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Mass Transit Infrastructure and Urban Health

Rae Zimmerman

ABSTRACT *Mass transit is a critical infrastructure of urban environments worldwide. The public uses it extensively, with roughly 9 billion mass transit trips occurring annually in the United States alone according to the U.S. Department of Transportation data. Its benefits per traveler include lower emissions of air pollutants and energy usage and high speeds and safety records relative to many other common modes of transportation that contribute to human health and safety. However, mass transit is vulnerable to intrusions that compromise its use and the realization of the important benefits it brings. These intrusions pertain to physical conditions, security, external environmental conditions, and equity. The state of the physical condition of transit facilities overall has been summarized in the low ratings the American Society of Civil Engineers gives to mass transit, and the large dollar estimates to maintain existing conditions as well as to bring on new improvements, which are, however, many times lower than investments estimated for roadways. Security has become a growing issue, and numerous incidents point to the potential for threats to security in the US. External environmental conditions, such as unexpected inundations of water and electric power outages also make transit vulnerable. Equity issues pose constraints on the use of transit by those who cannot access it. Transit has shown a remarkable ability to rebound after crises, most notably after the September 11, 2001 attacks on the World Trade Center, due to a combination of design and operational features of the system. These experiences provide important lessons that must be captured to provide proactive approaches to managing and reducing the consequences of external factors that impinge negatively on transit.*

KEYWORDS *Environment, Equity, Health and safety benefits, Security, Transit, Vulnerability.*

INTRODUCTION

Mass transit provides critical transportation services, in the form of speed, flexibility, and accessibility to meet a wide variety of user needs throughout the world. For over a century, these services have supported an urban way of life. To continue to accomplish its important social role, we have to address environmental issues and factors beyond mass transit's control. These factors potentially impinge on mass transit, making it vulnerable to reduced performance, limiting its ability to provide benefits for which it was designed. The benefits, discussed below, include environmental quality and energy conservation, speed, and safety, all of which contribute to human health and safety. The factors that impose vulnerabilities and obstacles

Dr. Zimmerman is Professor of the Planning and Public Administration and Director of the Institute for Civil Infrastructure Systems at the Wagner Graduate School of Public Service, New York University, New York, New York.

Correspondence: Rae Zimmerman, Robert F. Wagner Graduate School of Public Service, New York University, 295 Lafayette Street, New York, NY 10012. (E-mail: rae.zimmerman@nyu.edu)

for mass transit to achieving these benefits include physical condition, security, external environmental conditions, and equity. A more fundamental overarching problem, however, that affects the achievement of the benefits of transit is that though society may place a high value on transit, individuals may not. To tackle these issues, we defined first the mass transit concept, followed by a presentation of patterns and trends in transit usage, and an identification and evaluation of benefits and vulnerabilities.

Definition

The common elements that distinguish transit from other modes of travel are that its services are known, relatively stable or fixed, and available to the public. Mass transit has been defined as "urban transport services open to everybody, usually upon payment of a fixed charge, following a defined route, having specified stations or stops, and running according to a set schedule."[1] Mass transit is generally available to all members of the public, though accessibility can be limited by the inability of users to pay, the location of users relative to the services, and the inability to accommodate handicapped persons. Mass transit encompasses many types of services and modes of transport, and various terms are used to portray even a single type of transit, discussed in a comprehensive way elsewhere.[1] This article focuses on passenger rail transit, and henceforth, the term transit is used throughout to connote all forms of rail-based public transportation (i.e., subways and commuter rail) for passenger transport as well as the terms mass transit and mass transportation.

Trends in Transit Usage

Transit is necessary for many people. Ironically, transit arose in the United States at about the same time as the private automobile, yet it has struggled over the years to maintain ridership. Transit ridership increased through World War II when it peaked; then it steadily declined for several decades as auto travel became a more attractive means of reaching distant suburbs; and finally ridership increased again (though year-to-year trends are uneven) after the early 1970s.[2] In 2002, US transit ridership stood at 9 billion passenger trips.[3] Ridership is geographically concentrated within a few areas in the United States. About half of all trips occur in two states, New York and California, and New York City (NYC) accounts for almost a third of the ridership. Nevertheless, more areas are availing themselves of transit. The turning point in new system construction was the Bay Area Rapid Transit (BART) system that opened in 1972.[4] Other primarily heavy rail systems followed soon afterward, for example, the Washington DC Metro (1976), Metropolitan Atlanta Rapid Transit Authority in Atlanta (1979), Baltimore's Metro (1983), Miami's Metrorail (1984), Metro Los Angeles (1993), and many others including light rail systems.[5]

Rail transit use outside the United States in many cases exceeds US usage. In 2001, Japan had 385 billion passenger-kilometers, exceeding ridership in all other organization for Economic Co-operation and Development countries, and Japan accounts for about a third of the total passengers transported by all modes, followed by France (73.5 billion) and Germany (70.8 billion).[6] For urban areas, ridership in the NYC system was 1.631 billion passenger trips in 1999, exceeded, for example, in the mid–1990s by Tokyo (12.594 billion in 1995), Paris (1.953 billion in 1996), and London (1.810 billion in 1995).[7] Since then, however, shifts in ridership moved New York City's rank to fifth in the world (see Gershon, et al. in this volume). Transit systems were opened in about two dozen cities worldwide, summarized by Grava,[1] during the 1980s and 1990s in Europe, the Middle East, Latin America, and Australia.[8]

HEALTH AND SAFETY BENEFITS OF TRANSIT

Environmental Quality and Energy Conservation

The primary human health benefits of transit are related to air quality. Air pollutants from transit are not generally emitted where the service is consumed unlike other modes of travel, in particular, auto travel. In 2002, transportation (other than transit) accounted for 82% of total emissions of carbon monoxide, 56% of nitrogen oxides, 42% of volatile organic compounds, 12% of lead, and under 10% each of sulfur dioxide and particulate matter emissions.[9] These substances are regulated under the U.S. Clean Air Act National Ambient Air Quality Standards. The health effects of air pollutant emissions, such as particulate matter, have been long associated with a variety of respiratory problems,[10] and more recently with myocardial infarction.[11] In contrast to auto emissions, rail transit emissions occur indirectly at electric power production plants providing electricity for electrified rail lines. Direct emissions at the site of transit usage occur where diesel locomotives are used (primarily for long-distance transit). Shapiro, Hassett, and Arnold[12] estimate the direct environmental benefit of transit in the US as reducing annual emissions of volatile organic compounds by more than 70,000 tons, nitrogen oxides by 27,000 tons, and carbon monoxide by 745,000 tons. In addition, carbon dioxide reduction is estimated at 7.4 million tons per year. That is, "Moving a person a given distance by public transportation produces, on average, only about five percent as much carbon monoxide, less than ten percent as much volatile organic compounds, and nearly half as much carbon dioxide and nitrogen oxides, as moving a person the same distance by private automobile, SUV [sports utility vehicle], or light truck."[12] These air quality benefits imply considerable health benefits, documented extensively in the U.S. Environmental Protection Agency air quality-criteria documents accompanying National Ambient Air Quality Standards.

Transit uses less electricity than vehicular travel on roadways, whether one measures usage as total energy consumption or energy efficiency (intensity). In 2003, transportation overall accounted for 27% of the total US energy consumption of 98.2 quadrillion British thermal units.[13] Highway transportation has in the past (1997) accounted for 82% of this portion and rail only 2%.[2] In terms of energy intensity, in 1998, British thermal units per passenger mile averaged 5,255 for automobiles, sport utility vehicles, and light trucks and in contrast, transit used a smaller amount, ranging from 911 to 1,612, for heavy rail, light rail, and commuter rail.[12] Fuel consumption in the form of gasoline for private vehicles amounts to more than ten times what transit generally consumes.[14] Implicit in lower energy consumption by transit relative to private vehicles is lower emissions from power generation to supply that energy. In interpreting energy utilization figures for transit on a per capita basis, it should be kept in mind that these computations are often made for transit vehicles that are not fully occupied, which overestimates per capita energy use.

Speed

Transit is designed to provide higher speeds and hence shorter travel times relative to comparable private vehicles, and as indicated below, with a better safety record. Given estimates for mileage covered for a 30-minute travel time,[1] "regular" subway and commuter rail service distances are at least comparable to the private car traveling at the "normal urban speed limit;" and regional express trains travel 22 miles and the Metroliner (one of the northeast high-speed rail services) averages 45 miles compared to a private car which covers an average of 27 miles traveling at 55 mph. Periodic studies of automobile congestion repeatedly confirm the increase in travel time, hours of delay, and cost as a consequence of congestion on the nation's roadways, and this condition is growing.[15] Moreover, many studies have shown that health effects such as stress are prevalent among automobile users especially under conditions of road congestion, bottlenecks, and associated delays.[16] For example, road rage and aggressive driving have been attributed in part to the act of driving, taking into account drivers' personal attributes, driver behavior, and other nonroad-related environmental conditions and the different definitions of stress used in these studies.[17] Thus, transit's higher speeds and shorter travel time, further reinforce the benefits of lower emissions, energy use, and potentially less stress for a given speed and duration relative to automobile travel, especially when road congestion occurs.

Safety

Transit has a very good safety record for passengers, reflected in patterns and trends in the United States cited by the U.S. Department of Transportation:

1. While passenger car occupants accounted for almost half of transportation fatalities (47%), heavy rail (subways) passenger trips accounted for a fraction of transportation fatalities–less than 0.2% and light rail less than 0.1% between 1999 and 2001.[18]
2. The number of accidents, fatalities, and injuries per vehicle mile of travel for transit has declined dramatically since 1990.[19]
3. Between 1990 and 2001, total transit accidents declined by close to 60%; injuries and fatalities generally also declined, though annual trends were uneven.[19]

These patterns and trends are impressive considering the greater speed on average that transit usually provides relative to automobile travel, as noted above, though problems posed by at-grade crossings may be an exception.

These observations generally hold true in countries other than the United States, for example, in Canada, transit accidents are about 5% of the rate for automobile users.[20]

Yet, when accidents do happen on rail systems, they are highly visible and can undermine public confidence. A single crash involving transit tends to involve more people than single car accidents, and transit passengers have little control over the vehicle, unlike private vehicle operators. The risk perception literature shows that individuals fear and overestimate risk of activities they do not control.[21] Thus, public perception of the relative risks of transit and auto travel need to be addressed to take full advantage of transit's safety record.

VULNERABILITIES

Physical Condition and Its Implications for Health and Safety

The condition of transit systems and the lack of investment to support regular upkeep dominated public transportation policy debates for many decades. "State of Good Repair" is used to define a standard for all infrastructure conditions. The American Society of Civil Engineers 2003 scorecard for the Nation's infrastructure noted a decline in the condition of transit systems (by an unspecified amount) from its 2001 grade of C-, though the roadway condition was ranked slightly lower (a D+ grade).[22] The Federal Transit Administration and American Association of State Highway and Transportation Officials estimated the cost of maintaining existing transit condition as ranging from $14.8 to $18.9 billion and $20.6 to $43.9 billion to improve transit condition; the estimates for maintaining and improving roads (not including bridges) are many times larger than for transit, however, estimated in the American Society of Civil Engineers scorecard by American Association of State Highway and Transportation Officials and the Federal Highway Administration as $75.9 to $92 billion for maintaining condition and $106.9 to $125.6 billion for improvement.[22]

Age of transit vehicles is one factor often associated with condition. Average age of rail passenger vehicles has increased slightly between 1985 and 2002, and the average age of commuter rail self-propelled passenger cars has more than doubled between 1984 and 2002.[23] Age is not necessarily a clear indicator of condition, since it does not reflect renovations, does not necessarily mean that vehicle design lifetime has been exceeded and does not reflect the age and condition of track that may be more significant for safety. Nevertheless, increasing age points to infrastructure and investment levels are not keeping up with declining transit condition, and greater caution in operating procedures.

Improving condition will also improve safety. When safety improvements are made together with other condition improvements, the combined cost of both improvements is likely to be reduced.

Security

Security is a key vulnerability for transportation systems and is an important public policy issue for transit, since transit is a tempting target for terrorism and sabotage. In 2004, the Senate passed the Public Transportation Terrorism Prevention Act of 2004 (S 2884) and the House passed the Public Transportation Terrorism Prevention and Response Act of 2004 (HR 5082). The U.S. Department of Homeland Security and the U.S. Department of Transportation Federal Railroad Administration and Federal Transit Administration have undertaken transit vulnerability assessments.[24] Experiences outside the United States point to US transit infrastructure security needs. The Mineta Institute chronology indicated that between 1920 and 1997, 631 security attacks occurred on public transportation, primarily outside the United States, and 27% of these involved subways and trains, 13% involved stations, and 8% involved rail.[25] For all transportation systems, not only public transportation, U.S. Department of Transportation estimated in 1998 subways accounted for 1% of the attacks and rail accounted for another 10%.[2] According to the Mineta Institute study, attacks on transportation tend to be concentrated in a few countries, primarily in India and Pakistan,[25] which may be a function of the prevalence of terrorism in general there and the attractiveness of transit as a terrorist target given the very large number of users of these systems.

Historically, federal critical infrastructure protection policy has emphasized physical and cyber threats to the infrastructure, rather than biological, chemical, and radiological contamination that impact public health. Yet, these threats warrant attention because not only can such attacks occur on transit but also transit can be used as a weapon of mass destruction with biological, chemical, and radiological agents. The 1995 sarin attack on Tokyo subways was a wake-up call to such chemical threats. The possibility of such attacks that are more sophisticated and involve extensive planning could produce far greater consequences. According to the Mineta Institute chronology, chemical or radiological attacks comprised approximately 1% of the attacks over the 1920–1997 period.[25] Once a chemical or other toxic agent is used in an attack, especially in older underground transit systems, the configuration of the transit system is often such that dispersion of contaminants can occur rapidly and magnify the consequences.

Transit nodes and links are especially vulnerable to attack. Links are highly distributed track networks, and nodes are centralized locations such as power supplies and control points, stations, signaling points, storage facilities, and maintenance yards. Nodes, such as stations, are vulnerable because of high concentration of people there. Links, such as tracks, are vulnerable if they are single, branched lines, because a single break will impair large parts of track for service.

The vulnerability of transit to attack is not limited to incidents in which public transportation is the initial target. Electric power system failures can disable transit. Nearby water, oil, gas, and chemical pipeline and storage facility ruptures can also intrude on transit's ability to function. These environmental factors external to transit systems potentially pose critical threats to transit viability and to the health and safety of its users.

The External Environment

The response of public transit systems to one type of threat provides lessons for other types of threats. Thus, experiences from natural hazards and accidents provide lessons about the consequences we can expect from terrorist attacks. This perspective is typically called an "all-hazards" approach and has been formalized for national security response in the National Incident Management System.[26] The impact of accidents and natural hazards on infrastructure upon which transit depends can be substantial, depending on the type of infrastructure affected. Water impacts can occur from distribution system breakages, weather, and hydrologic conditions. Electric power impacts include electric surges that can affect the integrity of metal components, electric power lines falling on tracks, and underground fires and exploding manholes in electric power distribution systems. Transit systems can also be impacted by other transportation, for example, from vibrations from heavy vehicles on roadways above or next to transit line and corrosion from chemical contamination such as salt from snow and ice removal. Each of these environmental factors has dramatically different effects and each can potentially undermine the system's reliability. Examples are given for the effect of water, electric power, and information technology on transit systems.

Water A common source of water inundation of transit systems is from water distribution system breakages or leakage. Other sources include excessive and sudden rainfall (such as flash floods) and high-water table. The NYC Mayor's Management Report of 2004 cited breakage rates in NYC of between 500 and 600 per year, and in fiscal year 2004, 607 breaks were reported citywide.[27] Water accidentally released or leaked from distribution systems is called unaccounted for water or nonrevenue water, and a benchmark for most urban areas is about 6%, with developing countries typically having higher percentages.[28,29] Both underground and aboveground transit lines are vulnerable to inundation from the accidental release of water given the historical proximity of water lines and transit tracks. Underground tracks are typically below water mains, so they act as drainage paths for accidentally released water. The degree of impact depends upon how fast the water can be removed and what other systems necessary for train operations are affected, in particular, electrified rail, which inevitably has to be shut down for safety reasons during a sudden release of water. The ability to manage a water problem once it occurs depends on how fast pumps can be obtained and deployed and the ability of drainage systems to accommodate the additional water. New York City has a large (several hundred thousand gallon) pump and according to the Metropolitan Transportation Authority has 301 pump rooms with the capability to pump 17 million gallons of water per day.[30] Water main breakages have routinely caused the shutdown of subway service for extended periods primarily because tracks are flooded or electric power has to be shut down. Some dramatic examples of events that have occurred throughout the country reflect the vulnerability of transit to water intrusion and are given below.

1. On August 26, 2001, and September 8, 2004, subway line shut downs occurred for several hours because of severe storms in NYC and were attributed in part to the incapacity of drainage facilities to remove the water quickly enough.
2. On April 18, 2002, a water main break closed the number 2 and 5 subway lines for eight hours in Brooklyn, disrupting 60,000 commuters.[31]
3. On March 2, 2000, subway tracks were flooded and service on the N, R, and L lines was disrupted for several hours because of a water main break in Union Square in Manhattan.[32]
4. On May 9, 2001, MARC commuter rail service between Baltimore and Washington was halted because of a water main break.[33]
5. On February 7, 2000, track supports were undermined because of a break in a 36-inch water main under the Chicago El, causing service to be interrupted for a day as a precaution.[34]

Electric Power Electric power is a key resource for transit, since it consumes large amounts of electricity, and outages make transit vulnerable. According to the Metropolitan Transportation Authority, NYC maintains 524 power facilities, estimated to be sufficient to power the City of Buffalo, NY, for one year.[35] The NYC transit system once had its own power substations,[36] but since 1959, relied on Con Edison for electric power and outages in that system can affect transit. Examples are noteworthy of how power outages have affected transit in NYC, where transit use is the highest in the country:

1. On August 14, 2003, a massive electric power failure affecting 50 million people in the United States and Canada resulted in widespread stoppages in transit systems, including the NYC transit system which was halted for about a day.[37]
2. On July 29, 2002, several subway lines lost power between 59th Street and Brooklyn in NYC when a transformer explosion occurred at a Con Edison plant on the west side of Manhattan.[38]

Other parts of the country have had similar problems:

1. Between December 13 and December 15, 2002, a series of storms disrupted BART and other transit service. On December 13, a power failure shut BART service in the San Francisco Bay area, between the two stations of Richmond and El Cerrito Del Norte.[39] On December 15, also in the San Francisco Bay area the same weather problems caused a tree to fall on the lines, and this disrupted service on the Pittsburgh/Bay Point portion of the system, until the

tree was removed. Delays on BART were also experienced because of continued bad weather.[40]

2. On December 8, 2000, in the San Francisco Bay area, 17 of 57 transit trains were closed for a half a day by a power outage at rush hour, and many trains were stuck in tunnels.[41]
3. On October 8, 2000, the Chicago Transit Authority suspended train service because of an electric power transformer fire that shutdown its signaling system.[42]

Information Technology Transit is increasingly dependent on information technology (IT). Automated train service is increasing. For example, the BART system has been computerized for some time, the JFK air train is automated,[43] and more trains are slated to become computer operated in the NYC system.[44] Information technology provides considerable benefits for health, safety, and security by improving transit performance at all levels, detecting malfunctioning components before they occur and providing transit users early warnings of adverse conditions, for example, such as those posed by water or electrical problems, so they can avoid exposure and reduce consequences. Given the considerable benefits of IT, reliability improvements are needed to avoid IT-initiated service outages. Although IT offers many opportunities for improved service, the vulnerabilities associated with automation if computerized control systems fail should and can be addressed to avoid or reduce such vulnerabilities.[45] At the present time, manual control often compensates for automated control systems. For example, in New York City when a fire disabled a critical switching vault in January 2005 controlling the A and C subway lines, manual resetting of signals allowed some capacity to be restored almost immediately.

Equity Issues: Access and Affordability

Equity shapes many of the health dimensions of transit, and environmental justice is one aspect of equity. Federal policy defines environmental justice as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies."[46] Human health and safety have been identified as critical environmental justice concerns.[47] Equity issues in transit systems arise when certain population sectors needing transit services do not have an equal share of them by virtue of where the users live, whether or not they are able to access or afford transit services, or have available a sufficient amount of such services. A related issue is the relative level of investment in transit in ways that benefit low income or disadvantaged populations, that is, whether or not all sectors of the population are getting an equal share or their "fare share" of the investment and its benefits. Hodge presents two geographically based approaches to evaluate these equity issues: how public transportation accesses different kinds of land use (and hence, different types of users) and how public investment in transportation is distributed across different sectors of the population.[48] The lack of availability and access to transit makes user populations vulnerable by encouraging them to resort to other means of transport that can compromise health, for example, greater dependence on automobile travel and ownership of older vehicles.[49] One way to address problems of differential access to public transportation is increasing the total amount of transit services available. Many trends point to an increase in the amount of transit services coming on-line. The latter part of the 20th century saw a dramatic increase in the number of new rail systems and an increase in the mileage of rail nationwide and the number of rail transit stations that potentially increase access (increasing by almost 20% between 1990 and 2000 and 7% between 2000 and 2002).[50] Overall increases in facilities, however, do not necessarily increase accessibility for those in need.

CAPACITY TO RECOVER

A critical factor in maintaining public confidence in transit after a failure is the system's ability to recover after a disaster. The post-9/11 story in NYC illustrates some of the lessons learned about how transit systems recovered from the terrorist attacks.[51]

The overall sense is that the transit system in NYC performed extremely well during and immediately following the attacks on the World Trade Center, though some service was not available in the hours immediately following the disaster. No lives were lost in the subway system, because managers and operators used an "all-hazards" approach to emergency preparedness—they used their experiences with other disasters.[52] The notable performance of the system occurred even though a length of track was disabled, one station was demolished, and many others were severely damaged. After an initial shutdown of the entire system, service was restored in a matter of hours on the same day of the attacks. More long-term recovery, however, has taken far longer, but at least transit riders were provided with alternatives in the short term.

What contributed to the ability of the NYC Transit system as well as surrounding commuter and long-distance rail lines to recover so quickly in the near term given the scale and unexpectedness of the disaster? Four factors explain this–flexibility in routing (rerouting of trains away from the area after the destruction), the ability to access and use alternative transportation modes (such as ferries and buses), the implementation of mechanisms to reduce consequences of disruption by removing passengers rapidly from stalled trains, and the ability to draw substantial new resources to rehabilitate the system quickly. Whether this relatively rapid recovery is unique to NYC is an important question, and one that requires more comparative research into the relative recovery of transit systems that have been destroyed or damaged, by terrorism and nonterrorist causes.

CONCLUSIONS

Transit has been generally designed as a robust and resilient system, that is, it is potentially resistant to or can recover quickly from adverse effects of external factors beyond its control. Consumers of the service, whether by choice or necessity have availed themselves of the services transit provides, and US ridership in 2002 stood at 9 billion passenger trips.[3] Yet, many factors potentially threaten its important role in protecting the health and safety of the population, namely, general lack of improvements in condition within older systems, the impacts of water inundation and electric power outages, the potential for security breaches, and reductions in the availability of service to certain population sectors as a consequence of equity issues. Transit recovers from crisis in innovative ways that serve as lessons for the management and design of transit to prevent or reduce unhealthy and unsafe conditions that may arise from terrorist attacks or natural hazards. To react to catastrophes proactively, transit policy and planning need to incorporate lessons learned from previous catastrophes as well as strategies to reduce external factors impeding transit operation. A fundamental obstacle to greater investment in and use of transit and the realization of its benefits is that individual choice of mode of travel generally is not consistent with public support of transit—individuals generally will choose other modes of travel over rail transit.

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REFERENCES

1. Grava S. *Urban Transportation Systems. Choices for Communities*. New York, NY: McGraw-Hill; 2003:810, 29, 475.
2. U.S. Department of Transportation, Bureau of Transportation Statistics. *The Changing Face of Transportation*. Washington, DC: U.S. DOT; 2000.
3. U.S. Department of Transportation, Bureau of Transportation Statistics. *2002 National Transit Database*. Washington, DC: U.S. DOT; 2003:Table 19, 49.
4. San Francisco Bay Area Rapid Transit District. *BART History and Facts*. Available at: http://www.bart.gov/about/history/history_1.asp. Accessed November 10, 2004.
5. *The Columbia Electronic Encyclopedia*. 6th ed. New York, NY: Columbia University Press; 2004. Available at: http://www.infoplease.com/ce6/sci/A0841157.html. Accessed November 10, 2004.
6. OECD. OECD in figures: 2004 statistics on the member countries. *OECD Observer*. Available at: http://trb.org/news/blurb_detail.asp?id=4390. 2004:34.
7. Citizens Budget Commission. *Transportation Infrastructure and New York's Competitiveness*. New York, NY: Citizens Budget Commission; 1999:Table 12.
8. Drawn from Jane's Information Group Limited. *Jane's Urban Transport Systems*. UK: Jane's Information Group.
9. U.S. Environmental Protection Agency. *National Air Quality and Emissions Trends Report*. Washington, DC: U.S. EPA; 2003. Available at: http://www.epa.gov/air/airtrends/aqtrnd03/toc.html. Accessed November 11, 2004.
10. U.S. Environmental Protection Agency. *Air Quality Criteria Document for Particulate Matter*. Washington, DC: U.S. EPA; 2004. Available at: http://cfpub.epa.gov/ncea/cfm/partmatt.cfm. Accessed December 22, 2004.
11. Peters A, et al. Exposure to traffic and the onset of myocardial infarction. *N Engl J Med*. 2004;351:1721–1730.

12. Shapiro RJ, Hassett KA, Arnold FS. *Conserving Energy and Preserving the Environment: The Role of Public Transportation*. Washington, DC: APTA; 2002:2. Available at: http://www.apta.com/research/info/online/shapiro.cfm. Accessed November 11, 2004.
13. U.S. Department of Energy, Energy Information Administration. *Monthly Energy Review*. Washington, DC: U.S. DOE; 2004.
14. U.S. Department of Transportation, Bureau of Transportation Statistics. National Transportation Statistics 2003. *Table 4–5: Fuel Consumption by Mode of Transportation*. Washington, DC: US DOT, BTS; 2003. Available at: http://www.bts.gov/publications/national_transportation_statistics/2003/html/table_04_05.html. Accessed November 5, 2004.
15. Schrank D, Lomax T. *The 2004 Urban Mobility Report*. College Station, TX: Texas Transportation Institute; 2004.
16. Koslowsky M, Kluger AN, Reich M. *Commuting Stress: Causes, Effects, and Methods of Coping*. New York, NY: Plenum Press; 1995.
17. Walters CH, Cooner, SA. *Understanding Road Rage: Evaluation of Promising Mitigation Measures*. College Station, TX: Texas A&M, Texas Transportation Institute; 2001. Available at: http://tti.tamu.edu/documents/4945–2.pdf. Accessed February 4, 2005.
18. U.S. Department of Transportation, Bureau of Transportation Statistics. National Transportation Statistics 2003. *Table 2–4: Distribution of Transportation Fatalities by Mode*. Washington, DC: US DOT, BTS; 2003. Available at: http://www.bts.gov/publications/national_transportation_statistics/2003/html/table_02_04.html. Accessed November 5, 2004.
19. U.S. Department of Transportation, Bureau of Transportation Statistics. National Transportation Statistics 2003. *Table 2–31: Transportation Safety and Property Damage Data*. Washington, DC: US DOT, BTS; 2003. Available at: http://www.bts.gov/publications/national_transportation_statistics/2003/html/table_02_31.html. Accessed November 5, 2004.
20. Noxon Associates Limited. Promoting better health through public transit use. Available at: http://www.cutaactu.ca/pdf/BetterHealth.pdf. Accessed June 5, 2001.
21. Slovic P. *Perception of Risk*. London, UK: Earthscan; 2000.
22. American Society of Civil Engineers (ASCE). *Scorecard. 2003 Progress Report*. Washington, DC: ASCE; 2003. Available at: http://www.asce.org/reportcard/. Accessed January 13, 2004.
23. U.S. Department of Transportation, Bureau of Transportation Statistics. *National Transportation Statistics 2003*. Washington, DC: U.S. DOT; 2003.
24. U.S. Department of Homeland Security. *Fact Sheet: Rail and Transit Security Initiatives*. Washington, DC: U.S. DHS; November 15, 2004. Available at: http://www.dhs.gov/dhspublic/interapp/press_release/press_release_0376.xml. Accessed November 15, 2004.
25. Mineta International Institute for Surface Transportation Policy Studies. *Protecting Surface Transportation Systems and Patrons from Terrorist Activities*. Washington, DC: The Institute; 1997.
26. U.S. Department of Homeland Security. *National Incident Management System (NIMS)*. Washington, DC: U.S. DHS; 2004.
27. City of New York. *The Mayor's Management Report Fiscal 2004*. New York, NY: NYC Office of the Mayor; 2004.
28. Chowdhury MAI, Ahmed MF, Gaffar MA. Management of nonrevenue water in four cities of Bangladesh. *J American Water Works Assoc*. 2002;94:64–75.
29. Zimmerman R. Water. In: Zimmerman R, Horan T, eds. *Digital Infrastructures: Enabling Civil and Environmental Systems through Information Technology*. London, UK: Routledge; 2004:75–95.
30. Lapp K. The challenge of congestion in the New York region. Paper presented at: New York University; October 26, 2004; New York, NY (citing information in ref. 35).
31. Raftery T, Grace M. Pipe break floods Flatbush. *Daily News*. April 19, 2002;News Section:22.

32. Kennedy R. Union sq. bubbles over as water main bursts. *The New York Times*. March 3, 2000;sect B:1.
33. Water main break halts MARC Camden line service. *The Associated Press State & Local Wire*. May 9, 2001;sect: State and Regional, BC cycle.
34. O'Donnell M, Herguth RC. Commute a washout; flood affects 200,000 CTA users. *Chicago Sun-Times*. February 08, 2000; Late Sports Final Edition:1.
35. Metropolitan Transportation Authority (MTA). Proposed Capital Program 2005–2009. New York, NY: MTA; undated, circa 2004: Slide 12. Available at: http://www.mta.nyc.ny.us/mta/budget/pdf/capitalprogram_proposed.pdf. Accessed November 24, 2004.
36. Payne C. *New York's Forgotten Substations. The Power Behind the Subway*. New York, NY: Princeton Architectural Press; 2002.
37. Zimmerman R. NYC needs systems to blunt new blackouts. *Newsday*. August 27, 2003:A31.
38. Tucker E. Thousands lose power after explosion at Con Ed plant. *The Associated Press State & Local Wire*. July 20, 2002.
39. Horowitz D. Storms pummel travelers; Trains, planes delayed—PG&E stand by for power failures in continued foul weather. *The Oakland Tribune*. December 14, 2002.
40. Oberthur A. California braces for more wild weather. *The Associated Press State & Local Wire*. December 15, 2002.
41. Warren M. Widespread power outage hits San Francisco. *The Associated Press State & Local Wire*. December 8, 1998.
42. Sheehan C. Downtown power outage strands shoppers, snarls traffic in Chicago. *The Associated Press State & Local Wire*. October 8, 2000.
43. Diamond D. JFK AirTrain tour of 7/13/02 [NYCRail.com]. 2002. Available at: http://www.nycrail.com/misc/airtrain.htm. Accessed April 7, 2004.
44. Luo M. The next stop for the subway is a fully automated future. *New York Times*. June 23, 2004:B1.
45. Zimmerman R, Horan T, eds. *Digital Infrastructures: Enabling Civil and Environmental Systems through Information Technology*. London, UK: Routledge; 2004.
46. U.S. EPA. *Environmental Justice*. Washington, DC: U.S. EPA; June 17, 2004. Available at: http://www.epa.gov/compliance/environmentaljustice. Accessed November 24, 2004.
47. Forkenbrock D, Sheeley J. *Effective Methods for Environmental Justice Assessment*. Washington, DC: Transportation Research Board, National Cooperative Highway Research Program; 2004:4.
48. Hodge DC. My fair share. Equity issues in urban transportation. In: Hanson, S, ed. *The Geography of Urban Transportation*. New York, NY: The Guilford Press; 1995:372.
49. Murakami E, Young J. Daily travel by persons with low income. In: *Proceedings from the Nationwide Personal Transportation Survey Symposium, October 29–31, 1997*. Washington, DC: U.S. DOT; 1999:69.
50. U.S. Department of Transportation, Federal Transit Administration. *Hidden in Plain Sight*. Washington, DC: U.S. DOT; 2004.
51. Zimmerman R. Public infrastructure service flexibility for response and recovery in the September 11th, 2001 attacks at the World Trade Center. In: *Beyond September 11th: An Account of Post-Disaster Research*. Boulder, CO: University of Colorado; 2003:241–268. Special Publication; No. 39.
52. Jenkins BM, Edwards-Winslow F. *Saving City Lifelines: Lessons Learned in the 9–11 Terrorist Attacks*. San Jose, CA: Mineta Transportation Institute; 2003.