are experiencing as much as 30 hours of delay/commuter in 2014. Trucks account for 18 percent of urban congestion, though they are only 7 percent of the traffic mix.

Deficient Bridges in U.S.

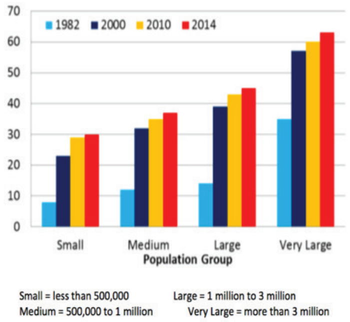


Federal Highway Administration. 2015

Percentage of Weight-Limited Bridges in U.S.

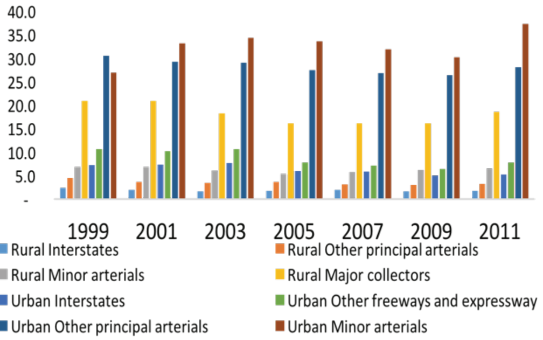


Urban Congestion Trend: Hours of Delay per Auto Commuter per Year



Texas Transport Institute, 2015

Percent of IRI above 171 Percent by Roadway Type



Bureau of Transport Statistics, 2013

About 10 percent of highway bridges have been posted – having legally reduced load limits due to their condition. Pavement condition on Interstate highways is better than on lesser roads, with more heavily used urban facilities showing deterioration.

Increasing highway expenditures, static HTF revenue, increasing transfers

Public spent $165 billion in 2014; non-federal: $120 billion; federal $45 billion.

$ 55 billion from general funds in the past seven years.

Public Spending on Highway by Source

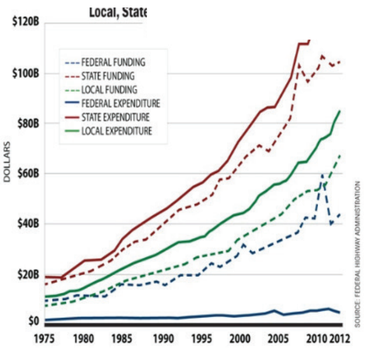


Figure Source: fleetfinancials.com

Highway Trust Fund Revenue and

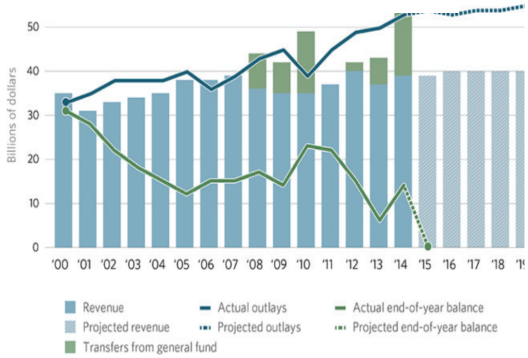


Figure Source: pew charitable trusts

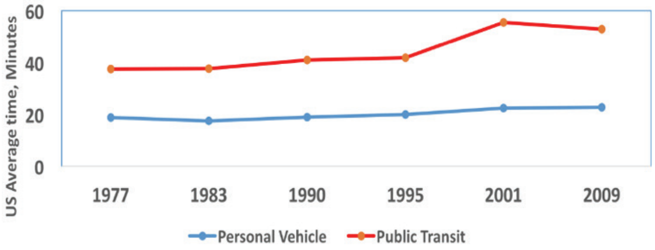
Highways and Bridges Costs and Performance Impacts Reduce Productivity, Efficiency, and Global Competitiveness; 2014 congestion impacts: $160 billion drain on economy; $28 billion by trucks; 3.1 billion gallons of fuel wasted.

Mass Transit

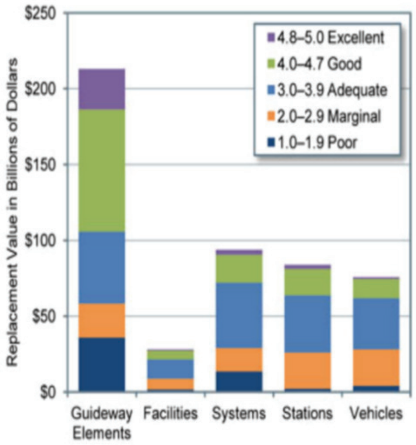
Longer commute times in transit, widening the gap with auto commute

Growing transit commute times indicate potential deteriorating performance or increased accessibility. The widening gap between transit and auto commute translates into a decreasing competitiveness of transit travel with respect to auto travel.

Average Commute Times – Drivers and Transit



A third of transit assets remain in poor to marginal condition with growing backlogs



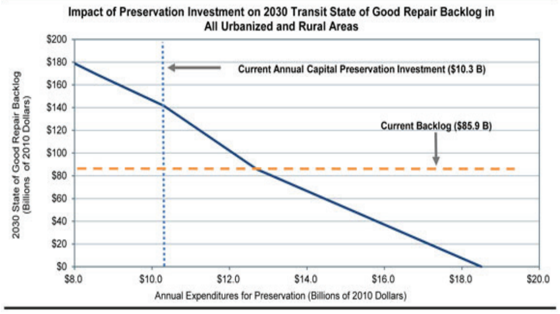
Data source: FHWA, 2011

Figure Source: FHWA, 2013

State of Good Repair

The current estimated transit capital preservation backlog is $86 billion annual reinvestment is $10 billion. This rate of reinvestment would have to double to clear the backlog by 2030. Large regions with high levels of transit utilization generally do better at maintenance and preservation than smaller communities, where the need for quality transit is less apparent.

Figure Source: FHWA, 2013



Capital renewal and investment funds not meeting current needs; Trends are not promising in the long-run

Currently, state and local governments provide nearly 80 percent of the funds for transit infrastructure, mainly maintenance and rehabilitation but many governmental units at these levels are strapped for cash.

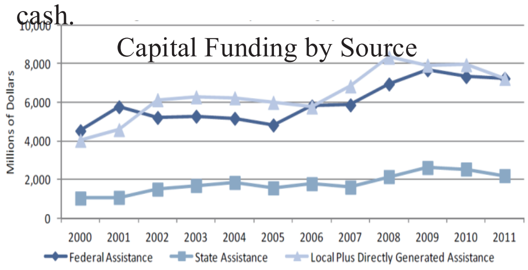
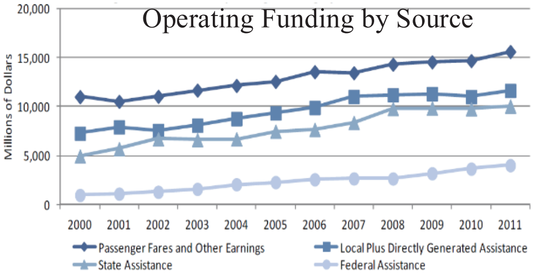


Figure Source: APTA, 2013



An efficient and accessible public transit system benefits society and the economy through access to jobs and healthcare to transit-dependent users

<u>The risks:</u> cash starved transit systems have experienced extensive slow zones, as well as breakdowns, derailments, and fires, wasting time, discouraging ridership and sometimes resulting in injuries and fatalities.

Freight Railroads

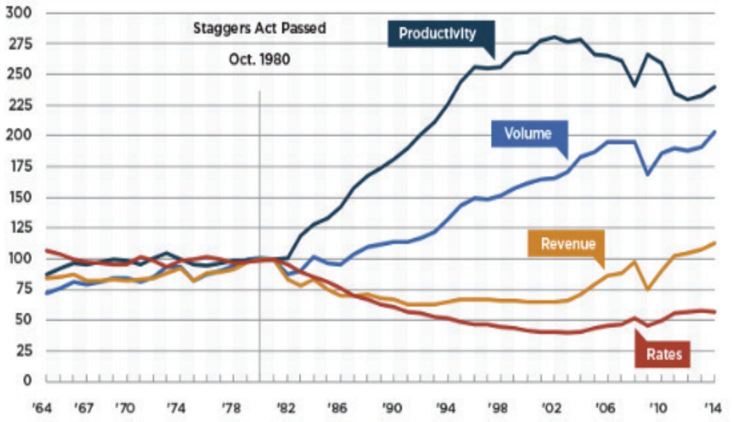
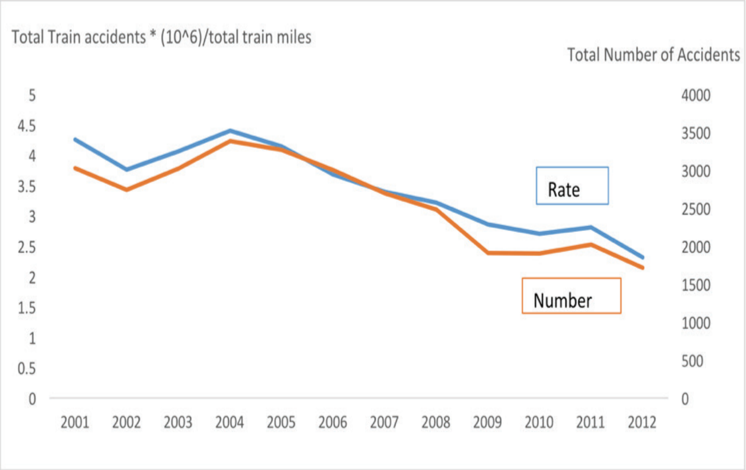


Figure Source: AAR, 2015

Critical bottlenecks at interchange and intermodal hubs – e.g., Chicago (trains passing through Chicago are delayed as up to 30 hours) and ports of LA/LB. Increased productivity reflects increased investment in the system.

Decreasing train derailments reflecting improvements in conditions

Rail Train Accident Trend

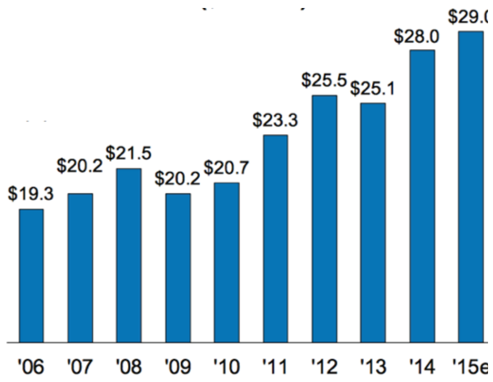


Data Source: FRA 2012

Spectacular derailments continue to exist and are notable because of major spills of hazardous materials.

An increased number of the population is exposed to crude oil moving from mid-continent oil fields to coast refineries and its potential dangers.

Increased freight railroad investments in infrastructure and equipment driven by market growth and consistent earnings. Railroad Investments improve rail freight service to customers-capacity, times, travel and reliability



*Capital spending + maintenance expenses. e - estimated
Data are for Class I railroads. Source: AAR

Railroads invest at a substantially higher rate than most manufacturing industries.

Waterways

Inland waterways vessel delays reflect insufficient lock and channel capacity

Percent of vessels delayed in the U.S.

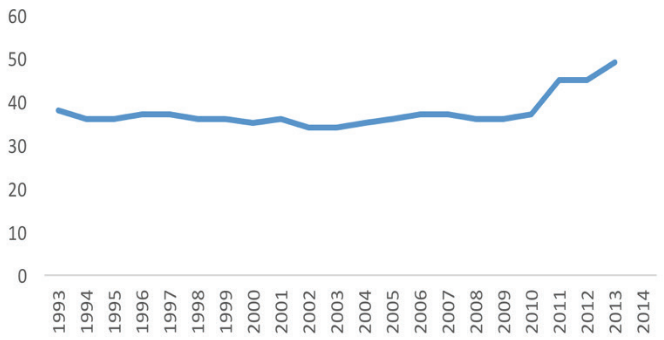


Figure Source: USACE, 2015

Queue delays occur mostly on the Ohio system (12,000 hours in January 2012), followed by the upper Mississippi system (6,000 hours in January 2012).

Port congestion is mainly in the largest container ports in Los Angeles and Long Beach, Seattle, Virginia, New York and New Jersey.

Decreasing lock unavailability indicates some improvement in condition. However, it does not address capacity limitations

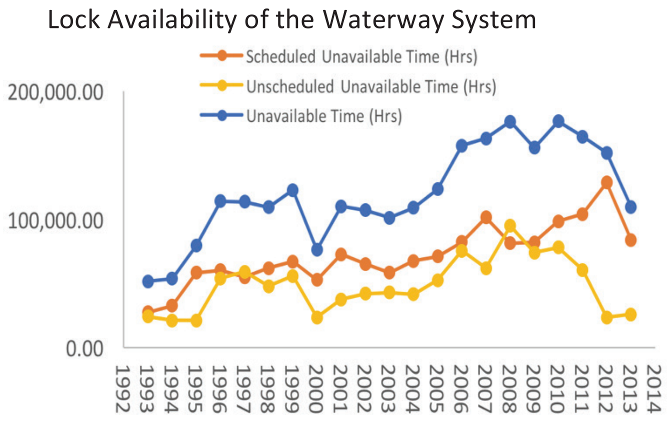


Figure Source: USACE, 2015

Limited lock capacity, locks out of service, and channel conditions (e.g,, depth) cause system bottlenecks.

The fraction of time that locks are unavailable due to unplanned maintenance has been decreasing. In 2013, there were 15,937 hours of unscheduled unavailable time compared to a peak of approximately 95,000 hours in 2008.

Strong reliance of federal funding on fuel tax, decreasing Trust Fund balance

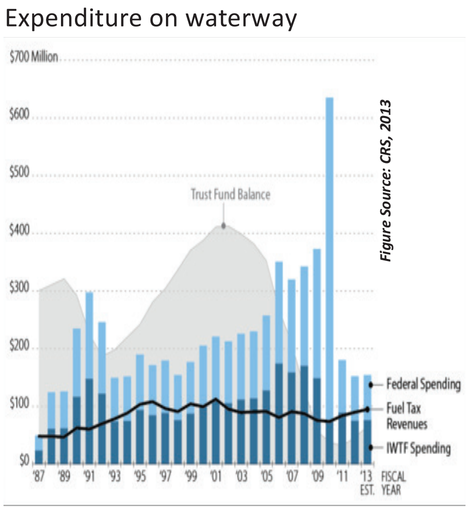


Figure Source: CRS, 2013

Delays in the waterway and port systems affect the ability of energy and agriculture businesses to compete in global markets.

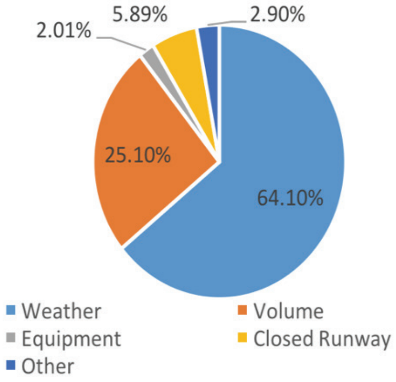
While cargo flows on the inland waterways are bulk commodities, the growing trend to use the marine highway network for container freight increases the importance of keeping locks, dams and channels in good condition and with sufficient capacity.

Airways

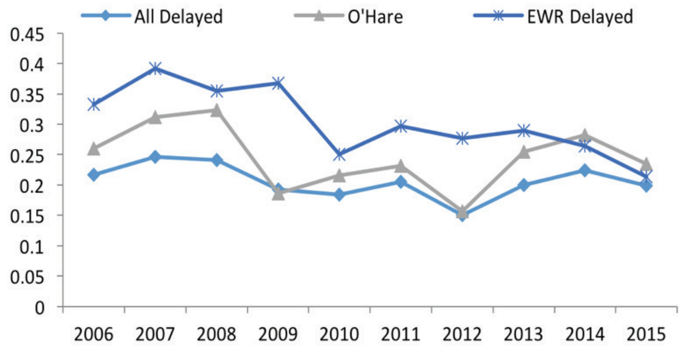
Airport delays reflect physical and operational airport capacity limitations

Only a few U.S. airports operate close to capacity many hours each day – Newark, Chicago O'Hare, Boston, New York LaGuardia, Atlanta, and Miami. However, delays at major airports ripple through the national airport system and affect many flights. Over the past decade, delays at U.S. airports have been decreasing.

Share of National Aviation



Percentage of flights delayed



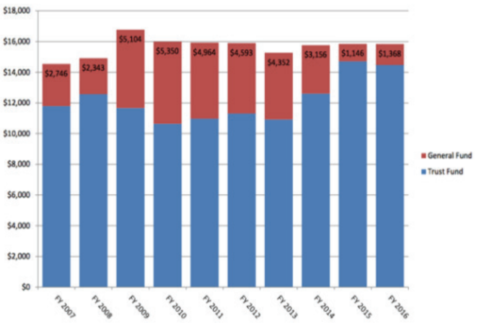
Data Source: BTS, 2013

High percentage of airport pavement in good condition but deficiencies remain, mainly in runway operational capacity – number and length

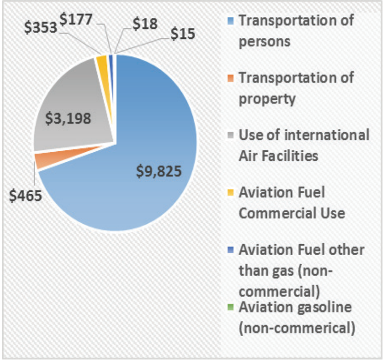
Adding capacity through infrastructure expansion is difficult because most airports are land-constrained. Capacity gains will continue to come from advances in air traffic control technology (NexGen). At some airports these gains will be blocked by taxiway, terminal, and ground access constraints.

Strong federal interest in airports, airways for interstate shipments, travel

Yearly Expenditure from General and Trust Fund



Airport an Airway Trust Fund Tax Revenues in 2014



Data Source: FAA, 2015

Since funds come largely from user fees – passenger and fuel charges, aviation is reasonably self-sustaining as long as public funds are well-spent. Delays experienced by passengers flying for business meetings or tourist destinations, and by cargo are closely connected to capacity of airport infrastructure.

The performance and condition of the U.S. air infrastructure play a significant role in long-distance mobility of people and high value goods

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CHAPTER THREE

Transportation Infrastructure and Economics

By Ian Savage

Introduction: Macroeconomic shocks shape future infrastructure

What will the transportation system in North America look like in the year 2050? How will the underlying economics of transportation, and potential changes in the economics, affect the evolution of the transportation network? What will these changes mean for the economic vitality of the continent?

In the next 35 years, macroeconomic shocks as large and as unpredictable as those seen in the last 35 years can be expected. There will be periods when the economy is in recession, and there will be a slowdown in traffic and a shortage of capital to expand transportation infrastructure. There will be other periods when swift economic growth leads to a surge in traffic and chokepoints will emerge in the network. Both phenomena have been experienced in the past decade. Surging demand led to a capacity crisis in all modes of transportation that figured in the deliberations in 2006 and 2007 of the National Surface Transportation and Revenue Study Commission.[1] In contrast, there was a period of excess capacity that followed the 2008 financial crisis.

This chapter does not make any predictions about the business cycle but it does look at long-run changes in the economy and changes in the inherent economics of the transportation sector that will shape the future. It is organized geographically, starting out with considering infrastructure within cities, then looking at intercity transportation (subdivided into highways, and then other modes),and then finally infrastructure to support international trade.

Urban transportation: The interaction between infrastructure and urban form

Defining the transportation infrastructure needs for cities in 2050 is co-determined with thoughts on how cities will be structured in 2050. It is co-determined because there is a "chicken and egg" relationship. The structure of cities determines transportation infrastructure needs, yet building of infrastructure can help shape the cities of tomorrow.

The long running general drift of the U.S. population from rural to urban areas is expected to continue. But what about the structure of the cities themselves? One way of thinking about the future direction of cities is to consider how they have evolved during the past 150 years. To do so, the terminology and diagrams that were proposed by J. Michael Thompson will be used.[2]

Prior to 1850 in the U.S. and Europe, and until the 1960s in many places in the developing world, people lived close to their places of work. Stores for daily purchases were located nearby. There was generally a downtown area devoted to finance and government business. Thompson describes these cities as the "Low Cost" city archetype (Figure 1).[3] Such cities have limited private vehicle ownership and a limited need for infrastructure as most people's daily existence was within their local neighborhood. Walking or bicycling (and long ago, horses) were the predominant forms of transportation and people lived at high densities. To a great extent, Chicago in the early 1890s still resembled this type of city.

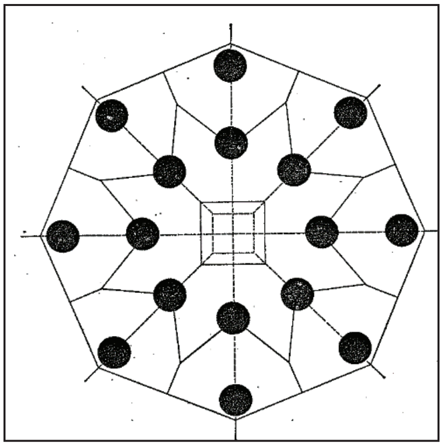

Figure 1: "Low Cost" city

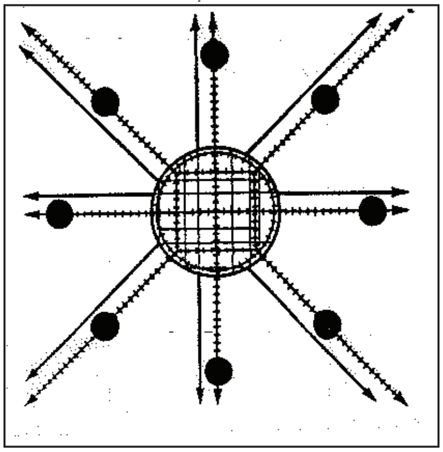

Figure 2: "Strong Center" city

At the turn of the 20th Century in the U.S. and Europe, cities metamorphosed into the "Strong Center" archetype (Figure 2).[4] People were able to use the new streetcars and commuter railroads to live at lower densities and commute to the factories, shops and offices located in the center of town. The boulevard road systems and the rail systems are all oriented toward the center. Smaller sub-centers arose around the suburban residential areas that were linked to the center by rail transit. Almost all of the major cities in the U.S. were of this form at the end of the World War II.

The biggest challenge to this form of city came with the automobile age. Post-war affluence led many people to purchase single-family homes on the edge of existing cities. Manufacturing businesses moved from inner city locations close to rail yards to suburban locations close to truck terminals near Interstate highways. Despite these changes, a small number of cities retained a strong central core. New York is the classic city of this type in North America and perhaps it might be the only example. Cities of this type have often adopted, by design or geography, a "Traffic Limitation" strategy (Figure 3)[5] whereby roadways have not been improved so transit is still the superior option, even in off-peak periods. Geography also plays a large part. In New York, the coastline and the rivers limit expansion, and by necessity, people have to live at high densities.

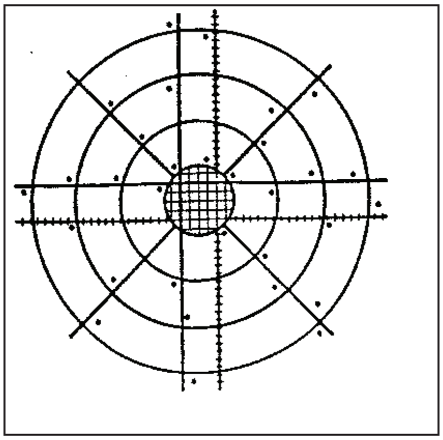

Figure 3: "Traffic Limitation"

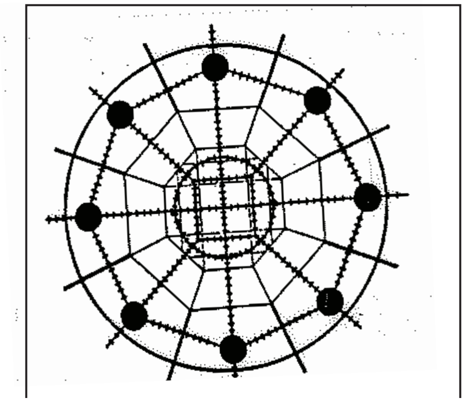

Figure 4: "Weak Center" city

However, many secondary cities have yielded to the auto age. These "Weak Center" cities (Figure 4)[6] have lost much of their downtown employment to suburban centers. The result has been urban sprawl and increasing congestion in the suburban "edge cities." Typically, a downtown remains to host government, regional financial and business centers, art galleries, specialty stores, theaters, and "café society." The size of the downtown, typically representing about 15 percent to 20 percent of city employment, requires a transit system to supplement urban freeways. However, in the off-peak, the road system can cope with the traffic, so there is limited off-peak transit demand. This leads to costly peak only transit systems with poor financial performance. Classic examples in North America include Chicago, Philadelphia, and Toronto. In the 1960s and 1970s, social problems emerged as the inner city decayed and poorer inner-city residents did not have good transportation links to better paying jobs that had moved to the suburbs. Mayors of Weak Center cities are typically preoccupied with ensuring that their downtowns do not get any weaker. They do so by subsidizing transit to make commuting to downtown easier and cheaper, investing in infrastructure downtown, giving tax breaks to downtown businesses and exercising planning controls. Transportation policy has become a major part of the response to ensuring the survival of downtown in these types of cities.

Most cities that emerged after the auto age in the southeastern, southern and western United States (such as Tampa, Dallas and to some extent, Los Angeles) are of the "Full Motorization" archetype (Figure 5).[7] There is no real downtown to speak of, there are many smaller sub-centers around the region, and the low density living and working means there is often only a token transit bus service. In addition to the newer cities, there are a number of former weak-centered cities that have turned into the full motorization archetype. These range from smaller places like Memphis to the large ones such as St. Louis and Detroit where flourishing downtowns of 100 years ago, supported by a large streetcar system, have virtually disappeared.

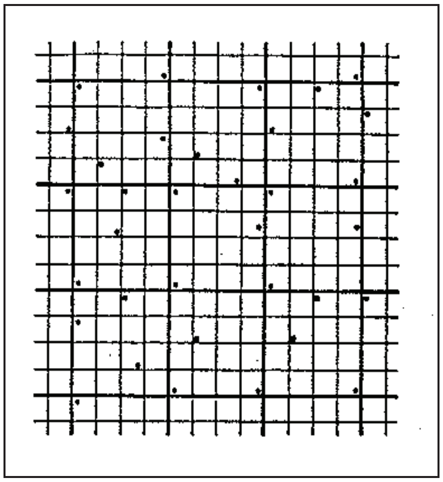

Figure 5: "Full Motorization" city

Urban transportation: The drivers of urban change

In considering the 150-year evolution of American cities, there appear to be two major underlying economic drivers of these changes:

- Declining transportation costs. Out-of-pocket expenses declined and travel time fell as new infrastructure was built radiating out from city centers. This made cheaper land on the periphery of cities more attractive for both employment and residential purposes. Companies and individuals who valued, and still value, the benefits of low density living and working opted to move to the periphery.
- Declining "agglomeration economies." It is no longer as essential for businesses to locate in physical proximity to each other to transact commerce. Even within individual companies there was a declining need for the front office, the back office, the manufacturing facility and the warehouse to be situated on the same site. Functions that do not have to be located downtown can be relocated to the suburbs. The movement toward intercity trucking meant that manufacturing and warehousing no longer needed to be located around historic

downtown railroad yards. Modern railroad intermodal facilities followed industry to the suburbs.

What is likely to happen to these underlying economic drivers in the next 35 years? It is clear that electronic commerce reduces agglomeration economies. So while some tasks will continue to require face-to-face contact, the demand for face-to-face contact as opposed to video conferencing and the like will decrease over time, further undermining the economic necessity for a “downtown.”

A continuation of the declining costs of transportation evident in the 1950s through 1970s in future years is perhaps more questionable. The congestion-free roads of 1950s suburbia are history. Nowadays living in suburban areas and commuting to downtown is frustrating and time consuming whether commuting by automobile or public transit. As congestion has grown worse, basic urban economics models of the “monocentric city” (a single central business district surrounded by rings of housing) suggest that people will move their residences back from the suburbs into more central locations. The urban gentrification of decaying inner city areas witnessed since the 1980s is consistent with this hypothesis.

Of course, congestion on the roads connecting the suburbs to downtown could also lead to decentralization. If households continue to desire low-density living, and there are declining agglomeration economies, then even more firms would relocate activities to the suburbs and exurbs to attract employees. The city would then trend toward the full motorization archetype.

How these trends will play out is partly beyond the transportation sphere. For gentrification to continue, the quality of public education has to improve to make the city appealing for families. There is no doubt that inner-city density leads to urban amenities such as dining and entertainment that are attractive to singles and empty nesters. To the extent that people are marrying later, and living longer, there would seem to be a growing segment of the population that has a desire for dense urban living. But for families this is not true, and for companies looking for a workforce that is not solely in their 20s, it is not clear that downtown will continue to be a desirable place to locate.

But some of the trends may be determined within the transportation sphere. Perhaps the most intriguing is the introduction of semi- and fully autonomous vehicles that free drivers of the aggravation of the driving task for at least part the journey. It seems highly likely that these vehicles will come to fruition and may even dominate the highways by 2050. What will this mean for urban form? The basic urban economics models suggest that autonomous vehicles will reduce transportation costs. Perhaps they will allow for more efficient use of highway space and reduce travel times. More likely, depending on the technology and legal changes, people will regard travel time as less onerous as they can multi-task and engage in other activities while in their car. The intuition from traditional urban economics models is that sprawl will increase, and there will be a further need for infrastructure investments at the edges of existing cities.

There are several counterarguments that might result in autonomous vehicles increasing density. One is that vehicle automation will remove the biggest headache of urban driving which is finding parking. If one could arrive at one’s home or workplace and be dropped off at the door and then the vehicle is commanded to go automatically to a distant parking lot (and the same occurs in reverse when the vehicle is needed again), living in a dense neighborhood may become a lot more attractive. Of course, all these unoccupied vehicles shuttling back and forth to and from remote parking lots may, rather paradoxically, make downtown traffic congestion worse rather than better.

Another counterargument is that autonomous vehicles might change the nature of how people consume automobiles. Proponents of this counterargument argue that consumers will no longer own vehicles but rather rent shared vehicles by the hour or trip. This changes how the costs of travel are perceived. With an owned vehicle, most of the costs such as the initial purchase and insurance are "fixed costs" and the marginal cost of a trip is just the cost of fuel. With a rented shared vehicle the fixed costs are now spread out and recouped on every trip. Consequently, the marginal cost of a trip will be higher in a rented rather than owned vehicle, and the urban economics models predict that people will live closer to the center of cities and density will increase. For such a counter argument to hold there would need to be a large change in preferences from owning assets to sharing them. The counter argument also presupposes the pricing scheme for shared cars. Pricing schemes with a higher annual or monthly fixed payment and low per trip costs (called "two-part tariffs" by economists) are also likely, and these would perpetuate the existing incentives for trip making and residential location.

All-in-all, there is a strong suggestion that the trends set in motion after World War II of increasing sprawl and weaker downtowns will continue. Albeit, there will be a limited regeneration of some inner-city areas as singles and empty nesters move into neighborhoods with plenty of amenities. Blighted neighborhoods that had suffered from segregation, outward migration of industry and population, and social strife in the 1960s could again become desired residential locations. But what about the poorer people who are displaced from the gentrifying areas close to downtown? It is likely that displaced populations will move to older inner suburbs. These suburbs will then struggle to maintain their municipal infrastructure as their tax base declines.

Overall, there will be continued pressure to provide additional infrastructure on the edge of cities and a rebuilding of some infrastructure in inner city areas that have been underutilized and under-maintained for 50 years. At the same time, there may be a decline in the condition of the infrastructure in older inner suburbs.

Urban transportation: Regional competition between cities

The previous section dealt with the infrastructure implications of the tension between downtown, suburbs and exurbs within an individual city. Overriding this is inter-regional competition between cities. During the next 35 years, it seems likely that the megatrends of a movement of population and economic activity from the northeast to the south, southwest and northwest sections of the country will continue.

In this scenario, Atlanta will flourish and Akron will languish. Some cities such as Nashville will see explosive growth that outstrips the infrastructure (both in downtown and on the edges) that was designed for a much smaller city. Cities that are successful will respond by investing to ensure mobility, water supply and other public infrastructure. Cities that fail to do so will be passed over as firms and households make location decision. If Austin, Texas becomes hopelessly congested, then firms will look to other places.

A wide swath of Pennsylvania, Ohio, southeast Michigan, and inland areas of New York and other northeast states could see cities with stagnating or declining populations and economic activity. In some cases, the infrastructure put in place in the 1950s and 1960s will be excessive compared with current demand but will decline in quality as the tax base erodes the funds for maintenance.

Urban transportation: Public transportation infrastructure

How the structure of cities evolves in the coming decades has implications for public transportation infrastructure as well as highway infrastructure. Outside of New York City, there appears to be a trend for a weakening of city commercial centers. The decline in the density of downtown workplaces undermines the need for an extensive transit system to support peak work journeys to downtown. Even in those cities where an active commercial downtown remains (such as Chicago, Boston and similar cities), the financial base has been and will be weakened as off-peak trips switch to private transportation. Consequently the financial base to support transit infrastructure renewal and maintenance is eroding and will continue to do so.

The financial undermining of transit infrastructure in traditional transit cities stands in stark contrast to the construction in the past 30 years of new rail-based systems in southern and western cities that had not seen rail services in the previous half century. Dallas and Denver are good examples of such cities. Los Angeles is unusual in that the rail service is in some ways replicating the electric rail system that helped shape the city a century earlier. Other cities such as Salt Lake City, Portland, Oregon, and Houston and many others have seen the construction of more modest systems using light-rail technology.

The problem is that the construction has been entirely funded by the government, including federal funds through the “new starts” program, with fares only covering a fraction of operating costs and none of the capital costs. In some cases, bus service has been reduced to pay for the expanded rail service. John Kain, in his study of Atlanta, concluded that the citizens would have been better off if the expenditures used to construct and operate a rail system had been used for better bus services.[8]

So is the construction boom in light-rail witnessed since the 1980s coming to an end? Will the public tire of the bond issues and local taxes necessary to build and operate these systems? Some of the systems (Sacramento and San Jose, California, to name just two) have had very disappointing ridership. Rather paradoxically, some transit lines, with their highly subsidized fares, may encourage people to live further from work than they would otherwise, leading to more rather than less sprawl.

Bus Rapid Transit (BRT) has had many vocal proponents for many years, but few systems have been built in the U.S. BRT covers a range of options, from exclusive lanes and signal priority for buses at one extreme to separate rights of way at the other. BRT has much lower capital and operating costs than rail-based alternatives. It might be seen as an alternative to some light-rail lines, and even to some heavy rail lines in corridors with only moderate ridership. Perhaps a stronger case can be made for BRT as an alternative to some existing heavily traveled bus routes, where it promises to deal with the big disadvantage of bus service, the slow travel times as the buses travel in congested regular traffic lanes and stop frequently. If BRT became more common, one could imagine that many city streets and intersections would need to be reconfigured to provide dedicated bus lanes for part or all of the day.

Public transit, both bus and rail, has been largely in the public sector since the 1950s and 1960s. There is well-documented evidence that costs rose rapidly, particularly in the 1970s. The workforce pay and conditions set in the 1970s have persisted for a third of a century and are now well entrenched. The U.S. generally did not follow the post-1980s trend in Europe, Australia and South America of a greater private sector involvement. Full deregulation and competition are rare worldwide but competitive contracting is common whereby private companies compete in government tenders to provide service at the lowest net subsidy. In effect, the operation of services has been decoupled from political decisions regarding which services to provide. Large multinational firms, primarily based in Europe and Asia, have emerged to provide these services. These firms have made limited inroads into the scheduled urban transit market in the U.S., although they do have a large presence in the school bus and inter-city bus market.

What would happen if certain states or cities decided to emulate London and Sydney and reintroduce the private sector into transit operation? If costs fell would there be more bus service or expanded rail service for the same or fewer subsidy dollars? While privatization does not seem likely in the near future, developments that are occurring in a related market might bring about a situation where competition emerges in the transit market.

The ride-hailing companies, such as Uber and Lyft, are controversial and receive a disproportionate amount of press at the moment. But these companies are responding to a genuine market problem. An alliance between taxicab companies and local politicians over many decades has led restrictions on entry to the market. The result has been poor taxi availability and expensive services. Whatever one may think of how Uber and its competitors run their businesses, they have exposed an entrenched situation that has not served the public well.

What might happen if some derivative version of the current ride-hailing service becomes legal and widespread? To some extent it might make living in cities more attractive. One of the big disadvantages of living at high density is finding parking. If a new taxi market offers lower prices and more service, living in the city and not owning a car becomes more attractive. One could imagine that an attractive market for deployment of autonomous vehicles would be in taxi service. The cost of taxi service would fall even more and the overlap between a taxi, a shared automobile, and a traditional rental car would become even more blurred.

Of course, while these new taxi services largely take customers away from traditional taxi services, they also are attractive to some people who would formerly have driven and also to some who currently take transit. Particularly if shared-ride taxis become legal (that is a taxi shared by more than one unrelated parties with a similar destination), one could imagine that these services could offer faster travel times than transit (certainly for buses) at attractive fares. If slightly larger vehicles are used as shared taxis, it is likely that the shared taxi could match the (highly subsidized) bus fare.

In these circumstances the world would have come full circle with a reintroduction of the "jitney" that transit companies and local governments had legislated out of existence in the 1920s. Clearly, this would be detrimental for existing public transit companies and their employees, and may act to further undermine the case for light-rail construction. But it would be a boon to riders in many cities, especially in smaller cities (such as Birmingham, Alabama and many similar cities) where traditional public transit has withered.

All-in-all, it would appear that transit construction, other than retrofitting highways for BRT, is likely to be less prevalent in the next 35 years than it has in the past 35 years.

Urban transportation: City center congestion pricing

From Singapore to London to Copenhagen, there has been an interest in dealing with downtown traffic congestion by establishing a toll cordon. Drivers wishing to travel by auto within the cordon at busy times of the day have to pay a fee. A similar scheme was recently proposed for Manhattan, but was blocked in the state legislature. With the exception of Manhattan, and perhaps downtown Boston, congestion in the U.S. is very different from that in Europe and Asia. Many cities on those continents have a legacy of city centers with medieval land use and streets. Most congestion in the U.S. is on the links from the suburbs to downtown. Circulation in the downtown area, while difficult for short periods of the day, is often less of a problem. Therefore, it seems more likely that the economists' solution to traffic congestion in the form of pricing will occur on individual links rather than by establishing a cordon around downtown. Pricing on individual links will be discussed in the section on intercity highway transportation.

Urban transportation: Parking

The biggest change in the economics of transportation in the coming decades will occur in the previously staid world of parking. In recent years, transportation economists have started to model the effects of changes in parking rates, and planners have debated how the quantity and pricing of parking effects land use and economic activity.[9] In the business world there has been entry into the market of firms offering innovative technology to provide drivers with information about vacant parking places, and even incumbent large firms who own and operate parking lots have experimented with innovative products and pricing.

Some of these changes have and will manifest themselves in ways that affect infrastructure. These include:

- Installing sensors under on-street parking spaces to detect occupancy.
- Providing information on available on-street spaces to drivers to reduce "cruising" to find parking.
- Providing information on availability and pricing of off-street lots.
- Dynamic pricing of on-street parking to ensure that some spaces are always available.
- Using parking prices as a surrogate for a toll cordon around congested downtown areas

This will mean that the traditional uniformity of parking prices at meters (the same cost per hour at most times of day, and similar prices for all spaces within a certain area of the city) will disappear. Prices will fluctuate to regulate demand, and will vary geographically even within small areas as people are given incentives to save money by parking one street away from their destination.

As soon as on-street parking becomes a commodity with a price that reflects its value, some infrastructure questions that have been dormant for decades will re-emerge with a new urgency. What is the optimal mix of traffic lanes and parking lanes? Is displacing parking to provide bicycle lanes or BRT lanes wise? What happens when parking is displaced for (non-highway related) construction?

Intercity highway transportation: **The movement to tolls and managed lanes**

Economists have been discussing pricing to deal with highway congestion for decades. Writers such as William Vickery and Alan Waters developed the concept in the 1950s.[10] However, such pricing only existed in academic journals for the next 30 years. But a perfect storm has occurred that has transferred these abstract ideas into practical implementation. The first part of the perfect storm was the worsening of congestion. The problems that Vickery and Waters were concerned about became more rather than less pressing.

Second, technology changed. In the 1970s, Singapore deployed a congestion pricing scheme based on stickers on a windshield and monitoring by police officers in the equivalent of toll booths. Today, transponders have eliminated traditional toll booths. Drivers no longer have to stop and pay. Electronic pricing means that it is possible to charge complex tolls schedules that vary, for example by time or day or by the actual level of congestion. In former days cash payments meant that toll schedules had to be simple.

The third part of the perfect storm has been the decline in the traditional form of paying for roads which is to say the tax on gasoline. For decades, the gas tax had been an effective method of paying for highway infrastructure with a generally low cost of collection and limited tax evasion. The erosion of the real value of the federal gas tax due to inflation, and the introduction of more fuel efficient and alternative fueled vehicles, has led to the well documented undermining of the federal highway trust fund. Diversion of trust fund monies to transit and other uses has also been part of the story.

Faced with declining revenues from traditional tax instruments, the newfound technical ability to collect tolls, and the existence of plenty of congested roads have led to an explosion of interest in directly pricing highways in some form or another. This trend is likely to continue as the federal gas tax becomes even more of a shadow of its former self, and as users see the benefits of better traffic flow and reduced travel times from highways where capacity is regulated by price.

When economists talk about congestion pricing they mean tolls that vary with the level of traffic. Some intercity highways in the eastern U.S., and also many bridges and tunnels, charge tolls that do not vary by time of day (and hence traffic levels). These would not be considered congestion prices. Albeit that with electronic toll collection, the conversion to more sophisticated pricing schedules is quite easy. That said, even if tolls do not vary by time of day, the direct financial relationship between drivers and the providers of specific highway infrastructure in these circumstances changes the incentives for the infrastructure provider. Poor infrastructure condition and bad travel times reduces traffic and the revenue flow. Therefore, many of the comments in this section also apply to tolled facilities where tolls do not vary with congestion.

Most of the interest in tolling and congestion pricing in the past decade has been on routes that are used by commuters within metropolitan areas. Therefore to some extent, the discussion in this section should be considered in conjunction with earlier comments on urban form. In addition to commuting routes, there are also highway links outside of metropolitan areas that have become congested. Much of the congestion on these routes comes from truck traffic. Therefore, the discussion that follows applies both to limited access highways that are commuting routes as well as busy inter-city highway links.

The good news for infrastructure provision is that tolling, both congestion-based and flat rate, creates a direct consumer-to-producer relationship between drivers and highway agencies. The gas tax was an indirect pricing mechanism where there was limited market signaling and no market feedback for poor service. But when drivers are paying directly, they will expect that an adequate and properly-maintained product is provided. Conversely, highway agencies can justify higher prices if consumers can see that the extra monies are used to rehabilitate or expand the facility and to provide for good maintenance. Further discussion of capacity expansion and the possibility of the introduction of private capital will be discussed in the next two sections.

The remainder of this section will deal with the infrastructure aspects of “managed lanes” that arise when congestion-based tolling is introduced. In many locations, especially in urban areas, the width of the right-of-way is limited and physical expansion is not possible. Tolling can facilitate making better use of the existing pavement by managing the some or all of the traffic lanes. Manifestations include:

- Allowing additional vehicles to buy into existing underutilized high-occupancy vehicle (HOV) lanes;
- Shifting of some price sensitive traffic from the height of the peak to the shoulders of the peak, or to the off-peak;
- Shifting other low-value traffic to alternatives routes and modes;
- Increasing total traffic capacity by pricing a subset of the lanes to be paid “express lanes;”
- Ensuring swift minor repairs, and effective snow removal as poor road condition will reduce traffic and revenue;
- Scheduling rehabilitation activities so as to minimize disruption to traffic and hence revenue loss and structuring contracts with construction firms to incentivize prompt completion of the work and avoiding project overruns; and
- Dynamically managing traffic flows to avoid reaching the threshold at which very high lane volumes lead to flow breakdown, where traffic flow actually falls and does not recover until the peak period is over.

As soon as traffic flow becomes the basis of the revenue stream, the highway authorities have incentives to seek out other ways to make best use of a space constrained facility. These can include:

- Eliminating one of the shoulders when two shoulders exist on each carriageway;
- Permitting shoulder running at busy times of day; and

- Narrowing existing lanes to create additional capacity at all times of day or just at certain times of day by using dynamic lane striping.

The great advantage of the trend away from the gas tax and toward tolls is that highway agencies now have direct incentives to manage their assets and to make the best use of them.

Intercity highway transportation: Dealing with new capacity

The move from indirect pricing of highways by gasoline taxes to direct tolling not only affects how highway authorities decide on making most efficient use of existing infrastructure but also how they decide on whether to expand that infrastructure. A basic theory of the transportation economics literature dating from work by Herbert Mohring, Mitchell Harwitz and Robert Strotz in the early 1960s[11] is that, with a number of caveats, congestion fees will just cover the cost of expanding the facility to an "optimal" size. In effect, a congested facility will generate funds to self-finance congestion relief. To an economist, an "optimally" sized facility is not necessarily a congestion-free facility, but rather one in which the marginal cost of capacity expansion is equated with marginal travel time savings.

Consequently, when roads are tolled to control congestion, justified infrastructure expansions are paid for by the existing users. Rather paradoxically, the decline of the highway trust fund may actually lead to more rather than less infrastructure investment if tolled highways become the norm.

The self-financing principle should mean that for congestible tolled facilities, there is no need for additional external funding from other tax instruments. Conversely, it suggests that monies from optimally-tolled facilities should not be diverted for non-highway purposes.

Intercity highway transportation: Public-private partnerships

As soon as some highway links become viewed as a commercial proposition, it is possible that there will be capacity expansions that differ from traditional methods of design, construction and management.

The past decade has already seen the entry of commercial toll road operators both in bidding for leases of existing facilities, and in building and operating new facilities. New public-private partnerships (P3s) have emerged in providing new highway capacity in Washington, D.C., Miami, Dallas, Denver and other places. In many cases, these private firms have had to use public-sector bonding for various tax and legal reasons but they have also introduced new private capital. As highways become more congested and tolling more commonplace, P3s are likely to become more common for both construction and operations.

The commercialization of highways may also lead to innovative and new designs. The most likely are separate truck-only facilities. In highly congested corridors, the trucking industry may be very willing to pay for exclusive additional facilities that are designed for the dimensions, geometry and axle loads of large trucks. Conversely, it is not inconceivable that other facilities may be built exclusively for light-duty vehicles featuring narrower lanes, steeper grades, thinner pavement and reduced vertical clearance.

However, a congested highway is a "scarce resource" and it is possible that private highway concessionaires could treat it as a "cash cow." They could charge excessive prices to earn super-normal profits that are not plowed back into maintaining and improving the highway. In fairness, it should be said that this can also occur when highways remain in the public sector when excess revenue is collected that is diverted to non-highway uses. An example would be the bridges and tunnels into New York City. When private profit is involved in highway provision, it is likely that there may need to be a resurrection of the type of government regulation that ceased to exist in other transportation modes in the 1970s. It is quite conceivable that a regulatory framework will need to be established to prevent private toll road operators charging excessive prices or underinvesting in product quality.

Intercity highway transportation: Inter-regional competition

It is likely that there will be continued movement of population and economic activity from the northeast to the south, southwest and northwest of the country. Some areas will require expanded intercity highway capacity while other areas will not face that pressure. In addition, changes in the location of industry and a likely increase in international trade will pose particular demands on trade routes.

It seems likely that manufacturing capacity will continue to grow in Mexico. The infrastructure on the border and along the major trade routes, particularly Interstate 35, is already overwhelmed, and major upgrades may be necessary in these corridors. Likewise, expansion may be necessary on the highway routes out from the major ports on the west coast, gulf coast and eastern seaboard.

Inland waterways

Barge traffic on the Mississippi River system is an unheralded part of the nation's freight system. Much of the infrastructure discussion has focused on renovations and expansion of the locks on the upper Mississippi River above St. Louis which were constructed in the 1930s. At 600 feet in length, the 1930s locks suffer from additional congestion as 1,200-foot barge tows have to be split to pass through them.

Agricultural products for export are the majority of the traffic but there is also a sizeable traffic in oil products and chemicals. As with highways, the funding system has not encouraged infrastructure investments. A tax on marine diesel fuel goes into a trust fund. However, this trust fund is not sufficient to pay for investments. Indeed, projects that do move forward are half funded from the trust fund and half from appropriated general tax revenues. Operational expenses come from general tax revenues.

Consequently, only a small proportion of the reconstruction, maintenance and operational expenses of waterways are paid for by users. With the direct beneficiaries shouldering so little of the costs, it is no wonder there has been insufficient investment.

Major investments in the upper Mississippi River are only likely in two circumstances. The first is if agricultural interests have sufficient political influence to obtain a major investment program. The second is if the financing of the waterways – which currently dates from the Inland Waterways Revenue Act of 1978 – is significantly changed. Revenue would need to be increased and perhaps the structure of pricing will have to change. Congestion-based lockage fees might be needed. If this happens in a similar fashion to the emerging toll highway network, there would be a commercial consumer-producer relationship between barge companies and the U.S. Army Corps of Engineers and incentives would be in place to reinvest in the infrastructure.

Freight railroads

In their recent book on American railroads, Robert Gallamore and John Meyer [12] titled their first chapter "The Enduring American Railroads." Railroads have been a large part of the American landscape for more than 150 years, and there is no reason to doubt that they will be part of the landscape for the next 150 years. For long-distance bulk freight, the railroads have a natural superiority, and North America is a land of great natural resources and immense distances.

The freight railroads are largely privately owned and funded. The recent purchase of the BNSF Railway by investor Warren Buffett's Berkshire Hathaway Inc. indicates that railroads can be seen as long-term investments. A dark spot on the horizon might occur as environmental regulations result in declining markets for coal. Coal represents about two-fifths of rail freight tonnage and one-fifth of revenue.

In terms of investment, the booming railroad industry in the period since the Staggers Act of 1980 has had to renovate and restore capacity that was either run down or abandoned during the difficult financial times of the 1960s and 1970s. Clearly, railroads internalize delays and lost traffic opportunities when the specific infrastructure becomes congested and have incentives to invest.

The exception occurs at interchange points, most notably Chicago where a "tragedy of the commons" has occurred. Because all of the major railroads meet in Chicago, the problems of interchange and coordination have led to considerable delays. The Chicago Region Environmental and Transportation Efficiency (CREATE) program has dealt with some of these issues, with the public purse paying for a large part of it. Interestingly, when north-south cross-Chicago traffic came under common ownership with the combination of the Wisconsin Central and the Illinois Central under Canadian National Railway ownership, the company purchased a bypass route around Chicago (the former Elgin, Joliet and Eastern). There has not been major merger activity in the railroad industry since the late 1990s. If future mergers led to the formation of one or more transcontinental railroads, it would be interesting to see whether the combined operations would have an incentive to sort out the interchange problems in Chicago themselves at their own expense or elect to move interchange traffic to alternative gateways such as St. Louis or Memphis.

High-speed passenger rail

There has been plenty of discussion concerning deteriorating railroad infrastructure in recent years. Much of the discussion has centered on bridges, tunnels and electrical systems along the Northeast Corridor between Boston and Washington, D.C. The root of these concerns is systemic funding problems of the publically funded National Railroad Passenger Corporation (Amtrak) that owns the majority of the track and of some commuter rail systems that operate over portions of the Northeast Corridor.

It is tough to see a quick resolution to the funding needs in the Northeast. As long as Amtrak is funded from federal sources, there will be opposition from other parts of the country to spending money to resolve a regional problem. The only foreseeable break in this impasse would come if Amtrak ceased to be a national network and became separate regional entities. One would imagine that if funding for rail service in the Northeast became the responsibility of a consortium of states along the eastern seaboard, they might form a consensus concerning significant investment.

Discussion of the Northeast Corridor naturally leads to consideration of investment in high-speed passenger rail services. It is clear that truly high-speed passenger trains (of 125 miles per hour and above) and freight trains cannot easily coexist on the same tracks. Despite considerable enthusiasm for the types of services seen in Europe and Asia, and the potential availability of seed money in the American Recovery and Reinvestment Act of 2009, high-speed passenger rail appears to be no further forward than it was 10 years ago.

However, there may be an opportunity for more high-speed rail in the United States by 2050. This may occur in places where proposals have been unsuccessful in recent times. Highway and airway congestion along the east coast of Florida and in the Houston-Dallas-San Antonio triangle will eventually make rail options quite attractive both to users and investors. In contrast, the low density land use and the long distances in the Midwest will be less attractive to any commercial schemes. It is unclear whether the California scheme currently in the early stages of construction will end up being attractive to users. However, shorter markets in congested corridors such as Los Angeles to San Diego, and radiating from the San Francisco Bay area are strong potential rail markets.

Airlines and airports

As with highways, many airports are severely congested. The congestion is not only on the taxiways and runways but also in the airspace.

The Federal Aviation Administration's (FAA) Next Generation Air Transportation System (NextGen) is designed to improve capacity in the skies by moving from ground-based control systems to satellite-based systems. These would potentially make better use of the available air space and open up air space that was not used by traditional control systems. There are also benefits that could be obtained on the ground from better management of aircraft on taxiways. There is continued controversy about the speed at which this project is deployed. Critics point to procurement constraints within the government-run air traffic control system and contrast it unfavorably with Canada and some other places where the air traffic control system is operated by a quasi-governmental company.

On the ground, there is a continued concern that demand outstrips the physical number of runways. New airports have been constructed in relatively few places in recent decades, most notably Dallas-Fort Worth and Denver. Additional runways have been constructed at Atlanta and Chicago O'Hare. But travel delays persist in many major cities. Construction of new runways is constrained by space and environmental concerns and not just a lack of finance.

Congested airport runways have the same economic problem as congested highways. The user fee is unrelated to the degree of congestion, and - because it is aircraft weight based - to runway occupation time. This has led to inefficient use of runways by general aviation (private) aircraft and a trend to offer more frequent commercial flights on some routes using regional jets rather than a smaller number of flights utilizing larger aircraft. The current weight-based pricing system does not give the correct incentives for an “optimal” aircraft size.

It can be argued that at some hub airports, where a single carrier dominates, the costs of congestion are internalized by the airline. Hence, the airline would have incentives to decide whether to bunch its connecting flights together or spread them out over time. But that would not be the case at airports such as Los Angeles, Seattle, Las Vegas, Chicago O’Hare, Boston Logan, Atlanta, New York’s LaGuardia and Kennedy, Washington National and Miami where there are multiple airlines competing.

There has been a discussion during the past few decades concerning introducing congestion prices to flatten out the peak and spread out clusters of flights. Proposals to implement such pricing at Boston Logan in the 1980s and Newark in the 2000s never came to fruition. General aviation interests tend to be vociferous in their opposition.

Economists would argue that the case for pricing airport runways has similar benefits to the pricing of highways discussed earlier. A more efficient use would be made of the existing capacity, and optimal runway prices would generate the funding for any needed expansion.

Efforts to price runway space in this way will probably not come to pass. Unlike highway agencies, airport authorities have access to both bonding and other revenue streams such as passenger facility charges to raise revenue for capital projects. Unfortunately, these other funding vehicles do not have the advantage of giving incentives for efficient use of the existing facilities.

International maritime and ports

Probably the greatest change in the past two decades in maritime transportation has been the off-shoring of manufacturing to Asia, and in particular to China. This has led to a considerable increase in traffic at west coast ports. Prior to the economic downturn in 2008, there was much discussion as to whether these ports were at full capacity. In addition, there was a discussion of whether new or expanded ports would be constructed or expanded in either Canada (Prince Rupert) or in Mexico rather than an expansion of existing U.S. ports.

In 2016, there will be an increase in capacity through the Panama Canal both in terms of throughput and in the maximum dimensions of individual ships. This will allow Asian traffic using larger vessels to access ports on the Gulf Coast and Eastern Seaboard. As with inland waterways, there is a debate as to whether the Harbor Maintenance Tax (which is assessed on imports) is sufficient to pay for necessary dredging and navigation, and which parties should bear the cost of these facilities.

Perhaps the biggest port constraint comes on the landside rather than the waterside. Intermodal traffic has to access the interstate rail and highway systems through old neighborhoods that surround the ports in many cities. These neighborhoods have concerns about road congestion, trains blocking highway-rail grade crossings, noise (from 24-hour operations) and vehicle emissions.

Proposals have been offered in Long Beach, Miami and Seattle, where considerable investment has already occurred, to expand landside access and mitigate negative spillovers in the community. Similar joint ventures between federal and state governments, port operators and railroads may be necessary in the next 35 years.

Concluding comments on the economics of transportation

Economic theory and modelling have made two major contributions to understanding the future direction of infrastructure investment.

The first area is in understanding how changes in transportation costs may contribute to the nature of major cities and with it the need for infrastructure provision either in the center or on the periphery. In general, urban economics models provide some support for understanding the modest regeneration of inner city neighborhoods. Rising congestion has made long commutes from the suburbs less attractive. But is this just a modest reversal in a long-term trend to suburbanization and automobile-centric urban form? In general, it would appear that the suburbanization trend will continue. Moreover, cities in the areas of the country with growing populations evolved in the automobile era and the areas with more “traditional” cities that developed in the 19th Century are declining in relative terms.

But are there any “game changers” on the horizon that may upset conventional wisdom on urban form? Perhaps the biggest game changer would be outside the transportation sector, and involves improvement in school systems that would attract families back into the city. In the transportation arena, will the advent of autonomous vehicles lead to greater or lower urban density? Convincing arguments can be made in both directions. Perhaps the revolution currently sweeping the taxicab market may spread to reforms in urban transit, which might lead to easier and cheaper (to both users and the public purse) urban mobility.

The second area is central to transportation economics and concerns the efficient pricing and use of infrastructure. Traditionally, transportation infrastructure has either not been priced, or is priced in a way that is not related to the true costs users impose on the infrastructure and other users. This applies equally to highways, airport runways and maritime facilities. Economists have long called for “congestion pricing,” which considers the delays that one user imposes on all other users of a facility. The benefits of such pricing are twofold. The first is that some users, when faced with the true cost of using a facility, may decide to travel in the off-peak or by another mode or by a less-direct route. An existing facility will be used more efficiently. The second is that congestion prices will generate revenue that can be used to pay for any needed expansions in capacity.

It would seem very likely that this style of pricing will become more common in the relatively near term especially for limited-access highways. The decline in importance of the gas tax and the increased practicality of electronic tolling makes pricing very attractive for cash-strapped infrastructure providers. Increased congestion, and the need to rehabilitate highway facility constructed in the 1960s and 1970s, will probably be the events that trigger these changes. It is possible that the decline in importance of the Highway Trust Fund and a movement to direct pricing may actually spur infrastructure investment rather than reduce it. Moreover, it will create more of a producer-consumer commercial relationship between infrastructure providers and users that can only be beneficial.

Concluding comments on transportation and the economy

The preceding discussion has focused primarily on economic insights on the workings of transportation markets and how changes in the underlying economics may influence the demand for infrastructure investments. So far, little attention has been given to the wider economic benefits that accrue at both a local and national level from transportation infrastructure investments. Stated conversely, how large is the economic drag caused by insufficient or poor quality infrastructure?

At some level, one might think that determining the economic consequences of poor and insufficient infrastructure is quite straightforward. If a facility is congested, the extended travel times for both passenger and freight traffic can be easily quantified. Similarly the effects of rerouting due to current weight restrictions can be quantified. But the more indirect effects of poor infrastructure are more difficult to quantify and are open to question. For example, how could one quantify the extent to which companies are adopting less efficient distribution networks than they would in a world with better infrastructure? Moreover, people might live or work in different places if the infrastructure was better, and it is difficult to measure how much better off they would be as a result.

One might also think that there is plenty of evidence that new infrastructure attracts economic development, at least at a local level. The office parks and retail facilities that have been built close to highway interchanges bear witness to this. But how much of this development is a true gain at a national level as opposed to just a redistribution of economic activity from one location to another is open to question. There are also distributional consequences.

If an infrastructure improvement results in some localities gaining economic activity and others losing, there may be a concern if the area losing activity was already impoverished.

Perhaps the question of redistributing economic activity is best illustrated by considering the effects of poor infrastructure on international trade. In these circumstances policies may not (for better or worse) place any weight on the welfare of consumers and producers located overseas. If poor domestic infrastructure makes U.S. exports more expensive because it is more expensive to ship them from their origin to a port, U.S. farmers and manufacturing workers are clearly worse off as the U.S. is less competitive in international markets. But what if poor port facilities increase the cost of imports? On one hand, this is bad for U.S. consumers because the price of imported goods will go up. On the other hand it may benefit U.S. workers if, as a consequence, more goods are produced domestically.

That said, major infrastructure investment programs have repeatedly led to greater mobility, happiness and the ability to fully harness the economic riches of this resource-rich continent. These investments include the construction of the canals in the early 19th Century, the building of the railroads somewhat later that century and the expansion of highway and aviation systems primarily in the second half of the 20th Century. Are there any new technologies that might emerge between now and 2050 that will have similar transformative effects?

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CHAPTER FOUR

Technological Innovation and the Future of Urban Personal Travel

By Hani S. Mahmassani

Introduction: Smart cities

Cities are the summation and densest expression of infrastructure, or more accurately, a set of infrastructures, working sometimes in harmony, sometimes with frustrating discord, to provide us with shelter, contact, energy, water, and means to meet other human needs. The infrastructure is a reflection of our social and historical evolution. It is a symbol of what we are collectively, and its forms and functions sharpen our understanding of the similarities and differences among regions, groups, and cultures.[1]

In their monograph, Jesse H. Ausubel and Robert Herman went on to define the *physical infrastructure as consisting of various structures, buildings, pipes, roads, rails, bridges, tunnels, and wires*. Even in 1988, more than 25 years ago, they recognized that *equally important and subject to change is the "software" for the physical infrastructure, all the formal and informal rules for operation of the systems*—which anticipated the era now emerging of intelligent connected systems, and the associated vision for so-called smart cities. The distinction between the physical infrastructure, and how it is operated and managed is essential to understand how cities and mobility can evolve through the influence of technology to meet changing economic requirements and social expectations. A central thesis of this chapter is that one is functionally useless without the other—physical condition alone with antiquated operational rules is no more effective than advanced operational strategies for a decaying physical infrastructure. Thus, consideration of likely future technologies that affect how people and vehicles travel and use transportation and related infrastructures is essential to a discussion of likely scenarios for urban infrastructure development. Likewise, social and economic forces that may be shaping future urban travel are increasingly relevant to the discussion of the associated infrastructure.

The objective of this chapter is to delineate likely futures for urban travel in 2050, based on trends and likely technologies reflected in ongoing developments. Naturally, given the rapid rate at which several relevant technologies are evolving, any attempt to define a single future point in time is likely to miss the mark in some respect. Hence, this work views the future as a blend of various factors and trends the origins of most of which are now apparent, while recognizing that others are possible and still unknown. Hence, rather than formulating mutually exclusive scenarios, neither of which may be particularly likely, this chapter examines a range of possibilities, and seeks to identify infrastructure implications and enablers that may favor or preclude some of these possibilities, with particular emphasis on those that point in directions that society may broadly consider to be more desirable.

The objective is accomplished by reviewing and interpreting developments in three main areas: (1) technologies, primarily relating to vehicles, information and communication technologies for both "things"/systems and individuals, and eco-friendly personal mobility tools; (2) societal preferences that impact on mobility and travel; and (3) service delivery models, particularly with regard to the respective roles of the public and private sectors. While some developments in each of these areas are independent and have their own dynamic, several are interdependent and synergistic. Developments in each of these areas will be blended and associated vignettes will be sketched. The picture that emerges is that infrastructure implications are likely to be equally qualitative as they are quantitative, meaning that provision of more of the same types of existing infrastructure would not be the most effective investment for our urban futures—rather, the urban mobility infrastructure must be reconceived and reinvented to better serve and enable these futures.

Technology trends

The primary types of technologies discussed in this section have been enabled by more fundamental developments in sensing, communication and computing (information) technologies. The intent is not to discuss the basic technologies per se but to discuss their application to transportation systems and/or their impact on travel and activity behavior of individuals. Three main trends that draw on the above basic technologies are discussed: (1) Personal mobile communication devices (e.g., "smartphones") and telemobility, (2) Connected vehicle systems and the Internet of Things (IoT), and (3) Autonomous vehicles. While all result in one way or another from advances in computing and the ubiquity of microprocessors, they have taken place in different industry sectors to address different applications and market motivations.

Personal communication devices and telemobility

Taken for granted in most of the world, mobile phones have probably been one of the most impactful personal technologies of the past 20 years. Coupled with wireless access to the Internet, GPS location, audio and high-definition video processing capabilities, handsets have morphed into so-called smartphones, with the computing power of high-end workstations, enabling essentially continuous anytime/anywhere access to a growing realm of virtual opportunities. Impacts of smartphones are seen across the spectrum of human and social interaction, enabling a seemingly endless stream of work, personal maintenance (e.g., commercial and financial transactions), social, and recreational activities.[2]

Transportation and travel are no exception to the realm of activities supported and enhanced by smartphones and similar connectivity devices (to include tablets, tabs, pads, pods, etc.). The area of traveler information systems, delivering real-time navigation and route information to travelers, has seen a major shift from a vehicle-based functionality to a person-based application delivered via GPS-equipped mobile devices. At the same time, expectations for delivery of traveler information shifted from something the public agencies that operate the infrastructure provide users of that infrastructure, or vehicle manufacturers to drivers of their vehicles, to the realm of third-party providers who compete for users' loyalty by adding value through crowdsourcing, prediction, and improved path-finding algorithms to real-time information delivered directly via smartphones. Services such as WAZE[3] that rely on crowdsourced information and reports to provide real-time route information, are hugely successful with the traveling public in places where they are available. Companies providing such services also seek to leverage the loyalty of users by offering location-based services, including promotional offers (e.g., discounts on products and services), targeted at users' specific location.

Two major trends in information supply can be observed, with direct applicability to how individual travelers interact with the transportation infrastructure and related services in an urban context: [4] (1) personalization or customization, and (2) socialization. The former provides individualized information that considers the user's current location, preferences (as expressed through previous choices or responses to stated choice queries) and is therefore more directly relevant to his/her needs. The latter shares information about one's activities with a social network of *friends*, and provides information that reflects the experience of socially connected individuals, thereby influencing, for example, the destinations visited and the choice set of considered alternatives. [5] With both trends underway, the implications for activity and travel behavior remain insufficiently documented.

Information Personalization

- *Customized information specifically for user location and preferences ("where is my bus?")*
- *My information, My preferences, My route, My location…*
- *My experience, tracked for me*
- *Special offers, just for me and my friends*

Information Socialization

- *Growing role of social media, and location-based apps that receive people's check-ins ("Where are my friends"?)*
- *I trust information I receive from my friends*
- *I go where my friends are (or tell me to go)*

In terms of the demand for travel, mobile Internet access has further enabled and helped expand an important phenomenon that started with fixed Internet access in the 1980s and 1990s, namely the ability to conduct activities remotely that otherwise required physical presence. These include work (telecommuting), shopping, and transactions ranging from financial and legal to passport applications and payment for traffic fines. A considerable literature emerged in the 1990s addressing the travel implications of information and communication technologies.[6] Increasingly, there has been growing convergence between individuals' physical and virtual worlds, and mobile broadband access to the Internet via smartphones has been an important factor in this process. Such telemobility may entail changes in the nature and spatial characteristics of the activities conducted, along with their social dimensions, making the process of activity generation (i.e. formation of potential activity choice sets) and scheduling considerably more dynamic.

In the area of urban mobility, the past five years have seen an explosion of specialized smartphone apps targeting some aspect of urban transportation, from multimodal traveler information to mobility service procurement. Bus trackers, which rely on GPS information on bus locations, provide travelers with estimated arrival times of buses at a given stop. Real-time ride hailing applications, such as Uber and Lyft, provide a complete platform for ordering, procuring and purchasing rides. The ability to track the location of one's driver is often claimed as a key benefit of the system, as is the efficient manner of transacting payments. Parking spot location and reservation apps are emerging in several urban markets around the world, for both public on-street parking as well as privately operated garages. The ability to match demand with supply in real-time, while providing a convenient mechanism for completing the transaction, as well as a platform for tracking and rating one’s experience, is disrupting conventional services such as the taxicab industry, and areas such as visitor accommodations and trucking.[7]

Figure 1: Smartphone apps are used for bus trackers, ride hailing and parking spots

A development worth watching is the increased reliance on smartphone apps to influence behavior through gamification (feedback, keeping score, milestones, rewards) and personalized incentives. Areas of intervention include getting the user to make better choices for the environment, for their health, or aimed at reducing traffic congestion and unreliability experienced by the user and others. An example that adapts ideas from physical fitness to urban commuting is the “quantified traveler” project at the University of California at Berkeley.[8]

An equally important opportunity lies in the fact that smartphones de facto turn every individual traveler into a potential traffic probe. Beyond travel time information on different portions of the network, which several companies have begun to leverage commercially, smartphones could provide information on choices higher up the hierarchy (e.g., destination choice). In addition to real-time applications for improved state estimation, these provide a serious augmentation of data available for planning purposes.

There is widespread recognition that new technologies are continuing to enable new ways to measure and track individual choices.[9] This goes a long way toward observing actual choices of modes, routes traveled, destinations visited, and so on. Coupling these data with social networking information, planners can also analyze spatial and temporal patterns of joint travel choices by related individuals. While concerns for privacy will continue to remain paramount, much useful information for transportation planning and analysis can be obtained while maintaining anonymity of the individual travelers. The transportation domain is seriously lagging other domains (e.g., online and retail marketing) when it comes to mining and leveraging the vast amount of data that is accumulating through non-traditional sources such as smartphones, Internet transactions, as well as video images of the transportation system itself (e.g., at train stations and on many highways and intersections).

Connected vehicle systems, the Internet of Things and smart cities

Connected vehicle technologies provide the opportunity to create an interconnected network of moving vehicular units and stationary infrastructure units, in which individual vehicles can communicate with other vehicles (i.e. Vehicle-to-Vehicle, or V2V communication) and other agents (e.g., a centralized traffic management center through Vehicle-to-Infrastructure, or V2I, communication) in a collaborative and meaningful manner. The real-time information provided by V2V and V2I improves drivers' situational awareness and enhances safety and efficiency of operating vehicles. It also improves the reliability of the traffic system through online monitoring and dynamic management while providing data for both on-line operations management and off-line planning applications.

As envisioned by the U.S. Department of Transportation Connected Vehicles program, this connected environment serves three main purposes: improving safety, enhancing mobility, and reducing emissions.[10] Connected vehicles technology is expected to address 81 percent of all imminent crashes by improving drivers' situational awareness[11] while reducing/eliminating congestion, decreasing energy consumption and reducing negative environmental effects of driving (e.g., by reducing emissions and greenhouse gases).

Leaving aside the issue of individual vehicular safety, which is important in its own right but only incidental to the discussion of the urban mobility infrastructure, the principal opportunity from connected systems arises from the ability to monitor both infrastructure and operational aspects of the system and operate it in ways that maximize societal benefits in terms of efficient mobility, reliability and external costs. The conceptual framework shown in Figure 2 illustrates the data flows from users and physical and operational elements of the infrastructure to support different levels of decision-making at different time scales. These range from operational system manager decisions in real-time, to medium-term interventions (over hours or days), to longer-term strategic decisions including planning and policy choices.

From a traffic operations perspective, a key focus of connected vehicle systems is to enable coordinated strategies that improve the quality of flow along highways and at intersections, including speed harmonization, coordinated cruise control and queue warning[12]). In general, the more vehicles are connected together, the greater the opportunity for coordinated interventions to improve the quality and reliability of flow. In an urban setting, connected vehicles technology enables more responsive operation of traffic controls, especially traffic signals, and more efficient sharing of right of way by different types of vehicles, including transit vehicles along priority corridors. Connectivity will also enable more effective demand management by integrating information to and from travelers into the overall system and improving the overall user experience and multimodal mobility.

Beyond the immediate scope of transportation vehicle and infrastructure systems, connectivity, technology companies have put forward the notion of an Internet of Things (IoT) in which machines, objects, people, vehicles of all types are interconnected. For an individual, the typical image envisions one's home, office and vehicle (or other means of travel) all interconnected, placing the user at the center of a web of seamless connectivity – where physical and virtual worlds become a continuum of activity engagement.

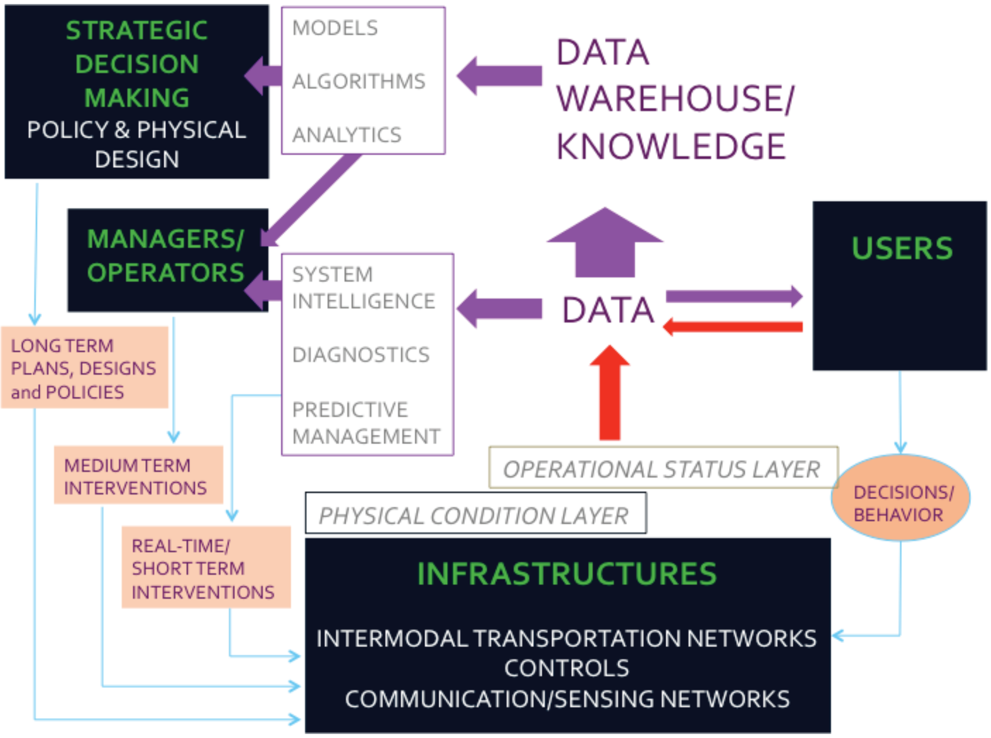


Figure 2: Framework for data use to support decision-making on different time scales in a connected environment

Early forms of this vision were articulated nearly 25 years ago. In 1991, Mark Weiser, then of Xerox PARC, coined the term Ubiquitous Computing to describe "… a world in which objects of all kinds could sense, communicate, analyze, and act or react to people and other machines autonomously."[13] The value proposition is quite simple; by connecting more devices, the IoT enables a more complete view of interacting machines, devices and systems, thereby enabling better prediction and more effective interventions, as well as entirely new views and the opportunity for a wider range of interventions. Technological advances in both hardware and software now enable this vision (see Figure 3 for key enabling technologies), but realizing the full benefits even in a single sector like transportation or mobility, let alone across the range of sectors and activities at an urban scale, requires considerable coordination across various public and private entities.

The kind of data and systems integration envisioned under an Internet of Things, when applied at the level of an urban area, results in so-called smart cities, where a web of connected sensors of all types along with shared data platforms enable realization of efficiencies across urban services in different sectors, e.g., education, health care, electric power, water, in addition to mobility services (see Figure 4). The concept of smart cities has been around for at least the past decade, reflecting a natural evolution and adoption of ICT technologies in urban services.[14] In terms of personal urban mobility, the quality, scope and relevance of real-time information would contribute to reducing waiting times for transit services, enable reservation and payment for parking spots at congested locations, simplify access across a spectrum of urban modes such shared bikes and vehicle fleets, facilitate seamless access to airports and major terminals, and so on. For users, this means greater convenience; for cities and operators, greater efficiencies and better utilization of resources; and for society, more livable and environmentally sustainable cities.

Technology	Definition	Examples
Sensors	A device that generates an electronic signal from a physical condition or event	The cost of an accelerometer has fallen to 40 cents from $2 in 2006. Similar trends have made other types of sensors small, inexpensive, and robust enough to create information from everything from fetal heartbeats via conductive fabric in the mother's clothing to jet engines roaring at 35,000 feet.
Networks	A mechanism for communicating an electronic signal	Wireless networking technologies can deliver bandwidths of 300 megabits per second (Mbps) to 1 gigabit per second (Gbps) with near-ubiquitous coverage.
Standards	Commonly accepted prohibitions or prescriptions for action	Technical standards enable processing of data and allow for interoperability of aggregated data sets. In the near future, we could see mandates from industry consortia and/or standards bodies related to technical and regulatory IoT standards.
Augmented intelligence	Analytical tools that improve the ability to describe, predict, and exploit relationships among phenomena	Petabyte-sized (1015 bytes, or 1,000 terabytes) databases can now be searched and analyzed, even when populated with unstructured (for example, text or video) data sets. Software that learns might substitute for human analysis and judgment in a few situations.
Augmented behavior	Technologies and techniques that improve compliance with prescribed action	Machine-to-machine interfaces are removing reliably fallible human intervention into otherwise optimized processes. Insights into human cognitive biases are making prescriptions for action based on augmented intelligence more effective and reliable.

Figure 3: Technologies enabling the Internet of Things[15]

Today…	What if a city could…	Already, cities are…
People • Cities have difficulty using all the information at their disposal. • Citizens face limited access to information about their healthcare education and housing needs.	• Reduce crime and react faster to public safety threats, by analyzing information in realtime? • Use better connections and advanced analytics to interpret vast amounts of data collected to improve health outcomes?	• Putting in place a new public safety system in Chicago, allowing realtime video surveillance and faster more effective response to emergencies • Giving doctors in Copenhagen instant access to patients' health records, achieving the highest satisfaction and lowest error rates in the world.
Transport • Transporting people and goods is dogged by congestion, wasted hours and wasted fuel.	• Eliminate congestion and generate sustainable new revenues, while integrating all transport modes with each other and the wider economy?	• Bringing in a dynamically priced congestion charge for cars to enter Stockholm, reducing inner-city traffic by 25 percent and emissions by 14 percent, while boosting inner-city retail by 6 percent and generating new revenue streams
Communication • Many cities have yet to provide connectivity for citizens. • "Going online" typically means at slow speeds and at a fixed location.	• Connect up all businesses, citizens and systems with universal affordable high-speed connectivity?	• Merging medical, business, residential and government data systems into a so-called ubiquitous city in Songdo, Korea, giving citizens and business a range of new services, from automated recycling to universal smartcards for paying bills and accessing medical records.
Water • Half of all water generated is wasted, while water quality is uncertain.	• Analyze entire water ecosystems, from rivers and reservoirs to the pumps and pipes in our homes? • Give individuals and businesses timely insight into their own water use, raising awareness, locating inefficiencies and decreasing unnecessary demand?	• Monitoring, managing and forecasting water-based challenges, in Galway, Ireland, through an advanced sensor network and realtime data analysis, giving all stakeholders – from scientists to commercial fishing – up-to-date information.
Business • Businesses must deal with unnecessary administrative burdens in some areas, while regulation lags behind in others.	• Impose the highest standards on business activities, while improving business efficiency?	• Boosting public sector productivity, while simplifying processes for business in Dubai through a Single Window System that simplifies and integrates delivery and procedures across a range of almost 100 public services.
Energy • Insecure and unsustainable energy sources.	• Allow consumers to send price signals – and energy – back to the market, smoothing consumption and lowering usage?	• Giving households access to live energy prices and adjust their use accordingly, as in a Seattle-based trial, reducing stress on the grid by up to 15 percent and energy bills by 10 percent on average.

Figure 4: IBM's typology of urban issues for Smart Cities[16]

Connected cities with shared data platforms and intelligent processes that leverage the data offer opportunities for end users (city dwellers, travelers), system operators and managers, as well as a plethora of potential services delivered by third parties. For individual users, the value proposition translates into greater user convenience, seamless telemobility, and what has been referred to in popular tech jargon as the connected life. For system operators, the opportunity is one of greater efficiencies while delivering better service to consumers, through the application of advanced predictive analytics and intelligent control. Availability of large data streams from various public and private sources, with the ability to reach consumers near-instantly through mobile connected devices, creates many new opportunities for entrepreneurial third parties to improve existing services or offer entirely new categories of services and experiences.

From the perspective of urban scenarios for the year 2050, while the basic IoT technologies are mostly in place, several questions arise about the process by which their adoption and deployment into smart cities might unfold, and how this process may influence the resulting configuration. These questions include:

a. System architecture: Will a dominant IoT platform emerge, applicable across different domains (hence dramatically increasing opportunity)? Given the scale and scope of such an endeavor, it is more likely that smaller-scale, smaller-impact independent projects will first emerge, building on and upgrading legacy systems with greater integration taking place over a longer time frame.

b. Who leads (now) or will lead in this process? While there are several industry players vying for the distinction, no particular industry sector or company has emerged in a clear dominant role. Will it be the device side (manufacturers of devices), system integrators on the data side, or end application developers? What might be the role of public policy and public choice in this process?

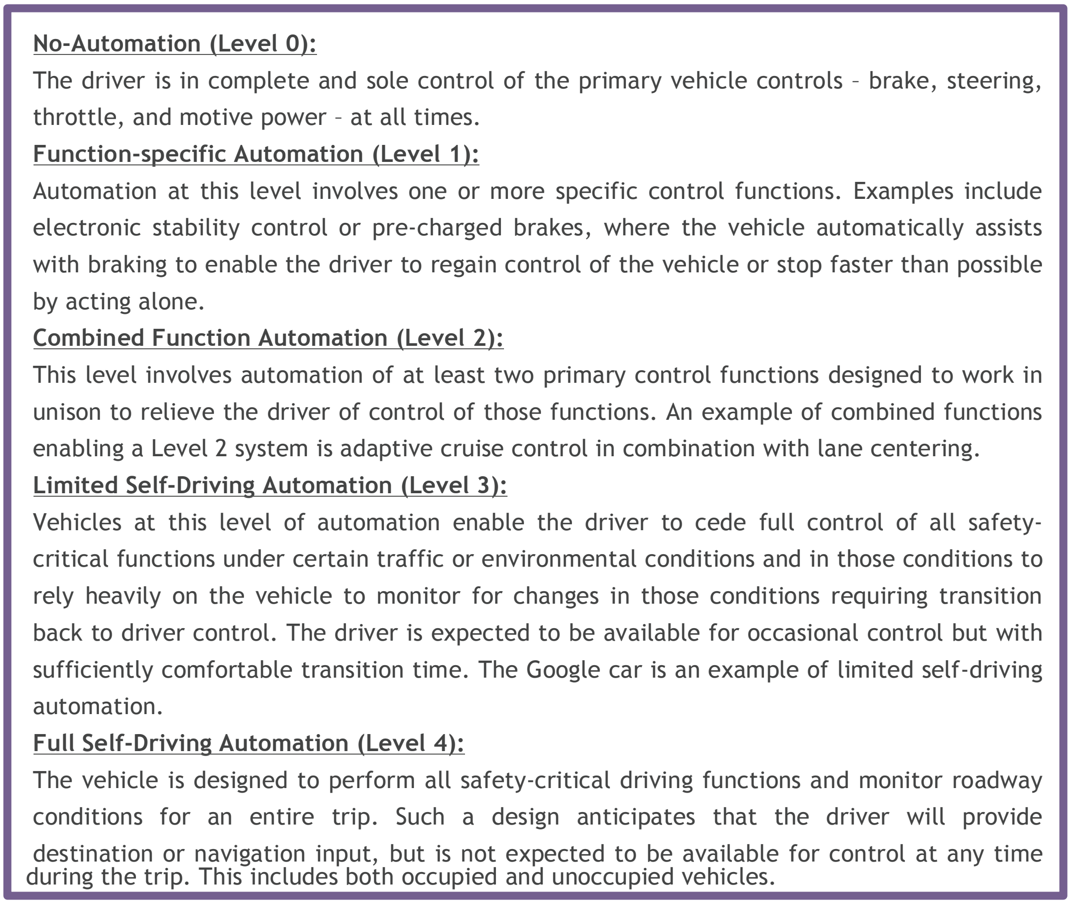
c. How open should the IoT data platform be in enabling a smart city? Greater openness and access encourages innovation and entrepreneurial risk taking, the emergence of new services but this may need to be tempered by concerns for privacy and commercial interests.

d. Smart cities also have implications for governance; urban planners in particular have cautioned that it takes more than technology to bring about smart cities. It also takes people, communities and institutional change, and an active program for community engagement.[17]

In summary, connectivity and IoT increase opportunity for users, for the overall system, and third parties. The more “things” that are connected, the more sectors integrated within a city (sources of data), the greater the potential. Transportation and mobility industries are likely to experience major disruptive influences in terms of technology, players and concepts. One of the substantial hurdles for achieving the kind of integration envisioned under smarter urban systems is likely to come from the public sector side which controls large sensor data sets and has a mandate to operate several critical infrastructures and services. Smart cities entail levels of intra- and inter-agency coordination and process redesign that may be more difficult to accomplish in certain cities than in others. Hence, there is likely to be different degrees of adoption, and different models of public-private engagement to deliver the potential benefits of urban-scale connectivity.

Autonomous vehicles

The popular media have been replete with images of autonomous, or driverless, cars over the past few years, especially the "Google car"—the well-publicized entry into the vehicular realm by the technology giant.[18] The vision is certainly not new, and one can find examples of images depicted of cars driving themselves while the occupants engage in work or recreational activities as far back as the 1930s.[19] However, advances in computing, robotics and artificial intelligence have enabled realization of near roadworthy vehicles, prompting serious efforts in the regulatory, legal and insurance spheres addressing the entry of such vehicles into everyday utilization.



No-Automation (Level 0):

The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.

Function-specific Automation (Level 1):

Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.

Combined Function Automation (Level 2):

This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.

Limited Self-Driving Automation (Level 3):

Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.

Full Self-Driving Automation (Level 4):

The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

Figure 5: NHTSA's four levels of automation[20]

A useful framework for thinking about autonomous vehicle capabilities was articulated by the National Highway Transportation Safety Administration (NHTSA) of the U.S. Department of Transportation. NHTSA defines four different progressive levels of automation, relative to a base level (Level 0) of no automation, as shown in Figure 5, with Level 4 corresponding to full self-driving automation, under which responsibility for safe operation rests entirely with the automated system, hence allowing the vehicle to also operate while unoccupied. Levels 1 and 2 can be viewed as driver-assistance functions, and are already essentially available in standard higher-end vehicles. These levels translate primarily into marginally greater levels of safety and convenience for the vehicle occupant, with no substantial impact on the overall traffic and mobility systems. Levels 3 and 4 introduce substantial "driverless" capabilities, with level 3 a likely interim stage in terms of market introduction and acceptance before full self-driving capability.

Autonomous vehicle capabilities are often discussed in conjunction with connected vehicle systems. But they are in effect distinct. Autonomy is envisioned by the likes of Google as the ability to drive with no external assistance, possible through extensive sensing and massive intelligence residing fully within the vehicle. All these functions could be enhanced through connectivity, e.g., when neighboring vehicles and/or the infrastructure convey messages to other vehicles about respective locations, road features or control displays. Additional coordinated strategies could thus be enabled to further enhance safety and flow quality. However, in this case more of the intelligence resides in the infrastructure, or the vehicle-infrastructure system instead of exclusively on individual vehicles. All these factors have important implications for deployment, coordination, vulnerability and resilience of the associated system design and deployment scenario. Most notably, connected vehicle systems require a much greater degree of coordination among auto manufacturers and traffic management authorities (generally public sector), whereas autonomous vehicles are envisioned as fully self-sufficient (given the existing physical infrastructure).

Three distinct, but inter-related aspects of autonomous vehicles are of particular interest to questions of urban mobility and its implications for the infrastructure. These are: (1) extent and pace of market adoption; (2) system level impacts on flow quality and capacity; and (3) new models for mobility service delivery. The first two are briefly discussed hereafter, while the third is the subject of a separate section of this chapter.

Market adoption. A major determinant of the impact of autonomous vehicles on traffic flow and urban mobility will be the extent to which these vehicles are adopted and accepted by users, and the fraction of the total vehicle mix that they constitute. This will naturally depend on when they are introduced commercially, how they are marketed, what restrictions, if any, are placed on their use, and the price at which they are offered. It will also depend on the manner through which their use is made available to the public; as discussed previously, greater availability through shared fleets might mean less need to own the autonomous vehicle, which could be ordered when needed—in a mode Professor Alain Kornhauser of Princeton refers to as "buying mobility by the drink instead of by the bottle." [21] Whether in shared fleet use or individually owned, adoption by users will likely depend on four key factors: (1) trust, (2) ability to drive, (3) benefit perception, in terms of safety, mobility, and efficiency—time saving, activity constraint reduction, and (4) affordability.[22] Whether Rogers's classic curve (Figure 6) of technology adoption will hold in this case is not evident, at least not with regard to the respective durations of each phase in the adoption cycle, but it remains a useful framework for thinking about the process.

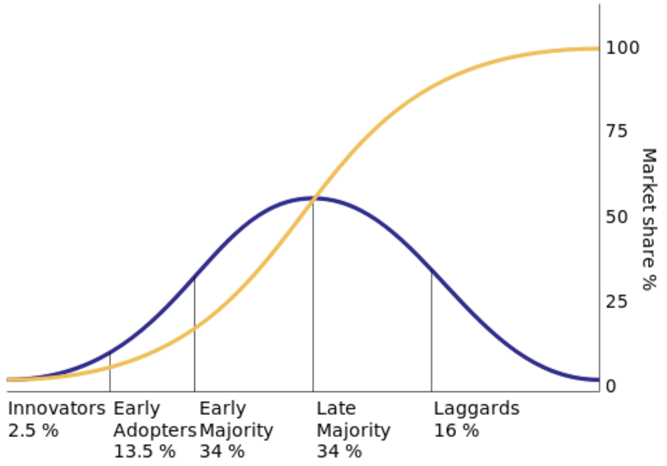


Figure 6: Rogers's classic curve for adoption of new technologies[23]
(Graph depicts market share (y-axis) over time (x-axis) as a result of adoption by different segments of the market.)

Going beyond the trust issue, and assuming legal and institutional matters are satisfactorily resolved at least to allow comparable levels of peace of mind as with current automobiles, potential users' perception of the technology's benefits is especially important, as it also determines the manner in which the vehicles might be utilized in fulfilling individuals and households' activity patterns. This, in turn, would determine the extent of vehicle-miles traveled, resources consumed, carbon impact and other externalities. The benefits derive from two functions of the autonomous vehicle: (1) as a mobility tool, it is expected to provide greater safety, as well as efficiency, enabling multitasking especially over longer spans of travel; and (2) as a robotic assistant, which could now shop, pick up kids, and perform similar mobility chores imposed by auto-centric suburban lifestyle. For small businesses, the autonomous car could go make deliveries, pick up supplies, and so on. As such, autonomous cars may save their owners/users money and time, enabling activities previously either not done, postponed or chained, perhaps along with major reorganization of activity patterns, especially for caregivers (of young people, elderly).

Flow quality and capacity. Several studies of both autonomous and connected vehicles have been conducted first in the 1990s[24] and more recently in the past five years[25] to investigate the flow properties of vehicular traffic streams with varying fractions of autonomous and/or connected vehicles. While these properties will be determined by the specific technologies and how they are implemented, e.g., the specific logic by which a driverless car would follow other vehicles, change lanes and so on, the sensors used and the pattern recognition algorithms, and the interaction protocols for vehicles with different levels and types of technologies, investigations to date suggest meaningful improvement in most flow performance indicators. Nonetheless, these studies have been limited to simulation-based analyses, with some field information from small-scale technology demonstrations. Hence, considerable additional effort is required to fully ascertain the flow impacts of these technologies for specific deployment scenarios.

Four main performance indicators have been considered: (1) safety, (2) capacity, (3) stability, and (4) reliability. As noted, substantial safety benefits are expected by the very potential of eliminating one of the main causes of crashes in existing vehicular traffic, namely driver limitations—in cognition, time lags and response. Capacity benefits derive in principle from the ability of autonomous/connected vehicles to follow one another more closely while maintaining higher speeds than is the case with human driven vehicles; the latter require more separation at higher speed to allow driver-vehicles to safely react to sudden deceleration ahead. Since throughput is the product of density and speed, higher throughput can be expected when vehicles can maintain higher speeds at higher densities. Theoretical calculation assuming all-autonomous vehicles with no lane changes suggests throughput gains as high as four or even five times presently observed capacities. This would be huge, but it assumes idealized conditions of "extreme platooning" with no regular vehicles in the mix, and no lane changing. More realistic estimates would place an upper bound of about two, with an increase in the range of 30 percent to 50 percent to be more conservative even for high market penetration rates.

More important than maximum possible flow rates is the potential for sustaining higher throughput levels without the occurrence of the flow breakdown phenomenon (sometimes referred to as "capacity drop") during peak periods, as is currently the case in most congested cities. The introduction of autonomous vehicles is predicted to increase the *stability* of flow processes—whereby perturbations induced by phenomena such as braking do not amplify while propagating upstream, a phenomenon that causes shock waves that may induce flow breakdown. This increase in stability has been established theoretically as well as through simulation, when even a small fraction of autonomous vehicles are introduced in the traffic mix.[26] The reduction of the likelihood of flow breakdown in turn results in more reliable travel times on the facilities.

These benefits in flow quality and capacity would mean greater ability to absorb increases in demand due to greater utilization of the vehicle in autonomous mode (e.g., in return mode when used by multiple household members, or when performing shores for the household). Similarly, they may imply reduction in the cost of daily travel for individuals. However, they would not diminish the need for highway infrastructure in congested areas.

Authoritative projections of market adoption are not yet available, especially in the absence of an official timeline of commercial availability. However, it is generally believed that level 3 vehicles may be commercially available as early as 2018, and level 4 within a couple of years after that, at least based on technology readiness.[27] Whether cities will be fully ready to accommodate them, and to take full advantage of the benefits that they may provide, is another matter. Some cities around the world are clearly ahead of others (e.g., Dubai, Singapore); most, however, have not gone through the planning exercises necessary to understand the full implications of autonomous vehicle introduction and adoption, nor have they formulated strategies and plans to advance their public infrastructure, management structures or related services not only to accommodate but also to realize the potential social benefits of improved mobility through automated and connected technologies.

Shifting societal preferences: Are millennials really different?
Much has been made in the popular press about millennials (the cohort born between 1981 and 2000), their attitudes, preferences, consumption patterns, mobility and travel habits, and so on.[28] The main aspects relevant to the infrastructure question pertain to millennials' greater preference for living in cities (than older age groups now and when the latter were younger), stronger desire for environmental sustainability, walking and bicycling when practical (and making residential choices accordingly), and less reliance on the private automobile for all travel purposes.[29] By far the major differentiator of millennials is their facility with and dependence on information technology, including mobile technologies, which they have known and experienced since birth. As such, they spend more time and conduct a greater fraction of their activities online, achieving more convergence of the virtual and physical worlds. Accordingly, many have readily embraced app-based "sharing economy" ideas and services, such as AirBnB (accommodations), recommendation systems (Yelp), goods and services bartering (Craig's List), and ride-hailing services (Uber, Lyft).

Several possible implications of these trends, should they continue, directly impact travel and urban mobility, and thus their associated infrastructure needs. These include:

a. Less travel by private, own automobile; instead, greater reliance on non-motorized modes, and when motorized, then shared modes either in the form of public transit or ride-hailing/sharing services. While the former is indeed environmentally desirable, as auto trips are replaced by bicycling, walking, and occasional transit use, the latter is not necessarily so, especially in the case of ride hailing and similar sharing economy alternatives.

b. A corollary of the above is that there will be less need for millennials to own private automobiles, individually and at the household level. This would not, however, mean less need for road and highway infrastructure

c. Greater differentiation than at present in the types and modes of travel for different purposes, as technology continues to reduce the need for time-wasting travel by decoupling spatial location from function where not essential (e.g., ability to do certain types of work from home) and providing better, closer destinations for various activities.

d. Stronger integration of connected systems technologies and transportation modes and services. Infrastructure will need to be smarter in terms of providing more information to users, and in return, will become more resource-efficient and deliver better service quality as more of its users share intent and experience.

Increasingly though, various studies are suggesting that (1) while millennials are early adopters of mobile-based technologies and services, other (older) cohorts appear to be following in their footsteps, closing the so-called digital gap[30] and (2) millennials themselves may be reverting back to the general population trends with regard to travel and mobility—especially as they enter the (heretofore delayed) child-rearing phase of their life cycle. The evidence for the latter remains sketchy, and likely exhibits considerable regional variability across the U.S., reflecting different socio-economic and land use characteristics.

Thus, while social preferences may in aggregate be shifting toward more sustainable urban lifestyles, suggesting a continuing improvement in the vitality of urban cores and near suburbs, the implications for infrastructure may be more qualitative than quantitative.

Emergence of new mobility service delivery models

The emergence and adoption of autonomous vehicles is expected to accelerate certain trends already underway in terms of shared urban mobility, and to enable new mobility service models that bridge traditional transit service and personal mobility, resulting in new hybrid forms. These emerging service concepts further leverage personal mobile technologies, enabling greater personalization not only of information but also of the services delivered. These potential changes in the supply of transportation and mobility at the urban scale are difficult to predict and characterize for the purpose of developing specific planning tools and forecasting the demand for these services over time.

While it may be difficult to predict exactly which services may emerge in a certain locale, and the extent and type of demand these might serve, the following aspects can be noted based on current understanding of travel behavior and the expected features of autonomous vehicles.

a. It is a given that driverless vehicles will enable new forms of mobility supply. By eliminating the cost and performance limitations of human drivers, and increasing the ease of communicating instructions to both vehicles and travelers, autonomous vehicle fleets can be operated efficiently to deliver dynamically scheduled services to individuals riding privately or in shared vehicles.

b. New forms of car sharing with greater convenience may reduce the motivation for individual ownership. With driverless cars, availability of a vehicle in sharing services such as Zipcar and Enterprise car share (formerly Igo) is not limited to the nearest lot. Vehicles can be repositioned dynamically to the user's location from anywhere in the city.

c. Ride and car sharing marketplaces will likely expand with driverless vehicles, following, for example, platforms developed by ride-hailing app companies like Uber and Lyft. This would contribute to reducing the cost and uncertainty of the sharing model by increasing the supply pool and enabling rapid dispatch of driverless vehicles.

d. The realm between personal transportation and public mobility can widen considerably to include various hybrid forms. Many agencies have already embraced a spectrum or suite of services in order to reduce operating costs in lower-density metropolitan areas. Experimenting with a fleet of smaller vehicles, casual sharing, and more traditional vanpools and guaranteed ride home programs, agencies have explored many options to move people over low-density areas or at odd times of day. Services in this spectrum, which fall between purely fixed-route and purely demand-responsive and can be described as "semi-flexible."[31] These services typically include a set of stops with a predetermined schedule along with sections of a service area where service is flexible (e.g., route deviation), possibly with door-to-door service. The premise of these services is in low-density areas, certain points will have higher demand at different times of day (e.g., hospitals, dedicated guideway transit, major employment/retail centers). Imposing some structure but still allowing flexibility can create more efficient tours while remaining intuitive and user-friendly. With autonomous vehicles, greater dispatching flexibility is possible, enabling the equivalent of personalized service at times, and shared rides at others, depending on the prevailing demands at a certain time.

e. What will become of public transit as we know it? With transit companies adopting a broader portfolio of services, possibly in conjunction with third parties, one could envision disappearance of conventional fixed-route, fixed-schedule bus service in most lower-density communities. This may be supplanted by driverless, personalized service at low density and shared hybrid forms at medium densities; and greater focus on frequent rapid service along dedicated right of way (rail and/or BRT) in higher-density travel corridors, made more efficient and accessible via driverless hybrid options.

Some of these trends are beginning to emerge today. Several communities are experimenting with hybrid forms of public transit. Car sharing programs are thriving in many cities. Ride-hailing app companies (Uber, Lyft) that dramatically increase the pool of available vehicles to serve customer requests (albeit on still controversial regulatory grounds) have become household names in many cities around the world. Some of these same companies, especially Lyft, are making a concerted effort to tailor services to better complement existing transit services by, for example, providing access to rail transit stations.[32]e.g., In Finland, the city of Helsinki received a lot of attention in transportation planning circles when it announced its goal of no more private car ownership in the city, all the while offering individual and shared public personal urban mobility through a city-managed virtual platform.

Putting it all together: Key factors for urban future scenarios

The future infrastructure for urban personal travel depends on answers to questions regarding the following three factors: social preferences, the urban fabric and technology. Specifically:

1. Social preferences: Will today's millennials continue their preference for urban living, walkable neighborhoods, shared economy, away from automobile dependence?
2. Walkability and non-motorized/lightly motorized forms of personal transportation: Will the desire for attractive walkable urban spaces extend beyond the larger, denser cities in the U.S. (New York, Chicago, San Francisco, Boston), and will the trend toward rent premiums in walkable, accessible neighborhoods continue? Such trends would then naturally drive changes in the urban fabric toward patterns conducive to such lifestyle preferences as attractive walkable environments with multi-use, denser development, and access to public transportation.

3. Technology: How will ongoing developments in vehicle and information technologies impact urban transportation and travel? While technological forecasting on such time scales is fraught with uncertainty, the best prediction based on what is known today includes the following trends:
    - More personal connectivity, with smartphones (or similar personal mobile devices) increasingly becoming a hub of virtual, social and physical activity.
    - Internet of Things (IoT) will enable smarter cities, with greater information and convenience for users.
    - Autonomous vehicles will come to market, likely within the next five years, though the extent of large-scale adoption is still not clear.
    - Connected vehicle systems, especially vehicle to infrastructure (V-to-I), while still lagging in deployment experience, will be part of a larger IoT.

Several implications of the above factors for the transportation and mobility infrastructure in cities can be identified:

a. Major improvement to flow systems is required to accommodate requirements of mixed traffic and heterogeneous users, particularly with regard to non-motorized traffic sharing the right of way in greater numbers with vehicles, connected or otherwise. With potentially substantial increases in bicycle traffic, safety concerns will likely become more critical. Creative solutions will be required to adapt streets to flexible operational strategies while retaining the desired quality of urban spaces. Left unabated, these problems can reverse the very features that make cities attractive places for a growing portion of the highly skilled workforce.

b. Infrastructure deployments must be considered from a more integrated, multi-sectoral perspective. Operationally, smart cities envision leveraging powerful data platforms for multiple, previously seemingly unrelated uses, such as transport and education, or education and health. Similarly, we must join road and transport infrastructure planning and deployment with telecommunications and information technologies, as well as the smart electric power grid, at a minimum. These are the lifelines of modern urban living, and they will continue to become increasingly intertwined over the next few decades. Failing to plan adequately across these critical infrastructures will result in missed opportunities, decreased competitiveness, and higher future costs.

c. In addition to the physical infrastructures, software platforms for connected vehicles and more generally IoT applications in smart cities will still need to emerge—or rather be built through concerted action to bring about the desired connectivity benefits and efficiencies. This is probably one of the most complex pieces of infrastructure to develop and implement, in light of the potential involvement of both public and private sectors.

d. The ability to track and measure travel by multiple modes, physical as well as virtual, might lead to the emergence and adoption of new payment schemes for infrastructure access that better reflect the way people use their infrastructure. Financing infrastructure improvements is looming as a major challenge for public entities under current revenue models. Various forms of charging users for their use of the infrastructure are emerging -- tracking technologies and smartphone payment systems will facilitate the emergence of novel ways of delivering mobility services.

e. One of the big questions going forward pertains to the capacity of public sector entities such as city transportation departments and public transit agencies to bring about the realities of connected cities and transportation systems, for a combination of technical, managerial and financial reasons.[33] With technological innovation, private sector companies particularly from the technology sector are showing growing interest in the transportation arena, from shared economy platforms, to ride hailing apps, to autonomous vehicles. Accordingly, new models of ownership/operation reflecting more flexible forms of service delivery are likely to entail greater role for private sector and public-private agreements.

Under all the technology scenarios discussed in this chapter, wheeled vehicles will remain the primary modes of transport for individuals in our cities. While rail systems, both underground and aboveground, will likely remain the most effective and efficient means of transporting very large volumes of people over long metropolitan commuting distances, most other forms of travel will entail smaller, more personalized vehicles. Bus transport, as we know it today, namely in the form of large buses negotiating their ways slowly on fixed schedules along fixed routes that travel through congested streets, may well not survive in that form. Bus rapid transit variants will be deployed for dense corridor service during peak periods but the rest may well be delivered by hybrid transit forms consisting of on-demand personal transport that may be shared with other riders or entirely personal, especially under level 4 autonomous scenarios.

Under all of these scenarios, the need for the equivalent of highways and urban streets is not likely to go away. As virtual and physical worlds continue to converge in terms of individual activity engagement, mobility needs may continue shifting and evolving, but all indications point toward more, not less travel, as telecommunications create more, not less, opportunities to meet in person and activities to fulfill at common destinations. Driverless cars still need good roads, perhaps even better ones to achieve the efficiencies that may be delivered through automation. Hence while the needs for urban road infrastructure may be quantitatively similar to what we have today, they will likely be qualitatively different—enabling greater diversity of urban travel modes and mobility services to be delivered in an efficient seamless and safe fashion.

Getting there from here

In examining scenarios that may be likely to unfold with regard to urban mobility, it can be safely stated that any scenario is likely to involve a continued and growing role for information and communication technologies in most aspects of peoples' lives. Even the most conservative "business as usual" scenarios will see greater use and integration of smartphones and other mobile devices in everyday life and greater convergence of individuals' virtual and physical worlds. They will also experience the benefits of at least partial connectivity of vehicles, and various other objects through some IoT implementation. As discussed previously, autonomous vehicles will also make their appearance, and play some role in the overall mobility spectrum. Essentially, most innovations with potential for market adoption and revenue generation are likely to be introduced in one form or another through private sector engagement.

Less evident is how the broader smart cities visions with vehicles, people, homes and so on, all connected through an integrated platform, will come together to support applications across a spectrum of urban sectors. It is likely that different cities will take various pathways toward achieving different types of functionality that reflect local priorities and opportunities. “Business as usual” scenarios (Scenario 1: Static policy in a changing world - more of the same) would see various private sector initiatives and services with limited or incremental engagement or investment by public entities. “All green” scenarios (Scenario 2: Resilient and sustainable communities) would see greater public investment in sustainability-oriented smart city initiatives, though perhaps not necessarily delivering functionalities where the primary objective is user convenience (though the two are by no means mutually exclusive). “Peak economic performance” scenarios (Scenario 3: Competitive success) will likely demonstrate strong public-private cooperation and investment enabling local businesses to gain a competitive advantage both regionally and globally.

It is unlikely that existing cities in the U.S. will become connected and smart by government fiat through some top-down program. Some of the challenges facing U.S. cities in their quest for smart functionality (and branding) include the following:

a. The urban infrastructure system is too complex, too fragmented, with too many owners, jurisdictions, and so on. Any process of integration in most U.S. cities would need to go through a lengthy, deliberative, participative effort that may not be the most direct route to introducing technological innovation and may possibly even hinder it.
b. The administrative processes themselves would need to be re-engineered to recognize the drastically expanded availability of data, and deliver the functionality and services expected and possible through integrated platforms. It is no secret that public agencies do not embrace such changes rapidly and smoothly.
c. The overall system is very dynamic, especially with the rate at which new functionality is introduced by private sector technology companies, start-ups and app developers. Such developments will likely not wait for some “final” design to materialize, be tested, revised, or stabilized.

Accordingly, a likely pathway would be through relatively loose coupling of smart apps, developed by entrepreneurial entities, and/or agencies with specific needs in particular domains (e.g., electric power, health, traffic systems). The main opportunity for user benefits in a smart city environment is in facilitating data sharing, transparency, and access across different apps; achieving this is as much a matter of culture as it is of technology. Cities with strong, visionary leadership and civic-minded entities would likely be in the vanguard of such developments. Around the world, places like Singapore, Dubai or Helsinki are likely to be in position to be in the lead of bringing some of these visions to reality.

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CHAPTER FIVE

Information and Communication Technologies and Transportation

By Fabián E. Bustamante

Introduction

Transportation is a key enabler of social and economic activities and a main contributor to a nation's overall success. Over the last 60 years, the transport infrastructure [1]of most advanced nations has been formulated around personal vehicles and expanding road infrastructure, many times at the cost of public transport services, increased road congestion and environmental impact.

Today's transport infrastructure faces a number of challenges and increasing pressure from different fronts – from rising urbanization, growing population and changing work patterns, to aging infrastructure, lower public investment, and growing demands for lower emissions. Congestion continues to expand (particularly in major and rapidly growing urban areas) with its known economic cost and negative impact on the environment. As a whole, transport is the second largest contributor to CO_2 emission in the U.S. (27 percent in 2013)[2], lower only than electricity generation. Without aggressive and sustained mitigation policies, transport emissions are expected to increase at a faster rate than emissions from any other energy end-use sectors.[3]

Information and Communication Technologies (ICT) can play a transformative role in the future of transportation, allowing it to better face many of these challenges. The impact of ICT on society at large is undeniable. Combined with globalization, climate change and urbanization, ICT is helping to transform society and the economic structures this nation has depended upon for the last 100 years. The adoption of ICT in transportation can multiply capacity without added physical infrastructure, extend the life of existing infrastructure and significantly shape demand.

Still, it is important to be cautious of overly optimistic predictions about the benefits of ICT in transportation, as the relationship between the two has proven to be rather complex. For instance, early views of telecommunication as a direct substitute for transport left many puzzled by the continued increases in traffic flows, travel time and congestion. We have learned since that some activities do not have a direct ICT counterpart, such as those that require people to be at specific locations (e.g., house repair). Other activities may either be technically challenging from an ICT perspective, beyond the reach of today's technology, or simply preferred to an ICT alternative (e.g., a professional society meeting).[4] What is more, some ICT trends can simply change or actually increase the demand for transportation services. Production and distribution practices in urban freight, for instance, are changing with progress on ICT, shifting toward low inventory and just-in-time delivery. While facility and inventory costs are lower, retail transportation is significantly less efficient (lower benefits from aggregation). Electronic commerce has also created an explosion in freight transport for personal delivery. For passenger transport, ICT increases the opportunities for travel (e.g., with people having more free time), reduces its cost and improves the enjoyment of travel time – sometimes resulting in an increase, rather than a reduction in travel. Similarly, it is possible that faster, more efficient communication technology[5] and a push toward universal broadband access may translate into more decentralized land use patterns with the associated longer travel distances.[6]

Considering these complex interactions, rather than attempting to predict the future of ICT and transportation, the following paragraphs review the role of ICT in transportation, potential barriers that could prevent or delay ICT adoption, and some of the most notable trends in ICT and their potential impact on transportation.

ICT in transportation

ICT has a relatively long history in transportation, having played an influential role since the 1960s. Early on, ICT adoption resulted in improved operation efficiencies in what were disconnected, function-based business processes, from inventory management and billing to – most critically to infrastructure – transport routing and scheduling.

In the 1970s, Material Requirement Planning (MRP) and Material Resource Planning (MRPII) offered ways to more effectively plan all resources of a manufacturing company by connecting software and hardware elements through a central database. This integration resulted in better control of inventory and improved scheduling, among other benefits. By the 1980s, network-compatible MRP packages running on local area networks (LAN) enabled more rapid and efficient planning at lower costs. These 1980s systems were predecessors to the Enterprise Resource Planning (ERP) of the 1990s which offered an integrated view of business processes from financial and management accounting to human resources to supply chain management. The advent of the commercial Internet and the Web in the mid to late 1990s also brought significant changes to transportation and logistics with Internet-based inter-organizational systems and the subsequent development of new e-business models such as Electronic Marketplaces.[7] Combined with more affordable, distributed computing resources and services, connectivity has started to change the demand on and management of the transport infrastructure with higher efficiencies in road transport through vehicle tracking and fuel recording systems, a better understanding of the wear and tear and maintenance approaches, better planning optimization and routing, and close-to real-time management of intermodal freight with better load consolidation and fewer empty vehicle trips.

In freight transport, ICT has aimed to improve operational efficiency and safety and provide more opportunities and incentives for intermodal cooperation.[8] Due in part to economies of scale and scope but enabled by advances in ICT, freight transport and logistics have become globalized and streamlined, providing scale, volume and efficiency to satisfy the movement of goods internationally.

ICT's role in passenger travel is comparatively more recent but not less important. The growing adoption of ICT in households and businesses has increased businesses' geographic reach and potential contact network and redefined traditional human activities like working, shopping and leisure since the late 1990s. Rapidly expanding network connectivity and the more recent proliferation of small-scale consumer technology have brought progress in Intelligent Transportation Systems (ITS) that enable users to be better informed and to make safer, more coordinated, and smarter use of transport networks -- from better trip planning to real-time update of route conditions and seamless travel across multiple transport services.

Barriers to ICT

Although the growing role of ICT in transportation is undeniable, a number of barriers have limited its adoption throughout the transport industry and its potential benefits to infrastructure. The barriers can be grouped into three key categories based on their area of impact:[9] user-related, policy-related and technology-related.

User-related barriers range from the lack of skilled ICT personnel,[10] resistance to learning about new technology, and the difficulties in recruiting and retaining ICT specialists, to the complications with securing the financial support needed for early ICT investments and quantifying the potential benefits of such investments. A 2007 study of freight and ICT in the U.K. showed that while ICT was important to the majority of freight carriers, the industry seemed split, with smaller operators still dependent upon traditional communication and process systems and large carriers that controlled the majority of vehicles and freight movements increasingly adopting ICT.[11]

Policy-related barriers include legal requirements and regulations on safety, security and privacy, different transportation policies, company policies (e.g., with respect to telecommuting[12]), and variations in administrative procedures and standards across states and countries that complicate interstate and international transport. Different safety and security standards between transportation modes and/or across states can hinder ICT adoption for inter-modal transport. The development of standardized interfaces and open communication mechanisms, key technology-related barriers, also requires promotion and support from related policies.

Technology-related barriers encompass problems with system interoperability and integration, standardization, security and data protection. The rising amount of data, while potentially beneficial, needs to be collected, analyzed and applied appropriately, which in turn depends on the existence of common interfaces, shared security and protection policies, and agreed upon data formats. The transportation sector faces problems sharing information quickly and easily between multiple systems, with much of the data being kept in silos due to implementation, proprietary concerns, regulatory restrictions or lack of clear standards. This lack of standards complicates not only the interconnectivity between applications and across industries but also the integration with both legacy and future applications.

Lack of trust in online transactions and consideration for security and liability issues regarding the information to be exchanged can be obstacles to the adoption of Internet-based applications. While people, cargo and vehicle trackability offer a number of potential benefits, this capability forces companies to ensure the protection of personal information so as not to lose their customers' trust and thus further hinder information sharing.

Similar trust, security and liability concerns can become obstacles to the widespread adoption of connected vehicles. If the only thing that was linked to the outside world were an infotainment system, having that system hacked would be annoying but not particularly dangerous. When connectivity moves beyond entertainment to include an increasing number of electronic control units (ECU) within the vehicle and across vehicle-to-vehicle or vehicle-to-infrastructure communication, the risks are radically different. While vehicles have relied on on-board computers for a few decades, these circuits primarily managed low-level components. Today, however, ECUs control or finely tune a wide array of critical functions, including steering, acceleration, braking, and dashboard displays. The associated software is becoming increasingly large and complex with hundreds of millions of lines of code,[13] more than a modern operating system such as Windows or Mac OS. Considering that the number of bugs and vulnerabilities in software is known to be a direct function of the number of lines of code,[14] the high probability and potential implications of errors and security breaches can become significant barriers.

Technology trends

The fast pace of ICT advances – in degree of integration, computational power, and communication capacity and reach, and their ever-redefining role in society, requires periodical review of the potential impacts on transportation. Many of these advances can also help remove or reduce some of the barriers to ICT adoption identified here. High-capacity, ubiquitous broadband, for instance, can improve experiential technologies favoring home delivery or pickup location models for online channels. Recent progress in cloud computing, to cite another example, could facilitate widespread ICT adoption across the transportation industry.

Ubiquitous broadband and richer interfaces

Broadband availability and performance continue to improve rapidly, propelled by government and private investments.[15] These investments are motivated by the recognized social and economical benefits of connectivity. In just a few years, broadband capacity has grown from the common 56Kbps of the 1990s to recent offerings of 100Gbps.[16] Availability in the U.S., while not universal, is growing rapidly with several community, state and nationwide efforts.

An element of science fiction not long ago, augmented reality (AR) – where interaction with the real world is enhanced with virtual images and other data – is getting closer to being the new normal. While the technology has been in research labs and in specialized settings (e.g., pilot training) for a few years, recent commercial developments, such as the acquisition of Oculus Rift by Facebook, suggest that the technology is getting ready for mainstream consumption. Indeed, in the retail sector Tesco has already been using AR technology to allow customers to view life-size projections of products before purchase. De Beers has an AR tool that lets customers try on jewelry virtually, [17] and SnapShop [18] is an app that allows users to try out new furniture in their house. There are other developments in richer experiential technologies, including touch and smell (with companies like TriSenx offering a device that releases scents under computer control). Ubiquitous, high-performance broadband and these recent developments in augmented reality and other experiential technologies could bring some of the early ideas of ICT as transport substitute closer to reality.

While some of the related barriers discussed above may persist, such as preferences for face-to-face interactions that will remain hard to replicate, ICT improvements – supported through private investments, community efforts or federal plans – will change where and how people work, shop or look for entertainment, and these changes will result in different travel times and patterns, and, potentially, less congestion at peak hours. Even if early forecasts appeared to have been overly optimistic about the potential transportation impacts of ICT, it is also true that the extent and degree of change telecommunication was to bring and the pace of advancement on this front was clearly underestimated.

Cloud computing

Cloud computing enables ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.[19]Through the “cloud,” ICT services can be provided by experts on existing infrastructure, avoiding many of the user-related barriers mentioned in the previous section, including the high-cost of investment and management of IT resources and the complications of recruiting or training expert personnel. Companies using cloud services can adopt ICT and pay on an as-needed basis, addressing some of the economic and financial barriers to its adoption, while avoiding the complexities of managing in house ICT.

While these tools can benefit the business side of the transportation industry, the real value comes when the cloud intersects directly with fleet management devices. By connecting devices in transportation directly to the cloud, companies and transportation agencies can bring multiple pieces of data together for a more accurate and dynamic picture of system performance. Cloud computing can provide the benefit of more immediate, near real-time data, allowing managers to see realistic snapshots of deployment and activities of mobile resources and shipments at any given moment.

Pervasive sensing and communication, Internet of Things

The increasing use of sensors and mobile devices and the availability of pervasive communication across all aspects of transportation translate into rising amounts of data that could be leveraged in innovative ways. For instance, road and rail infrastructure are among the most extensive and important components of the transport system. Sensor technology would help monitor and sustain much of this legacy infrastructure. There are projections for 1 trillion sensors by 2024 and 100 trillion by 2036. [20] Sensors and sensing information collection, communication and processing will shift the monitoring of infrastructure from periodic checks and repairs to constant monitoring and prevention and early intervention for roads, bridges and railroads. More information could allow for smarter prioritization of maintenance and repair tasks, thereby extending the lives of infrastructure.

Sensors can not only report on road and infrastructure condition but also record fine grain information on utilization and congestion which might help to manage the existing system more efficiently and to decide, with better information, when and how to expand capacity to handle congestion and delay. Sensors could be part of the transport infrastructure or be embedded in every device carried or worn, from phones, watches and vehicles to shoes and jackets. This vision is rapidly becoming a reality and having a direct impact on transportation. Companies like Inrix and Waze process publicly available and crowdsourced data to improve transparency in urban transportation and reduce friction (moving ticketing to the smartphone, calculating prices for multi-trip options, for example). The significant volume of data on drivers, vehicles, driving patterns and vehicle responsiveness being collected can be used to improve driving (for example, controlling a truck in real-time as with the Volvo’s I-See) or to reward good drivers (through plug-in devices such as Progressive's Snapshot and Allstate's Drivewise), reduce congestion and avoid accidents.

Networked sensors and actuators could support totally automated collision avoidance, increasing infrastructure utilization by enabling the mixing of vehicle types (e.g., eliminating the need for dedicated bike or bus lanes), automated management of traffic signals to minimize average wait time for the green light, and smart street parking systems that let users park anywhere in the street, identify the car and charge their account.

Smart, connected and self-driving vehicles

Driverless technology is already here and has been surreptitiously taking over vehicles but its greatest benefit will come when human hands are totally off the steering wheel. Recent years have brought significant advances in this front. Today, much of the technology in driverless vehicles is in the cloud, where the heavy processing of road and obstacle data happens but this should change rapidly to make it feasible in every vehicle - truly autonomous of both driver and datacenters. This would require multiple forms of communication, short-range fast communication with other vehicles on the road, roadside units and the road itself, and long-range communication with datacenters that leverage the common experience/shared knowledge of roads and traffic conditions.

In the 3rd quarter of 2014, AT&T added more vehicle-related data subscribers (500k) than smartphone or tablet subscribers (446k and 342k, respectively). These data plans deliver software updates, traffic data to the navigation system and Internet connectivity to passengers. In the immediate future, hand-free and feet-free driving like Tesla's autopilot and GM's Cadillac "super cruise" will become widely available. Connection will also enable new tools for predictive and preventive maintenance by automakers and even provide information about relevant modal options. For instance, the BMW iSeries uses Inrix to take into account public transport options in multimodal routing to get people to their destinations.

Fully autonomous vehicles are not far behind, with nearly every industry player having a program for its development and the rapidly dropping costs of the necessary technology. For instance, LiDAR laser sensors used in the Google car cost more than $70,000, while this year a miniaturized version is available for one-tenth of the price. Sharing economies would accelerate the adoption process as they would enable economies of scale through third-party provided services - a sort-of driverless Uber or ZipCar. [21]

Conclusions

Transportation is facing a number of challenges and increasing pressure on different fronts, from growing population and urbanization to higher demands for increased reliability, lower emissions and reduced unproductive time spent traveling. ICT has ample potential to address these challenges by changing the patterns, and potentially reducing, the amount individuals travel through substitution effects, increasing the efficiency of freight operation, and improving the management of infrastructure itself with advance sensors and communications systems. There is already evidence of ICT's transformative power and its impact on transport infrastructure. Today, the largest taxi company (Uber) owns no taxis, the most valuable retailer (Alibaba) has no inventory and the largest movie house (Netflix) owns no cinemas. However, the overall impact of such changes on transportation infrastructure demand is not straightforward as, for instance, the demand for freight movement is likely to increase, particularly at the local level, with changes in supply chain models; and ICT improvements may make it easier and provide more opportunity for longer trips. Overall, the needs for a quality transportation network infrastructure will change but, in evolving form, infrastructure will remain essential to economic success and ICT a critical part of it all.

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ENDNOTES

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CHAPTER SIX

Supply Chain Management, Logistics and Transportation Infrastructure

By Mike Hewitt

Introduction

Transportation infrastructure plays a critical role in the success of many firms. For consumer product manufacturers, transportation enables the supply chains that produce their goods, enabling them to leverage manufacturing expertise and efficiencies in different parts of the world to produce their products. Transportation also enables the distribution of those goods to retailers and/or consumers. For a brick-and-mortar retailer, transportation services deliver the products they stock on their shelves. Finally, transportation infrastructure enables employees to staff and customers to shop at brick-and-mortar stores.

Transportation infrastructure is even more important for eCommerce retailers. From a customer relationship management perspective, delivery may be the only point of physical contact they have with their customers. From a customer satisfaction perspective, delivery reliability is particularly important. A brick-and-mortar store can fall back on inventory to satisfy customer demand when a delivery from a supplier is late. In an eCommerce transaction, the customer has to wait when a delivery is delayed. Transportation also drives demand for an eCommerce retailer. It is well known that faster and cheaper deliveries impact customer behavior.[1] But it is both forward and reverse flows that are important for these retailers; easy and inexpensive (if not free) returns have enabled the success of online clothing retailers like Zappos.com. Reverse flows are fundamental to the business model of online personal stylists like Chicago's Trunk Club, where personal shoppers pick out clothing items they think a customer will like, then ship to the customer's home, fully expecting many items to be sent back.

The demands placed upon transportation infrastructure by supply chains are expected to grow; the American Trucking Associations U.S. Freight Forecast predicts that freight volumes will grow more than 23.5 percent by 2025.[2] They forecast that the market share of tonnage transported by truck will increase from 69.1 percent in 2013 to 71.4 percent; this can be attributed partially to a belief that there simply isn't 20 percent more capacity in other modes.

This chapter will focus on the five attributes (connectivity, capacity, performance, flexibility or adaptability, and greener technologies) of transportation infrastructure and how they can impact different metrics of firm performance. Much of this chapter will focus on one of the primary metrics of firm performance: inventory levels.

There are many links between inventory and firm performance. Inventory levels can impact both the short and long-term financial position of a firm. In the short-term, inventory ties up a firm's capital and incurs costs for handling, storage, and insurance. To give perspective, many manufacturers report spending 20 percent of an item's value each year it is held in inventory. In the long term, financial analysts often use inventory levels to measure how well retailers are doing, with high inventory levels often interpreted as a sign of impending trouble. Proponents of lean manufacturing often correlate high inventory levels with quality issues as they can delay the time when a manufacturer discovers issues with its (or its supplier's) production process. Inventory is also a source of risk for firms, with many facing a risk of obsolescence of their finished goods and devaluation of the components used to manufacture those goods. Finally, less tangible links have been observed, including managers feeling reluctant to innovate products they hold at high inventory levels because of a perception that existing inventories must be sold before new products are developed.

One of the most common reasons for holding inventory, either at a retail store that needs to meet customer demand, or at a manufacturing facility that faces downstream demand from a customer-manufacturer or distribution network, is to satisfy that demand while waiting for a replenishment order, i.e. during the lead time. Of course, the longer that lead time (or the slower the transportation that delivers the replenishment order) the more inventory that must be held to meet demand. Similarly, the less reliable the transportation service that delivers the replenishment order, the more inventory that must be held.

The costs of failing to meet demand can be great and the impact on customer satisfaction and retention can be long lasting: A retailer faces the immediate lost sale which may never return. A 2015 survey by GT Nexus of 1,000 customers in Germany found that 63 percent of customers who experienced a stock-out either purchased the item from a competitor or never purchased it at all. The impact of a stock-out can also be long-term; a 2011 study of 1,021 U.S. shoppers found that 68 percent would avoid shopping at a particular retail store if they encountered empty shelves. For a manufacturer, stocking out of a needed supply can lead to hours if not days of lost production. Trends in manufacturing, such as just-in-time manufacturing, place greater expectations on transportation infrastructure, as a consumer product manufacturer likely won't have enough inventory to fall back on to accommodate late component deliveries.[3]

Of course, transportation infrastructure also impacts the bottom line of a consumer product manufacturer. A critical number for manufacturers to calculate is the total landed cost for the products they produce and deliver. This cost (typically) includes both direct transportation costs as well as other transportation-related costs such as insurance and customs duties. This cost is often one of the factors used by a manufacturer when determining the price it charges its customers.

This chapter partitions freight movements into two categories: (1) intercity and, (2) intracity to examine how different attributes (connectivity, capacity, performance, flexibility or adaptability, and greener technologies) of transportation infrastructure relate to inventory (and other metrics of firm performance, particularly costs). The chapter continues this analysis in the context of the scenarios identified in this study: (1) static policy in a changing world - more of the same, (2) resilient and sustainable communities, and, (3) competitive success.

Types of freight movements

One classification of freight movements is by origin-destination pair, with intercity movements connecting origins and destinations in different cities and intracity connecting those in the same city (or a terminal outside of and a location inside a city). The attributes (connectivity, capacity, performance, flexibility or adaptability, and greener technologies) of transportation infrastructure impact firms differently for different types of movements.

Intercity freight

Intercity freight movements enable the supply chains that support the production of consumer goods and the distribution networks that get those goods to retail shelves and customer doors. These supply chains are often global with intercity freight movements connecting different modes of travel, such as moving products entering the U.S. port from China through Los Angeles by rail to Midwest and eastern destinations, with the final leg on a truck. How the attributes of transportation infrastructure relate to intercity freight movements will be examined next.

Connectivity: Proximity to transportation infrastructure is one of the main drivers in the decision-making process for firms that are looking to locate facilities (manufacturing sites, warehouses, etc.) that support their supply chains. For example, Chicago is a key U.S. logistics hub due to its connections to six Interstate highways, six of the seven major railroads, one of the largest inland cargo ports and two highly trafficked airports. Retail outlets that are not connected to fast and reliable transportation services will need to carry higher levels of inventory to cover demand while waiting for replenishment orders. Conversely, firms with manufacturing facilities in locations that are not connected to faster or more reliable modes of travel will need to preposition inventory to satisfy customer demands for short delivery times. All this (excess) inventory that is held to offset poor connectivity incurs extra costs and reduces the firm’s profit margin.

Capacity: The capacity of transportation infrastructure partially determines the speed of travel. Low-capacity transportation links, such as highways with an insufficient number of lanes, can be extremely congested. This congestion leads to increased travel times, which in turn leads to longer lead times and subsequently higher inventory levels. Similarly, low capacity transportation links in terms of the weight or number of containers that can be carried (e.g., bridges or tunnel clearances that do not support double-stack rail transport) can also lead to route diversions and congestion, all increasing shipping costs and perhaps reliability. In addition, node capacity, such as the capacity at intermodal or port facilities can also have a significant impact on lead times. Ports with insufficient capacity (berth, storage, and throughput capacity) can add significant amounts of time to the transportation of goods as they can force ships and/or trucks to wait for unloading resources.

Like connectivity, capacity also plays a role when manufacturers decide where to locate facilities that support their supply chains. Firms with logistics/supply chain facilities (such as distribution centers) that are not in close proximity to high-capacity transportation infrastructure may need to open extra centers to ensure they can meet customer demands in a timely manner. At the same time, it has long been observed that the greater the number of facilities in a supply chain or distribution network, the higher the inventory levels (i.e. two regional warehouses will often end up with higher combined inventory levels than one centralized warehouse). To be precise, supply chain researchers have derived from empirical data the following equation relating inventory levels in supply chains with different numbers (N1, N2) of facilities:

$$\text{Inventory level with } N_2 \text{ facilities } = \text{Inventory level with } N_1 \text{ facilities } * \sqrt{\frac{N_2}{N_1}}$$

Capacity can also directly affect costs. For example, the U.S. Department of Transportation has estimated that increasing allowable truck weights on Interstate highways from 80,000 to 91,000 pounds would reduce costs for shippers by 1.4 percent annually, yielding a savings of approximately $5.6 billion. Others have argued that such an increase could also have a positive impact on the environment; the University of Michigan Transportation Research Institute estimates that the increase could reduce fuel consumption 13 percent as allowing trucks to carry heavier loads would significantly reduce the number of trucks on the road. Conversely, insufficient capacity can lead to carriers increasing the rates they charge shippers, potentially impacting both the bottom line of manufacturers and the prices they charge their customers.

Performance: When determining how much and how often to order, supply chain managers consider the length of time needed for an order to be fulfilled (the lead time) and the demand that will occur during that time (lead time demand). They hedge against uncertainty in customer demands which is greater the longer the lead time, and supplier reliability with “excess” inventory (often referred to as safety stock). These uncertainties directly impact inventory levels; the greater these uncertainties, the more safety stock is kept. As such, the ideal scenario for supply chain/inventory managers is one where they know that every order they place with a supplier will arrive quickly, at the time expected, and in good condition. In such a scenario, a short travel time means they will have a shorter period during which they need to have inventory to cover demand. Being on time/high reliability means they need little safety stock to cover demand in case the order arrives late.

Flexibility or adaptability: With major environmental events like Hurricane Katrina and severe winter weather as seen in winter 2013-2014 becoming a routine part of the operating environment for supply chain managers, adaptability is of critical importance for transportation infrastructure. In the absence of the ability to reroute freight quickly in anticipation of weather events, supply chains will be forced to carry more inventory to offset the risk of orders not arriving on time because of weather. Similarly, to mitigate the risks associated with severe weather events firms may move toward more geographically distributed supply chains. This would put greater demand on the connectivity of transportation infrastructure.

In December 2007, weather conditions (heavy rain and melting snow) closed a 20-mile section of I-5 near Chehalis in western Washington for four days. Later, in January of the following year I-90 was closed at Snoqualmie Pass for nearly 100 hours. To adapt to these closings, WSDOT established a detour along I-84 in Oregon, which added 440 miles and nearly 8.5 hours of driving to what should have been a 200-mile trip from

Portland to Seattle. Estimates associated with these disruptions suggest that the I-5 disruption cost roughly \$47 million.[4] Some of these costs were due to orders not being delivered to customers on time (e.g., perishable goods). Others were due to an increased cost of transportation for trucking companies, including increased wages and overtime pay for drivers. In addition to the detour simply being a longer route, it was reported that the extra time caused some drivers to have to rest due to federally mandated hours of service regulations (a driver must take a 10-hour rest after 11 hours of driving). Ultimately, it was estimated that the cost of taking the I-5 detour was between \$500 and \$850 per truckload.

The globalization of supply chains introduces another point of failure for transportation infrastructure that can dramatically impact U.S. manufacturers, particularly those that have adopted just-in-time inventory strategies. It has been estimated that the long waiting times and closures at borders immediately following 9/11 led to a halt of auto production at more than 60 plants in the U.S. and Canada due to the inability to get critical inventory. It has also been estimated that 52,636 units of production were lost in the first week after 9/11 across all automakers with North American facilities. In a world where such border issues (or precipitating security events) are recurring, and few alternate options are available, manufacturers will be forced to hold greater inventory at their facilities.

Greener technologies: Many transportation companies (UPS, FedEx, DHL) strive to operate in a manner that is sustainable, both with respect to the environment and society as a whole. David Abney, CEO of UPS, stated in the company's 2014 Sustainability report[5], that "Among our largest challenges is balancing the benefits of global trade and growth with the reality of increasingly constrained resources." FedEx states that it "is committed to providing global connections while minimizing our environmental impact."[6] These companies also appreciate the importance of the environment to their stakeholders, including customers, shareholders, and employees. One way to reduce the environmental impact of transporting products with current technology is to counter the trend of global supply chains and instead make products closer to the customer's location. However, by foregoing the benefits of a global labor market, product prices will likely go up. And, one of the primary strategies for reducing inventory levels is to pool customer markets as variations in customer demands can offset each other (e.g., with one warehouse serving all of the Southeast, a distributer can tolerate an increase in demand in Atlanta if there is a near-simultaneous reduction in Nashville).

Intracity freight

Intracity freight includes what is called the "last mile" of delivery to a customer, whether an individual or a retailer receiving goods to stock its shelves. A distinguishing aspect of freight traffic in urban areas is that it typically consists of high volume movements of low-value consumer packaged goods, goods that are consumed in daily life such as personal care products, packaged foods, etc. These are goods that are consumed regularly, often weekly or daily, and thus their inventory requires frequent replenishment. While consumers in urban areas may expect to have easy and inexpensive access to such goods, they rarely appreciate the presence of the trucks that make access possible.

To a greater extent than intercity freight, urban freight distribution involves multiple stakeholders, from shippers to freight carriers to residents to city administrators/policy-makers. Each of these stakeholders likely has his/her own objectives. Shippers are focused on getting their products to store shelves in urban retail outlets quickly, reliably, and profitably. Carriers are focused on providing transportation services at low cost which can be particularly challenging given that individual shippers likely do not provide full loads to transport. Residents are focused on the pollution (both noise and air) and road congestion and safety concerns that come along with delivery trucks on the road. Finally, city administrators are focused on the quality of life, safety and security of their municipality's residents and congestion as well. Accommodating these stakeholders and their interests is the inspiration for "city logistics" which has been defined as:

"City logistics is the process for totally optimizing the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of a market economy."[7]

Note the explicit reference to different objectives, from environment to congestion to economics. In urban freight distribution, it is often a challenge to optimize any of these objectives. With regards to economic objectives, because shippers rarely provide full loads, there is an even greater opportunity for consolidation in urban freight distribution. For example,'s-Hertogenbosch in the Netherlands is a city of 140,000 individuals, and it is estimated that the goods now carried by 2,500 trucks that enter the city each week could actually fit in only 170. This lack of consolidation leads to 45 percent of all deliveries accounting for 80 percent of the traffic.

A model that individual carriers have long used for transporting freight to urban destinations is a tiered distribution system. In such a system, goods are transported to a distribution center outside of the city where there is less congestion. That center then consolidates freight for delivery within the city. As an example, in Utrecht, the fourth-largest city in Holland, Cargohopper, a private delivery company, has implemented a scheme that has led to a significant reduction in trucks and vans on the city's narrow streets. In this scheme, companies leave their goods at a warehouse six miles outside the city limits. These goods are then delivered to locations within the city using a 52-foot, solar-powered caravan of three boxes pulled by a golf cart-sized buggy. They estimate that the scheme saves 33 tons of CO2 and 5,200 gallons of diesel by taking other vehicles off the streets as the caravan does the job of five vans.[8]

Cargohopper's warehouse is an urban consolidation center. These are logistics facilities in relatively close proximity to the region they serve that function as consolidation points for multiple carriers. A few such centers have been established in European cities (La Rochelle, France; Leiden, The Netherlands) with the assistance of government subsidies. However, few have been able to survive once the subsidies ended. Various reasons have been identified, many of which are attributed to there being multiple stakeholders each with his/her own objectives involved. For example, researchers have noted that carriers and retailers may not value the environmental or congestion-related benefits of using such a center over the extra costs and inconveniences associated with the transshipment that would occur at this extra "hop." Carriers may also be unwilling to engage in public-private partnerships, such as an urban consolidation center, as they are competing and unwilling to share proprietary information.

Connectivity: Because of typically dense urban street networks, connectivity alone is less of an issue for intra-urban freight that the compatibility of freight movements with other functions and adjacencies of city streets. However, there are greater requirements on the location of a logistics facility in a near-urban setting. Specifically, for a logistics facility to be effective in an urban setting it must maintain two connections: (1) to external sources of freight, either through proximity to highways, railways, or waterways, and (2) to customers in the urban area itself. In the absence of a facility in such a setting a retailer in an urban center still must meet regular and frequent demand from customers. Again, the classical approach to doing so is with inventory. But, unlike long haul transportation, where large warehouses are located in suburban or exurban regions with ample storage space, a retailer in an urban environment may have very limited storage capacity, either on shelves or in the backroom.

One mitigating factor for the location of such facilities that logistics researchers are studying is to use existing, potentially passenger-oriented, transportation services to deliver freight. As an example, imagine a mid-morning (e.g., 10 a.m.) a Metra train originating in Chicago's western suburbs and destined for Chicago's Ogilvie Transportation Center. While not empty, the train is likely under-utilized. Metra reports that peak-period trains account for nearly 70 percent of their ridership. Yet the nature of public transportation systems is that Metra has an obligation to run trains in non-peak-periods. Such trains could also be used to bring goods to the city center. With such a capability, a near-city distribution center could be located anywhere along the Metra line.

Such opportunities for dual use of public transportation infrastructure are not limited to Chicago. Hartsfield-Jackson Atlanta International Airport is one of the largest air cargo hubs in North America and MARTA (Metropolitan Atlanta Rapid Transit Authority) has a rail line that ends right in the airport. Anecdotal evidence suggests that MARTA lines are greatly under-utilized during off peak hours.

Capacity

Nowhere is capacity and congestion more closely linked than in urban freight distribution. Narrow city streets and lack of loading docks can severely limit the size of trucks used to deliver goods. Retailers still require their deliveries, which in turn requires more vehicles to satisfy customer demand and increases congestion. Alternatively, retailers must hold inventory, which again can quickly exhaust their available storage space.

That said, congestion (and pollution) can be reduced through more effective and greener uses of existing capacity. Returning to Utrecht, in 2010 they introduced a zero-emission electric boat, the "Beer Boat" to transport goods. In addition to being cleaner than the previous diesel-powered boat, it is also larger; it is estimated that five fewer trucks are needed per day to deliver goods because of the new vessel.

Performance

In an urban setting, there is both a greater need for reliable transportation services and more obstacles to reliability. Some freight customers may operate businesses that necessitate narrow time windows for delivery, e.g., restaurants refuse deliveries during busy service hours. At the same time, congestion and travel times that can vary significantly within and across days can make planning routes that reliably meet those time windows more complicated. As is the case for inter-city freight transport, lower reliability will force firms to carry more inventory. Of course, for some freight customers that rely on fresh products, such as restaurants, higher inventory levels are not an ideal option and may leave them at a competitive disadvantage.

Flexibility or adaptability

Transportation systems that have rigid capacity levels will be unable to meet large increases in demand in a timely manner, leaving customers to wait for their goods to be delivered either to their home or their neighborhood store. As noted above, a stock-out at a neighborhood store often causes customers to consider other retail options completely, such as an online retailer. This trend will likely continue and be amplified as more and more online retailers offer next or even same-day delivery. And if manufacturing returns to urban areas, then those organizations will also be faced with carrying higher inventory or paying for more expensive transportation (e.g., air vs. truck or rail) to deal with fluctuations in demand that cannot be supported by existing capacity. At the same time, to add capacity in an urban setting where trucks serve the majority of deliveries, will likely lead to an increased number of trucks on the roads. On top of the resulting environmental impacts, more trucks in an urban setting can impact aesthetics and quality of life.

Customers in urban freight centers are particularly vulnerable to disruptions to transportation infrastructure. One technique used to mitigate risk in supply chains is to have redundant facilities to ensure business continuity in case of disruption to a main facility. However, the lack of available and appropriate real estate in urban areas can often make such a strategy hard, if not impossible, to implement. As a result, in the face of disruption, freight customers may have no options other than to turn customers away.

Greener technologies

A greater emphasis on managing and reducing the negative impacts particularly noise and air pollution of urban freight distribution will necessitate a change in transportation operations. One way to reduce these negative impacts is to simply allow fewer trucks to deliver in city centers. Such a shift could be mitigated by urban consolidation centers that ensure that the trucks doing deliveries are full. However, for retailers in urban settings, the use of consolidation centers will likely add to transportation cost and time.

Another way to reduce these negative impacts is to change how deliveries are made; either through the use of cleaner vehicles or by using existing capacity such as carrying cargo on passenger buses. While a greater use of clean vehicles may have little impact on the operations of urban retailers, non-traditional methods of delivery may add complexity. For example, Greyhound buses already offer the capability of delivering packages with offerings that differ based on whether the shipment is door-to-door or the recipient has to go to a bus terminal to pick-up/drop-off their shipment. Similarly, as the U.S. Postal Service already visits most addresses every day, leveraging its capacity to do last-mile delivery could be done with little incremental environmental impact. Yet doing so would also require carriers to integrate their distribution networks with the post offices. This is a developing trend for the delivery of small loads, particularly to residential customers.

Figure 1 illustrates the interrelationships between transportation infrastructure and business inventories.

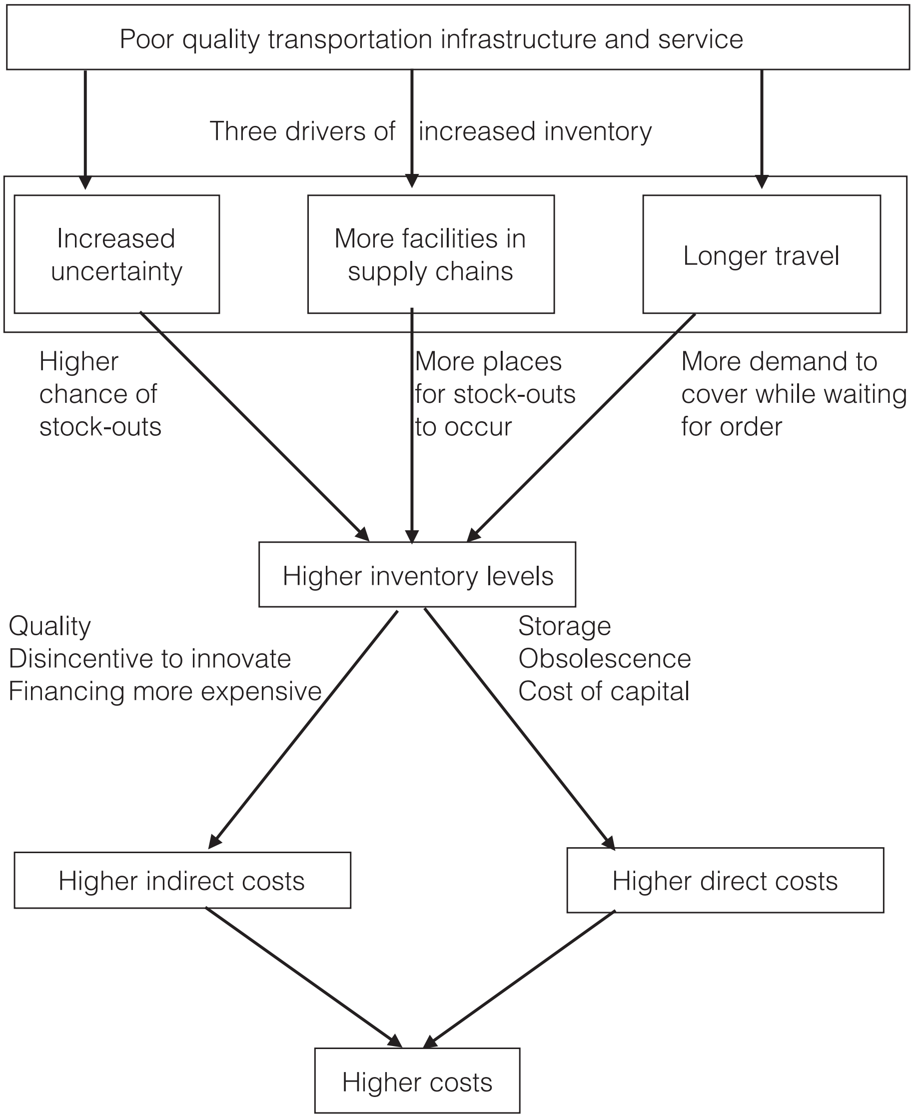

Figure 1: The primary drivers of inventory for a retailer/manufacturer

From a different perspective, poor quality or performance in each transportation infrastructure attribute leads to the logistics impacts shown below:

Poor Connectivity

- More facilities

Poor Performance

- Increased uncertainty
- Longer travel

Poor Flexibility/adaptability

- Increased uncertainty
- More facilities
- Longer travel

Low Capacity

- More facilities
- Longer travel

Lack of Greener Technologies

- More facilities
- Longer travel

Scenario analysis

The previous section outlined the impacts of attributes of transportation infrastructure on manufacturer and/or retailer performance. However, these impacts will also change under the various scenarios outlined in this report.

Static policy in a changing world - more of the same: In this scenario, without investing in more and better transportation infrastructure, one can anticipate increases in congestion, decreases in transportation services reliability, and increases in transportation costs (particularly to low-density areas). As a result, the following impacts on supply chain performance can be expected:

- Increased congestion will reduce capacity, increasing inventory levels and transportation costs.
- Increased congestion and other infrastructure-related vulnerabilities will degrade reliability in transportation services, causing firms to hold more inventory in anticipation of late deliveries, or to pay stock out or shut down costs.
- Insufficient transportation services to low demand locations will require supply chains to use and store inventory at more facilities. This will amplify the errors associated with forecasting demand, as there will be less aggregation of customer demands.
- Increasing travel and logistics costs will significantly raise the prices charged by retailers and faced by consumers.
- Increasing travel costs will lead freight customers to want to minimize the number of deliveries they receive. This will lead them to order in larger quantities and hold higher inventory levels.

Resilient and sustainable communities: In this scenario, as efforts and investments turn toward sustainability, the following can be expected:

- The use of automated vehicles will significantly raise the capacity of the Interstate highway system as U.S. Department of Transportation hours of service regulations for drivers will no longer limit freight movements by truck. Increased capacity will lower costs and firm inventory levels.
- Rail expansion, both high-speed intercity rail designated for freight and infrastructure investments that support using passenger rail for freight \transportation will also raise the nation’s capacity for freight transportation. Increased capacity will lower costs and firm inventory levels.

- Additive manufacturing techniques such as 3-D printing will drastically reduce firm inventory levels, as they will be able to meet customer demands in truly just-in-time fashion.

Competitive success: In this scenario, as infrastructure investments are directed toward economic growth, the following can be expected:

- As in the previous scenario, automated transportation systems will lead to an increase in capacity that will lower costs and firm inventory levels.
- More dispersed supply chains in North America may lead to higher firm inventory levels as inventory increases with lead-time. However, increased reliability could mitigate the increase in lead-time.
- Efficient and rapid responses to weather disruptions will lessen the need for redundancy in supply chains which will in turn reduce inventory levels and supply chain costs overall.

Conclusion and future vision

The application of philosophies and principles from the Toyota Production System (often just called "Lean") to supply chain management has enabled many manufacturing organizations to produce high-quality products at low cost. The core philosophy of Lean is to reduce waste which is often done by reducing inventory levels. As such, inventory is often seen as a key performance indicator for a supply chain. One of the critical Lean strategies for reducing inventory is to produce things when and where they are needed, or, in a just-in-time fashion.

As discussed, the state and quality of transportation infrastructure can have a direct and significant impact on the inventory levels that a firm must hold to meet demand from its customers, for retail outlets or for downstream participants in a supply chain. Similarly, insufficient and/or inefficient transportation infrastructure can lead firms to pay higher transportation costs. These higher transportation costs can in turn lead to higher inventory levels as organizations will want to minimize the number of deliveries they place/receive by ordering in larger quantities. Conversely, investments in transportation infrastructure that positively impact the attributes discussed above (connectivity, capacity, performance, flexibility or adaptability, and greener technologies) can help manufacturers and retailers support and fuel a growing economy.

Fundamentally, manufacturers develop supply chains and supply chain management practices to enable them to meet customer demands with a limited set of resources. While capital has always been one of the primary limiting resources, concerns about the environment now (at least) partially governs how supply chains are designed and operated. For decades, researchers have developed techniques and technologies to assist managers looking to optimize the performance of their supply chains subject to various constraints. Researchers will continue to do so, helping manufacturers and retailers utilize as much of the available capacity in the current network as possible.

Yet, the U.S. census forecasts that population will grow by a little over 19 percent by 2050. While investing in and maintaining current infrastructure is important, it is hard to imagine that the needs of nearly 80 million more people can be met solely by expanding the capacity of the current network. Adding more roads (or lanes to roads), ports, or rail hubs to meet what will likely be a very large growth in demand for transportation from supply chains seems unrealistic. As noted in the introduction, even supporting a 20 percent growth in tonnage by 2024 is thought to be too much for modes other than trucks to support.

Instead, to support this growth in an economical and environmentally-conscious fashion, consumer product manufacturers and retailers must switch from an attitude of using more transportation to meet rising demands to one where transportation capacity is fixed at a certain level and unlikely to grow. While such a constraint may seem extremely limiting, many observers and researchers have identified that innovation and creativity occur when an individual or organization is limited by rigid constraints.

Lean manufacturing itself came about because of a Japanese economy that had little capital to invest in automotive manufacturing and too few customers to justify the economies of scale achieved through mass production. Similarly, while they have recently undergone labor issues, Southwest Airlines has long held to an organizational value of not furloughing or laying off employees. Even in the aftermath of Sept. 11 when demand for airline flights plummeted, they found ways to cut costs other than reducing labor levels (the average airline laid off around 16 percent of its workforce after 9/11.[9]. By taking layoffs off the table as recourse to plummeting demand, Southwest was forced to innovate their operations in other ways. At the same time, Southwest Airlines was the best-performing (and profitable) airline in 2001.

To operate supply chains sustainably in 2050 and to support a successful and growing economy requires acknowledging that the utilization of U.S. transportation infrastructure is far from 100 percent. Even when highways are gridlocked, each car is typically occupied by a single driver and possesses ample room for goods and cargo. When commuter trains run in off-peak times, they are often severely underutilized; such free space could be used to bring freight and goods from suburban distribution centers into urban areas. Similarly, some cities with major airports provide rail transit to and from the airport. As these airports often double as points for transporting cargo, such rail might be used to bring freight and goods from distant points into urban areas. At the same time, in many cities, buses and subways provide connections between (nearly) all urban points. These vehicles could be used to provide urban freight distribution.

Instead of attempting to meet a need for more infrastructure, it will be important to assure that existing capacity is used at maximum efficiency. This calls for developing and deploying advanced sensors and control systems to optimize transportation network utilization, strategies to consolidate freight deliveries, and policies and technologies to facilitate shared use of fixed infrastructure, a “sharing economy” for logistics.

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ENDNOTES

[1] Pitney-Bowes reported in 2013 that 49 percent of customers have abandoned a shopping cart due to shipping costs.

[2] http://www.trucking.org/article.aspx?uid=41434598-4c60-444d-bc83-38f06ded539d

[3] http://www.nytimes.com/2013/02/13/realestate/commercial/new-hubs-arise-to-serve-a-just-in-case-supply-chain.html?_r=0

[4] NCHRP Report 732, "Methodologies to Estimate the Economic Impacts of Disruptions

[5] http://sustainability.ups.com/media/UPS-2014-Corporate-Sustainability-Report.pdf

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[8] FastCompany, "With Cargohopper Delivery System, a Dutch City Unclogs its Streets," http://www.fastcompany.com/1778938/cargohopper-delivery-system-dutch-city-unclogs-its-streets

[9] Jody Hoffer Gittell, Kim Cameron, Sandy Lim, and Victor Rivas, "Relationships, Layoffs, and Organizational Resilience: Airline Industry Responses to September 11," Journal of Behavioral Science 42, no. 3 (2006): 300-329.

CHAPTER SEVEN

Omni-Channel Retailing and the Role of Transportation

By Sunil Chopra

Introduction

The 21st Century has seen a major transformation in the retail sector of developed economies such as the U.S. Successful models from the late 20th Century such as Borders, Blockbuster and Circuit City have gone out of business. Whereas a decade ago, customers primarily visited stores like Blockbuster to rent movies, today they are likely to segment the channel they use based on the type of movie they watch. Most customers watch a variety of movies from Netflix while also visiting Redbox kiosks to rent recent releases. Whereas a decade ago, customers primarily went to an electronics mega store like Circuit City to fulfill all their electronics needs, today they are likely to segment the channel they use based on their electronics needs. They are likely to purchase their basic needs from a brick-and-mortar retailer such as Costco while also shopping online for a wide variety of consumer electronics. In each of these examples, a hybrid combination of a physical channel and an online channel serves customer needs more effectively than using a single channel.

Omni-channel retailing refers to the use of multiple channels to manage the flow of information, product and funds in a retail supply chain. A well-structured omni-channel supply chain can be both cost effective and responsive to customer needs. Online and brick-and-mortar retailers bring complementary strengths to the supply chain and a combination of the two is more effective than either channel by itself. Blockbuster found it quite challenging to provide a wide variety of movies to its customers from its stores while Netflix has no difficulty supplying customers with a wide variety of movies from centralized locations. Between shipping DVDs and streaming, the company offers over 100,000 titles. Whereas Netflix is very good at providing wide variety at low cost, Redbox is much better at making a small variety of new releases available close to customers at low cost. The combination of Redbox and Netflix provides customers with an omni-channel experience that is simultaneously cheaper and more responsive to customer needs than the Blockbuster supply chain.

The evolution of omni-channel retailing is likely to have significant impact in terms of the type of facilities, transportation (both inbound and outbound cost for the retailer and the travel cost for the customer), and information infrastructure required. Whereas Blockbuster operated with a network of about 3,500 stores at its peak, Netflix ships its DVDs from about 30 distribution centers, and Redbox rents its DVDs from over 40,000 kiosks. Compared to Blockbuster, customers do not travel to get their movie from Netflix but for physical DVDs Netflix has to ship them from centralized distribution centers to each address. For physical DVDs, the transportation requirements at Netflix are greater than that at Blockbuster. Customer travel, however, is less with the Netflix option. When movies are streamed there is no need for any physical transportation either by the company or the customer. The information infrastructure needs at Netflix, however, are greater than that at Blockbuster. The goal of this chapter is to consider the evolution of omni-channel retailing in the context of different future scenarios and the likely impact on infrastructure requirements.

The alternatives in omni-channel retail

Omni-channel retailing refers to the use of a variety of channels to interact with customers and fulfill their orders. The interaction between a customer and a retailer is primarily in terms of three flows – information, product and funds. The retailer provides product and pricing information to the customer who then places an order. The order information is used by the retailer to move the product to the customer. Finally, payment is transferred from the customer to the retailer. The use of different channels for each flow helps categorize the components of omni-channel retailing. In particular, information and product flows define channel categories because in the U.S. the channel used for fund flows tends to be the same as the channel used for information flows.

Information exchange between a customer and retailer can either be face-to-face or online. A customer shopping at a Tiffany & Co. for an engagement ring is getting information through a face-to-face encounter with the sales person and product. A customer shopping online for an engagement ring at Blue Nile gets information about diamonds and ring choices from the Blue Nile website. Product exchange between a customer and a retailer can either occur through a customer pickup or home delivery. If the customer decides to buy an engagement ring at Tiffany & Co., he picks up the ring at the store and brings it home. Blue Nile, however, uses Federal Express to deliver rings purchased by its customers to their homes. Most customers pay for their rings using the channel used for information flows. Customers shopping online tend to pay online while those shopping at stores tend to pay at the store. The choices for information and product flows define the following four alternatives for omni-channel retail as shown in Figure 1.

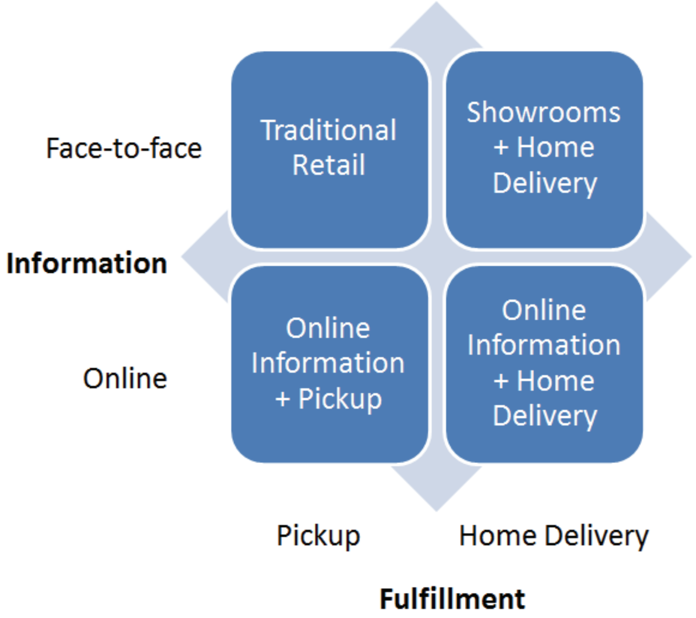

Figure 1: Alternatives in omni-channel retail

Traditional retail

Supermarkets, jewelry stores, department stores and book stores are all examples of traditional retail where a customer has a face-to-face interaction with the product and sales people and leaves the store with the product once a purchase has been made. Traditional retail tends to have many facilities to support the face-to-face information exchange and product pick up. These facilities tend to carry a high level of overall inventory because product must be stocked at each retail store. As a result, investment in facilities and inventory tends to be high for the traditional retail channel.

The high cost of inventory and facilities for traditional retail is particularly significant when selling high value items with small and unpredictable demand such as diamonds and jewelry or designer clothing. For example, Tiffany & Co. has about 300 stores worldwide, each carrying a significant amount of inventory for which the company must invest in high-cost real estate. Tiffany & Co. turns its inventory only about once a year because it is very hard to predict demand for its products. As a result, products are carried in inventory in its stores "just in case" the right customer arrives. For each dollar that Tiffany & Co. invests in property, plant, and equipment it generates only about \$5 of sales. Thus, traditional retail is a relatively high cost channel for high value items with unpredictable demand.

While facility and inventory costs are higher for traditional retail, transportation costs incurred by the retailer are lower because retail stores can be replenished efficiently using cheaper modes of transport (full truck rather than package delivery). Customers, however, must travel to the retail store to purchase the product, thus incurring a transportation cost themselves.

The lower cost of transportation makes the traditional retail channel very suitable for high demand, low value products such as groceries and other consumer goods. For example, detergent and paper towels are most efficiently sold through traditional retail. Given their large and predictable demand, retail stores do not need to carry many days of inventory of these products. Aggregation of inbound transportation allows retailers to lower the cost of bringing these low value products close to the customer. Given the relatively low value of these products, low cost transportation is a key to lowering their total cost. While customers must still incur transportation cost to travel to the retail store, the overall cost of bringing low value, high demand products to customers tends to be lowest through traditional retail. Costco is an excellent example of traditional retail selling high demand goods at low cost other channels are unable to match. A comparison between Costco and Amazon in 2011 for a standard basket of goods purchased at Costco found the retailer to be about 17 percent cheaper than the cheapest options available at Amazon[1].

Showrooms plus home delivery

An excellent example of this channel structure is Bonobos, an apparel retailer whose stores (Bonobos Guideshop) do not carry inventory. These stores serve as showrooms where customers can try different styles, get advice from sales people and also get fitted. These showrooms facilitate a face-to-face information exchange but do not carry inventory for customers to purchase. If a customer decides to make a purchase, the product is ordered online from the Bonobos website (or at the store) to be delivered to the customer's home. A similar channel is used by Tesla, where customers can see a car at a showroom, order it, then it is produced and delivered to the customer's home. The showrooms carry no inventory for sale, thus significantly reducing inventory and the size of the store required. Home delivery, however, increases the total cost of transportation relative to traditional retail because traditional retail can use fully loaded trucks to bring in product but home delivery requires a package delivery network. If the showroom also serves as a pickup location, the cost of transportation for the customer would be similar to traditional retail. Relative to traditional retail, this channel saves on inventory and facilities infrastructure but requires a greater investment in transportation and information infrastructure, especially with home delivery.

For high value products and products with a significant amount of customization that people want to touch, feel and see, this channel is likely to gain market share in the future because of the lower level of inventories required. A product category where this channel has started to gain significant market share is men's suits. A traditional retailer must carry a wide variety of suits so that customers can find an appropriate fabric, size and style. This significantly increases the amount of inventory that retailers need to carry and the amount of space they need to dedicate to this product. In contrast, Indochino, a provider of suits, has small showrooms that only carry enough inventory so that customers can select fabrics and styles. Customers are fitted in the showroom but suits are made off-site in low cost locations. Indochino carries its inventory at production locations in the form of fabric that is customized for each specific customer only after an order has been placed. As a result, it has no surplus inventory that must be discounted at the end of the season and is never short of a style or size that a specific customer needs. Indochino thus incurs much lower inventory and facility costs relative to a department store trying to sell suits. As a result, Indochino and other players with the showroom model are able to sell men's suits at a lower price than traditional retailers while providing customers with a more customized fit.

The showroom channel has always been the dominant channel for high-end cars like a Ferrari. It would be too expensive for the company to carry a large inventory of Ferraris at every dealer. Instead, each dealer primarily serves as a showroom and the car is customized and delivered only after an order has been placed. The current U.S. model of dealers carrying inventories of cars that customers buy from the lot is very expensive and likely to diminish in the future to be replaced with a model where the dealer largely serves as a showroom (and perhaps carries inventory of the standard models). As stated earlier, Tesla is fighting hard to make this model a reality for its cars.

Online information plus home delivery

Amazon is an excellent example of this channel where customers browse for products and order online to have the purchases then delivered to their homes. Aggregation of inventories in a few locations allow the online channel to have a much lower investment in facilities and inventory compared to traditional retail. A comparison between Amazon and Borders for 2009 (the year before Borders declared bankruptcy) highlights the strengths of inventory aggregation. Whereas, Borders with its traditional retail model carried 145 days of inventory in 2009, Amazon served its customers using the online channel with only 45 days of inventory. Whereas, every dollar invested by Borders in property, plant and equipment generated $7.2 in revenue in 2009, the centralized online model of Amazon generated $18.9 in revenue for every dollar invested in physical infrastructure. Clearly, the online channel allowed Amazon to centralize its inventories, thus reducing its investment in both inventories and facilities infrastructure.

The fact that every order has to be delivered to a customer's home, however, adds a lot to transportation costs for the retailer using the home delivery option. In 2014, Amazon's outbound shipping costs from its warehouses to customer homes were about 9 percent of revenues. This compares with an inbound transportation cost of less than 2 percent for a company like Costco. Customers do not incur any transportation effort with this channel but the total transportation cost incurred is generally higher than traditional retail.

Given the high cost of transportation, the online with home delivery channel is likely to be profitable for products where inventory and facility cost savings on aggregation are significant and where transportation cost is a small fraction of the value of the product. Products with low transportation cost (relative to product value) and unpredictable demand such as electronics are likely to do best online. For low value products with predictable demand (such as detergent and toilet paper), this channel is likely to be profitable only if customers are willing to pay a premium for the convenience of having the product delivered at home.

Online information plus pickup

The high cost of home delivery for the online channel has led several players to offer the option of a pickup location at a lower price. Peapod, for instance, has introduced pickup locations where customers can pick up their groceries at a lower delivery cost than having them delivered at home. The presence of a pickup location significantly reduces the outbound transportation cost incurred by the retailer. It does require the customer to travel to the pickup location but a suitable choice of pickup location can lower this travel cost if customers can combine order pickup with other activities they naturally perform at the location. For example, Amazon uses kiosks called Amazon lockers that are typically located in "shopping centers, retail stores, transit stations, and other access points in areas with high package density."[2] At the student union in Purdue University, West Lafayette, Indiana, Amazon has also built its first physical store where students can come and pick up orders that they have placed online. A pickup location significantly lowers Amazon's outbound transportation cost. A location at the student union at Purdue allows students to pick up their Amazon package without significant additional effort because they often visit the union for food and other purchases.

Similarly, Walmart allows a "free instore pickup" option where people can shop online and pick up the order at the store. This option clearly reduces Walmart's transportation cost because online orders can be shipped to the store along with other products being shipped there. Such an option may also not add much to the transportation cost for a customer if he or she is planning to shop at the Walmart store in any case.

The presence of a pickup location also significantly lowers the cost of handling a return. For example, customers can return a product purchased from Amazon at an Amazon locker. This allows Amazon to transport all its returns together, thus lowering transportation costs for returns.

Pickup locations are likely to grow for retailers selling relatively low value goods online. In the grocery industry in U.K., for example, pickup locations now dominate as the mode for online grocery shopping. Grocery retailers such as Tesco and ASDA offer a low cost "click & collect" service where customers place their orders online and collect them at a pickup location.

The relative performance of channels

The various channels discussed earlier have somewhat complementary strengths. An omni-channel portfolio should thus match each channel with customers and products it is best suited to serve. Once the customer comes to the store, traditional retail is very good at providing product information (and encouraging impulse shopping). Traditional retail also incurs low transportation cost because stock can be replenished at relatively low cost. Traditional retail, however, incurs high inventory and facilities costs. Also, customers must travel to the retail store, increasing their transportation cost and effort. Given its strengths and weaknesses, traditional retail is thus best suited to compete on cost for commonly used products such as detergent that have low information content and low value relative to transportation cost. For high variety, high value products, it can be successful only if customers are willing to pay a premium for the ability to see the product at the store and pick it up.

The online channel with home delivery in contrast, is weaker at providing product information (though it continues to get better) and incurs higher transportation cost. But it carries lower levels of inventory, thus decreasing the spending on inventory and facilities. It also saves on customer transportation and effort. The online channel can thus best compete on cost for high variety products with high value relative to transportation cost such as consumer electronics. For standard products with low value, it can be successful only if customers are willing to pay a premium for the convenience of not having to leave home.

The showroom plus home delivery channel is very good at providing product information while keeping inventory and facility costs low. Transportation costs, however, are the highest among all channels. This channel can best compete on cost for products with a lot of customization (as a result these products have high information content) and high value relative to transportation cost.

The online information plus pickup channel is primarily designed to reduce the cost of home delivery incurred by an online retailer for customers who are willing to put in the effort of going to the pickup location. Inventory and facility costs are lower than traditional retail but somewhat higher than the online channel. Transportation costs, however, are somewhat higher than traditional retail but much lower than the online channel with home delivery.

The relative spend for the retailer in terms of information, inventory, facilities, and transportation is summarized in Figure 2 for each channel choice.

	Inventory	**Facilities**	**Transportation by retailer**	**Transportation by customer**	**Information**
Traditional Retail	High	High	Low	High	Low
Showrooms + Home Delivery	Low - Medium	Medium	High	High	High
Online Information + Home Delivery	Low	Low	High	Low	High
Online Information + Pickup	Low - Medium	Medium	Medium	Medium	High

Figure 2: Spending for various omni-channel alternatives

Factors influencing the relative share of each channel

Across most products today, customers are served by an omni-channel portfolio. For example, groceries can be purchased at a supermarket, ordered online for home delivery or ordered online to be picked up at a pickup location. A key question is the share of customer demand met by each channel in this portfolio. As the share changes, the investment by retailers in facilities, inventory, transportation, and information will change. The relative share of each channel is impacted by the evolution of the following factors that are likely to drive future scenarios:

- Customer preferences
- Experiential technologies
- Production technologies
- Transportation technologies

Customer preferences

There are two key dimensions of customer preference that are likely to impact the omni-channel portfolio – convenience and instant gratification. Convenience is considered in the form of how much effort customers are willing to put in to reduce the cost and environmental impact of a purchase. Instant gratification is considered in terms of how much time customers are willing to wait to get a product. While it seems clear that channels that share information online are likely to gain greater market share in the future, the relative share of channels will depend upon how much customers value convenience and instant gratification.

The more customers value convenience over cost and environmental impact, the greater share the online information and home delivery channel are likely to capture because they require the least effort from the customer in terms of travel. Such a scenario will result in greater overall spending on transportation and information while reducing the spending on facilities and inventory. If customers are willing to put in more effort to reduce cost and environmental impact, the online information with pickup option is likely to gain greater share for standard products while the showroom option is likely to gain market share for higher value, potentially custom products. For standard products, customer willingness to go to a pickup location can significantly reduce transportation cost relative to the home delivery option. For example, if customers are willing to go to a Walmart store to pick up a Walmart.com purchase, they do not have to pay shipping cost. From Walmart's perspective, this makes sense because the company no longer has to provide last-mile delivery that can be quite expensive. For higher value custom products like men's suits, a customer's willingness to visit a showroom allows the retailer to significantly reduce inventory and facility costs relative to having traditional retail. The growth of this channel for men's suits because of its ability to provide variety and customization at lower prices than traditional retail has been discussed earlier.

If customers increase their desire for instant gratification, channels will have to locate closer to the customer and provide quick home delivery. Such an outcome will increase spending on inventory, facilities and transportation. This scenario is likely to result in the highest transportation costs because quick delivery limits the ability to aggregate orders onto a single vehicle. The impact of customer preferences is summarized in Figure 3.

Experiential technologies

A major challenge for any online channel arises when customers want to touch, feel and see the product. This is rarely the case for standard products like detergent but is often the case for high value products like designer clothing or jewelry and somewhat customized products like shoes. Such products have a complex set of information content that helps the customer fully understand the product. For designer clothing, a customer may want to know how it fits and looks on her body. For shoes, a customer may want to know how the shoe feels on his foot. At present, the typical way customers can fully experience such products is through a face-to-face

Customer preferences	High value for convenience	Willing to put some effort
Instant gratification	Online information + home delivery will grow with quick delivery options.	Channels using pickup locations are likely to gain greater share.
Willing to wait	Online information + home delivery will grow with standard delivery options	Channels using pickup locations will gain share for standard products. Channels using showrooms will gain share for high value, custom products.

Figure 3: Impact of customer preferences on omni-channel portfolio

interaction with the product. This favors the traditional retail channel. For customers that value convenience, online players like Zappos send customers multiple shoes and accept the return of any product that the customer does not want. For such products, traditional retail has high inventory and facility costs while online players like Zappos that facilitate returns have high transportation costs.

From a cost perspective, products like shoes, designer clothing and jewelry are best held in centralized locations because of the significant savings in inventory and facility costs upon aggregation. If experiential technologies using virtual reality get to a point where a customer can try on a shoe, apparel or jewelry virtually, online channels using pickup locations or home delivery are likely to grow significantly for such products. The growth of experiential technologies has the potential to reduce transportation costs for a company like Zappos and make it a very strong competitor in terms of both cost and its ability to provide a wide variety of shoes. The growth of experiential technologies also has the potential to eliminate the need for physical locations to carry expensive apparel or jewelry. The impact of experiential technologies on the omni-channel portfolio is summarized in Figure 4.

Status quo: Weak experiential technology	Very strong experiential technology
Favors traditional retail or an online channel like Zappos with significant returns to sell high value and high variety products.	Favors the online channel with pickup locations (for value conscious customers) and home delivery (for convenience preferring customers).

Figure 4: Impact of experiential technologies on the omni-channel portfolio

Production technologies

A key characteristic of production technologies that influence the omni-channel portfolio for products with a lot of customization and variety is the ability to quickly customize a product. An example of this impact is evident in the paint industry. Twenty years ago, paint was produced in final form at large factories and shipped in cans by color to retail stores. This resulted in a large amount of inventory and square footage dedicated to the paint department which held cans of every color. Today, paint retailers have mixers that they use to create the final color of the product as per customer demand. Inventory is held in the form of base paint which is mixed on demand to the color required by a customer. The local presence of this production technology has allowed retailers to reduce inventories and space dedicated to paint. It has also allowed them to reduce inbound transportation costs because a predictable amount of a standard product (base paint) is now being transported to stores.

Besides availability, the cost of these production technologies will have a large impact on the omni-channel portfolio. The cheaper these production technologies become, they are likely to be decentralized into traditional retail stores, allowing retailers to provide highly customized products at locations close to customers. The more expensive these technologies are (or the more limited their available capacity), the more centralized production will have to be, favoring channels with home delivery or pickup locations. An example of this difference is in the men's suits market where Indochino has tailoring done in a centralized low cost location rather than having tailors at every showroom. Given the high cost of tailoring capacity in the U.S., it would be very expensive for Indochino to have tailors in every showroom. If very inexpensive tailoring was locally available, it is likely that customers best could be served with production available inside the showrooms. For example, in India, department stores carry pants that are separated by waist size but not by inseam length. Tailors onsite customize the inseam length to the precise customer. The availability of low cost tailoring capacity to customize length onsite allows department stores in India to significantly reduce the inventory and space dedicated to pants. The impact of the customization capability of production technologies on the omni-channel portfolio is summarized in Figure 5.

Poor customization capability or expensive production technology	**Inexpensive production technology with customization capability**
Favors centralized production with home delivery or pickup if online information is effective. Favors centralized production and traditional retail (but with high investment in inventory and facilities) if "face-to-face" information is required. Requires transportation of finished goods to the sales site.	Favors localized production with showrooms or traditional retail. This structure requires transportation only of raw materials to the sales site.

Figure 5: Impact of production technologies on omni-channel portfolio

A key production technology that has the potential to facilitate customization is 3D printing. The impact of 3D printing is likely to be most significant in high variety environments where demand for any specific variant is likely to be low. An example is industrial supplier W.W. Grainger. Grainger currently has nine distribution centers used to serve customers through the online information plus home delivery model. Grainger currently spends a lot of money using UPS trucks to ship packages to customer locations. If 3D printing is successful (in producing all desired products relatively quickly), there are two possible scenarios based on the cost of the printing. If 3D printers are expensive, it is likely that Grainger will install 3D printers at its warehouses to produce and then ship finished goods to its customers (still keeping UPS trucks busy). If 3D printers are inexpensive, customers themselves may install these printers cutting out Grainger as a supplier entirely (and eliminating the need for some UPS trucks). In this case, only raw material will have to be shipped to customers, reducing overall transportation cost.

Transportation technologies

Autonomous vehicles on the road are likely to make transportation quicker and cheaper because these vehicles can easily be operated for 24 hours each day. Autonomous vehicles are likely to benefit aggregate deliveries to a much greater extent than individual home deliveries because home delivery requires suitable unloading of the autonomous vehicle even when there is nobody at home. Aggregate deliveries for inbound shipping for traditional retail as well as deliveries for online channels using pickup locations, however, could become much quicker and cheaper with autonomous road vehicles. Thus, a growth in autonomous road transportation technologies is likely to help traditional retail and the online channel using pickup locations by reducing their inbound transportation cost.

Autonomous vehicles in the air, or drones, have the potential to play a more significant role for home delivery, especially where the customer places a high premium on getting the product quickly. Most companies have dropped their experiments for one-hour delivery because customers have not been willing to pay a high enough premium to cover the high cost of making these deliveries. Drones have the potential to reduce this cost but that will depend on the regulatory framework put in place to manage drones. If flying a drone requires an individual to be dedicated to this effort, the cost of drone delivery will be too high to attract a significant customer base. If the regulatory framework allows an individual to manage many drones simultaneously, speedy home delivery could be supported cost effectively using drones.

Conclusion

The evolution of the factors discussed above leads to a large number of potential scenarios for the future. Rather than discuss each scenario, the potential impact of a few of the extreme scenarios on transportation infrastructure will be highlighted.

An extreme scenario that will significantly increase the demand on transportation infrastructure involves impatient customers who want their product quickly but do not want to expend any effort getting them, weak experiential technologies that do not allow a customer to experience the product at a distance, production technologies that cannot customize products at low cost, and the absence of autonomous drones. The absence of low cost customization technologies will continue to push manufacturers to go to low cost locations for production, even if they are far from the market. The absence of good experiential technologies will require a face-to-face interaction between the product and the customer. As a result, product will continue to be brought closer to the customer before a purchase is made. In the extreme case, this might involve shipping multiple products to a customer who keeps the one she selects and returns the others (as is the case with Zappos). The more impatient customers become in such a setting (after all, Zappos customers must be patient and it is this patience that allows Zappos to carry inventory at a few warehouses), the more retailers will be pushed to carry inventory closer to where customers are located (the less patient Zappos customers become, the more locations the company will be forced to carry inventory in). This will lead to a loss of aggregation in transportation, further increasing the pressure on road transportation infrastructure in the absence of autonomous drones.

The opposite extreme where the demand on transportation infrastructure will decrease significantly (compared to today), involves patient customers who are willing to put in some effort themselves, good experiential technologies, and inexpensive customization technologies.

Consider the case where customers in Chicago looking for men's suits can use virtual reality to customize and select a suit. Imaging technology is then used to get precise body measurements which are transmitted to an inexpensive automated machine that cuts and sews the suit and is situated in a frequented location in Chicago (such as a train station). Once the suit is ready, the customer picks it up on his way home. In this scenario, the only product to be transported is the raw material to the production site (this will be done infrequently and only to replenish stock) with all other transportation being eliminated. The demands on the transportation infrastructure in this scenario are much less than any current option available to purchase a suit.

The future is likely to be a mix of these extreme scenarios, driven by customer preferences and production, transportation, and experiential technologies. As a result, the need for transportation services and infrastructure to support retail activities may vary in quantity and location over the next 35 years, but it is not likely to diminish, and transportation performance will continue to play an important role in costs and quality of life.

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ENDNOTES

[1] R. Lieber, "Adding it up: Amazon Ship vs. Costco Shop," New York Times, March 4, 2011

[2] Retail Innovation, "Amazon lockers popping up everywhere," http://retail-innovation.com/amazon-lockers-popping-up-everywhere/ (accessed January 19, 2016)

CHAPTER EIGHT

Addressing the Challenges of Transportation Infrastructure Condition

By Gianluca Cusatis

Current condition of transportation infrastructure
Sustainability -- the ability of being durable, reliable, and economically affordable during the entire service life -- is one of the most important properties of modern infrastructure. Unfortunately, much of our critical transportation infrastructure, such as bridges and roads, falls short of fitting within this definition. In the U.S. and around the world, transportation infrastructure suffers from serious deterioration and damage from aging after only a relatively small portion of its expected lifetime, which can be as much as 100 years.

It is quite common to see roads and bridges, as well as other transportation infrastructure that look like the ones shown in Figure 1. Physical aging and deterioration is a recurring theme discussed in technical meetings and publications[1] and it is at the forefront of the national political discourse.[2]

Inspection, maintenance, and repair costs are on the rise and the U.S. does not seem on track to meet the required commitment to maintain a state of good repair of our national infrastructure. The American Society of Civil Engineers (ASCE), for example, estimates that a $3.6 trillion investment will be needed by 2020 in order to improve the condition of American infrastructure to an acceptable level. This is $2 trillion over the currently anticipated funding level.

The repair and retrofit of the four million miles of roads and the more than half million bridges is severely underfunded and public transportation funding has decreased from almost 1.4 percent of GDP in the 1960s to around 0.8 percent of GDP in the 1980s and it has remained basically constant to the current time.[3]

Generally speaking, the rate of physical degradation, which in many cases increases as a function of age, has consistently exceeded the rate of repair and retrofitting for most transportation infrastructure. Currently, for example, the average age of U.S. bridges is more than 40 years old and one in nine is deemed structurally deficient.[4]

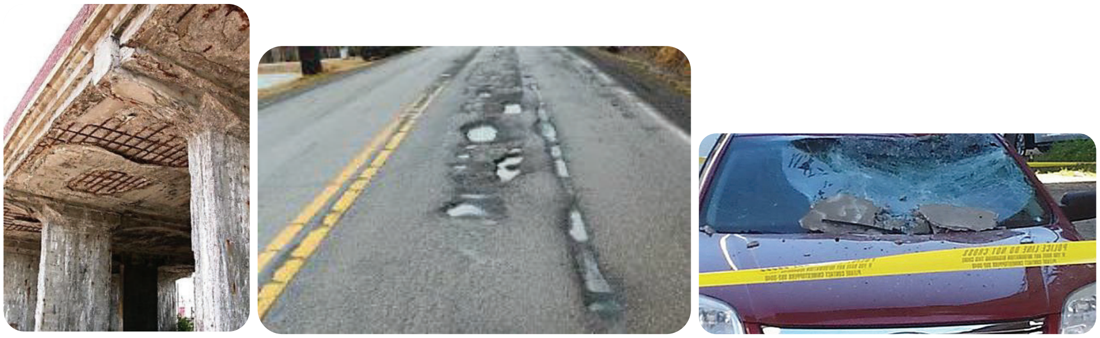

Figure 1: Deteriorated bridges and roads and a car damaged by falling concrete from deteriorated bridge**.**

This situation affects the lives of millions of people in multiple ways. First and foremost there is a safety issue.

Obviously, deteriorated bridges are less safe than pristine ones, even though the collapse of entire bridges is still a rare event. Serious danger often comes from partial, localized failures. Recently, various occurrences of large blocks of concrete detaching from deteriorated bridges and falling on cars have been reported. In September 2014, a car was hit (Figure 1) by large concrete pieces falling from the Brent Spence Bridge in Cincinnati, Ohio. In February 2015, the windshield of a car proceeding on Interstate 495 in Prince George's County, Maryland, was struck by concrete pieces falling from a bridge. The bridge in question was built in 1963 and is on the list of the about 80 structurally deficient bridges in Maryland.[5]

The condition of most highways as well as state and county roads is not any better. Analysis of recent data on traffic fatalities shows that in about one third of those, deteriorated roadway conditions were a significant contributing factor.[6]

Severe safety issues are also associated with traffic congestion and incidents during construction work. In August 2007, the collapse of the I-35W Mississippi River bridge in Minneapolis, Minnesota, while likely caused by a design flaw, occurred 40 years after its initial construction during an evening of heavy traffic on a limited number of lanes. At the time of the collapse, half of the lanes were closed for deck work construction and several tons of construction materials and equipment were on the bridge.[7] The collapse resulted in 13 fatalities and several injuries. More recently in April 2015, the fall of a large concrete slab during construction of a barrier on a bridge in Bonney Lake, Washington, killed a family of three.[8]

Significant economic losses are also associated with these tragic events and even with minor events such as driving over a pothole on a commuting route. As matter of fact, increasing car maintenance costs are directly related to road conditions and lack of road maintenance. [9] Traffic congestion and diversions are often experienced during maintenance and rehabilitation work on key transportation facilities, leading to delays which in turn produce physical and psychological discomfort for drivers and passengers, increased fuel consumption, freight delays increased logistics costs, and local impact on air quality.

Last, but not least, the continuous, everyday exposure to infrastructure degradation can produce a reduced quality of life with diminished aesthetic satisfaction, increasing sense of uncertainty for the future, and augmented perception of societal decline and loss of competitiveness.

The most common cause of physical degradation of transportation infrastructures is a complex combination of chemical reactions, mechanical loadings, and environmental effects. For example, for bridges, the most prevalent deterioration mechanism is corrosion of steel, which can significantly reduce the load carrying capacity of affected structural elements. In the case of reinforced concrete construction, corrosion of reinforcing steel is often associated with extensive concrete spalling and surface damage even before becoming an issue from the overall structural point of view. This is the reason why deteriorated reinforced concrete bridges that are still structurally sound might still pose a risk to the public.

The corrosion of main components in steel bridges or of steel reinforcement in reinforced/prestressed concrete bridges is accelerated by environmental conditions and several other physical/chemical mechanisms. Humid conditions, poor deck drainage and an environment rich in chlorides (e.g., from deicing salts) typically set the stage for the initiation and evolution of corrosive processes. In concrete, chemical reactions such as, but not limited to, alkali silica reaction, delayed ettringite formation, and carbonation cause volume changes eventually leading to cracking. Most of the time, such damage is not of concern for the structural performance but cracks provide additional paths for water and corrosive agents to reach the reinforcement, accelerating corrosion and overall structural degradation.

In addition, the effect of stress induced by the bridge weight itself and traffic loads interacts with the other aforementioned mechanisms, inducing additional damage and cracking. In extreme situations, the combination of all these effects and the occurrence of unusual load conditions (for example during earthquakes, wind storms, and other catastrophic natural or man-made events) can lead to the sudden failure of structural elements and possibly to the failure of the entire bridge.

Another common deterioration mechanism observed in bridges is foundation scour that occurs over time and can lead to collapse during flooding events. For example, the recent collapse of a small bridge during a heavy rain storm closed a section of Interstate 10 in southern California, forcing 250-mile detours. In 1987, the Schoharie Creek bridge in upstate New York was undermined by storm water and 10 people lost their lives. A further complication with this type of failure is that the progressive deterioration might go undetected due to the inherent difficulties of monitoring and inspecting submerged or underground structures. This may have occurred on a bridge that settled on Interstate 65 near Lafayette, Indiana, in the summer of 2015.

For road pavements, damage and deterioration are mostly associated with cycling mechanical loading due to traffic and seasonal freeze-thaw cycles. Often such damage is concentrated in joints where water can easily accumulate during rain events and expand when exposed to below-freezing temperatures.

In addition to the problems of aging infrastructure, there is also a compelling need to develop new transportation and communication infrastructure technologies to sustain and stimulate economic growth. These technologies will likely be required to be built and used in increasingly more severe environmental conditions due to climate change and/or more demanding service conditions (e.g., increasing traffic, including heavier trucks) to fit societal needs which places high demand on the structural performance, resulting in increased construction costs. Furthermore, worldwide increasing consciousness for sustainable use of natural resources has made "overcoming the apparent contradictory requirements of low cost and high performance a challenging task" [10] as well as a major concern for the civil engineering community.

Rational evaluation of structural performance

Transportation infrastructure in the U.S. and in most western countries is on average 30 to 60 years old. While age is an important indicator to estimate the evolution of material and structural degradation, it might or might not be well correlated with the structural condition and the expected present and future performance of the structure under current and foreseeable loading/usage conditions.

For example, when evaluating the structural condition of a bridge and planning for its maintenance, repair and retrofitting, several questions need to be answered. Is it safe to drive through or under the bridge today? Will it be safe in five or 10 years? If investments are made today for repair and/or retrofitting, when are similar problems likely to appear again in the future? Have loading conditions for traffic and natural events changed since the initial construction and are they likely to change in the future? For example, there is consistent pressure to increase permitted truck size, weight and daily traffic on some major bridges has doubled in the last 15 years. Is repair/retrofitting a viable solution or are demolition and rebuilding a necessity?

Answering these questions is key for infrastructure owners to make informed decisions and prioritize repair, retrofitting, and maintenance work over their entire infrastructure inventory. This is particularly important with the public funding outlook stagnating or declining.

Despite the recognized importance of such issues, entrenched practice and remediation approaches are, for the most part, empirical and fundamentally related only to the lifetime experience of few capable professionals. In many cases, the ability to answer the aforementioned questions retires with the "expert" and very little improvements are achieved over time. Such "modus operandi" is only slightly better than predicting the future of infrastructure by looking into a crystal ball – it is more magic than science.

Alternatively, a more rational approach to the evaluation of structural performance and its evolution in time can be formulated through service lifetime predictions. These are based on a rigorous structural reliability framework supported by physically-sound computational models, rigorously validated and continually updated on the basis of reliable experimental data obtained from both destructive and non-destructive evaluation techniques.

The prediction of the service lifetime of infrastructure requires the accurate prediction of the evolution in time of the probability of failure that is associated with a specific possible structural collapse (e.g., falling concrete blocks, tearing of gusset plates, damage of supports, etc.) or a combination of such collapses resulting in the complete destruction of the structure. The probability of failure is, in simple terms, the likelihood that something bad happens should particular conditions arise. For example, current design guidelines for bridges are based on a probability of failure of about 10^{-6} which means that under exceptional loading events the expectation is one in one million bridges will collapse. The probability of failure can be computed (and often only estimated) on the basis of the current condition of the structure and the likelihood of certain loading conditions.

Recent studies[11] have shown that the probability of failure of infrastructure systems increases with time in either continuous or discrete increments (Figure 2). Such continuous increments often result from a gradual deterioration of the system properties due to various deterioration and aging phenomena. The rate of increase is inversely related to the degree to which deleterious phenomena can be prevented or mitigated through proper maintenance.

Discrete increments can be due to shocks that cause sudden changes in the system properties. These include loads and deterioration mechanisms that are active for a short duration of time such as impact loads, seismic events, and other man-made and natural hazards. Discrete decrements, i.e. an improvement of the infrastructure “health,” are associated to repair and retrofitting interventions.

Figure 2 depicts the evolution of the probability of failure for a structure in two different situations. The first situation (red line) is a case in which an increase of the probability of failure beyond a level requiring retrofitting and/or repair is not followed by any action, leading to the end of the service life of the structure at a certain point in time shortly after – especially if unexpected events occur. In contrast, the second situation (blue line) shows a case in which the probability of failure is reduced through appropriate structural retrofitting and/or repair.

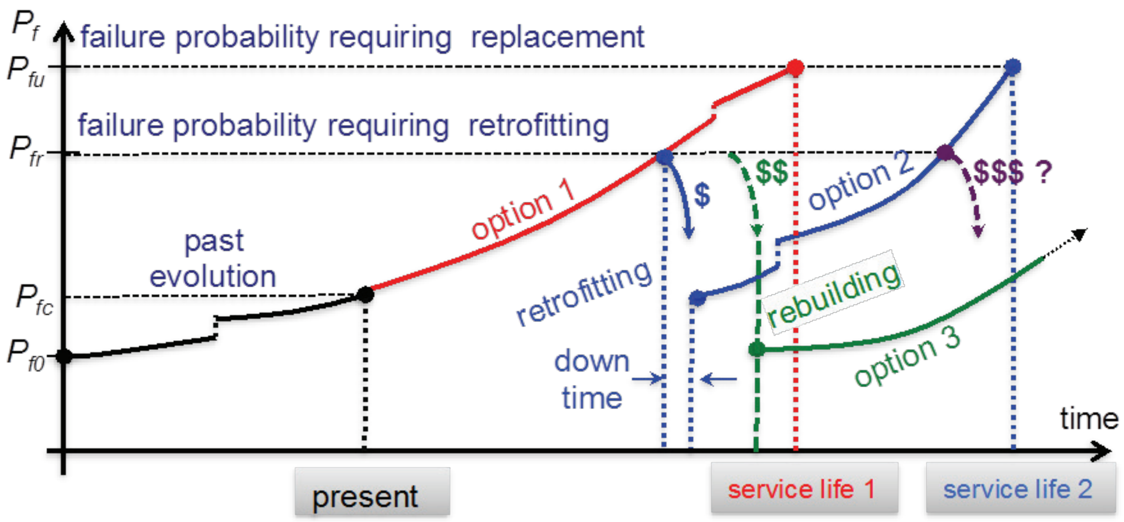

Figure 2: Evolution of the structural performance of infrastructures

As a consequence of investment, the service life of the structure is increased; the magnitude of such increase is directly related to reduction of probability of failure, which, in turn, depends on the extent, and consequently the cost, of the performed repair and/or retrofitting. Of course, multiple retrofitting/repair situations can be envisioned during the service lifetime of the structure with the understanding, however, that subsequent repairs do require increasing, often hard to estimate a priori, resources for achieving the same reduction in the probability of failure.

In addition, partial or limited reduction in capacity of the structure during rehabilitation work, and the resulting increase in user and environmental costs due to congestion and diversion, need to be considered when devising an overall repair and/or retrofitting strategy.

Finally, the third situation (green line) is the one in which the probability of failure is brought back to the initial one by rebuilding the structure. In this case, more resources are needed but the service life might be greatly increased not only because the structure is new but also because the new construction is performed with materials, design practices, and technology that are better than the ones used at the time of construction of the deteriorated structure.

The current societal demand for sustainability calls for the optimal management of infrastructure. This can be achieved only by accounting for numerous conflicting requirements associated with, for example, economic costs, environmental impact, safety, aesthetics, transportation need of the public, etc. For this reason, infrastructure owners need a quantitative characterization of all these requirements so that they can find an optimal solution to their management and maintenance goals.

At any given time in the life of a structure ("present" in Figure 2) there are two aspects that contribute to the estimation of the remaining service life of a structure: (1) the assessment of the current probability of failure ("the status quo"), P_{fc}, and (2) the prediction of the evolution of the probability of failure in the future and, in particular, the prediction of the time needed for the structure to reach some predetermined values of the probability of failure associated with the need of retrofitting/repair or replacement (P_{fr} and P_{fu}, respectively). The latter corresponds to the service life of the structure.

Ideally, the technical community should agree upon these two values on the basis of a certain level of risk that the public may be willing to accept. For example, for an initial (at the time of construction) probability of failure of one in a million – typical for modern structures – one may consider acceptable a degradation that reduces it to one in 500,000 but certainly not to one in a thousand or less.

When these levels are set, operating a facility beyond its service life (unfortunately a real possibility under the current underfunded conditions) means that the public is exposed to an unacceptable risk.

In the current practice, the combination of destructive, (where small material samples of the structure are extracted for testing) and nondestructive (without extracting samples, leaving the structure untouched) evaluation technologies provide a robust procedure for the assessment of the status quo from a qualitatively point of view. A quantitatively accurate assessment of the current probability of failure is still hampered by the lack of a comprehensive framework able to link destructive and nondestructive measurements to the fundamental deterioration and failure mechanisms of the material.

For example, a very common procedure to assess damage in bridge decks is the so-called "chain drag test". In these tests, the operator listens to the sound of a chain being dragged over the surface of the deck. A hollow sound is an indication of probable occurrence of a large air void that, in turn, is an indication of possible damage. However, there is no way to assess, for example, what is the current strength and stiffness of the material, what is the reason of the degradation, and how fast it will progress. In other words, one can detect that something bad is happening but it is much more difficult to determine how bad it is and how bad it will be for the entire structure.

This is even more an issue when the evaluation is solely based on nondestructive evaluation, an essential approach because destructive evaluations tend to be too invasive as far as the infrastructure operations are concerned and too expensive to be performed on a regular basis. Furthermore, for infrastructure with no specific evidence of deterioration, no one would consider performing destructive evaluations. However, it is common practice to perform preventive nondestructive evaluations as part of continuous structural health monitoring and periodic maintenance activities.

Once evaluation of the current performance level has been completed, it is even more complicated to predict the future. Such predications need to be performed with advanced multiscale and multiphysics theories and computational tools the development of which is still in its infancy. Advancing these tools requires further scientific and technological achievements.

In addition, a cultural change is required within relevant agencies and infrastructure owners that currently do not adopt long run, life-cycle cost views, basing decisions more on short- to medium-term horizons.

What to expect in 2050

What will transportation infrastructure look like in 2050 from the point of view of its structural performance? This largely depends on the driving forces that will shape the next 35 years of our society. This section attempts to view the future with reference to the possible scenarios discussed earlier in this report and to potential technological and scientific advancements that might serve as "game changers."

Should the "more of the same" scenario become reality, acceleration of infrastructure degradation is likely. Large disparities in conditions will appear depending on the geographical location. Few areas with more available resources will see some improvements in infrastructure condition and performance but on average, the infrastructure condition will become progressively worse. Conceivably, rural communities will fare worse than urban ones, continuing the trend observable today.[12]

For the majority of transportation infrastructure, the failure probability curve depicted in Figure 2 would show steeper positive slopes and have positive jumps of larger magnitude in the case of extreme loading events; see option 1 (red line) in Figure 2.

Structural failures and associated fatalities would become more frequent, spurring public outcry that might lead to isolated, local public investments in repairs and retrofitting.

Furthermore, the continuing structural deterioration will make any infrastructure rehabilitation and repair more expensive and complicated, hampering both routine infrastructure management as well as prompt rebound from extreme natural events, leading to loss of resilience of infrastructures, infrastructure systems and, consequently, communities.

Of course, even under these less than ideal conditions, technological innovations would still provide avenues for improvement. New retrofitting materials with rapid setting properties and new, less disruptive construction methods have been explored recently with success. For example, by using prefabricated structural elements three deteriorated highway bridges around Trenton, New Jersey,[13] were replaced each in one weekend without affecting rush hour traffic. Similar technology has been also implemented in FHWA pilot projects for roadway repairs. In most cases, these techniques not only reduce downtime but lead to cost savings and to final products of better quality and enhanced durability.

Transportation infrastructures are likely to follow a very different evolution in a society where resilience and sustainability are given priority and shared values drive scientific research, technological developments, and investments toward improving transportation infrastructure. In such a scenario, necessarily characterized by significant, public funding for basic, fundamental research, new materials with self-healing properties (e.g., bacterial concrete), lower carbon footprint (e.g., green concrete), and better resistance to environmental attacks (e.g., inexpensive corrosion-free steel) might appear and become viable commercial products. Also, more efficient automated construction technologies, (e.g., based on additive manufacturing or 3D printing), might further improve offsite prefabrication of structural elements and rapid construction techniques.

To take full advantage of such innovations, however, a “tear-down-and-rebuild” approach would need to become more prevalent than the “repair and retrofit” approach. This would also allow embedding in the new structural components different types of new technologies such as sensors for damage detection and structural health monitoring, sensors to guide autonomous vehicles, technologies for energy harvesting, and others.

Bridges and roads would become “living” subjects, exchanging (most probably wirelessly) a continuous, real-time flow of information with all entities involved: users, local transportation agencies, law enforcement, infrastructure owners, and other interested parties. This would produce a large amount of data that – if properly analyzed[14] and interpreted [15]will lead to an improved ability of the technical community to predict future evolution of infrastructure and to fine tune subsequent maintenance investments.

Under such a scenario, the transportation infrastructure of the future would be characterized by a failure probability curve (Figure 3) with small slopes (i.e. less effected by aging) and variations and, most importantly, with much less uncertainty in the predictions of the future evolution, the effect on continuous maintenance, and the effect of repair and/or retrofitting work. The failure probability curve would look like option 3 (green line) depicted in Figure 2.

Arguably, this overall change in how deteriorating infrastructure is dealt with would require significantly larger short- and medium-term investments but could lead to overall savings over the entire service life of infrastructure systems. Investment would be needed to support basic research, for the technological implementation of such research and for retrofitting/rebuilding infrastructure components so that they can benefit from such technological advances. On the other hand, these rehabbed and new facilities would be more durable, more resistant to environmental attacks and more resilient to extreme events. Hence, they would require significantly less resources for routine maintenance and to rebound from damage due to earthquakes and windstorms.

For example, for bridge decks, current research on embedding in the concrete mixture particles and fibers of different size (from nanometers to centimeters), type (e.g., steel, carbon, and plastic), and functionality (e.g., enhancing toughness, wireless monitoring of damage, delivering self-healing agents) is still in the early stages and more research investments are needed to demonstrate the effectiveness of these techniques.

Similar advances are coming along in other materials, including weathering steels that produce their own protective coatings that do not need to be painted; carbon fiber and other composite materials that are far lighter, more flexible, and more resistant to environmental degradation; and advance non-destructive assessment technologies that spot and report incipient failures early.

Investments will be required to support not only development, but also technology transfer and to transition from the scientific endeavor to commercial products that are sustainable from an economic point of view – which means producing materials that are not substantially more expensive than currently available options. Finally, to exploit these new materials, , they need to be applied to rehabilitation and reconstruction projects, which may be more expensive than implementing focused repairs, but in many cases these higher initial costs will be offset by reduced costs for long term monitoring and maintenance.

Under this scenario, significant changes will be required through new policies and regulations in the way transportation agencies and institutions manage the national infrastructure inventory, a "cradle-to-grave" approach, where the life cycle costs are minimized, must replace current, short-term approaches, characterized by few-year-horizons and the minimization of only initial costs.

Another possible working scenario highlighted earlier in this report, the so-called competitive success scenario, is the one in which economic growth and competitiveness are the main drivers. Under this scenario more resources will be available for strategic infrastructure repair and retrofitting from both public and private sources. However, since privatization of the infrastructure management is more likely in this scenario, with the right incentives, private entities may accelerate the rate of progress.

Research investments would be geared more toward technological innovation than basic, fundamental research. Consequently, instead of the revolutionary changes discussed in the resilience and sustainability scenario, evolutionary changes will be more likely. In this case, the technical community will pursue incremental improvement through widespread adoption of repair and retrofitting techniques that are already in use today.

Infrastructure condition and performance would see improvement but large disparities based on geographical location and economic considerations might persist and possibly increase. For example, repair and/or retrofit work on bridges and roads producing significant revenues from tolls or critical for particular economic enterprises would have priority over other infrastructure regardless of other circumstances, including condition and performance. Infrastructures serving wealthier and more economically developed areas (e.g., urban areas and cities), might be the main beneficiaries of the improved economic situation and improved infrastructure management. Poorer and economically declining communities (e.g., rural areas) might see little or no improvement.

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ENDNOTES

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CHAPTER NINE

Transportation Infrastructure and the Future of Cities

By Kimberly A. Gray

Introduction

There are a multitude of possible future tracks along which the transportation sector may move. The purpose of this chapter is to evaluate two possible trajectories of change for transportation infrastructure and how these two futures are linked to economic development. The first scenario envisions how transportation infrastructure would evolve along a business-as–usual (BAU) path by 2050. In contrast to this, the second scenario describes how the goals and principles of sustainable urban development would direct changes to transportation infrastructure along very different paths over the next 35 years.

The chapter is divided into four sections. In the first section the focus on urban infrastructure is explained and the general picture of the current state of infrastructure in cities is described. In the second section, the BAU trajectory is considered by first reflecting on how cities have changed over the last 35 years and then extrapolating these patterns to the next 35 years. This is followed by a discussion of the types of changes expected to accompany the sustainable transformation (ST) of the urban metabolism, particularly in relation to mobility and accessibility. In the final section of this chapter, the two scenarios are compared with reference to representative North American cities and the economic, technological, political and social drivers of these dueling trajectories are discussed.

Today’s cities and their infrastructure

This section focuses on the scale of urban neighborhoods and metropolitan regions because cities are the world’s economic engines, driving 75 percent of global productivity. The high concentration of human capital in cities is the raw material of discovery and invention. Urban density sparks human creativity, making cities centers of innovation and rapidly spreading ideas. Cities magnify human strengths and are “our greatest invention mak(ing) us richer, smarter, greener, healthier and happier.”[1] It is at the scale of cities, rather than states and nations, that rapid and transformative change occurs, reflecting shifts in attitudes, values, and economic possibility, all responding to global challenges and opportunities.

Before exploring the myriad ways in which cities and their infrastructure systems can evolve over the next 35 years, a rough sense of the baseline conditions that describe the average North American city today must be established. Cities are not simply spaces, places or locations. Cities are dynamic and constantly changing. Urban dynamics are best conceptualized as complex systems of flows and networks.[2] In this context, cities behave much more like living organisms than machines, and their functions are analogous to metabolic processes. At the present time, however, few urban infrastructure systems are interconnected and coupled as the analogy to organisms suggests is possible. System coordination and integration, among transportation, energy, and land use cycles, for instance, define a potential pathway to greater efficiency and more reliable performance that cities of the future could exploit.

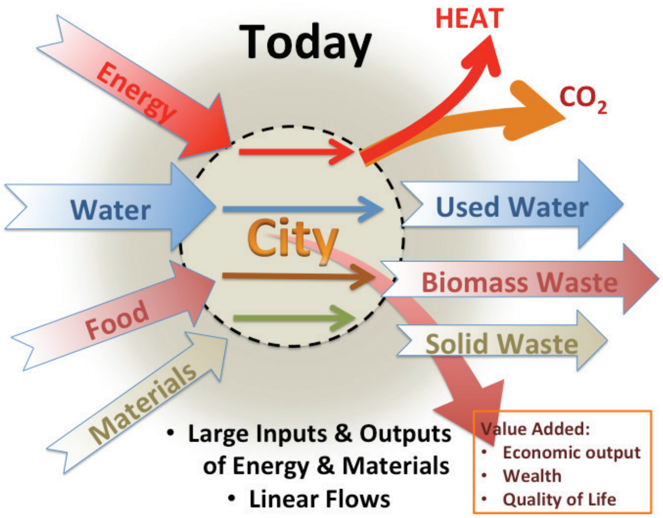


Figure 1: Schematic picture of today's North American cities showing large inflows, linear throughput and hence, large outflows of energy and materials, diffusive growth without defined boundaries and value added benefits of economic output, wealth and quality of life.

The most salient feature of the 20th Century North American city is its expansive suburban development. Very few North American cities have defined growth boundaries, their sprawling growth and diffuse reach made possible by the automobile (Figure 1).3 Throughout the Midwest, for instance, older, industrial cities may show shrinking populations over the entire city proper but expanding populations in certain neighborhoods or the surrounding, metropolitan region. Regardless of where growth is occurring in metropolitan areas, either through suburban expansion or urban redevelopment, the built, physical, public framework of cities – roads, bridges, rail, stations, and terminals– is deteriorating. As discussed elsewhere in this report, dwindling funding sources have delayed basic maintenance on roads and bridges and failed to support new high-speed transit routes.

One result of this infrastructure deterioration is worsening congestion that chokes mobility into, out of and around cities. Overburdened freeways, airports and ports cost time and hundreds of billions of dollars every year. Since congestion is proportional to economic activity, recent economic recovery in the U.S. has been accompanied by the recovery of traffic congestion to pre-recession levels. According to the 2015 Urban Mobility Scorecard,[4] travel delays due to traffic congestion cause drivers to waste more than 3 billion gallons of fuel and keep travelers stuck in their cars for nearly 7 billion extra hours or 42 hours annually per rush-hour commuter. This translates to a total national cost of $160 billion, or $960 annually per commuter. The most congested city in the nation is Washington, D.C., with 82 hours of delay per commuter, followed by Los Angeles (80 hours), San Francisco (78 hours), New York (74 hours), and San Jose (67 hours).

A return to strong vehicle sales is another index of the U.S. economic recovery and the second decade of the 21st Century has seen continued growth, particularly in large vehicles and trucks. A significant amount of urban land is dedicated to parking and some cities such as Chicago in need of revenue have privatized parking meters with guaranteed returns and long contract periods (e.g., 75 years). The net result is that land use planning has been sold or squandered far into the future and 20th Century parking requirements will likely extend into an age when they are no longer needed. The decline in oil prices and cheap gasoline have encouraged both the recent increase in large vehicles sales and in annual vehicle miles traveled in the U.S. (Figures 3, 4), and have undercut hybrid, electric and small auto sales. Furthermore, low interest rates tend to promote leasing and the acquisition of bigger vehicles than one might otherwise afford. This trend, however, does provide the flexibility to change models in the near future should economic conditions change.

The provision of food to cities is highly dependent on transportation infrastructure. An often quoted estimate, that food travels on average 1,500 miles from farm to market, is probably only true for certain cities (e.g.,, Chicago) and certain produce (e.g.,, oranges).[5] But, approximately 17 percent of food (110 billion pounds) is imported into the U.S. and can travel very long distances, far in excess of 1,500 miles – lamb and beef from New Zealand, grapes from Chile, shrimp from Thailand.[6] Another important feature of the flow of food through U.S. cities is that about 40 percent is discarded as waste.[7]

The organization of other urban infrastructure systems influences the performance of transportation infrastructure. Water and wastewater are treated at large central facilities and are transported to and from buildings in networks of pipes buried under roads and walkways. Repairs or changes to these networks require excavation and that can cause significant traffic disruptions. Stormwater management has a more direct effect on transportation efficiency and is dealt with in a wide variety of ways. The primary objective of stormwater management is to whisk the water away as fast as possible to prevent flooding, protect public health, and maintain mobility, accessibility and economic activity. Currently, stormwater may be drained and routed to streams untreated or it can be captured, stored and treated in a variety of engineered systems onsite or in centralized facilities. Although the design of green infrastructure is gaining favor due to cost and adaptive advantages,[8] these strategies require green space or permeable surfaces that may rival the mostly paved and impervious roads, walkways and parking areas of typical cities.

Almost a quarter century after the birth of the World Wide Web, most Americans today have computers and Internet access. As expected, Internet connectivity is greatest in urban areas and tracks education and income. According to the Pew Research Center's analysis of Census Bureau data, 84 percent of U.S. households own a computer and 73 percent of these computers have broadband connection to the Internet.[9] Yet, the nation exhibits a wide variation of connectivity. For instance, only 57 percent of the households in Mississippi have broadband connection. Among metropolitan areas, 73 percent in the Miami area are connected in comparison to 84 percent in the Washington, D.C., metro area. The Pew Research Center also found that greater than 90 percent of adults use cell phones, making mobile phones the most quickly adopted consumer technology in the history of the world.[10] About 64 percent of adults own smart phones but a smaller percentage (approximately 20 percent) rely exclusively on their smart phones for Internet access.[11] The National Center for Health Statistics reports that over 40 percent of U.S. households no longer have landline telephones, depending only on wireless phones.[12] Young adults are most likely to have abandoned landlines, with nearly two-thirds of the 25 to 29 year olds living in wireless-only households.

For transportation, though, the salient question is whether this revolution in communication technology has changed consumer shopping habits. And it has. As more and more shoppers turn to online purchasing, U.S. retailers are confronted with a steep and persistent drop in store traffic, which has fallen 5 percent or more each month from the previous year.[13] Consumer tastes are changing and instead of wandering through brick-and-mortar establishments in search of sales or to be lured into impulse buying, shoppers are using their smart phones and computers to compare prices and make lowest-priced targeted purchases. As of June 2015, online or e-commerce sales were 7.2 percent of total retail sales.[14] There are serious repercussions to traditional merchants which range from the slowing of new store construction and openings to the collapse of entire shopping malls. In fact, the rate of shopping mall failures in the U.S. is climbing with dozens of malls closing over the last couple of years and another 60 teetering on the brink of solvency.[15] The picture is particularly bleak for mid-level malls, which are dragged down by the closures of department store anchors such as Macy's, JCPenney and Sears.

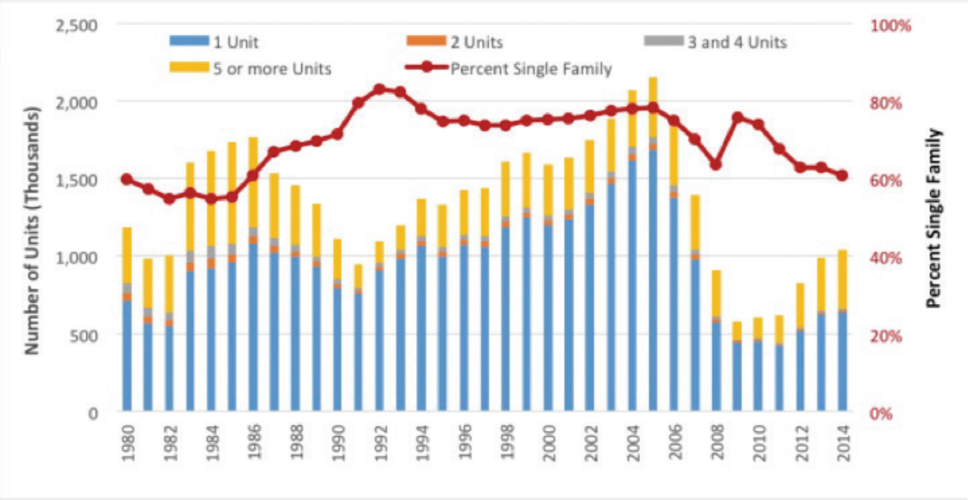
The critical challenge for the future of transportation infrastructure, though, is to determine what these dramatic changes in consumer habits mean for travel and traffic. The typical U.S. household makes about 10 trips per day, mostly (83 percent) in their vehicles, and about 42.5 percent for shopping and errands.[16] It will be interesting to see how these changing consumer patterns will influence overall urban traffic. Will the overall number of household trips decrease or will there simply be a shift to different types of vehicles (e.g. delivery trucks) moving in cities in greater numbers and causing more congestion?

Cities are among the greatest human inventions but in 2016, the typical U.S. city faces many near and long-term challenges related to the way it transports its citizens and goods, supplies information, manages its water supply, produces food and energy, and treats its wastes. In other words, the urban infrastructure systems of most North American cities need serious attention and the basic question that underpins these challenges is whether to repair and rebuild the designs that are in place and that were largely envisioned over 100 years ago; or to seize upon the present, deteriorating state of urban infrastructure as an opportunity to reinvent the many physical systems that support the operation of cities for the well-being of all their inhabitants?

Business-as-usual scenario of future infrastructure change

Before envisioning how cities will be built and function in a future where change occurs according to a Business-As-Usual (BAU) scenario, it is instructive to reflect on how much has changed over the last 35 years. First, it is important to note that "Infrastructure, including our inventory of housing and our transportation systems, doesn't change very fast".[17] This is because the investment costs and long-time intervals over which these projects are amortized essentially obviate rapid changes. As illustrated in Figure 2,[17] the percentage of single-family homes relative to the total number of dwelling units has fluctuated between 60 and 80 percent over the last 35 years. Single-family housing comprises 71 percent of the total housing units and favors low-density development. Currently new housing construction is about even with population growth, although it does not account for housing demolition.

More than half the U.S. population lives in suburban areas and 75 percent of the housing construction since WWII has been in the suburbs. Given the strong preference for single-family dwelling units and the many decades required to change the housing inventory composition even given the recent trends shown in Figure 2, the BAU scenario suggests continued urban growth at the fringes of cities in auto-dominated, low density suburban and exurban developments. In fact, an interesting statistic reflective of continued suburban growth is observed in settlement patterns of new immigrants. Since the end of the 20th Century, the number of foreign-born U.S. residents choosing to live in suburbs immediately upon arrival exceeds the number in central cities, reversing the patterns of initially locating in the central city and then moving to the suburbs with increased socioeconomic status and cultural assimilation.[18] This may be explained in part by the fact that diverse suburban neighborhoods outnumber diverse city neighborhoods.[19]



Source data: http://www.census.gov/construction/bps/stateannual.html

Figure 2: U.S. dwelling unit permit trends by dwelling units per structure

Although suburbs are likely to continue to grow, the nature of suburban growth is expected to change in the future. For the first time in 100 years, the rate of urban population growth has been reported to exceed suburban growth.[19] There are a number of factors stimulating a return to urban living among certain age groups, particularly millennials (born between 1980-1999), such as deindustrialization of central cities, changing lifestyle preferences and shifting demographics (increased number living single, marrying later, having smaller families). Some of the increase in urban growth is a localized phenomenon. The city that had that greatest increase in central city population from 2000-2010 (defined as within 2 miles of city hall) was Chicago, where 48,000 people moved into the area but over the same time interval, Chicago lost 200,000 or about 7 percent of its population, mostly African-Americans from low-income neighborhoods.

Large urban areas are evolving to be networks of urban nodes, some of which are suburban communities that are becoming urbanized. The distinction between some suburbs and cities may be fading as suburbs are becoming more ethnically and socioeconoically diverse and are

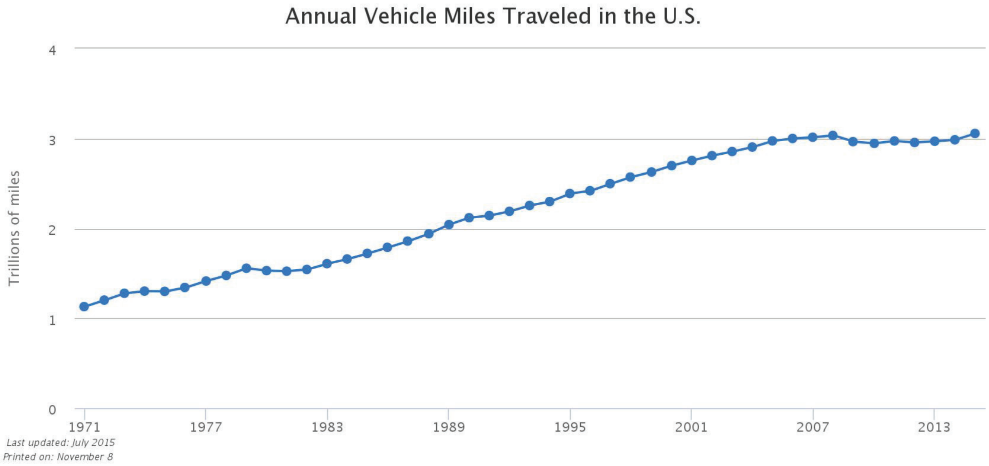


Figure 3: Annual vehicle miles travel in the U.S. between 1971 and 2015[20]

being redeveloped with mixed-use or high-rise construction around high-quality mass transit – transit oriented development - to ease the pains of commuting. A major trend over the next 35 years, then, may be to urbanize the suburbs incorporating both high and low density housing.

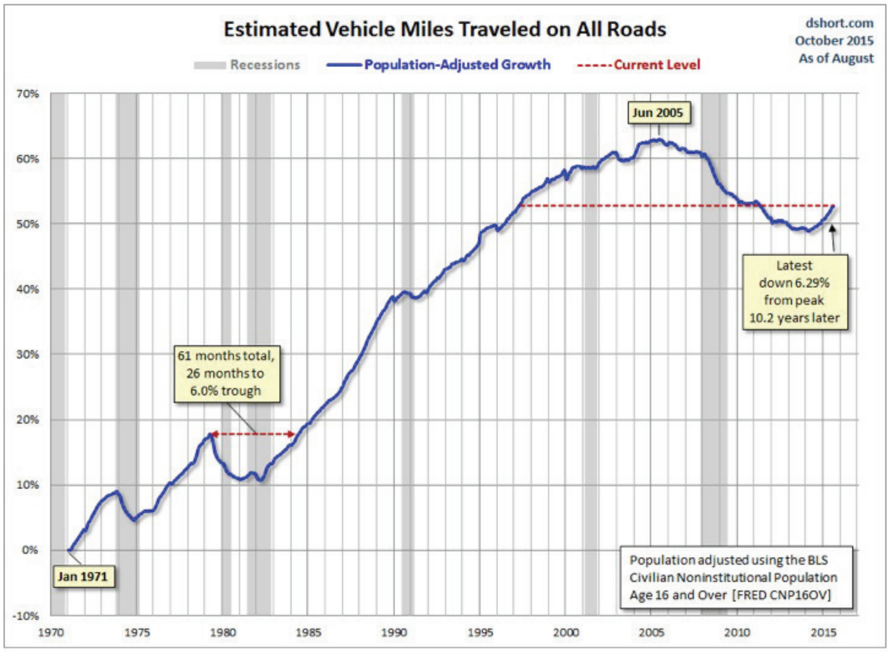


Figure 4: Annual vehicle miles travel in the U.S. between 1971 and 2015 adjusted for population age 16 and over[21]

Trends in urban /suburban growth and housing developments are also reflected in auto-mobile use. Total vehicle miles traveled (VMT) in the U.S. from 1971 through 2015 is plotted in Figure 3.[20] From 1971-2008 VMT increased steadily until hitting a plateau from 2009-2014 due primarily to the Great Recession. VMT, however, has hit another inflection point in 2015 increasing substantially in response to low petroleum prices and economic recovery. When these data are adjusted for population growth, using population age 16 and over, as illustrated in Figure 4, VMT peaked in June 2005, declined through early 2014 and has since risen sharply, although the latest 2015 population adjusted figures are still about 6 percent less than the 2005 peak.[21] These trends indicate that VMT declines temporarily during periods of economic recession and high fuel costs but rebounds quickly with economic recovery and lower fuel costs.

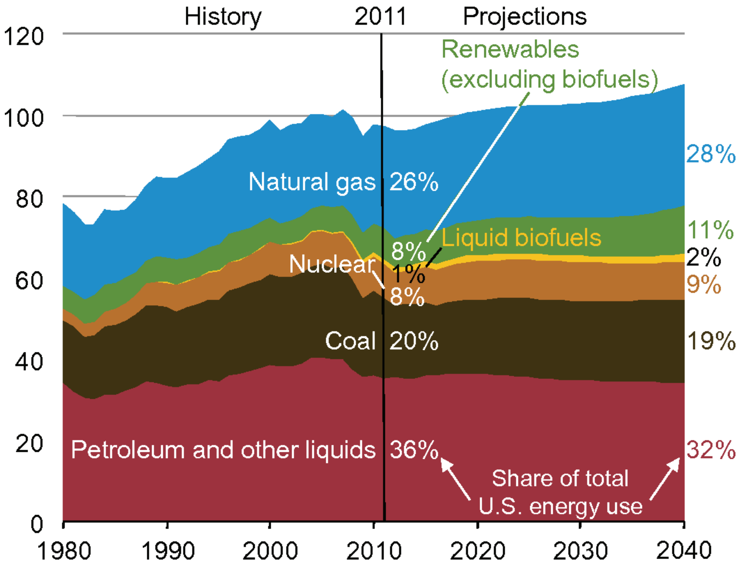


Figure 5: Trends and projections in U.S. primary energy (Quad BTU), 1980 – 2040, from Figure 54 in EIA Annual Energy Outlook, 2013[22]

The patterns of development and VMT are heavily influenced by energy sources and prices. Figure 5 shows the trends in total primary energy consumption in quadrillion BTU, how the various sources of primary energy have changed historically from 1980 – 2011, and how total energy and sources are projected to grow to 2040.[22]This graph illustrates a number of salient points that heavily influence transportation infrastructure past, present and future.

In the early 1980s, about 90 percent of total primary energy demand was met with fossil fuels, with the largest fraction contributed by petroleum and other liquid fuels primarily for transportation use. By 2015, total primary energy demand increased by 25 percent (from 79.3 QBTU in 1980 to 98.3 QBTU in 2014)[23], but the fossil fuel fraction diminished slightly to about 82 percent, due to a combination of factors: increase in renewables, decrease in petroleum use in a sluggish economy, and improvements in efficiency. The 2040 projection of the fossil fuel share of total energy use is expected to fall further to 78 percent and renewable use will make up this difference with growth from 9 percent in 2011 to 13 percent in 2040 in response to the federal renewable fuels standard, availability of federal tax credits for renewable electricity generation and capacity during the early years of the projection, and state renewable portfolio standard (RPS) programs.[22]

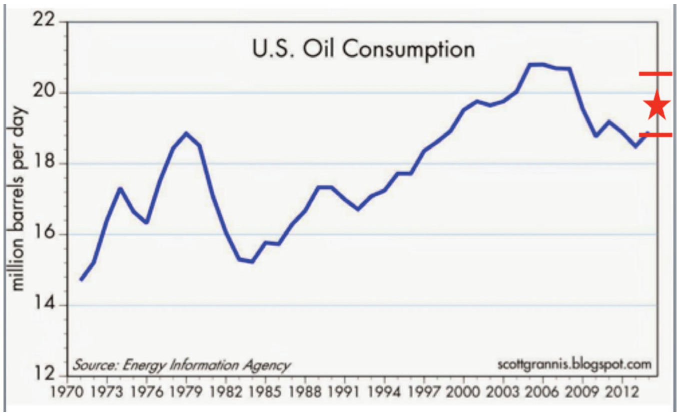


Figure 6: U.S oil consumption 1970 – 2014, where red star and brackets represent 2015 demand estimate based on first quarter data.[24]

As shown in Figure 5, historic trends in energy demand reflect economic booms and busts. In general, energy demand grew at a high rate from the 1980s through 2008. In comparison, future total demand is projected to grow more slowly and some sources are expected to decline, petroleum and coal, for instance. Given the U.S. EPA's Clean Power Plan, the consequences of which were not included in the energy outlook of Figure 5, coal use will diminish more rapidly to a smaller future percentage than shown here (in 2015 it is 18.3 percent of the total energy consumed, already less than that projected for 2040) and will be replaced primarily by natural gas (in 2015, already approximately 28 percent of the total primary energy use).[23]

Future increases in vehicle fuel economy are expected to offset energy demand growth in the transportation sector, resulting in a decline in the petroleum and other liquids fraction of fuel use even as total consumption of liquid biofuels increases. Biofuels, including biodiesel blended into diesel, E85, and ethanol blended into motor gasoline (up to 15 percent), are projected to account for 6 percent of all petroleum and other liquids consumption by energy content in 2040.[22] In the short term, however, petroleum demand is showing a strong rebound to pre-recessionary levels (Figure 6). U.S. oil consumption hit a maximum in 2005 at 20.7 million barrels/day. For the first 24 weeks of 2015, U.S. oil consumption averaged 19.51 million b/d, a 4 percent increase over the same time frame in 2014.[24]

The resurgence in oil consumption in 2015 is tied to the low price of crude oil, as shown Figure 7.[25] In late 2014, the price of a barrel of oil fell from about $80 to $45 and the price had remained depressed, on average less than $50 /barrel throughout 2015. There has been tremendous and unexpected volatility in oil prices over the last decade. Near term projections made by the World Bank and IMF, however, only show gradually increasing prices, but well below $100/barrel.[26] These data indicate the reality of energy demand can change quickly in response to policy, global events and economic conditions. For these reasons, the energy forecast projected in Figure 5 may already be obsolete, but it also indicates that fossil fuel dominance is expected to prevail far into the BAU future.

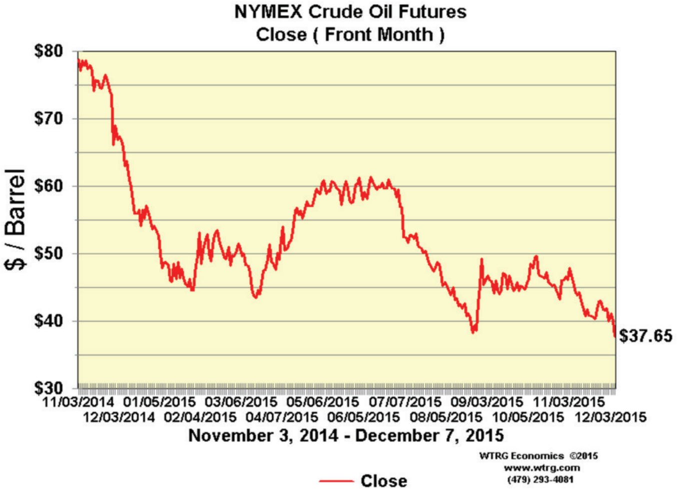


Figure 7: Crude oil futures, Nov. 2014 – Dec. 2015[25]

Personal mobility and large vehicles are both hallmarks of American culture. As illustrated in Figure 8, over the last 40 years, U.S. auto sales show distinct decadal patterns of growth, sharp declines and increases (1976-1991), steady growth (1991-2000) and thereafter, a slow decrease until 2009, when they plummeted in the worst sales year since 1982.[27] Since then, a return to strong sales tracks the economic recovery and low fuel costs. In 2015, auto sales have reached record levels not seen since 2000. Yet, the most surprising characteristic of these strong sales in 2015 relative to 2014 is the 12.7 percent increase in light duty trucks and SUV sales, which occupy 11 of the top 20 best-selling spots.[28] It is important to note, though, that the Ford F-150 Series Truck, specifically, has reigned as the top-selling vehicle in the U.S. for the last 38 years running. In contrast, car sales declined 1.6 percent over the same time interval.[28] The resurgence of large vehicle sales is consistent with the trends in petroleum prices and demand.

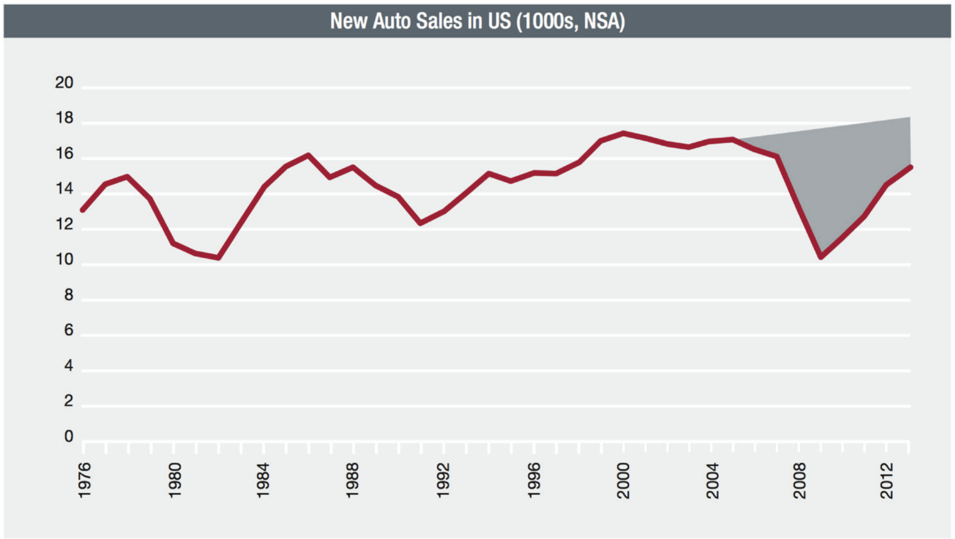


Figure 8: New auto sales in the U.S., 1976-2013, where shaded area reflects estimates of pent up demand. Source: U.S. Bureau of Economic Analysis; Equifax.[27]

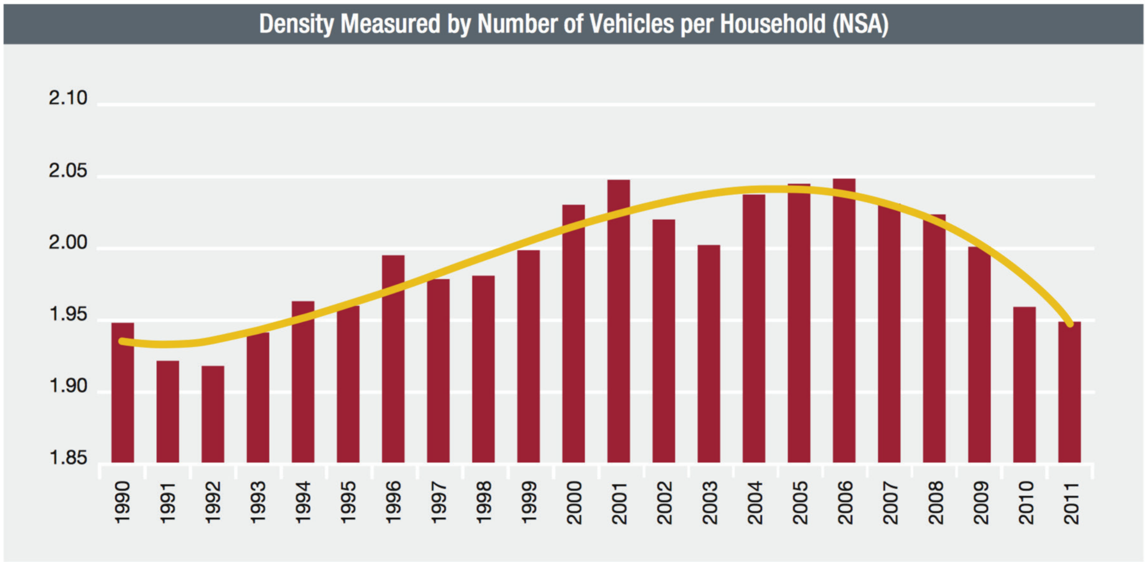


Figure 9: Auto density measured by the number of vehicles per household, 1990-2011. Source: U.S. Census Bureau; Federal Highway Administration; Equifax.[27]

Yet, another index of automobile demand is auto density, the number of automobiles per household. As shown in Figure 9, prior to the early 2000s, this ratio was increasing but has been in sharp decline since 2006 which preceded the start of the Great Recession by several years and may be related to the observation that millennials appear to be less interested in auto ownership, possibly due to the combined effects of the Great Recession and student loan debt. Auto density can have a large effect on the annual number of new cars sold. For instance, a 1 percent change in this index is equivalent to about 1 million new car sales annually.[27] Thus, if the recent trend observed in Figure 9 is structural, rather than cyclical, it would represent a major obstacle to growth in the vehicle market.

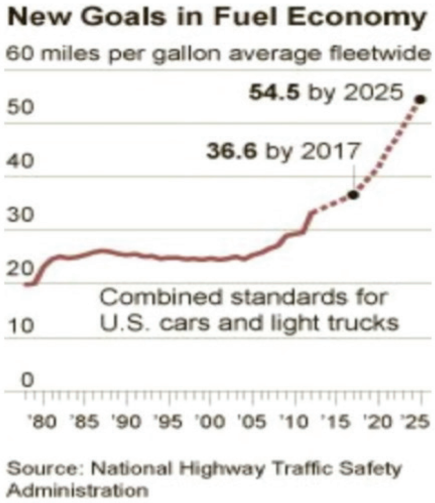


Figure 10: Trends in U.S. Corporate Average Fuel Economy, 1980 – 2015.[29]

Fuel efficiency has only begun to improve in the U.S. in the last 10 years (Figure 10).[29] In fact, for many vehicles it decreased from the late 1980s through 2004 due to the power demanding features desired by consumers. For the F-150 Series, fuel efficiency has doubled, but is still woefully low (19 mpg city, 26 mpg highway; ranked 4th on Top 10 Best Mileage Trucks).[30]The average fuel economy of the most efficient pickup trucks is 18.4 mpg, city (range 13-21 mpg) and 24.2 mpg highway (range 18 – 29 mpg).[30]

In 2012, new rules were issued that require automakers to nearly double the average fuel economy of new cars and trucks by 2025 to 54.5 miles per gallon, which is expected to pressure manufacturers to accelerate the development of electric vehicles (EV). In general, though, Americans have not embraced alternative technologies such as hybrid or electric vehicles. For instance, hybrids made up a smaller percentage (2.75 percent) of the overall U.S. auto market in 2014, down from 3.19 percent in 2013, whereas in California, the hybrid market share is about 6 percent and in Japan 20 percent.[31] Hybrid systems are expected to show only modest increases in market penetration in the near term[31], although Toyota aims to sell 1.5 million hybrids annually and by 2020 to reach 15 million in cumulative sales.[32] Since hybrid technology is not yet mature, there are many innovations and improvements, such as higher density batteries, that will emerge to bring down costs, at which time hybrids will become just another technology that manufacturers offer to enhance efficiency and drivability. Some automakers will focus their efforts on improving the engines and transmissions of the traditional gasoline- powered automobiles, as well as making vehicles lighter.

Approximately 86 percent of Americans commute to work in an automobile and of these, only about 10 percent carpool (Figure 11).[33] Since 1980, driving alone to work has increased from 64.4 percent to 76.4 percent, although there has been little change in this figure over the last 10 years. Carpooling has steadily declined since 1980, when it was 19.7 percent to the 2013 value of 9.4 percent. Yet, over the last 20 years, mass transit ridership has increased about 14 percent and in 2014, public transportation trips reached 10.8 billion, the highest in 58 years.[34] This growth is almost entirely attributable to heavy rail (e.g., subway) ridership in urban locations. In contrast, use of light rail, commuter rail and buses have increased much more slowly or declined over the last decade. Recently, however, light rail showed a 3.6 percent increase in 2014 with 16 out of 28 public transit systems reporting increases.[34] In contrast, bus ridership has been relatively flat over the last 25 years, declining 11 percent in the last decade and 1.1 percent in 2014, although a number of large cities saw increases (e.g., Baltimore, Portland, Atlanta, San Francisco, Seattle). About 60 percent of transit trips are work commutes and the greatest increase in transit ridership is in areas with growing economies and improving job markets. In general, property values located near transit tend to be higher.

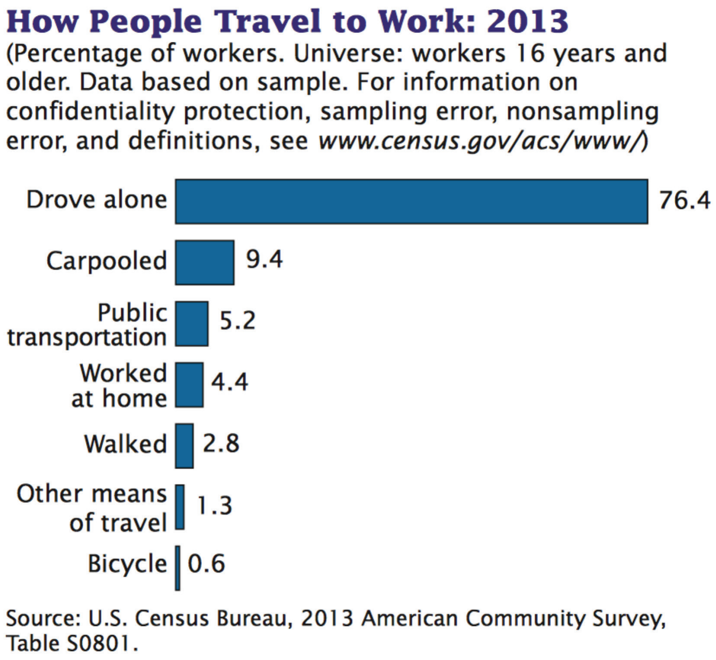


Figure 11: How people travel to work 2013[33]

Over the last 30 years, the number of public transit systems has increased by a factor of 8 from about 1,000 to 8,000. The demand for public transit is spurred by economic activity and also by reduced travel costs since taking mass transit to work can save individuals as much as $10,000 annually. Of the 33 light rail systems in the U.S., 27 extending a total 800 miles have been built since 1980 (20 since 1990).[35] The cities consistently cited for having the best rapid mass transit systems based on investment, ridership, accessibility to jobs and safety are New York City, San Francisco, Boston, Washington, D.C., Philadelphia, Chicago, Seattle, Los Angeles, Denver and Portland.[65-67] While it is no surprise that NYC, with some form of public transit within a 10-15 minute walk from almost anywhere, is at the top of every list, Los Angeles with an extensive light rail and bus system, is also included among the top cities. Yet, these are also the cities that suffer the most congestion and time spent in traffic.[4] Thus, although many U.S. cities have excellent rapid transit systems that operate at maximum capacity at rush hours, they lack necessary investment, reliability and capacity to reduce automobile traffic. Furthermore, the construction or expansion of transit systems alone will not reduce congestion and promote mode shifts from automobiles to public transit. Rather, the design and operation of successful transit systems must be integrated with effective land use policies, such as witnessed in Portland.

Based on this analysis, then, it is reasonable to use the transportation infrastructure trends of the past 35 years to predict the BAU trajectory over the next 35 years. Accordingly, in the BAU future, settlement patterns are expected to remain largely unchanged with half the population living in suburban developments dominated by low density, single family homes and privately owned vehicles (POV). Household and work travel will continue to be made mostly by automobiles fueled by refined petroleum, the price of which is expected to persist at relatively low values. Although there are some subtle signals that suburbs are experiencing urbanizing pressures and that economic growth is driving the extension and embrace of rapid transit systems in more prosperous cities, for the most part, transportation infrastructure systems are characterized by enormous inertia that resists rapid change. There are two trends, however, that are gathering momentum and have been largely absent historically. The first is the smart cities movement located at the intersection of the information and communication technology (ICT) revolution and urban development. The second is climate change.

The smart city is the ICT approach to improving the performance of urban systems and the overall urban experience. Created by the interplay between ubiquitous, wireless, broadband connectivity and computerized sensors embedded into the urban fabric, the aim of the smart city is to promote better living through data. The information that is gathered and relayed to and from users in a smart city promises to increase well-being and efficiency, decrease operational costs and resource use, engage citizens more actively in governance and provide a much faster response time to changes and challenges. The notion of the smart city originated with big technology corporations, such as IBM, Cisco, Siemens, and in many ways embodies business-led urban development that has a market potential of trillion of dollars by 2020.

The technologies and their integration into the fabric and function of a smart city were envisioned long ago and have been slowly emerging over the last 20 years. A classic example in transportation is the electronic toll collection (ETC) system which is based on radio frequency identification transponders and dates back to the 1960s. ETC reduces congestion at toll booths and provides opportunities for monitoring traffic flow and vehicle speed, as well as vehicle tracking. Tolls are metered and collected electronically, ideally without drivers having to reduce their speed. Thus, ease of driving is maintained. Networks of sensors now exist that monitor traffic on major urban roads, track the arrival of trains and buses at stations and stops, and signal available parking spots, all in real time. This information is made available to users through the Internet and various smartphone apps.

Efforts are also being made to install networks of sensors to monitor urban air pollution from both mobile and stationary sources in order to understand interactions between sources, dispersion and sinks and to improve pollution control and protect public health. These efforts, however, are complicated by the fact that many, if not most, contaminants are very difficult to monitor in real time and that different pollutants require different types of sampling strategies. For instance, there are six categories of pollutants from combustion regulated by the National Ambient Air Quality Standards and of these only four chemicals can be monitored easily and continuously in real time (CO, NO_2, SO_2 O_3). In contrast, there is a list of 187 hazardous air toxins regulated by the U.S. EPA and over 80,000 common chemicals manufactured that lack any human or ecological health data. The revolution in nanomaterials adds to the burden of exposure creating even more complex soups of chemicals and materials. At the present time, sensor networks are beginning to be deployed in smart cities that can monitor weather, vehicle and pedestrian traffic and a few air pollutants. But these networks and data fall woefully short of the claims being made that such efforts will eliminate urban health disparities, mostly because the networks do not extend to the communities of vulnerable populations and it is not yet technologically feasible to measure the constituents that actually pose health risks. Rather, the data being collected routinely today and in the near term and made available to the public, are valuable mostly for improving convenience of individuals.

ICT is changing consumer behavior with the shift to e-commerce. Although not reflected in current data, truck delivery of goods could be made more efficient than individual consumer shopping trips. This change, though, will likely propagate a shift from automobile to truck traffic. Yet, the emergence of crowdsourcing and the sharing economy could result in a net reduction in vehicle traffic. However, the marketing potential and demand for same-day delivery could undermine these efficiency gains.

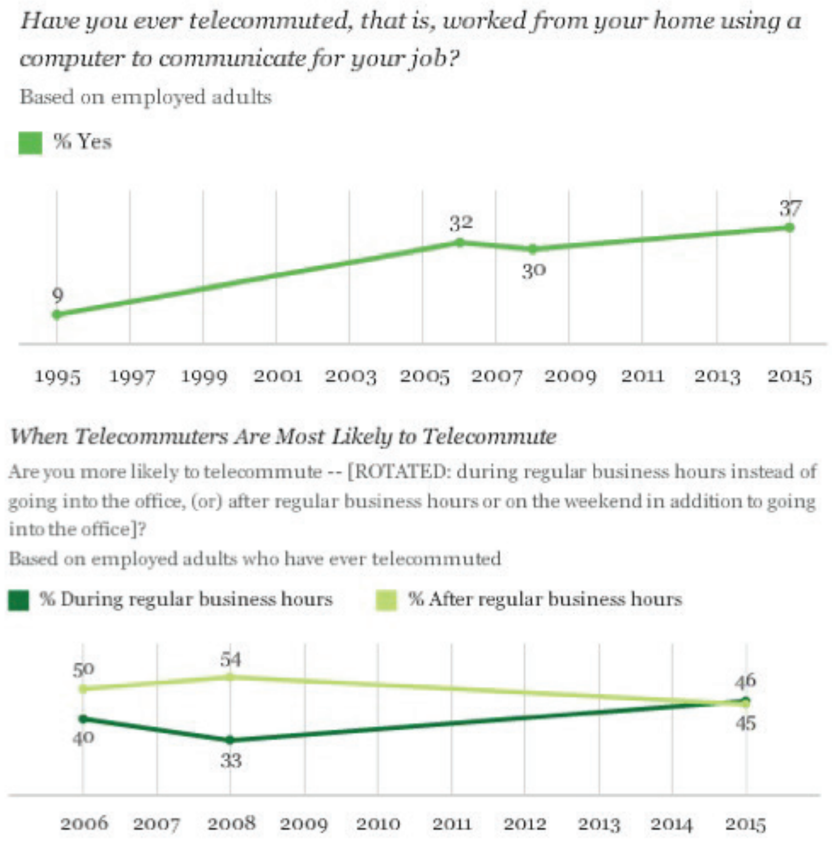


Figure 12: Results from Gallup's 2015 Work and Education poll on trends in worker telecommuting[36]

ICT has made working remotely easier for employees, and telecommuting has gained in acceptance, with almost 40 percent of workers saying they have telecommuted to their jobs at least two times per month. As illustrated in Figure 12,[36] however, the increase in telecommuting has leveled off in the last decade relative to the previous decade (1995-2006). More significant, though, is the shift in what working remotely has come to mean. Whereas telecommuting used to refer to work done outside business hours in addition to going to the office, since 2008, there has been a significant increase in workers who telecommute during business hours replacing going into the office. According to the 2015 Gallup poll on Work and Education, while more Americans now than ever before work remotely for some fraction of time each month, the overall numbers are still small and are restricted to those whose work involves computers. Furthermore, growth in the practice has slowed in recent years. If telecommuting were to grow substantially to be a more regular feature of employee behavior in the future, then journey to work traffic may be reduced but the recent trends in telecommuting do not suggest that this is likely.

Since the early 1990s, global concern has been growing over climate change caused by the emissions of greenhouse gases (GHG) far in excess of the earth's homeostatic levels. Leaders of the wealthiest countries have promised to keep GHG emissions to a level that allows no more than a 2°C increase in the average global temperature over preindustrial levels, an increase that is considered to be within nature and human's ability to adapt. In June 2015, the G7 countries agreed to phase out fossil fuels by 2100, which would require meeting targets of between 40-70 percent GHG reduction relative to a 2010 baseline by 2050.[68]

Despite repeated attempts to hammer out international emissions reduction agreements, however, there are no binding pledges that have resulted in reducing emissions globally and efforts have largely remained voluntary. At the COP21 meeting in Paris at the end of 2015, negotiators from almost 200 countries agreed to take concrete steps to cut GHG emissions, but again, with voluntary, not binding pledges. At the same time, however, these reductions pale in comparison to what is required to meet their own goal of limiting the increase in global temperature to 2°C.[37]

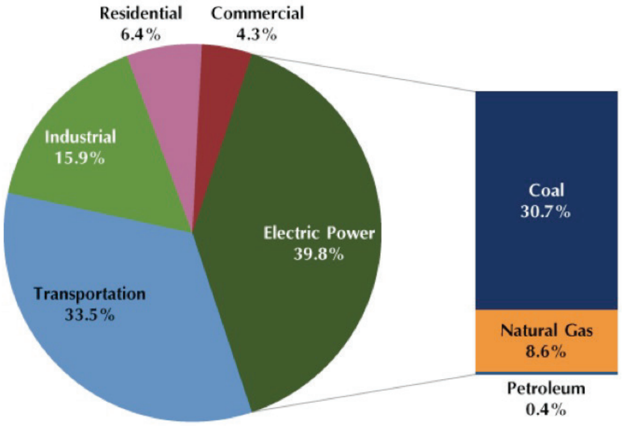
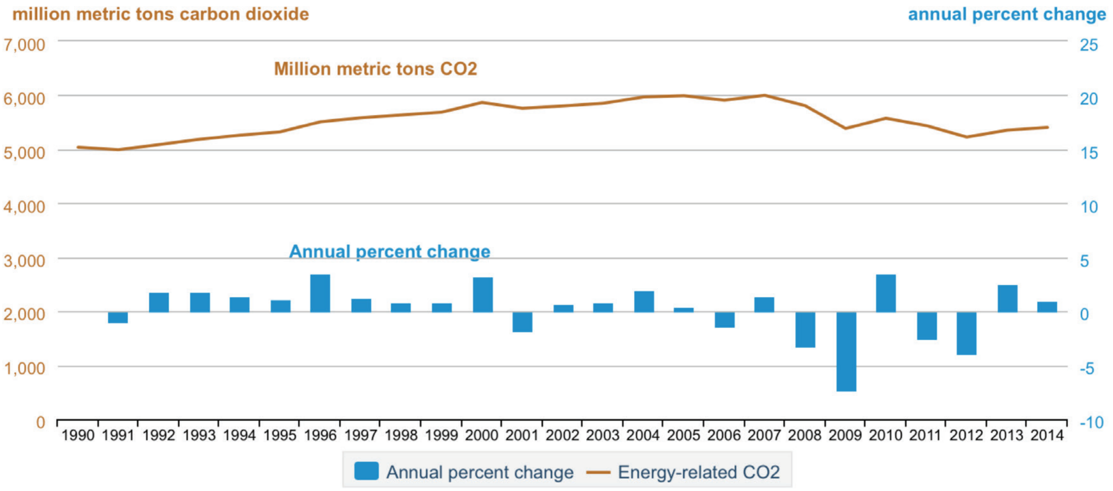


Figure 13: 2013 U.S. CO_2 emissions
Source: EIA.[38]

Since one third of U.S. CO_2 emissions are due to transportation, specifically the combustion of refined petroleum (Figure 13), targeted reductions in GHG emissions and phase-out of fossil fuels necessitate serious and deep changes in transportation infrastructure.[38] Yet, there is no single strategy, such as a disruptive technology shift to electric vehicles, that is going to change this picture rapidly. A new report issued by the Georgetown Climate Center explores various strategies to reduce GHG from 2011 levels by as much as 40 percent by 2030, pushing past the 29 percent reductions due to current state and federal policies.[39] The authors identify comprehensive strategies involving a transition to electric vehicles, increased use of rapid transit, smart growth and greater reliance on walking and cycling. In the Northeast and Mid-Atlantic regions of the U.S., the clean transportation policies that would promote these strategies would also result in cascading benefits of improved public health, job growth and net cost savings of up to $72.5 billion over the next 15 years for both businesses and consumers. Existing policies, however, are not sufficient to place the region on the path to achieve 2050 reduction goals to keep the temperature increases to less than 2°C.

Figure 14 illustrates energy-related CO_2 emissions from 1990-2014.[40] From the 2007 peak to the 2012 minimum, CO_2 emissions declined about 13 percent in response to a variety of factors such as reduced economic activity and the shift away from coal to natural gas. Since 2012, however, with the economic recovery, CO_2 emissions have increased 3.4 percent, although the carbon intensity of the economy has diminished due to the continued transition away from coal to natural gas. Over the last 35 years significant improvements in the energy efficiency of appliances, vehicles, homes, buildings, and industrial processes have been achieved. Yet, there has not been much reduction in total energy use because of the acquisition of more appliances, larger homes and vehicles, more buildings and GDP growth.

The BAU scenario is unlikely to produce the necessary changes in energy use that will reduce GHG emissions to global targets by 2050. Much more dramatic changes in lifestyles, travel choices, production and consumption are required.



Source: U.S. Energy Information Administration, *October 2015 Monthly Energy Review*, Table 12.1 Carbon dioxide emissions from energy consumption by source.

Figure 14: Energy –related CO_2 emissions and annual percent change from 1990-2014.[40]

Sustainable transformation of urban and transportation systems

As illustrated in Figure 1, today's cities are diffuse and rely heavily on large inputs, outputs and linear flows of energy and materials. Although these patterns certainly produce value and quality of life, the costs as measured by economic losses due to inefficiencies and resource waste, environmental damage and compromised public health are excessively high, especially when the risks and potentially irreversible changes posed by a rapidly changing climate are included. It is in response to these factors that the sustainable transformation (ST) of urban and transportation systems is envisioned. As shown in Figure 15, the sustainable city of the future reduces energy and material inputs and outputs by converting the linear flows of today to diverse and highly coupled cycles that mimic the engineering of nature to meet water, energy and other resource needs and link urban metabolisms more closely to a defined hinterland. It is important to note that major changes to urban water, energy and material cycles will necessarily alter transportation systems, if for no other reason than land use will be modified and less space will be dedicated to impervious areas and surface roadways. In addition, greater reliance on ecological goods and services to supply local urban needs of materials, food, water, energy, and waste management will require an extensive redesign of the urban landscape and hence, transportation networks. Thus, changes to other infrastructure systems will require dramatic changes to transportation infrastructure.

For all these reasons, the design of sustainable cities of the future will depart greatly from that of the 20th Century urban model. Sustainable urban design incorporates principles of density, diversity and flexibility around the "operating system of nature". Infrastructure is

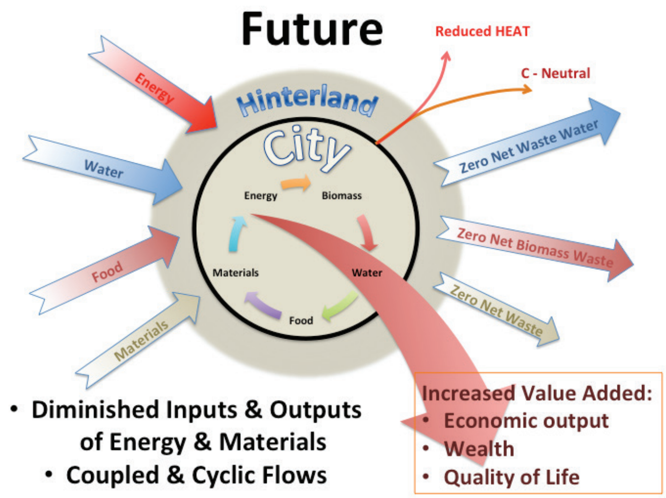


Figure 15: Schematic picture of a Future North American city showing diminished inflows and outflows of energy and materials achieved by highly coupled cycles of use and reuse, defined growth boundaries, and greater value added benefits of economic output, wealth and quality of life.

decentralized and integrated with natural ecosystems. Energy is harvested from renewable sources and transmitted along smart grids. The processes that support sustainable urban districts are linked and managed through a "central nervous" or information system, which optimizes resource recovery and maximizes profitability through integration, monitoring, communication and accurate pricing. Sustainable urban development is place-based, reflecting regional conditions and local culture. Sustainable urban districts are walkable and bikeable, diminishing the need for private automobiles, and they are ecologically regenerative, economically vibrant and socially equitable.[3, 41]

An architectural drawing of an idealized central business district in a sustainable city is shown in Figure 16. This chassis presents a menu of sustainable options that make up four interconnected networks or cycles: land use and mobility (green), energy (red), water (blue), and information (yellow). There are some very basic design principles that underpin the ST scenario for urban infrastructure and are based on high-density, compact and mixed-use development that meets the needs of the community for working and living in close proximity. In contrast to the BAU scenario where urban functions are zoned for separation, under the ST scenario urban areas and functions are zoned for integration. Growth boundaries are established that favor infill redevelopment and suburban retrofits[42] and discourage low-density, greenfield expansion. The strategic density for a neighborhood must be determined and met with diverse urban forms to promote high performance (e.g., resource and energy efficiency), productivity and livability.

Another essential feature of the urban chassis shown in Figure 16 is that the space dedicated to automobiles is drastically reduced and non-motorized modes of travel, as well as mass transit, are promoted. At the present time, walking and biking account for only a small proportion of commuting in the U.S. According to results of the American Community Survey, walking to work has declined from 5.6 percent in 1980 to 2.8 percent in 2008-2012.[43] In contrast, although the share of bicycle commuters is only 0.6 percent, biking to work showed a higher percent increase (60.8 percent) than any other commuting mode from 2000 to 2008–2012. Efforts to promote pedestrian and bicycle travel such as sidewalk modifications, pedestrian-oriented commercial centers, protected bike lanes and bike sharing programs can influence travel mode choice and have shown surprising results. For instance, as illustrated in Figure 17, in Portland more than 7 percent of workers commute by bicycle which is a direct result of the long-term city's infrastructure investments.[45] There are roughly another half a dozen large and mid-sized cities with about a 4 percent bike commute rate.

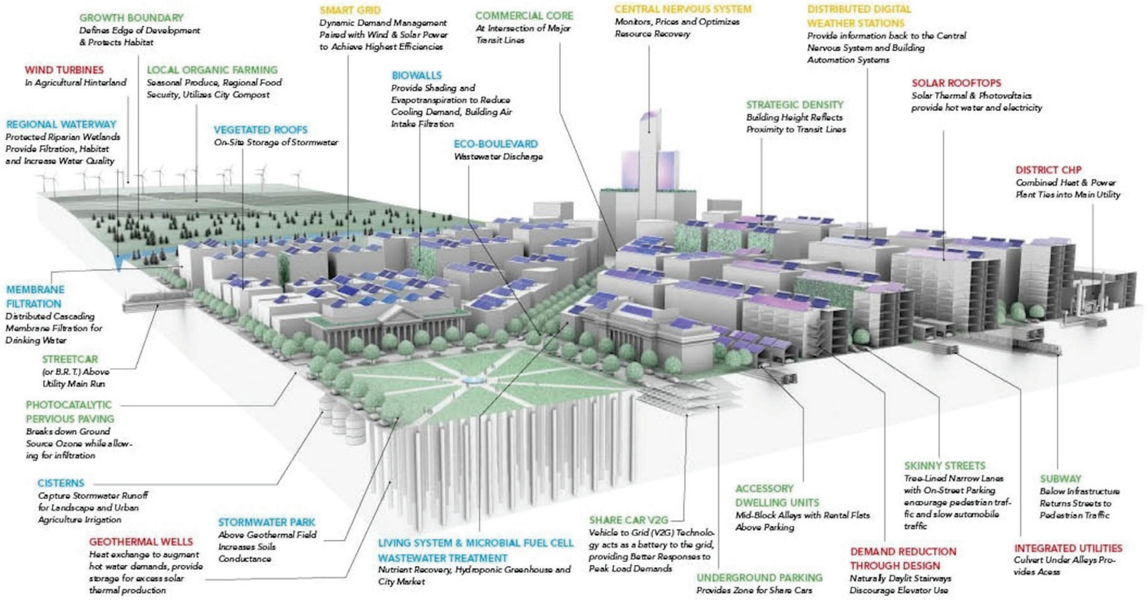


Figure 16: An architectural rendering of a sustainable urban district. Features labeled in green are part of the land use and mobility cycle; in red are features of the energy cycle; in blue are features of the water cycles; and in yellow are features of the information cycle.[41]

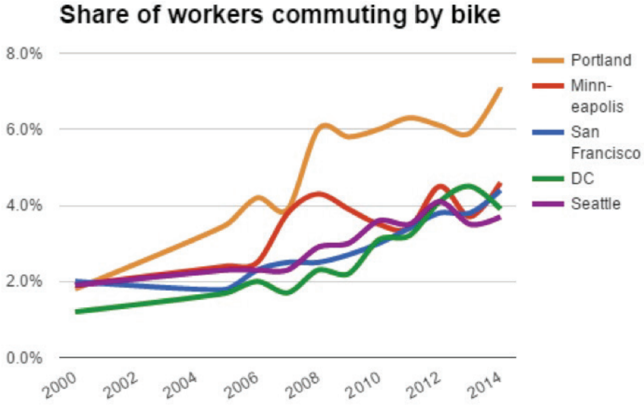


Figure 17: Mode share of travel to work by bicycle.[45]

In startling contrast, however, in the Netherlands 27 percent of all trips are made by bicycles and in the center of the country this proportion can be as high as 50 percent. In Amsterdam, bikes are used more often for errands than cars. From 1990-2006 trips by car decreased by about 14 percent in comparison to a 36 percent increase in bicycle trips.[44] Bicycles are an integral element of the fabric of Dutch cities, which is the result of a 30-year concerted effort by policy makers. A similar situation exists in Denmark, where 17 percent of all trips are made by bikes.

In general, infrastructure supporting biking and walking expands transportation options and may complement other forms of transportation by supplementing segments of trips.[43] The viability of nonmotorized travel modes improves when travel distances are covered in 20 minutes or less, which is common with compact and dense development. In addition to having the obvious positive effects on public health and GHG emissions, bike and pedestrian traffic enhances the commercial activity in a city. Walkability is a model for the future development, as well as the new economic foundation of the largest 30 metro-areas.[19, 46]

The ST scenario and the urban design depicted in Figure 16 favor the use of mass transit over privately owned automobiles (POV). People will readily choose rapid transit when transit stops are within 5–10 minutes of travel from their point of origin and final destination and if mass transit service is reliable and frequent. The ST scenario rests on a renaissance in mass transit supported by infrastructure investment and variety to include extensive networks of bus rapid transit (BRT), light rail, car sharing and an emerging system of autonomous vehicles.

In the ST city of 2050, there will still be automobiles but they will bear little resemblance to the fleets that exist today. There will be fewer POV and they will be much lighter and smaller, operating with plug-in electric motors and regenerative braking. The shift to electric vehicles will massively cut GHG emissions associated with transportation, since EV energy efficiency alone is many times greater than that of the internal combustion engine. Even in the case of electricity generated from the dirtiest coal fired plant, there is still a significant savings in CO_2 emissions. Based on an equivalency of 33.7 kWh of electricity equaling 1 gallon gasoline, most electric vehicles exceed 100 mpge (miles per gallon equivalence) and have ranges of 20-200 miles.[47] Moreover, while the initial purchase price of electric vehicles may be higher than traditional automobiles, the total cost of ownership is substantially less due to much lower operation and maintenance costs. Furthermore, there are substantial benefits to local economies associated with EVs.[48] For instance, 80 percent of the cost of a gallon of gasoline leaves the local economy, whereas locally generated renewable electricity costs do not. In addition, lower operational costs put more disposal income in the pockets of consumers to spend locally. In 2015, there were about 17 all electric or plug-in hybrid electric models that have been commercialized, although the market is dominated by four models (Nissan LEAF, Chevrolet Volt, Toyota Prius, Tesla Model S); new plug-in vehicle sales were less than 1 percent of all new car sales.

Today, the chassis designs of EVs are indistinguishable from conventional automobiles, but in the future more innovative designs such as the smart city car or the Hiriko will become common. The Hiriko was designed in 2003 by the MIT Media Lab and is a two-seat all electric microcar, and there is also a small truck model. Drive motors are located inside each of the four wheels allowing the car to fold and spin and to be easily maneuvered. Occupants enter and exit the car through the front hatch and three Hirikos can occupy a single conventional parking space. Although this vehicle was supposed to be commercialized by 2013 and sold in a few European markets, financing could not be secured and this innovative design has been mothballed as have many before it.[49] This design, however, is well suited to short trips in urban markets and for sharing. Since the primary advantage of this design is its very compact parked footprint, an autonomous vehicle that never needs to be parked may make this design obsolete. Vehicles that are always in motion, though, may end up squandering the potential of shared EV to reduce energy, carbon and traffic. Furthermore, as discussed below, EVs offer tremendous potential for energy production and storage when parked, and constantly moving autonomous vehicles would not support this combined function.

Charging is one of the biggest technology hurdles of EV disruptive technology that is rapidly being solved with innovation and becoming a business opportunity. Increased demand for EVs drives the development of smaller, lighter, more efficient batteries with longer lifetimes and faster charging. Over the next 35 years, charging stations will replace gas stations and there are a number of cities that have already begun making inroads into establishing charging station networks. The biggest rollout of smart charging infrastructure is taking place in Vienna, Austria, with the installation of over 400 interoperable stations by the end of 2015.[50] In the U.S., West Coast cities tend to be the friendliest for EV drivers, particularly Los Angeles and the San

Francisco Bay area, but Austin, Detroit, Atlanta and Denver have also moved onto the list of top 10 metropolitan areas identified as EV friendly.[51]

In addition to automobiles, electric buses, utility trucks and delivery vehicles will become commonplace. For buses, range is a huge issue, but this is quickly becoming resolved. For examples, the Proterra Catalyst XR bus[52] has a demonstrated range of 250 miles and an average energy consumption of 0.8 kWh/mi (approximately 42 mpge versus less than 10 mpg for diesel buses).[53] A particularly promising innovation for electric buses is induction charging that allows wireless recharging at strategic locations along a bus route or throughout a city. The Online Electric Vehicle platform was developed by the Korea Advanced Institute of Science and Technology and relies on magnetic charge plates beneath roadways and a counterpart inside the bus. When an induction-capable bus passes over the charging plate, the two magnets become "tuned," and current flows to charge the on-board battery.[54] Installing the plates in streets is much more efficient than tethering buses to electric cables.

The net result of these expanded mobility options in the sustainable cities of the future is to reduce, or ideally eliminate, traffic congestion. In addition, strategies such as congestion and demand pricing, and crowdsourced ride sharing will be implemented. In contrast to the BAU practices, the ST scenario does not seek to achieve traffic reduction by making driving easier, which typically fails. Rather investments are made that encourage and reward behaviors other than driving POVs.

As shown with red labels in Figure 16, a sustainable city will harvest energy from a variety of distributed, renewable sources. The materials and surfaces of the sustainable city create an urban fabric that reduces energy demand, produce a diverse energy supply and are reactive or self-cleaning. For instance, buildings are constructed from lighter and stronger materials that have high insulating properties to achieve enhanced energy efficiency and reduced energy requirements. Buildings, walkways and roadways are made of high albedo materials that can react with sunlight to be self-cleaning to maintain their whiteness and combat urban heat island effects. Day-lighting is optimized and highest efficiency lighting is provided. Under the ST scenario, urban designers tap every opportunity to produce energy from wind, sun, or geothermal source and to recover it from waste streams. Compelling quantitative estimates have demonstrated that it is technologically feasible to meet worldwide energy demand for electricity, transportation, building heating and cooling, and industrial production from renewable sources (wind, water, sunlight) by 2030 and the ST Scenario incorporates this thinking into urban design.[55] It is important to note that the conversion to renewable energy infrastructure reduces demand by approximately 30 percent due to efficiency gains associated with electricity compared to internal combustion, thereby further supporting the overall feasibility of replacing fossil fuel with renewable energy.

Buildings and homes are oriented to take advantage of passive heating and cooling due to seasonal sun and wind patterns. Passive ventilation is employed as well as heat recovery. Solar energy is used to produce both electricity and meet thermal needs in buildings (e.g., hot water and steam). Buildings are designed to be net zero energy and to feed excess energy to smart grids. Wind energy is harvested in the hinterlands of the city but is also deployed more widely in urban areas due to new technologies such as bladeless wind turbines that are designed to store energy harvested from wind vibrations.[56] Without moving parts, these types of wind turbines are half the capital and operating costs of traditional wind turbines and although individually they capture 30 percent less energy, they can be more densely packed spatially or deployed in a greater variety of locations. Geothermal resources are tapped to meet heating and cooling needs and can be integrated with waste heat recovery in combined heat and power district systems that use heat engines or power stations to generate electricity and useful heat at the same time.

In the ST scenario, urban energy systems are integrally coupled to transportation, land use and water systems.

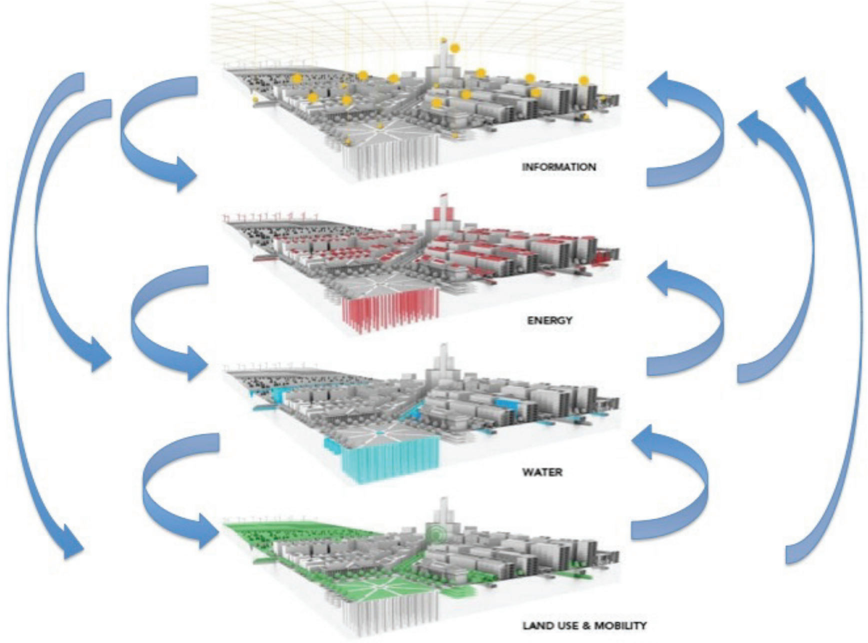


Figure 18: Interconnections between urban cycles of land use and mobility, water, energy and information.

For example, using bidirectional charging systems EV batteries can be incorporated into energy grids for storage (V2G), thereby regulating the frequencies on the grid to smooth the power load and lower usage during periods of peak demand.[57] The U.S. Department of Defense has invested around $20 million to install 500 V2G-enabled vehicles at bases around the United States. Such systems already exist in Japan and when there are power outages, the Nissan's Leaf to Home system can provide the average Japanese home with two days of electricity. The urban chassis in Figure 16 and Figure 18 illustrate the coupling of energy-water-land use in the form of a Geothermal Park (lower left-hand corner). The geothermal field is located in functional green space that may disrupt automobile traffic but facilitates walking and biking and is also tied into stormwater management systems by receiving rain runoff to maintain soil moisture optimized for the performance of geothermal heat pump systems.[58] In addition, cisterns are also installed below ground for rainwater harvesting and storage.

The water cycle of the 2050 ST Scenario has important direct and indirect impacts on future transportation infrastructure. With reference to Figure 16, absorbent and permeable materials and surfaces are utilized in order to integrate stormwater management with ecosystems using passive energy and reaping cascading benefits. To the greatest extent possible, pervious pavers are used to allow underlying soil to soak up rainwater. Green roofs are coupled to solar energy systems to absorb and filter precipitation and to dampen extreme rooftop temperatures to benefit not only the heating and cooling of buildings, but also the performance of solar photovoltaic cells.[59] Stormwater dissipation, contaminant uptake, and insulation are also provided by biowalls. The central boulevard of the district is an eco-boulevard that employs an urban stream/marsh system that receives and polishes both stormwater drainage and treated wastewater effluent discharge, replacing traditional infrastructure of pump and pipe networks. This aquatic system, which enhances low quality flows through ecological and biogeochemical processing, is a premium feature of the district along which higher rents can be charged. Finally, the eco-boulevard is another example of the tradeoff between diminished space allocated to automobile travel and ecologically based systems tied into water, waste, land use and energy cycles. Drinking water treatment is achieved with distributed membrane based treatment systems that have compact footprints and only treat water that is to be ingested to high quality. Lower quality water needs are met with onsite grey water and stored rainwater recovery systems. Decentralized wastewater treatment is coupled to energy recovery with microbial fuel cells that generate electric current through the degradation of organic material. Nutrients are recovered directly as fertilizer, especially phosphorus, used in urban farming operations such as hydroponic systems, or polished by the eco-boulevard wetland system.

Over the next 35 years, a growing threat facing urban areas, especially in coastal areas, is flooding associated with extreme storms and rising sea levels. Cities and regions are now facing difficult decisions about whether to harden the urban environment with flood gates, walls, levees, pump and pipes or to soften the urban environment with bioswales, wetlands, riparian zones, rain gardens and lagoon systems. Both types of systems can be designed to meet historic conditions effectively, but the differences between the two approaches emerge when considering the future uncertainties associated with climate change. The more costly hardening strategy whisks stormwater away quickly to remote areas and is the standard of practice in most cities. Basically, stormwater is managed as a waste material. The ecologically based system is far less costly, is more adaptive and resilient (self-repairing) in the face of uncertainty, has more cascading benefits, but also requires much more dedicated space. In addition, there is less experience with the design and use of green infrastructure on a large, urban scale. In the face of a rapidly changing climate and in response to the growing popularity of passive energy systems, more and more regions are adopting green infrastructure to deal with storm and flooding vulnerability.

As stated earlier, urban dynamics are best conceptualized as complex systems of flows and network and in this context, cities behave much more like living organisms than machines. Furthermore, since urban functions are analogous to metabolic processes, in an ideal sense the energy, material and economic flows of cities could be controlled and coordinated by a “central nervous” or information system.[2] The ICT systems that make up present day smart cities fall far short of the level of coordination and connection required by the interactions shown in Figure 17. Although the terms are often used interchangeably, there are key differences between the 2015 smart city and the 2050 sustainable city. As discussed under the BAU scenario, the present day corporate rhetoric around smart cities is focused on efficiency, optimization, predictability, convenience and security but typically in the context of a single application or to the benefit of the individual. Although present day smart cities are not necessarily on the ST scenario trajectory, conversely, the sustainable city of the future must be a smart city in which ICT senses the conditions of system use, monitors infrastructure performance, manages coupled infrastructure cycles, and nudges human behavior. The data collected by the information system shown in Figure 16 do not only serve to enhance the convenience of smart phone owners, the information orchestrates the interconnections that underpin the workings of the various infrastructure cycles shown in Figure 17. For instance, when a rainstorm occurs, the duration and intensity of precipitation are monitored and a calibrated volume of rainfall is stored in green roofs, rain gardens and cisterns of buildings. Flows above that volume are metered and routed along bioswales to larger public storage (public cisterns) and to geothermal fields to achieve a maximum soil moisture level that is also monitored. Volumes beyond that flow into eco-boulevards and wetlands designed to accommodate variable hydrology.

The level of integration and coordination described by the ST Scenario requires a degree of planning not typically practiced in urban development in the U.S. There are over 42,000 municipalities in the U.S. and very few engage in comprehensive metropolitan planning. Urban planners and engineers know how to design and build many of the elements of sustainable cities. There is a rich and well-established literature detailing urban sustainability strategies, many of which are ecologically based.[60] In fact, sustainable urban developments are found all over the world, in Curitiba, Brazil, in BedZed, England, in Copenhagen, Denmark, in Freiburg, Germany, in Singapore, in Portland and many have operated for decades. Yet, there is continued skepticism about the feasibility of urban sustainability and these strategies have been slow to scale up. Furthermore, there are very few urban districts that fully integrate all the sustainable features possible and as in the case of Curitiba, the icon of urban sustainability, population growth and the desirability of living in this city threaten to derail many of its core sustainable design features.

There are persistent questions about the compatibility of sustainability with the economic forces that govern cities. A complete view of sustainability must include economic imperatives for profit and growth to be competitive in the spatial hierarchy of complex global production processes. It is at this level that the most vexing questions of urban sustainability arise. While considerable success has been achieved in making individual buildings, developments or neighborhoods more sustainable, a city must also maintain sustainable connections regionally, nationally and globally. Sustainable urban design is an effective and strategic tool for economic growth, and as such, is evolving to meet the demands of moving people, materials and goods into and out of urban regions efficiently. The ST Scenario, however, requires long-term and deep investments and policies in order to accomplish the integrated redesign of urban infrastructure**.**

Charting a course between the reality of today's cities and the vision of tomorrow

Changes to settlement patterns and urban infrastructure systems happen slowly at the landscape scale, regardless of the scenario. Ironically, under the BAU scenario the biggest changes are occurring at the smallest scale with the revolutions in information and communication technology and nanotechnology. The BAU Scenario is primarily market driven and is the favored path in a milieu of reduced federal, state, and municipal funding for public works. In the U.S., the BAU path focuses on individual benefit and convenience. Planning tends to be ad hoc and cities are zoned for separation. Dominance of fossil fuels and combustion-based technologies continues, suggesting that governmental subsidies for fossil fuels will also remain in place.[61, 62]

In many ways, the ST Scenario will also unfold along a market-driven path but one that is directed by other forces such as comprehensive urban planning, integrated zoning and facility co-location and governmental mandates. The ST Scenario is propelled primarily by the economic, social and physical imperatives of climate change and other environmental factors. Governmental incentives and regulations are established to which the market then responds. The best example of this would be setting up cap and trade systems or taxing carbon emissions that would then provide economic incentives to adopt technologies and practices that release less GHGs. "Natural" market forces alone will not induce the degree of change that the ST Scenario requires.

There are many factors that are common to the BAU and ST Scenarios. At the most fundamental level, both scenarios involve the basic activities of human inhabitants. There are numerous common technologies and systems such as smart technologies, wind turbines, solar panels, electric vehicles, e-commerce, the sharing economy, etc. The two scenarios diverge relative to the details of human interactions with these technologies and the infrastructural fabric into which the technologies are integrated. In addition, under the ST Scenario, there is a greater reliance on nature and renewable energy that will perform with greater overall savings to society but will reconfigure urban space and necessarily subtract from areas dedicated to the automobile.

One of the major differences between the two scenarios is the rate of change. Efficiency gains alone will lead to further electrification of society which means at some point the disruptive technology of electric vehicles will take hold, but it is likely to take place more rapidly and smoothly under the ST Scenario. The same is true with renewable energy. In fact, the intermittency of renewable energy can be mitigated by EV storage and thus, the interdependence of and synergy between the two technologies illustrate the value of system integration.

Another major point of divergence between the two scenarios is that BAU infrastructure is centralized and standardized, achieving benefits from economies of scale. In stark contrast, ST infrastructure is distributed and locally tailored to geography and ecology, as well as to culture and history. Savings, and consequently economic viability, are achieved through co-location, interdependence and passive advantages provided by natural processes or savvy engineering. Hence, there is no single blueprint that maps out the transition to an adaptive and resilient future North American city. Rather, there are principles, explained herein, that point the direction.

The cost of renewable energy is falling rapidly with solar panel prices down 60 percent since 2011. Since 1980, the cost of wind energy has declined 80 percent with a 20 percent decrease alone from 2010-2012. Although upfront costs may be higher than conventional energy infrastructure, operational fuel costs are much lower or essentially free. In fact, EV off-peak charging and feed-in during demand peaks may lower overall electricity prices. In addition, renewable fuel costs are stable and predictable in contrast to fossil fuel costs which historically have shown wild fluctuations and require costly financial instruments to hedge future uncertainties. Renewable energy systems are distributed and modular and thus, are more flexible and reliable, especially in the face of climate change uncertainty.

An excellent example of how the likely path forward to 2050 is somewhere in the middle of the BAU and ST Scenarios is illustrated in the design of solar suburbs. A growing trend in single-family home developments is the incorporation of rooftop solar panels in conjunction with highly energy efficient homes, electric vehicles, smart two-way electric systems and home batteries for storage. Such suburban developments are being planned and constructed in Palm Springs, California, in Boulder and Denver, Colorado, and in Vermont. Suburban homes can generate excess electricity and send the surplus to the city in EV batteries. In Australia, 20 percent of the homes have photovoltaic panels and in the new suburb of Denman Prospect in Canberra, residences are required to meet half their energy demand with solar energy by installing a 3 kW system capable of generating annually over 4000 kWh.[63] In Germany, 7 percent of the electricity comes from solar. In the U.S., solar is becoming standard for about 60 percent of the largest home builders and is incentivized by federal investment tax credits up to 30 percent but this subsidy may drop to only 10 percent after 2017. A new business model to lease solar panels to homeowners is quickly becoming a game changer. Austin, Texas, was the first city in the U.S. to establish a comprehensive voluntary energy efficiency program in 1970, which then became mandatory in 2003. More recently, the city has established a “Zero Energy Capable Homes” program by 2015 and has set ambitious targets for both utility-scale solar (600 MW by

2017) and rooftop solar (200 MW by 2020), making Texas one of the leading solar markets in the U.S.

Sustainable urban development has been slow to gain traction in the U.S. in comparison to other parts of the world, but it is beginning to show progress in diverse projects and cities from Atlanta, to Washington, D.C., and from Boston and to Detroit.[64] Portland is the U.S. city best known for integrating sustainable practices into its long term planning and operation and is recognized for its Urban Growth Boundary and for policies promoting bicycling. San Francisco and Seattle are also adopting urban policies supportive of sustainable infrastructure. In fact, many cities are developing the knowledge capital to incorporate green infrastructure and tailor renewable energy portfolio standards to local resources. Those cities that embrace urban sustainability goals and objectives tend to show healthier economies, are more attractive to an educated and talented workforce and are considered to be more desirable and livable. Urban infrastructure in the U.S. is in urgent need of attention and any significant change to the present day systems, whether it is under the BAU or ST scenarios, will require concerted efforts and long-time horizons.

Sustainable Transformation of cities and their transportation infrastructure is a mammoth endeavor that will necessitate long-term planning and funding investments for mass transit, roadways, bridges, rail stations, etc. Integrated designs must be developed that support multiple modes, including non-motorized transit, coupled to other urban infrastructure systems such as energy and water. The most critical challenge of the ST scenario is finding ways to initiate and sustain a path of change. That path will include effective use of maintenance and rehabilitation projects that advance the transition to sustainable cities. The Sustainable Transformation of transportation infrastructure will not only repair the current state of dysfunction, it also promises to reinvent more efficient, adaptive and resilient cities that support successful economies and promote a high standard of living.

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CHAPTER TEN

Paving the Way for Future Transportation Infrastructure

By Joseph L. Schofer

Introduction

Delivering, operating, and maintaining transportation infrastructure requires sufficient and effectively used resources -- primarily money. Funds must be sufficient to prevent undesirable and unsafe deterioration of key facilities. They must be available in predictable amounts and at reliable intervals to permit thoughtful planning, selection, and staging of investments to prevent surprise failures and minimize temporary but costly service interruptions. Investment decisions should be driven by strategy and data to assure impactful and cost-effective actions, supported by an open accounting system that tracks the benefits and costs of transportation infrastructure investments to inform and improve future decisions.

When these requisites are not met, transportation infrastructure and the services it provides can fall behind the needs, manifested by increasing costs, unexpected failures, and declining economic vigor. This chapter examines patterns and trends in transportation infrastructure funding and investments and defines a future path to assure that transportation will continue to be an engine for success.

Is enough being spent on transportation infrastructure?

There is evidence that the U.S. is not spending enough on transportation (and other public) infrastructure to keep up with the need and not always investing effectively. There has been a continuing degradation of many elements of transportation infrastructure, as noted in Chapters 2 and 8 in this report. While the fraction of highway bridges posted with weight limitations has decreased, and the number of bridges classified as functionally obsolete or structurally deficient has been gradually declining, a number of recent and important failures have forced long detours and large delays, serving as reminders of the underlying vulnerability of that infrastructure. Congestion is growing on urban highways, at intermodal terminals, at ports of entry and on the inland waterways system.

Congestion and service disruptions undermine what is still the most efficient national freight system in the world, increasing the costs and risks of doing business. Small changes in the cost and capacity of the multimodal freight system that moves corn, grains, and soybeans from the fields of Iowa to the ports of China can significantly influence the competition between the U.S. and Brazil for prime agricultural markets.

The trend of increasingly frequent and severe weather events that challenge transportation infrastructure, including hurricanes, floods, rising sea levels, landslides, forest fires, tornadoes, and earthquakes, demands that increasing efforts be directed to assure transportation network resilience. Natural disturbances and disruptions due to component failure (bridge failures or multi-vehicle accidents and hazmat spills) can block a key artery for an extended period of time. The need for increased resilience is sometimes met by redundant networks that offer alternative paths to avoid a disrupted link. Backup capacity requires resources that may be called into service only infrequently but when they are needed, their value increases quickly. In some settings, there is little or no network redundancy. For example, the July 2015 failure of a bridge on eastbound Interstate 10 in the California desert forced detours as long as 250 miles because the surrounding road network is so sparse. This argues for investing proactively in protection for essential links and services. And when transportation infrastructure is underfunded, not only are service disruptions more likely to occur but their impacts will be amplified and their durations extended.

The consequences of inadequate and underperforming transportation infrastructure are both episodic and continuous. The episodic component is represented by unplanned (weather- and accident-related) and planned (maintenance-related) network disruptions. These forced delays, long detours, missed connections, and supply chain interruptions, all manifested in wasted time and money, spoiled cargoes, and sometimes the opportunity cost of lost business. The continuous component is more insidious in the form of subtle but important ongoing increases in costs because of long travel times, inefficient intermodal connections and poor reliability. These costs are a drag on individuals, businesses and the entire economy. They reduce U.S. competitiveness in the global market for certain products and commodities. Logistical inefficiencies and uncertainties influence decisions by businesses about where to locate sources, manufacturing facilities and distribution centers. Places where transportation is particularly efficient are low points on the logistics cost curve, and therefore advantaged in the competition for economic development.

The U.S. can productively spend more, and spend smarter, to maintain and expand transportation infrastructure. Network managers can make more efficient use of existing infrastructure through the use of technology and smart operating strategies. The alternative is a deteriorating and insufficient transportation infrastructure that reduces service quality and increases logistics and travel costs.

Public funding sources for transportation infrastructure

Most Americans would be surprised to learn that the much of the money for transportation infrastructure investments and operations comes from system user fees. For the highway network, most of these are in the form of motor fuel taxes (MFT), fees paid for the use of roads as measured by the consumption of gasoline and diesel fuel. Using the word “taxes” makes highway user fees a target for the “no new taxes” argument, but in fact these are fees paid in proportion to use of the road network, much like tolls.

At the federal level (and in most states) these fees go into a highway trust fund (HTF) which must be used to support the road network. At the federal level, 16 percent of highway trust fund monies are allocated to transit capital investments based on the logic that they help reduce road congestion.

The federal gasoline fee is 18.3 cents per gallon, and diesel fuel is charged at 24.3 cents per gallon. Neither has increased since 1993, while construction costs have doubled and mandated Corporate Average Fuel Economy (CAFÉ) standards have improved from 27.5 to 34.2 miles per gallon (mpg) for passenger cars. In fact, the average new passenger car performance has advanced from 28.4 to 36.0 mpg over the past 20 years.[1] Figure 1 illustrates the annual motor fuel taxes paid (federal plus Illinois, for example, at 19.1 cents per gallon) based on average vehicle fuel economy. Thus, a driver in a vehicle that delivers 30 mpg pays about 1.25 cents per mile or $150 for driving 12,000 in a typical year.

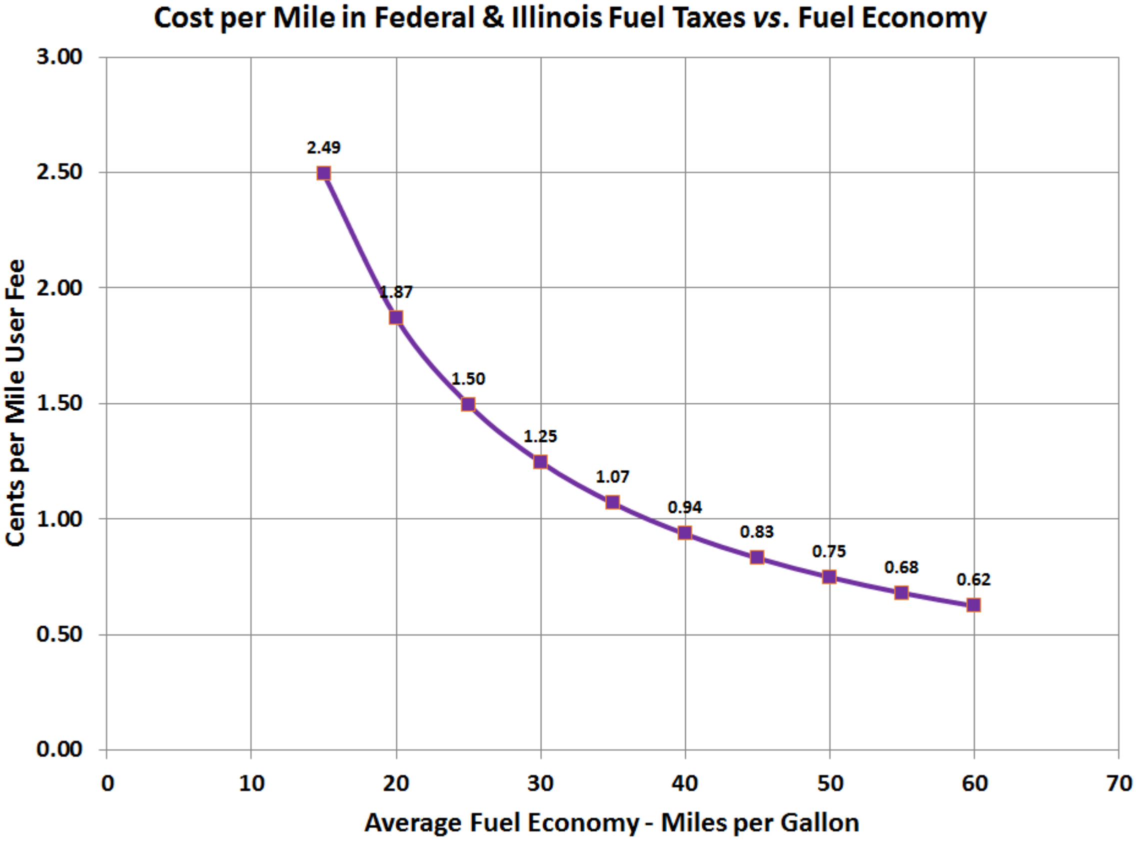

Figure 1: Motor Fuel Tax per Mile (Federal + Illinois) vs. Fuel Economy

Because of the structure of highway user fees, achieving energy efficiency and reducing greenhouse gas emissions by improving fuel economy leads to reduced revenue for highway infrastructure, but it does not reduce the need for transportation infrastructure.

During the recession of 2007-2009, there was a sharp drop in both total and per capita vehicle miles traveled (VMT) (Figure 2). The per capita VMT continued to fall as the recovery developed, a pattern that has been attributed to a declining preference for traveling by automobile on the part of millennials.[2] If this pattern were to hold as the 15- to 35-year-old cohort ages, it would signal a sea change in the way people will travel in the future, and it would accelerate the decline in motor fuel revenues. More recently, however, there has been a substantial rebound in total VMT and VMT per capita, probably attributable to a sharp drop in oil prices, as well as to the economic recovery taking hold. The rapid growth of online retailing may also be a factor, putting more package delivery miles on the roads. This recent upturn suggests that the demise of the automobile era may not yet be on the horizon. But that does not assure that a fuel-based infrastructure fee is a reliable, long-term source of infrastructure funding.

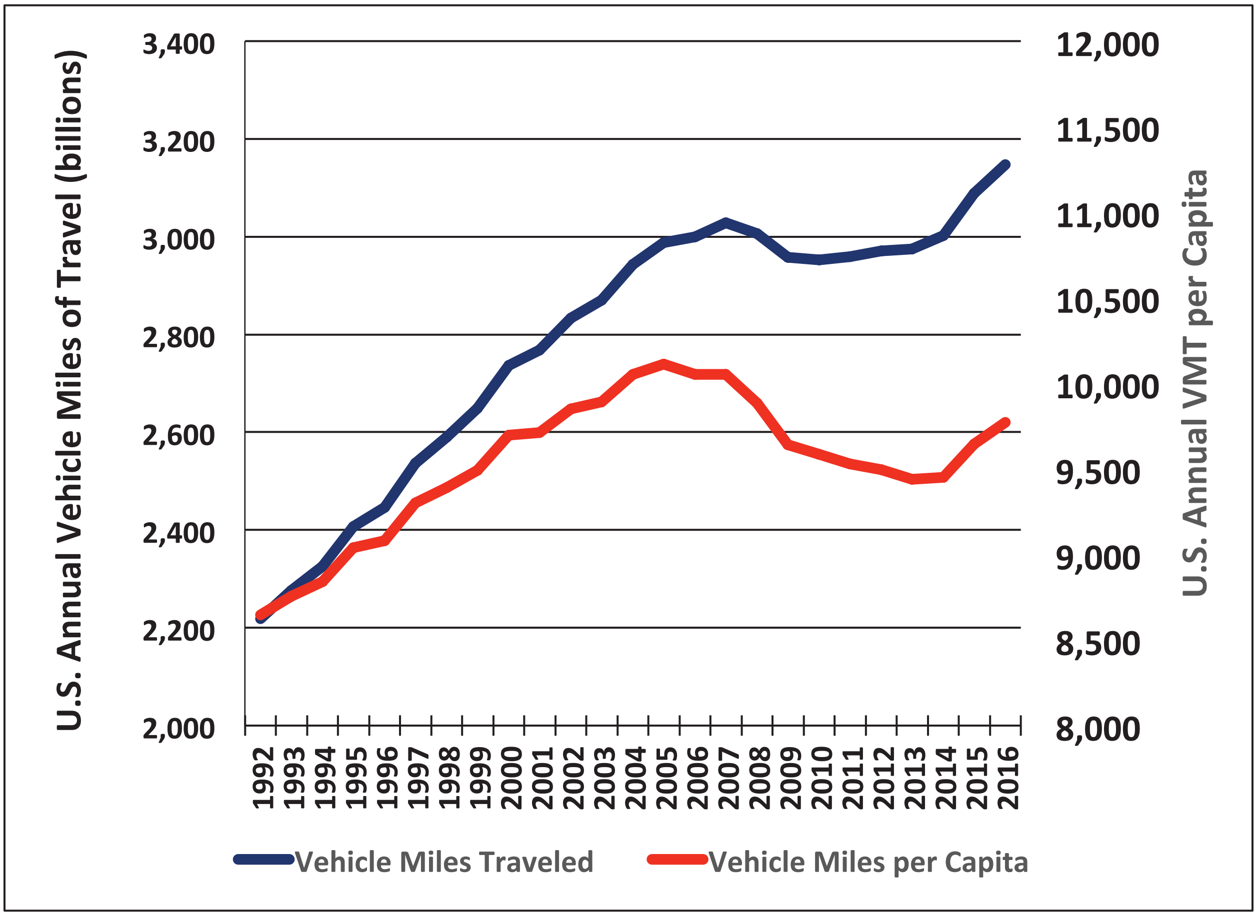

Figure 2: Total and per Capita Vehicle Miles of Travel 1992-2015

This is reinforced by Figure 3, which reports the trend in retail gasoline sales in the United States since 1992. As in the case of Figure 2, a variety of factors are at work here, but the fairly consistent decline in sales since 2007, likely due primarily to mandated and market driven advances in vehicle fuel efficiency, is a serious threat to the viability of the MFT as a source of support for highway infrastructure. The mandated fuel economy improvements will continue, and advances in electric vehicles may well accelerate the trend toward lower consumption of petroleum-based fuels.

Congress has elected to continue spending from the HTF at a rate that exceeds revenues from fuel-based user fees, and it remains unwilling to increase rates or to change the structure of those fees. This has brought the federal HTF close to bankruptcy. To avoid reducing spending, the Congress has repeatedly supplemented the trust fund with direct appropriations from general revenues: Between 2008 and 2014, $54.5 billion has been transferred to the HTF.

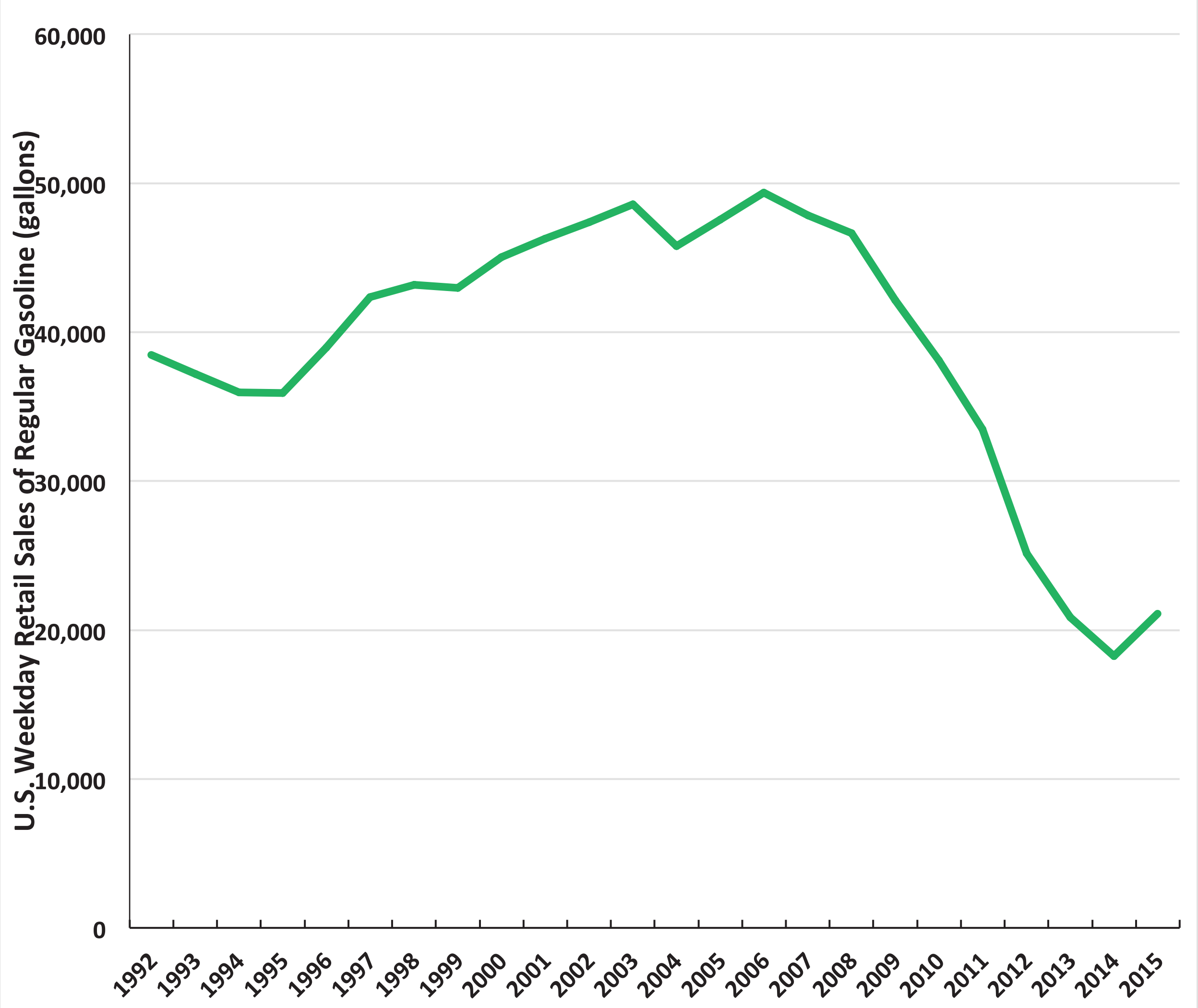

Figure 3: Average U.S. Weekday Retail Sales of Regular Grade Gasoline 1992-2015[3]

In December 2015, Congress passed a new surface transportation authorization act, the Fixing America's Surface Transportation, or FAST Act. This authorizes five years of spending on the surface network, amounting to $286 billion, funded only for the first three years with no MFT increase. Instead, funds have been cobbled together from multiple sources, including shifting the use of some Federal Reserve funds, collecting delinquent taxes more aggressively and selling off some of the strategic petroleum reserves at a time when oil prices are at record lows.

Relying on appropriations from general revenues and using short-term resources to support the highway program together introduce a major element of uncertainty into transportation funding because the appropriations must come through the Congressional process, and in the case of FAST, new resources will have to be found in the near future. This is not the sustainable funding that transportation infrastructure requires to ensure economic productivity, and it separates the flow of funds from users and uses of the road network, drifting away from the user-pays concept.

State and local agencies spend more on highways than the federal government. States have similar funding sources – user fees applied to motor fuels and certain vehicle parts – as well as licensing fees, and, increasingly, tolls. While many states have not changed their user fee rates for decades, more than 30 have changed rates or rate structures in the past decade to meet the needs of their highway networks (e.g., linking fees to the consumer price index or shifting to a percentage fee on fuel prices – not a solution when fuel prices drop precipitously).

Other transportation modes with substantial public sector involvement are also supported by some form of user fees. Airports and airways services are funded by fees levied on passenger tickets and air cargo tariffs that flow into a separate trust fund. Passenger fees are currently 7.5 percent on fares plus a $4 fee per flight segment; air cargo fees are 6.5 percent applied to tariffs. In addition, airlines pay a fuel tax of $0.043 per gallon or about $40-$50/hour for a Boeing 737-900. Airports, mainly owned by states or local governments, can (and do) charge their own passenger facility fees, capped at $4.50 per flight segment. These funds are used for local airport improvements including airside and landside investments. Rates for user fees flowing into the airport and airways trust fund have been adjusted only about as frequently as highway user fees but the commercial aviation fuel tax was added more recently.

Half of the costs for construction and rehabilitation of inland waterways are supported by federal fuel fees at the rate of 29 cents per gallon for commercial users. The remainder of the funds come from Congressional appropriations to the U.S. Army Corps of Engineers, the agency responsible for inland waterways. As in the case of highways, the dependence on Congressional action introduces an element of uncertainty into investment decisions.

Private sector infrastructure funding

The private sector has a massive stake in transportation infrastructure in North America. Railroads, for example, determine their own infrastructure needs and investments and their services are critical to the national interest in moving freight that supports manufacturing and distribution of all kinds of commodities and products. Railroads move about 20 percent of the freight shipments by value, and as much as 34 percent of the ton-miles. Along with privately-owned pipelines, they are the key modes for moving energy materials, and they play a large role in moving retail goods and food products through intermodal (truck-rail) services. Railroads and pipelines own extensive infrastructure offered for public use in their roles as common carriers; railroads, trucking firms, airlines, and inland barge operators also have massive investments in vehicles and equipment that are at the core of freight movement in North America.

Railroads and pipelines secure and maintain their own infrastructure, with regulatory oversight to protect public interests from safety and environmental hazards. Private investment follows markets and money. Railroads did not reinvest much in infrastructure during the pre-Staggers (deregulation) Act period (prior to 1980), when government regulation controlled routes, markets, and prices. In the three-plus decades since the U.S. rail industry was deregulated, railroads invested nearly $600 billion in infrastructure and equipment, with $29 billion expected in 2015 for about 100,000 miles of track.[4] During the same period, railroads abandoned more than 80,000 miles of unused or low use tracks to shed costs and risk.

There are important public interests in the rail freight industry, primarily in safety regulation and assurance, the responsibility of the Federal Railroad Administration (FRA) but also in assuring the availability of services that are essential to the economy (the Surface Transportation Board, STB). Government has a role in railroad finance, mostly through loans and loan guarantees under the Transportation Infrastructure Finance and Innovation Act (TIFIA), and grants under the stimulus-driven Transportation Investment Generating Economic Recovery (TIGER) program. State governments sometimes co-invest in rail projects to support economic development projects. Both federal and state governments subsidize Amtrak intercity passenger services, and as a part of the American Recovery and Reinvestment Act of 2009 (ARRA), the federal government offered some state grants for high speed passenger rail services in amounts too small to advance high speed rail in America. Compared with private railroad investments, all of these programs are modest in scale.

Logically, railroads are (or should be) spending enough to secure the infrastructure they need. If rail accidents are used as a simple indicator of rail infrastructure condition, the derailment rate has been flat to slowly increasing. On the other hand, the number of spills, fires, and explosions involving derailments of trains carrying North American crude oil and other hazardous materials rose rapidly as traffic grew, attributable primarily to greater exposure. The volume of such commodities carried by railroads from 2010 through 2014 grew by over 1,700 percent, (AAR). However, such events also indicate infrastructure inadequacies due to increased use of old infrastructure and destructive effects of heavily loaded trains. Flows of crude oil have dropped as a result of excess supply and low prices, but the long term infrastructure issues remain and are likely to return to the policy agenda in the future.

Pipelines have grown in length and capacity in the past decade, driven by the demand to move energy products and constrained by environmental and public policy issues. Safety and service regulations have imposed some limitations aimed at assuring that carriers address public policy concerns.

Investment in privately-owned transportation infrastructure suggests that it is possible to ensure the condition and performance of transportation infrastructure when the incentives are clear and well-directed, and when costs and benefits (revenues) are internalized and monetized. Private decision makers usually can see and respond to market opportunities, which drive revenues and motivate investments in operations and infrastructure. The connections between expenditures and returns are close and quantitative. The same factors can and should drive public investments, but for government, the returns do not appear in the financial accounts but come in the form of user benefits, signaled by utilization of facilities and services and transportation cost reductions. The value of these reductions is distributed throughout the economy and society; evaluating such benefits requires data collection and analyses, not simply counting cash flows, a more difficult process that is feasible and essential not only to ensure that good investments are made, but also to help make the case for sufficient infrastructure funds.

The risks of selecting poor projects

How the U.S. spends money to protect and improve transportation infrastructure is important. Piecemeal and politically driven transportation investments tend to waste scarce resources, sometimes buying projects for which the benefits are not commensurate with their cost, and failing to deliver a meaningful value proposition. Money is sometimes wasted on projects that do not solve problems, represent partial solutions dependent on other actions unlikely to be taken, or expensive actions that achieve what a cheaper project could do just as well. In the extreme, this is the "bridge to nowhere," but more commonly, the consequences of poor choices are more subtle: rail transit built where bus rapid transit would deliver similar benefits at lower cost; the Chicago CREATE rail congestion relief project which depends on a multi-element program which has been only partially funded; major efforts to build freeway projects that are not fundable from the start and promise economic development outcomes that are highly uncertain; or duplicative investments in Gulf and East Coast ports to attract larger ships passing through the expanded Panama Canal.

The danger of investing in projects that do not work, or do not work well, goes beyond wasting scarce resources; such actions undermine support for new funding for transportation infrastructure, and ultimately feed public mistrust of the political decision process. The absence of that trust makes it difficult to advance infrastructure funding actions in legislative bodies, and it may bring into leadership positions people who advocate no government action at all, effectively freezing the process that might otherwise work to ensure the future of infrastructure and economy.

Transportation must be managed as a network comprising links and nodes working together to support origin-to-destination movements. Piecemeal projects funded from unsustainable sources may satisfy short-term political objectives but they fail to ensure essential supply chain services at regional and national scales. Targeting one bottleneck may provide localized congestion relief but without planning and managing the entire network, the congestion only may be moved to the next bottleneck downstream.

The Transcontinental Railroad and the Interstate Highway System were built one link and node at a time but their development was driven by a vision of a large, connected network, from which the overall benefits of the investments were ultimately derived. To move transportation infrastructure forward, to assure that it supports the economy and society of the future, there is a need for a strategy to guide the evolution of the transportation system, sustained funding, and an objective basis for making investment decisions. That investment-reinvestment-decision process must be data-driven and self-adjusting through learning about what worked and what did not.

Some options to infrastructure (re)investment

Some needs for enhanced transportation infrastructure capacity and performance can be met by new technology, including system-wide operational control of networks on the ground and in the air and imbedded sensors to detect infrastructure deterioration problems before they become threatening. Real time traffic data combined with incentives for travelers and shippers to adjust their behavior to capacity, e.g., time-based pricing, can reduce delays without expanding the network.

Vehicle connectivity and automation offer real promise to increase both capacity and safety, and by or before 2050, this will relieve some of the pressure on fixed infrastructure (see Chapter 4).

Telecommuting and localized manufacturing can be expected to change the nature of travel and shipping, moderating peak period traffic, and reducing the frequency and length of shopping trips. While telecommuting has not yet delivered the expected travel reduction benefits, newer communication technologies and the increasing number of millennials in the workforce may make telecommuting more effective for congestion relief in the future (see Chapter 5).

With all of these changes, ample, high quality transportation infrastructure will be required to achieve the full potential of technological and behavioral changes. The responsibility of public and private system managers is to anticipate and respond to promising advances in technology so society may reap the benefits sooner and avoid the pitfalls of unsuccessful and dead-end concepts. Long term evolution of the transportation system and its infrastructure will always be a story of change, a path rather than a destination, and managing agencies must be agile, ready to adapt and move on to improved systems, processes and technologies.

Obstacles to sufficient infrastructure funding

There are several obstacles on the path to sufficient funding for transportation infrastructure, particularly if this means securing increased user fees. These must be addressed if infrastructure is to be restored and sustained. Some of these obstacles are discussed below.

Failure to understand how transportation infrastructure is funded:

Since the public and its leaders do not understand the role of user fees in supporting transportation infrastructure, or even that user fees exist for the road network, inland waters, and airports and airways, proposals to raise those fees are heard as efforts to charge for what is perceived to be free. MFTs are invisible because they are buried in the price of fuel.

The connection between motor fuel taxes, passenger facility charges and other user fees and infrastructure condition is also invisible. This makes it seem logical for people to resist fee increases while complaining about congestion or potholes. Toll road users previously understood the connection between tolls and infrastructure condition when tolls were paid in cash and at the point of purchase. That connection has eroded as a majority of toll road users pay with transponders on the fly, so the transaction is disconnected from the driving experience.

Hope that others will pay: PPPs and loans:

There is much talk of public-private partnerships (PPPs) as the ideal way to solve the infrastructure funding problem. Political leaders, advocates of less government, and even the press talk about PPPs as a way to get the private sector to pay for new infrastructure. PPPs are not new money but a finance and project delivery mechanism. Commonly in a PPP the private partner provides upfront money to build the infrastructure project, using its own or borrowed money. The private investor is financing, not funding, the project and that money must be repaid. It comes from user charges – tolls, or in the form of availability payments from government, with the funds coming from various sources, including user fees and fares, as well as general tax revenues. Projects often can be built sooner with PPPs than waiting for public funds to become available, and through thoughtful contracting arrangements, incentives to control project costs and timetables can help private partners deliver sooner and cheaper than a public agency,. However, PPPs are often the gateway to tolls in circumstances where elected officials want to avoid responsibility for charging (more) for infrastructure services. There is nothing wrong with using PPPs to finance new infrastructure, as long as the cost implications are made known and accepted by the stakeholders.

Of course, private investors are willing to take on only so much risk. They will rely on conservative, investment grade forecasts to assess the toll or fare revenue potential of a project, and thus to understand and bound their risk. This means that not every needed project is suitable for a PPP, e.g., low volume facilities in small markets won't pass the test. In the case of Denver's Eagle P3 project – East and Gold Line PPP – commuter rail project, the private partner was unwilling to accept the risks of relying on rider fares to cover costs and provide an acceptable return on its investment. Instead, the revenue risk was pushed to the public sector, which will collect all fares and use them to help pay the private partner a periodic availability payment to cover costs, capital repayment and profit. What did the Denver Regional Transportation District get for agreeing, in essence, to buy the service on an annual basis? It got the private partners to finance 36 percent of the $2 billion project, as well as to design, build and operate the system for 34 years at a defined price.

Borrowing is also a financing mechanism and thus a source of funds is needed to support it. Illinois and other states have "solved" the highway infrastructure funding problem by bonding. But bonds must be repaid, with interest, which might mean raising user fees through fuel taxes or tolls in the future.

Of course, a project that boosts economic development might actually lead to increases in local and state tax revenues, and those increases could be tapped to repay the loan, e.g., through tax increment financing (TIF). TIF can be a part of the financial plan but if the increase in tax revenues does not occur, government is still on the hook to repay the bonds.

Principled resistance to increased user fees:
Resistance to adjusting user fees to cover actual costs is sometimes ideologically-driven, perhaps amplified by lack of understanding, mistrust of government, and/or hope that money will come from somewhere else. However, recent surveys suggest that as many as three-quarters of the U.S. voting population would accept some kind of an increase in the MFT to pay for highway maintenance.[5] Yet, some elected representatives are more conservative than their constituents and choose to stand their ground for no new taxes. Surveys of the trucking industry have identified a strong and sometimes principled objection to tolls.[6]

Dodging doomsday

The public and its leaders should be skeptical of claims that "the sky is falling" and doomsday scenarios that predict that transportation infrastructure will soon disintegrate into dust. While system condition and performance will continue to deteriorate without a substantial influx of money well-spent, there is a natural equilibrium process that tends to keep the transportation system moving, although not at the highest levels of performance and certainly at higher cost.

The transportation system is highly adaptable because its users and operators behave to ensure their own survival and success. As discussed above, the absence of federal action to assure sufficient funding for transportation infrastructure has spurred some state and local governments to adapt and respond by raising user fees or finding other ways to adjust revenues to needs.

Most individuals and organizations are unwilling to stand idly by while failing transportation infrastructure becomes an increasing drag on their efficiency. Private actors – individuals, households, businesses – will adjust their operations and perhaps their locations to survive and thrive. The resilience of transportation users keeps the economy moving while covering up the costs of an underperforming infrastructure. The outcome may not be in the best national, strategic interest but the movement of people and goods will not stop for long and the transportation system as a whole will not fall apart. Invoking the doomsday scenario has not been effective at drawing support for increased infrastructure spending. Indeed, when doomsday does not occur, the impacts of such arguments evaporate.

A prescription for the future

What will it take to move away from the business as usual scenario to a future in which the connectivity, capacity, resilience, and performance of U.S. transportation infrastructure meet the needs of society and economy? Discussed below are some of the necessary actions.

Making the case for transportation infrastructure:

The current transportation infrastructure funding dilemma suggests that a case has not yet been made to the public and its leaders that an effective, efficient and resilient transportation infrastructure is essential for supporting and advancing the economy. There is a disconnect in understanding the link between infrastructure investment and daily transportation experiences – getting to work and the grocery store, finding the package ordered online yesterday at the doorstep today – and the broader effect that efficient transportation has on assuring national and global competitiveness, employment, and income. The value of a high performing transportation system sometimes becomes clearer in the face of disruptions, large and small, when there is a need to move people, emergency services, or resources smoothly and quickly. An inadequate transportation network can delay vital services, just as it can leave products headed for retail stores or factories stranded on the docks.

Many credible organizations (e.g., the American Society of Civil Engineers, the U.S. Chamber of Commerce, and the American Highway Users Alliance) have called for increased investment in transportation infrastructure. That this cause has not advanced beyond rhetoric at the national level and in many states suggests those messages have not worked.

The narrative needs to shift away from doomsday scenarios because such arguments have failed to be credible. While disasters are important, they are also rare; the public can be complacent about the condition of transportation infrastructure because, for the most part, it continues to work. It can be easier to secure public support with specific, local examples that show what insufficient capacity and infrastructure failures mean for the daily travel of individuals, the costs to manufacturing and retail businesses, and their effects on consumers and the quality of life in communities. There is a need to educate people about how publicly-owned transportation facilities and services are funded now, and how user fees (e.g., motor fuel taxes) affect the transportation system condition and performance they experience. The potholes that destroy a tire are filled using money from motor fuel taxes.

The educational process should include showcasing the benefits delivered by particular transportation infrastructure investments. Honest and objective post-project evaluations can show travel time savings, crash reductions and environmental improvements.[7] [8] The U.S. Department of Transportation Tiger Grant Program (Transportation Investment Generating Economic Recovery) requires both pre- and post-project evaluation, but this mandate applies only to a small fraction of transportation investments, and the quality of evaluations varies widely. The Government Accountability Office (GAO) does some before-after program evaluations, but the process is not systematically applied across major investments. The story of transportation investments must go beyond what is proposed and the ribbon-cutting ceremony: To earn the public trust, what really happened needs to be demonstrated so the benefits become visible and real. Routine use of post-project evaluation can help keep decision making honest by making the process more transparent and ensuring that promises are delivered upon. Where projects fall short, there is an opportunity to learn to deliver a better product next time.

Smart decision making:
Support for transportation infrastructure funding will come from making smarter investment choices that overcome the public mistrust of government. This calls for evaluation and decision-making processes that objectify choices and avoid promises made but not kept. This does not take the politics out of transportation investments: The political process is the way public resources are allocated, and objective data alone cannot capture the nuances of public need, equity and remedying past wrongs. But better results will be achieved by explicitly considering relationships between the benefits and costs of proposed actions.

Promises and results will come closer together by resolving the well-documented tendency to underestimate costs and overestimate the benefits of infrastructure projects.[9] These forecasting errors are not all accidental. Cost overruns are the norm, especially for large projects, but they need not be. Among the options are more careful a priori assessment of contextual factors, peer review panels, value engineering, transparent tracking of costs and performance, incentive contracting, and public private partnerships which shift the incentives for cost control to the private partner. The long-term costs of these errors are manifested in more distrust of public projects and lack of support for sufficient funding.

Moving to a sustainable funding source:
In the long term, because of changes in technologies and energy sources, a fee levied on motor fuels will not support transportation infrastructure. Different options must be explored, otherwise, the country could face the demise of what has become an unsustainable source of surface transportation funding. While general tax revenues have and will continue to be a source of support for transportation, particularly at the local level, there is strong logic and fairness in preserving the "user pays" philosophy. Together, these ideas point to increased use of tolls and eventually mileage-based fees in general. In the U.S., the mileage on toll roads increased 15

percent in the decade ending in 2013.[10] This does not confirm that toll roads are popular, it implies that in some cases they have become the only option, and they have gained acceptance.

The broad availability of toll payment transponders linked to credit cards has made tolling easier and less painful. There are currently more than two dozen different electronic tolling systems in the U.S. and Canada, clearly demonstrating the feasibility of this technology which can make mileage-based pricing and congestion tolling a reality.

Mileage-based road pricing may be not only a good way to pay for infrastructure but also a method for real-time network management. Experiments in Seattle [11] and Oregon[12] have shown that road pricing can be acceptable to travelers and can generate reasonable revenue streams collected with available technology while not being excessively intrusive. This will be a better way to go than trying to repair the MFT scheme.

Broader use of mileage-based transportation fees requires solving three problems: selling the public on the principle of paying for use of transportation infrastructure on a direct mileage basis; developing effective and credible ways to protect the privacy of users; and assuring equity of access for lower income users who may not have credit cards or bank accounts. Each of these obstacles can be addressed through experimentation and evaluation: Field tests like the Oregon road pricing pilot program, OReGO, can help pave the way. Privacy concerns should be addressed through a combination of technology and policy. Assuring access for low income travelers might be accomplished by distributing income-based prepaid travel vouchers, or by using credit-based schemes that provide all users with minimum monthly access to the road network.[13]

User fees in any form need to be linked to the cost of delivering transportation infrastructure and service. A fee-for-use structure will not be sustainable if there is no objective basis for adjusting fees for changing costs. Pricing adjustments schemes must be flexible to prepare for an uncertain future. The idea of converting per-gallon fuel taxes to a percentage fee made sense when oil prices were increasing. In 2016, with oil prices far below peak levels, the percentage indexing scheme does not look so promising.

A new social contract[14]

The path to sustainable transportation infrastructure calls for a new social contract with the user community, one in which it is clear to people and businesses what they are paying and what they are getting in return. Experience suggests that it can be easier to convince users to accept specific, sometimes higher, taxes or user fees if monies are dedicated to solving particular and generally accepted problems or building new, designated and desired facilities. This makes the connection between infrastructure fees and outcomes into a transaction that the public might better understand. California offers a number of examples of local option taxes where communities have voted to levy small sales tax increments, dedicating the proceeds to specific projects. Los Angeles County's Measure R, passed by voters in 2008, levied a one-half cent increase in the sales tax for 30 years to be spent on a specific list of highway and transit improvements. The Los Angeles County Metropolitan Transportation Authority (Metro) manages the program and maintains a website that reports on program plans and progress.[15] The specificity of the transaction between increased user fees and transportation projects in Measure R is mirrored in some of the recently successful arguments for increasing state motor fuel tax fees.

Explicit and ongoing reporting of progress and system performance trends will ensure accountability of the transaction, providing an information channel that makes use of transportation funds transparent and links user fees to products and performance.[16]

Putting it all together

Many factors and forces demand new actions to address transportation infrastructure condition and performance: aging and deteriorating physical facilities, changing social values, advancing technologies, economic competition, extreme weather events, scarce resources, energy and environmental concerns, and others. For the nation to compete and to succeed, its transportation infrastructure and the services it supports must again become best in class, the model for the world. The burden on the economy and society of not assuring a sufficient and high performing transportation system will far outweigh the cost of meeting the transportation needs of tomorrow.

Change is of the essence: The challenge is not simply to respond but to get ahead of these driving forces and seize the opportunity to define a sound and sustainable future for generations to come.

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[14] J. L. Schofer, “Moving the *Goods*: Performance Measures and the Value Proposition for Transportation Projects,” *Transportation Research Record 2460,* Data Systems and Asset Management Including 2014 Thomas B. Deen Distinguished Lecture, pp. 5-11, 2014.

[15] For example, see https://mtadash.mlmprojectservices.com/?portfolio=Measure+R+Rail+Projects

[16] The State of Washington Department of Transportation is a market leader in regular and comprehensive performance reporting; for example see http://wsdot.wa.gov/publications/fulltext/graynotebook/CCR15.pdf

CHAPTER ELEVEN

The road ahead

By Joseph L. Schofer

The preceding chapters make it clear that the future of transportation infrastructure is a future of change. Demands, threats, capabilities and costs will be different over the next 35 years. Demographic shifts will lead to an aging but more capable population. Values, particularly those of millennials, will change toward less interest in owning and a stronger focus on use of technologies and services. These changes are likely to emphasize experiences and outcomes rather than processes and mechanism. Sustainability may become a paramount goal.

Technological change will accelerate – information and computer technologies, automated vehicles, imbedded systems for more effective and pervasive monitoring and control of infrastructure systems will deliver more timely information about facility condition, support more efficient allocation and utilization of capacity, and provide the opportunity to act, protect, and prevent failures. Automation will change the cost and the experience of travel. Together, these changes will modify the demand for mobility, with a mix of reductions (through tele-work/-shop/-play) and increases (in product shipments and personal mobility) as costs and capability barriers are eroded.

Threats from natural and unnatural hazards can be expected to increase, demanding a new kind of resilience in transportation services, as well as increased reliance on ICT to work around temporary transportation disruptions.

Finally, resources and the competition for them will change in ways that are hard to predict: energy costs and availability will change. Currently, trends are favorable – prices are lower because availability is high. But types and sources of energy are shifting, and this alone is changing the demand for transportation of energy materials. The future can be expected to be different still, affected by national and global pressures on CO_2 emissions from fossil fuels, international competition and conflict, and technological innovation. There will be a premium on a skilled workforce, and global competition will broaden the market place and change – likely increase – the demand for the mobility of both people and freight.

The rate of change of almost everything can be expected to increase because of synergies between values, technologies, and competition. Not surprisingly, public policies will likely lag market-driven changes. The larger the lag, the less efficient will be the functioning of society and its economy. Stated differently, places where public policies move swiftly to coordinate with and support market changes will benefit more quickly and strongly from change and will do a better job of avoiding negative consequences. The future will be better to the extent that change is anticipated, positive change supported, and negative change defended.

But anticipation calls for prediction, and the future is hard to predict, especially in the face of multiple and rapid changes. The alternative, perhaps the only path to a successful future is through flexible and responsive decision making, which tracks changes, adjusts forecasts, and takes appropriate actions to ensure the condition and performance of transportation infrastructure and other core infrastructure systems.

There are at least three requisites for that kind of decision making:

1. Timely and accurate data and information to track changes, assess system condition and performance, and measure outcomes to provide a basis for informed actions. Navigating the future requires more than opinions and hunches. That means constructing and supporting data programs to track trends, detect problems and opportunities early, and provide a sound basis for making decisions.
2. Sustaining, sufficient and reliable resources to support necessary actions. This means the funds necessary to protect and adapt transportation infrastructure to meet changing needs and take advantage of new opportunities. It also means having the people with the skill sets necessary to use that information to decide, to act and to implement. A robust and reliable transportation infrastructure requires the people to build, operate and manage it.
3. The will and the ability to make decisions, to take the actions necessary to ensure the future of transportation infrastructure and services.

This calls for skilled leaders and managers, supported by data and information and supplied with sufficient resources to do the job. It also requires efficient institutional structures with the mandate to manage and develop transportation infrastructure networks to carry goods and people seamlessly from origin to destination. Effective strategic decision making to support transportation infrastructure demands a shared understanding of needs, threats and opportunities; agreement on the need for coordinated, collective actions; and a mandate to act.

Meeting all of these requisites is not a simple task. Money is critical, but it must be used, and used effectively, if transportation infrastructure is to meet the future head on.

The need for effective and resilient transportation systems and services must and will change in the coming decades. External forces, markets, and public and political pressures will cause some of that change. The challenge is to be proactive, to drive the changes systematically and positively, and thus to actualize scenarios that lead to a strong economy, an equitable society, and a sustainable balance of resources. This means assuring a future transportation system that is goes beyond the essential to be a force for advancing national goals.

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