# 6

# Climate change and urban transportation systems


**Coordinating Lead Authors:**

Shagun Mehrotra (New York City, Delhi), Benoit Lefevre (Paris), Rae Zimmerman (New York City)

**Lead Authors:**

Haluk Gerçek (Istanbul), Klaus Jacob (New York City), Sumeeta Srinivasan (Cambridge)



The authors would like to thank Irune Echevarría, Masahiko Haraguchi, Young-Jin Kang, and Somayya Ali, for their excellent research assistance. Clark Murray provided exceptional and timely inputs. The initial contributions of Deborah Salon are also gratefully acknowledged.

**This chapter should be cited as:**

Mehrotra, S., B. Lefevre, R. Zimmerman, H. Gerçek, K. Jacob, S. Srinivasan, 2011b: Climate change and urban transportation systems. *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*, C. Rosenzweig, W. D. Solecki, S. A. Hammer, S. Mehrotra, Eds., Cambridge University Press, Cambridge, UK, 145–177.

## 6.1 Introduction

Cities are key hubs of the transportation sector. According to the C40 Cities Climate Leadership group (www.C40Cities.org), cities contribute 75 percent of greenhouse gas emissions. Based on the IPCC assessments, "petroleum... supplies 95% of the total energy used by world transport. In 2004, transport was responsible for 23% of world energy-related GHG emissions with about three quarters coming from road vehicles" (Kahn-Ribeiro *et al.*, 2007, p. 325). Conditions in developing countries pose additional challenges on transportation systems – demand far exceeds supply, particularly for the growing number of urban poor. For instance, the United Nations predicts: "by 2030, the towns and cities of the developing world will make up 80 percent of urban humanity" (UNFPA, 2007) p. 1. And in these developing country cities, transportation systems are already severely undersupplied. In addition, geographical location poses additional challenges. Nicholls *et al.* (2008) p. 8 estimate that, by 2070, the "top 10 cities in terms of population exposure to climate change (including environmental and socio-economic factors)" will be located in developing countries of south and east Asia.[1] These cities have transportation systems that are currently navigating the challenges posed by mixed land use and a large proportion of the population living in poverty. In response to such diverse challenges posed by a changing climate to transportation systems, this chapter focuses on the construction and maintenance of the physical assets that account for the bulk of urban transportation investment and climate associated risks. Since urban transportation systems are built and managed by both the public and private sectors, the chapter also considers institutions and organizational structure, regulation, governance, and economic issues that play a role in the development of urban transportation and their response to climate change.

The quality of transportation planning and management is critical for the functioning of a city, and thus issues of urban climate change adaptation and mitigation require attention. Yet, in practice, climate change impacts and associated responses significantly vary by city characteristics and conditions. In addition to providing an overview of urban transport and climate interactions, this chapter has a three-fold purpose: (1) to define climate risk as it pertains to this sector and what general considerations create variations by city conditions; (2) to develop an understanding of pragmatic adaptation and mitigation strategies that cities can adopt and indeed are adopting; and (3) to derive policy lessons for the urban transport sector in the context of climate change in cities. The distinguishing attribute of this chapter is that it primarily focuses on urban transport. Further, a diverse range of country conditions – both developing and developed – are addressed. Finally, it presents a combination of adaptation as well as mitigation strategies allowing the articulation of co-benefits, of addressing mitigation and adaptation together as well.

### 6.1.1 Description of urban transportation sector

Transportation can be categorized based on what is being transported, the mode of transportation, and by its regulation and other institutional dimensions. Regarding what is being transported, the three subsectors in transportation – moving passengers, freight, or information – make different demands on transportation systems. Impacts on greenhouse gas emissions as well as mitigation and adaptation measures to reduce those emissions can vary widely depending on how passengers, freight, and information are transported. Further, transportation is expressed in terms of modes of travel, which are categorized broadly as occurring by land, air, and water. Within that broad categorization, transportation modes may also be classified in terms of the physical infrastructure that is used and include those that use rail, road, ships, and airplanes, each of which can be subdivided further. Land-based transportation systems are generally those with the highest usage in urban regions, and can be divided into rail- and road-based systems. According to Kahn-Ribeiro *et al.* (2007, p. 328), "road vehicles account for more than three-quarters" of total transport energy use and thus associated greenhouse gas emissions. This combination of what (or who) is being transported and the mode by which it is transported is significant because it provides a measure of the amount of greenhouse gas emissions by modes and types of uses. This measure of emissions in turn helps in devising adaptation and mitigation strategies. Finally, the nature of regulation and other forms of oversight and management of the transport sector have a critical effect on emissions.

This chapter primarily focuses on the movement of people or passengers, and where relevant, issues of freight or information are referenced. Many transportation systems, especially urban mass transit, particularly in developing countries, are predominantly publicly owned and operated, but other systems (such as air and water-based transport) are more often privately owned; as are cars, vans, and trucks owned and operated by individuals. However, the ownership and management patterns for transportation systems vary by city and country and are an important factor in the design of institutional arrangements to formulate and implement mitigation and adaptation strategies. The ability to mitigate and adapt to climate change related scenarios depends on ownership. For instance, a publicly owned facility may have access to direct and indirect subsidies and large-scale public investments that are unavailable for private sector operators. This issue of public and private sectors is further discussed in Section 6.5.

### 6.1.2 Role of transportation in climate change

In general, the influence of transportation systems on global climate change has been well documented by the Intergovernmental Panel on Climate Change Working Group III (Kahn Ribeiro *et al.*, 2007), and the impacts of climate change on the

1 The only exception is Miami, which is located in the United States.

transportation sector as a whole have likewise been summarized by the IPCC Working Group II (IPCC, 2007a). Bradley *et al.* (2007) p. 27 report that "transport accounts for about 14 percent of global greenhouse gas emissions, of which road transport accounts for the largest share, at 72 percent of sector and 10 percent of global greenhouse gas emissions". Some of the relevant findings are summarized below.

#### *6.1.2.1 Contribution of transportation sector to greenhouse gas emissions*

Greenhouse gas emissions vary according to types of transportation systems, geographic location, scale, and time period. Based on IEA estimates for 2004, Kahn Ribeiro *et al.* (2007, p. 328) find, "the transport sector was responsible for about 23% of world energy-related greenhouse gas emissions" (as distinct from total greenhouse gas emissions) and in addition, "The 1990–2002 growth rate of energy consumption in the transport sector was highest among all the end use sectors." Bradley *et al.* (2007, p. 27) note that in this period, although "transport-related emissions grew 20–25 percent in most industrialized countries, growth rates were higher in many developing countries". Their calculations suggest that the "fastest growth was in South Korea, Indonesia, and China, where transport emissions doubled over the 12-year period" (Bradley *et al.*, 2007, p. 27).

Different motorized transportation modes – automobile, transit, or two wheelers – have different carbon footprints, which are measured in tons of emitted carbon per passenger mile, or per ton-miles, respectively, depending on whether people or goods are transported. In cities with concentrated and distinct urban employment centers, mass transit is generally the most efficient urban transport system, with rail-based systems including subways or elevated rail systems usually outperforming bus systems, in terms of minimizing greenhouse gas emissions per passenger mile (also see Bertaud *et al.*, 2009). The choice of dominant transport systems, and in particular of urban mass transit with its intended capture of a large fraction of the total passenger miles traveled in an urban setting, can be an important contributor to reducing greenhouse gas emissions. According to the IPCC (2007a, p. 329), "the world automobile fleet has grown with exceptional rapidity – between 1950 and 1997, the fleet increased from about 50 million vehicles to 580 million vehicles, five times faster than the growth in population." It is noteworthy that "between 1999 and 2004, China's motor vehicle production increased more than 175 percent, approaching half of Japanese levels by 2004" (Bradley *et al.*, 2007, p. 27). The 2007 IPCC report also notes that "two-wheeled scooters and motorcycles have played an important role in the developing world", with a current world fleet of a few hundred million vehicles. The report further notes that buses, "though declining in importance against private cars in the industrialized world", are increasing their role especially in developing country urban areas where they account for a substantial proportion of the modal share of trips. However, individual case studies suggest that transit mode share may be declining in some cities as incomes grow. For example, a study by Gakenheimer and Zegras (WBCSD, 2004, p. 162) notes, for Chennai, which they identify as having a relatively low GDP per capita, "Chennai's public transport mode share declined by 20 percent in the 25 years preceding 1995, largely due to a rapid rise of the number of motorized two-wheelers."

#### *6.1.2.2 Impacts of climate change on transportation sector*

Transportation not only affects climate (Kahn Ribeiro *et al.*, 2007), but it is also affected by climate change. The Transportation Research Board (2008, p. 2) citing IPCC identified "increases in hot days and heat waves, arctic temperatures, sea level, intense precipitation events and hurricane intensity" as the climate change characteristics having the most significant adverse impacts for transportation. The list of impacts is extensive, covering structural and material damages of many different types and associated disruption of transportation services for users depending on the type of transportation facility, its location relative to waterways, and the types of materials and design used (Hunt and Watkiss, 2007; Transportation Research Board, 2008). A number of local transportation inventories exist and have been identified in climate change studies for particular types of impacts. For example, in New York City an extensive set of facilities has been identified in connection with sea level elevations (USACE, 1995; Zimmerman and Cusker, 2001; Zimmerman and Faris, 2010). Further, Rossetti (2002) investigates potential impacts of climate change on railroads for various timescales.

### 6.1.3 Urban transportation and land use

The relationship between transportation and the spread of urban settlements is interactive. The building of railroads and highways has influenced urban development, and conversely the growth of urban areas has influenced the development of road, air, and rail networks that facilitate travel within and across urban areas (Chomitz and Gray, 1996). As urban areas become vulnerable to climate change, addressing transportation issues in adaption and mitigation involves addressing the interactions between the sector and land use in cities.

Urban land use planning is based on functional designation of land for different human purposes including economic and leisure activities. Categories of land use typically include residential, commercial, industrial, recreational, natural protection, institutions, parking, vacant land, and transportation or utilities (for details see Chapter 8 on land use). Wegener (2009, p. 4) suggests that "the distribution of infrastructure in the transport system creates opportunities for spatial interaction." This "can be measured as accessibility". Further, "the distribution of accessibility in space co-determines location decisions" and results in changes in land use. And a combination of energy intensity as well as demand for transportation systems determines the degree of carbon emissions. Lower levels of fuel efficiency and increase in demand for transportation result in greater greenhouse gas emissions.

Individual land uses within the urban fabric, including transport infrastructure, in great measure determine the urban form.

Urban form can be measured through various density measures – for dimensions such as population or economic activity – and the spatial location of activities and households. Newman and Kenworthy (1989) find that urban population density is closely related to vehicle miles traveled (VMT). VMT is a key indicator for greenhouse gas emissions, and conversely, the greenhouse gas emissions from transport vehicles are related to VMT. However, the relationship is far more complex and other measures including the price of fuel, employment levels, trip origins and destinations and the size of cities have much influence on vehicle miles traveled. A recent study in Indonesia (Permana *et al*., 2008) also suggests that residents of locations with mixed land uses consume less energy than those who live in suburban locations even after controlling for income.

Cities show considerable variation in terms of urban form depending on the planning and economic goals that they choose to implement in the long term. Geurs and van Wee (2006, p. 139) in "a broad evaluation of relevant land use, transport, accessibility and related societal and ecological impacts" … "between 1970 and 2000 note that without policies to encourage compact city development, urban sprawl in the Netherlands was likely to have been much greater". Stone *et al.* (2007, p. 404) "found the densification of urban zones to be more than twice as effective in reducing vehicle miles of travel emissions as the densification of suburban zones, suggesting compact growth to be better for air quality" in the United States. The study finds densification of urban zones to be more than twice as effective in reducing vehicle miles of travel and emissions as the densification of suburban zones, suggesting compact growth to be better for air quality than historical patterns of growth in most cities of the United States.

The intensity of urban land use also results in urban heat islands that modify the local climate (see Chapter 3 for details on climate change process and projections). Thus, the relationships between urban land use, transportation infrastructure, and climate involve feedback loops that are significant in multiple physical scales – local, regional, and global – and temporal terms – long and short term (Figure 6.1). Just as accessibility is a goal for addressing the land use and transport feedback loop, the goal of sustainability addresses the multiple feedbacks between urban form, transportation infrastructure, air quality, health, and climate change. Research associating land use change with transportation and air quality in developed and developing countries suggests that sustainable urban transportation and land use policies may be vital to achieving greenhouse gas mitigation (see, for example, Iacono and Levinson, 2008; Kinney, 2008; Rogers and Srinivasan, 2008).

In Figure 6.1, the flow (or movement of goods, services, and people) pattern in the urban transportation system is determined by both the transportation system and the land use patterns. The current flow pattern causes changes over time in land use through the type of transportation services provided and through the resources

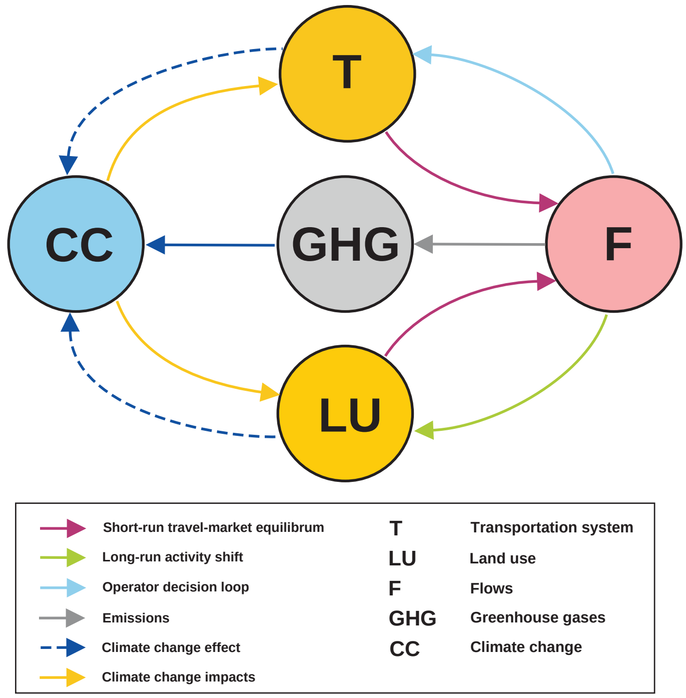



**Figure 6.1:** *Urban transportation, land use, and climate change interactions.*

*Source: H. Gercek, adapted from Manheim (1979).*

consumed in providing that service. The current flow pattern also causes changes over time in the transportation system in response to actual and anticipated flows, as entrepreneurs or governments develop new transportation services or modify existing ones. These interactive patterns in the transportation system and land use determine the degree of greenhouse gas emissions. Furthermore, transportation system facilities and land use also contribute to local climate change through urban heat islands. In sum, climate change will have impacts on both the urban transportation system and urban land use and vice versa.

### 6.1.4 Responding to climate change: adaptation and mitigation[2]

Adaptation to climate change means minimizing the potential impacts on the transportation system from climatic changes such as rising average temperatures, increased intensity of storms, rising sea levels, and increases in overall climatic variability. Adaptation of transportation and land use to climate change may involve changes in individual travel behavior as well as macro-scale urban development policy. Mitigation, in the context of urban transport, implies reduction in greenhouse gas emissions resulting from movement of goods, services, and people in cities. For instance, mitigation efforts may involve reducing VMT through a range of incentives and regulation.

Effective response to climate change requires that transportation plans consider both adaptation and mitigation to climate

2 Adaptation is "An adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007b, p. 869). Mitigation is "An anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks" (IPCC, 2007b, p. 878).

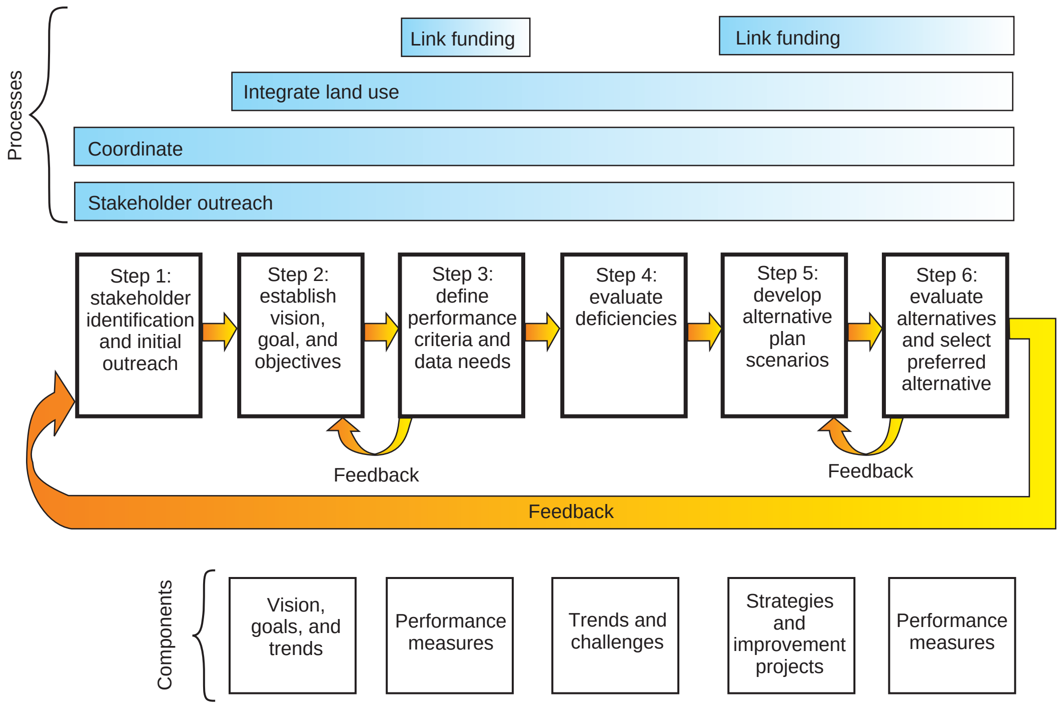



**Figure 6.2:** *Opportunities to integrate long-term transportation planning with climate change.*

*Source: Federal Highway Administration and ICF International (FHWA, 2008).*

change as well as establishing a process by which climate change can be integrated into long-term transportation planning processes that include land use planning as well as stakeholder outreach. A summary of the approach adopted by the United States Federal Highway Administration is summarized in Figure 6.2, where various processes and components of the transportation planning and management are outlined, each offering the opportunity to integrate aspects of climate change adaptation and mitigation. Details of such adaptation and mitigation strategies are presented below.

## 6.2 Risk management as a framework for adaptation and mitigation

Adaptation and mitigation of urban transportation systems to climate change can be defined as a form of risk management. Mitigation is a global mandate, while adaptation is a local necessity. The goal of risk management is to minimize future damages at affordable costs. The social context is: What risks are managed at whose cost and for the benefit of whom? Besides considering potential material damages, urban transportation managers have a broad array of cultural, social, quality of life, and ecological issues to consider in regard to climate change risks. The risk profiles of the transportation sectors in cities of developed countries are radically different from those in underdeveloped or rapidly developing countries. For instance, in several developing countries existing private and public urban transportation assets and systems are substantially undersupplied and less resilient to extreme events, and the vast majority of the passengers are poor people, many of whom live in informal settlements.

There are two fundamental options for risk management in the transportation sector. One is by mitigation measures in cities around the world that reduce *globally* the climate hazard factor by reducing greenhouse gas emissions. Mitigation measures implemented by a single city are insufficient to reduce the hazard factor for that city and thereby reduce climate risk. However, the cumulative effect of mitigation measures in cities around the world is likely to reduce total greenhouse gas emissions, and by extension climate hazards as a whole, including changes in extreme temperature, precipitation, sea level rise, and the like. The global hazard reduction can be achieved through the cumulative effects of local measures such as land use planning, zoning, and placing of assets. Mitigation affects the hazard factor only. The lower the hazard, regardless of the value of assets, the lower the vulnerability, and hence the lower is the risk for transportation systems. Hence, aggregate mitigation measure by cities around the world can reduce climate risk in cities. See Section 6.5 for mitigation strategies for urban transportation systems.

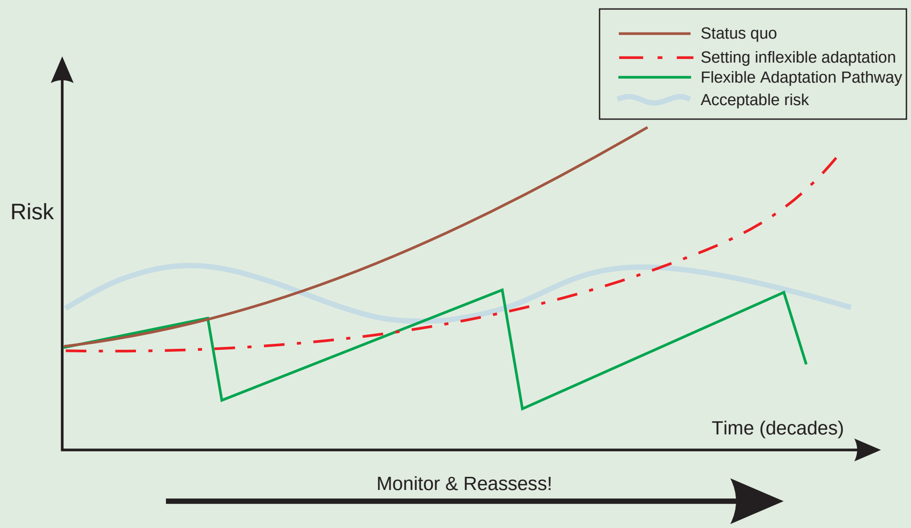
The second option in reducing risk is by adaptation. Zoning and land use planning can affect the spatial arrangement of assets and protective structures in an urban setting and hence modify their exposure to the spatially varying hazards. Risk is critically dependent on where assets are placed with respect to the spatial distribution of hazards. Settlements and transportation systems develop together, but often one precedes the other. Whichever comes first tends to occupy the less hazardous areas, and the latecomer ends up with the more hazardous areas. Commuter rails, bus routes, or tunnel entrances should not be located in high-hazard flood zones. If space is constrained, then the more valuable, essential, and critical assets should be placed in the safest areas, while the less valuable, ordinary, or non-essential assets may be placed in the more hazardous locations. In practice this rarely is the case in developed-country cities. Usually residences tend to occupy relatively safer areas in developed country cities. Some exceptions are along coasts where the ocean view and proximity are considered valuable assets, as is the proximity of forests that are prone to wildfires – and transportation routes and facilities tend to occupy the higher-risk locations in which residential settlements were deemed too risky to build. The converse tends to be true in developing countries (although there are exceptions), where the poor live in slums and tend to occupy the most vulnerable locations (see Chapter 8 on land use and

## [ADAPTATION] Box 6.1 London, UK, storm surge barriers

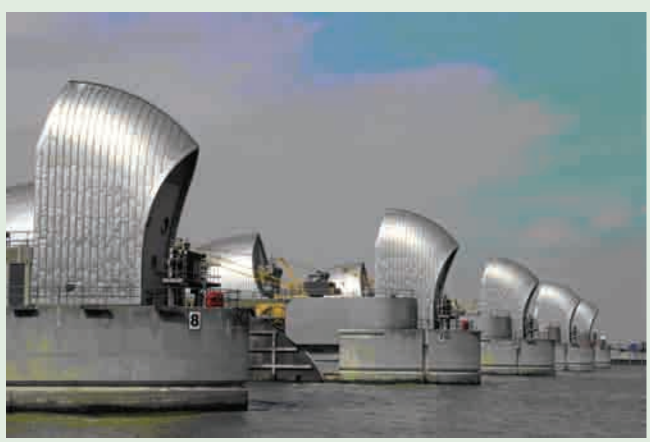
**Klaus Jacob**

*Columbia University*

Levees and barriers can radically change the character and functioning of a city and its transport system. Multiple adaptation paths may be pursued, where one path may be effective up to a certain climate threshold level, and then another adaptation path may have to be chosen, since the former may become gradually ineffective (Box Figure 6.1). London's Thames storm surge barriers are expected to become ineffective in a few decades due to rising sea level, and another new and larger barrier system is planned farther downstream, for later this century (Box Figure 6.2).




**Box Figure 6.1:** *Flexible adaptation pathways.*




**Box Figure 6.2:** *The London Barriers are the centerpiece of today's Thames Tidal Defenses that protect London and the Thames Estuary corridor where a significant proportion of England's wealth is produced (1.25 million people live and work in the flood risk area). The system provides at least a 1:1000 per year protection (to 2070). The system allows for a combination of risks (high tide/surge/freshwater floods). It comprises 9 tidal barriers (including the Thames Barrier), as well as, 35 major gates, 400 minor gates and over 300 km of tidal walls and embankments.*


*Source: Adapted from NPCC (2010)*

Chapter 9 on governance). Cumulatively, adaptation options related to residential and other forms of land use fall under the category of land use planning and zoning.

With respect to adaptation of transport systems in cities, Leonard, *et al*. (2008, pp. 5–21) have identified and discussed in detail three types of objectives for adaptation strategies: *protect*, *accommodate, or retreat*. Accordingly, one option is for climate hazards to be addressed by *protective* measures, some of which can be on a regional rather than local scales. For instance, as in the case of the London storm surge barriers, the flood hazards can be modified by adjustable protective structures such as levees, dams, flood barriers, and pumping stations, aimed at protecting large areas of cities, including the transportation systems (see Box 6.1). However, the experience of Hurricane Katrina hitting New Orleans has shown that, when the hazard exceeds the design specifications of the protective structure, or if the structure cannot be upgraded to keep up with local subsidence and sea level rise, or if the protective structure is not well maintained, such conditions can cause severe damage, loss of life, and assets. Due to the mismatch between perceived and actual protection, the individual firms and households, and also transportation agencies, may tend to neglect additional localized protective or adaptive measures behind these regional protection structures. Such additional local protection provides some localized resilience when regional protection structures fail.

Another way to minimize risk via adaptation is by reducing the vulnerabilities of individual assets. This adaptation approach comprises setting and enforcing adequate *engineering* and *performance standards*, including preparing, disseminating, and implementing technical guidelines, providing updated design and construction codes, and setting common climate protection levels, as is presently under consideration in New York City. Enforcing these, developing protective operational procedures, and putting them into practice are important to achieve the risk management targets. When this is successfully done, transportation infrastructure vulnerabilities to a given hazard at a given place can be reduced by good engineering, construction quality control, code enforcement, retrofitting (that could include elevating assets in their current place in case of flood hazards), reinforcing protective walls, increasing pumping capacity, and increasing drainage capacity of culverts, to name a few.

As capital improvements are made over time, transportation infrastructure may be raised in place to higher elevations, although in plan they may continue to be located in flood zones. The Taipei subway in Taiwan has raised subway entrances to avoid flash-flood and tidal inundations, and its high-speed intercity trains, similar to the Shinkansen in Japan, run largely on elevated tracks to avoid river flooding during frequent typhoons. Vulnerability reduction may include disaster preparedness as well as increase resilience to future effects of climate change, comprising installation of warning systems and having procedures in place that temporarily move the rolling stock out of harm's way.

## 6.3 Assessing climate risks to urban transportation

This section describes methods for assessing climate risks to urban transportation systems and then highlights specific hazards to the systems posed by climate change.

### 6.3.1 Defining climate risks and methods of risk assessment

Risk in general is defined as "the product of the likelihood of an event occurring and the magnitude of consequence should that event occur. For the purposes of this document, likelihood is defined as the probability of occurrence of a climate hazard" (NPCC, 2009, p. 62). In the context of urban transportation systems, the consequences are largely the direct damage to the transportation systems, the associated losses to the transportation systems' operators or owners, but they also include the impact on, and losses to, society at large from hazardous climate conditions or events. For instance, even when there is no damage to the transportation system, as during a heat wave, heat stroke fatalities occur, say, in a subway or underground system because of inadequate ventilation or cooling, it constitutes a climate-related transportation risk. Risk refers to the probability of future impacts, damages, or losses.

In sum, there are different approaches to risk assessment. Some are narrowly defined in engineering terms, and others are much broader and address the complex social context. The former tend to be quantitative, the latter qualitative because of the inherent complexity of social systems. Several quantitative definitions of risk have been put forward, the most general being: Risk ($R$) is the probability ($P$) of hazardous events ($H$) times their cnsequence ($C$) and can be expressed in an equation ($R = P(H) \times C$). For an urban transportation system, climate risk can be defined more specifically as the spatially integrated sum of the local products of the following two, spatially varying factors: First, probability ($P$) that the local climate hazards ($H$) of various magnitudes will occur; and second, the magnitude of the consequences ($C$).

The consequences $C$ are in turn the product of the *vulnerability* of the transportation assets times the *replacement value* of the assets that are exposed to the climate hazards. In engineering terms, vulnerability is often called *fragility* and is the *probability of failure* resulting in various *states of damage* such as light, modest, severe, or total damage; a measure of the outcome of these damage states can be, for instance, the *fraction of the replacement value* of the transport system that was damaged by the hazard. Component or system fragility is a function of the hazard magnitude. Modest flooding, for instance, will do only light damage to transportation systems with minor consequences, while severe flooding could totally destroy a given transport system, resulting in total loss of the assets and of their functionality, causing in turn major economic damages to society.

## [ADAPTATION] Box 6.2 Hyderabad, India, infrastructure adaptation planning

**Diana Reckien, Matthias Lüdeke, Fritz Reusswig, Oleksandr Kit, Lutz Meyer-Ohlendorf and Martin Budde**

*Potsdam Institute For Climate Impact Research*

In Hyderabad, Andhra Pradesh in South India, we investigate the magnitude and the impacts of climatic changes, and we develop planned adaptation options. The work is part of the research network Climate and Energy in a Complex Transition Process towards Sustainable Hyderabad: Mitigation and Adaptation Strategies by Changing Institutions, Governance Structures, Lifestyles and Consumption Patterns.[3] The project addresses the challenges of climate change and resource depletion in the context of so-called "megacities" by taking into account their complex social and economic characteristics. The aim of the project is to develop a Perspective Action Plan in close cooperation with the state government that will establish Hyderabad as a Low Emission City in Asia within 30 years.

Approaching adaptation in cities is a vital necessity to meet climate change and development goals, but it remains largely unnoticed by governmental as well as local climate policy, particularly in developing countries such as India. Hyderabad is one of the fastest growing cities in the country with a population increase of 27 percent from 1991 to 2001. With 5,530,000 million people (2001) it is the sixth largest city in India (Census of India). Population scenarios for the Hyderabad urban agglomeration (HUA) indicate a population of 7.7 million people in 2011 and 10.8 million in 2021 (GHMC, 2005). After Bangalore, Hyderabad is the second most important economic center for the Indian IT industry. Another strand of the local economy lies in the biotechnology and pharmaceutical industries (GHMC, 2005).

To assess the magnitude of potential climatic changes for Hyderabad (item (1)), we compare two AOGCM outputs (ECHAM5 and GFDL, more to follow) and their statistical downscaling to the region of Hyderabad. We focus on four climate variables, which are derived from expert interviews (with local authority officials, NGOs, community self-help groups) and which are candidates for inflicting damages in the city under present conditions: the frequency of extreme daily precipitation and the probability and duration of heat waves (indicators of extreme weather events), the total annual precipitation and the mean annual temperature (indicators of gradual climate changes).

Frequency of precipitation greater than 80 mm/day (medium to very high impact intensity and potential damages) is likely to double until 2100 (reference period 1980–2000) (B1 in comparison to A2 will only buy some time with stronger rain events occurring later in the century), and very strong rain events will increase significantly (160 mm/day events to potentially increase four-fold). With respect to heat waves, we looked at the number of days/year with night temperatures above 27°C. They will approximately triple until 2050, relatively independent of the SRES scenario. In 2100, A2 will lead to +560(±50) percent and B1 to +240(±50) percent increases with respect to the reference period. The frequency of heat waves longer than one week will double to triple until 2050 and increase further until 2100. Total annual precipitation is likely to change by −4 to +17 percent, whereby the difference between the AOGCMs is larger than between the SRES scenarios. The mean annual temperature is projected to increase monotonically up to 5 °C above present (A2 in 2100).

Accounting for an improvement in the city's current performance to climate occurrences will help to prepare for future impacts related to these climate projections, contribute to reaching development goals, and constitutes one way of adaptation. With respect to the current climate impacts (items (2) and (3)), we adopt a systems dynamics approach to urban development (Forrester, 1969) and draw so-called impact nets. We look at five currently affected subsectors of the urban system: food security and health, water supply and energy security, as well as transport.

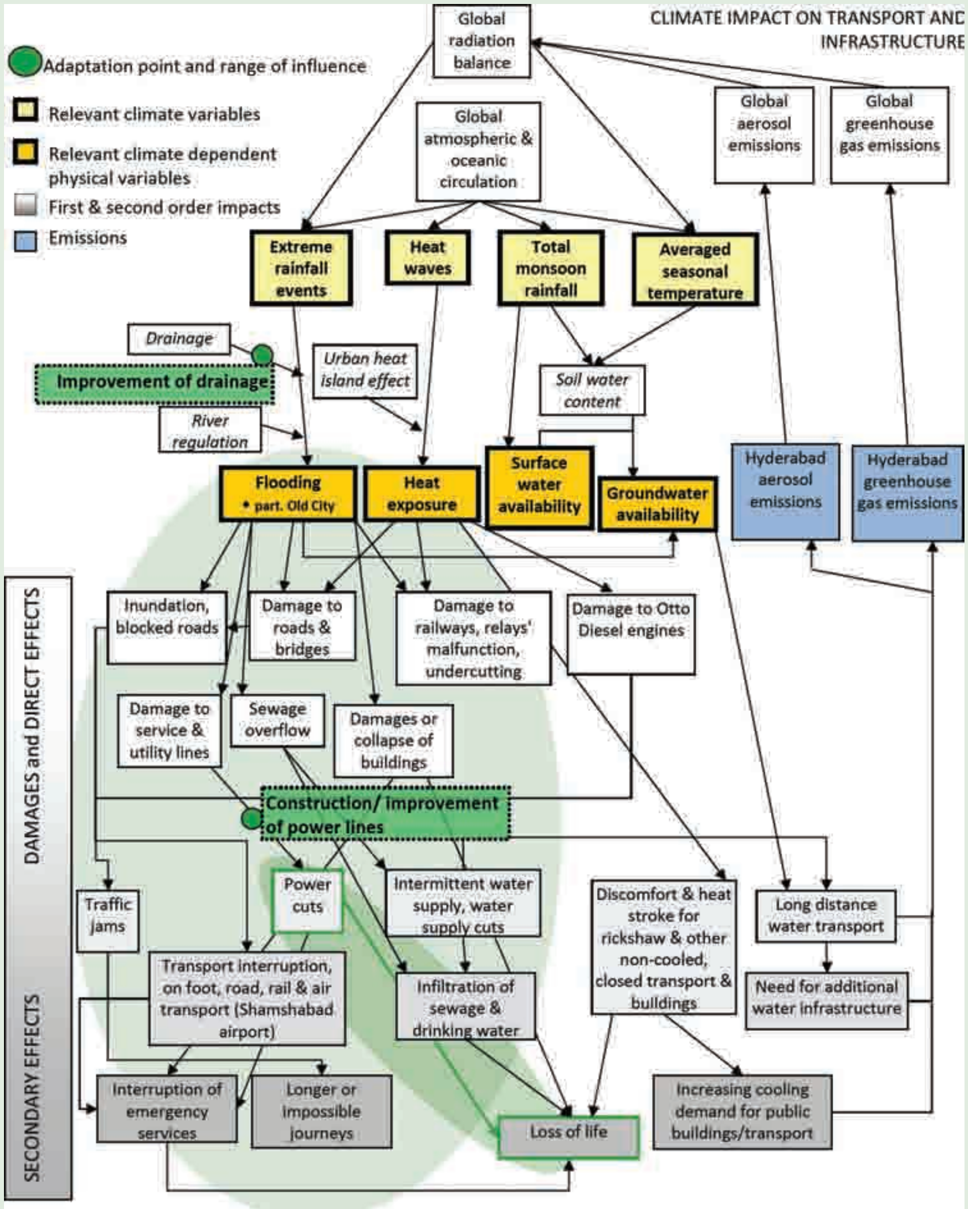
After a literature review, interviews with local stakeholders, NGO representatives, and community self-help groups, as well as more than 200 newspaper articles published since April 2009, we drew impact nets (see Box Figure 6.3).

Box Figure 6.3 illustrates how climate and certain climate events affect current subsystems of the city.

The key impacts in Hyderabad are generally situated in the area of supply and demand of a particular resource, be it water, energy, or goods and services for industry (van Rooijen, 2005). Extreme flood and drought events severely reduce the availability of quality water by either contaminating existing water resources or generating severe surface and groundwater scarcity. Droughts also lead to a reduction in hydropower generation, although the majority of electricity in Andhra Pradesh is produced by thermal power plants. With a further rise in average temperatures, the demand for energy rises too, as do shortages during heat waves (Sivak, 2009).

Climate extremes adversely impact transport infrastructure in Hyderabad in a way that makes it either inaccessible or uncomfortable. Floods directly result in infrastructure damage, the breakdown of transport/communication networks, and the slowdown of services (Shukla *et al*., 2003). Heat waves cause direct damage to electronic/electric devices and make public transport a very uncomfortable service to use, whereas a gradual temperature increase works in a more concealed way, slowly damaging railway and road infrastructure.

3 To this end, a consortium of Indian and German Research Institutes, partners from the public and private sectors, as well as NGOs has been formed. Lead partner and project coordinator is the Division of Resource Economics at the Humboldt University of Berlin. The project is funded by the German Ministry of Education and Research (BMBF) in the program "Research for Sustainable Development of the Megacities of Tomorrow" and will run over five years until May 2013. See www.sustainable-hyderabad.in.




**Box Figure 6.3:** *Impact nets on different urban subsectors in Hyderabad. Key: Yellow – climate and climate related events; Gray – multi-layered (primary/secondary…) impacts; Blue – feedback on the climate system; Green – possible adaptation points and their ranges of influence.*

Impacts of climate change on health relate to the direct exposure to heat and flooding as well as to second-order impacts. A direct effect of flooding and droughts is the interruption of food supply in some areas. Secondary impacts include the long-term influence on water availability for irrigation and of heat-related crop diseases on food production, malnutrition, and hunger. Hyderabad's ability to provide sufficient food to its inhabitants partly depends on the food availability in the surrounding areas (Smith *et al*., 2007). As a second-order impact, the contamination of fresh water with bacteria, chemicals, or other hazardous substances (Young *et al*., 2004) has to be identified. Their consumption can result in diarrheal diseases, cholera, and toxic effects.

The situation is particularly severe in areas of Hyderabad where sewage flows in open ditches close to water distribution pipes (Vairavamoorthy, 2008) and where people live in industrial areas close to factories (Kovats and Akthar, 2008). Climate-sensitive diseases such as malaria, dengue, and chikungunya might increase due to favorable climatic and breeding conditions for insects (Bhattacharya *et al*., 2006). Intermittent rainfalls, such as in June and July in Hyderabad, provide perfect breeding grounds in stagnant urban water such as wells, car tires, bottles, and cans. In particular, dengue cases have reached alarming levels in Hyderabad; it is increasing in the city while its trend is going down in the state as a whole.

The diagrams serve various purposes: (1) communicating aspects of climate change and initiating discussion, (2) understanding the impacts of climate change and picturing them accordingly, (3) generating adaptation options and assisting in their ranking and evaluation, and in a later stage of the project (4) laying the basis for a quantitative, computer-aided, assessment tool. Referring to (1) and (2), the diagrams will be further discussed with local and regional stakeholders, experts, and climate-related scientists, with other experts in the field (e.g., our project partners in Germany, currently underway), and at a later stage of the project with officials from policy and plan making in Hyderabad. With respect to point (3), the green-colored dots and shapes in Box figure 6.3 depict potential adaptation points and their range of influence. These adaptation points are placed at different locations within the nets and therefore have a different "size" of impact (shown as light green shapes). We assume that such an illustration can actively support decision-making for adaptation, particularly in developing countries where development goals and climate change adaptations have to be harmonized.

*Source: Division of Resource Economics, Humboldt University, Berlin, and www.sustainable-hyderabad.in*

These terms (risk, hazard, and fragility) have been used extensively for quantitative risk assessments in combination with Geographical Information Systems (GIS) as an organizing and computational tool. In the USA, for instance, a GIS-based risk assessment tool is HAZUS-MH, where MH stands for multi-hazards, since it allows the quantification of three different risk-producing natural hazards: floods, winds, and earthquakes (FEMA, 2009). The methodology used for these risk assessment tools is discussed below in more detail. It should be noted, however, that these quantitative engineering approaches tend to neglect or inadequately capture the *social risks* to vulnerable societies, which are more complex and much harder to quantify than the physical climate threats to the built environment (Wisner *et al*., 2004; Birkmann, 2006).

In quantifying risks to transportation systems, maps of climate hazards, for instance flood-zone maps or wind speed maps, related to a specific annual exceedance probability, are often used as input. These hazard maps (e.g., Figure 6.3) typically express the hazard of interest at a pre-selected annual probability, for instance, the flood height for the annual flood probability of 1 percent per year. This implies an *average* recurrence period of that flood height on the order of once every 100 years. Wind speeds are often mapped in km/h and associated with an annual probability of 2 percent per year, which in turn implies an average recurrence period for a particular wind speed on the order of once every 50 years. Alternatively, scenario events, such as a specific flood or storm scenario, with spatially distributed hazard amplitudes such as


**Figure 6.3:** *Mapping climate risks to urban transport. Shaded areas depict worst-track storm surge flood zones for Saffir-Simpson Category-1 in red, SS2 in brown, SS3 in yellow, and SS4 in green. Shaded lines are subways, black lines are rail sytems.*

*Source: Lamont-Doherty Earth Observatory, Google Earth, and New York State Emergency Management Office (NYSEMO), New York City Transit Authority subway lines.*

flood depths or wind speeds, can be defined as input for the risk calculations.

Similarly on the asset side, the vulnerability and monetary replacement values of the transportation systems can be mapped in their geographical locations relative to, or superimposed upon, the mapped hazards. In the case of transportation systems, their vulnerability is, for instance in case of flood hazards, a function of their location (and elevation) inside or outside of flood zones. This "mapping" and vulnerability assessment method can be applied to rail systems, stations, bridges, tunnels, roads and highways, bus terminals, or maintenance shops, etc. The mapped vulnerability is then used for the quantitative risk (loss) assessment, as an attribute of the indicated assets exposed to the mapped hazard conditions. The latter can be defined either for a given scenario event, or for a given exceedance probability of the hazard, for which the risk or expected losses are being determined. If such risk computations are made for many different probability levels (or average recurrence periods), then these various contributions from rare large events to frequent small events can be annualized (divided by their respective recurrence period) and added up to provide a total *annualized loss* to a city's transportation (or any other) system. Without such quantitative assessment methods, decision-makers are not aware of the impending climate risks and therefore may not be willing to invest in preventive measures. For a more comprehensive redefinition of a framework for city climate risk assessment where risk is defined and quantified as a function of climate hazards, physical and social vulnerabilities, and institutional adaptive capacity see Chapter 2 on cities and climate risk framework and Mehrotra *et al*. (2009).

### 6.3.2 Climate hazards to urban transportation systems

The climate hazards that may pose the greatest challenges to urban transportation systems are different for different kinds of physical hazards (see Table 6.1), cities in different geographical environments, and for different modes of transportation.

Physical hazards from global climate change that affect urban transportation systems can be expressed in terms of changes in average values and often higher variability of temperature, precipitation, storm frequency and severity, coastal storm inundations especially in conjunction with sea level rise, and other climate processes. The vulnerability of transportation assets to these physical hazards, stemming from the existing spatial and economic organization of the city and its transport system, depends on a range of factors, including: (1) design and spatial layout of transport infrastructure – flood hazards tend to be worse for underground infrastructure; storms affect land, marine, and air travel differently; (2) basic urban form – high-density settlements with mass transit systems, or mostly motorized transportation with low densities; (3) availability of resources to keep transportation systems functioning in both disaster and non-disaster conditions.

**Table 6.1:** *Impacts of climate hazards on urban transportation systems.*

| Physical hazard | Vulnerability of transport systems |
|---|---|
| **Water** | |
| Floods | Inundation of surface and subsurface infrastructure |
| | Undermining of support structures such as bridge footings |
| | Corrosion from salt water, where applicable |
| | Increased scour around bridge footings |
| Storms | Physical damage to roads and rail networks and vehicles from high winds and wind-driven rain and debris |
| Sea level | Similar to floods |
| | Clearances of some bridges might be diminished |
| **Other** | |
| Heat | Destruction or deterioration of materials |
| Wind | Physical damage to roads and rail networks and vehicles from high winds and wind-driven debris |
| Secondary hazards: fire from drought, landslides from rainstorms | Facility destruction and disruption of services |

*Source: From Special Report 290: Potential Impacts of Climate Change on U.S. Transportation, Annex 3–1 (table), pp. 117–123. Copyright, National Academy of Sciences, Washington, DC, USA, 2008. Reproduced with permission of the Transportation Research Board.*

### 6.3.3 Examples of climate change risk assessment of urban transport systems

A number of nations and cities have undertaken risk-related analyses of the impact of climate change on their transportation infrastructure. Revi (2008) provides a comprehensive climate change risk survey combined with an adaptation and mitigation agenda for cities in India. As part of a sequence of general risk assessments from climate change for the New York metropolitan region and discussion of adaptation and response strategies (Rosenzweig and Solecki, 2001; NPCC, 2010) several assessments were directly focused on its transportation systems (Jacob *et al*., 2000, 2008; MTA, 2009). However, preparedness and response remain a challenge. For instance, on August 8, 2007, a windstorm combined with an intense downpour caused urban flash floods, bringing large portions of the New York City mass transit systems to a near standstill (MTA, 2007).

Likewise, there are multiple analyses available on the impact of hurricanes Katrina and Rita on the transportation systems of New Orleans and other communities (Transportation Research Board, 2008). For the Greater London area, climate adaptations reports contain individual chapters with a focus on transportation (Greater London Authority, 2005, 2008). National perspectives on challenges posed by climate change, and guidelines on how to adapt transportation systems to these changes in the context of the United States are offered by the Transportation Research Board

(Transportation Research Board, 2008) addressing a wide range of geographic conditions, from Alaska to Florida, and modes of transport. While equivalent studies in the context of developing countries are sparse (an example for Jakarta, Indonesia, is given by Aerts *et al*., 2009; also see Box 6.3 for preliminary efforts), the work of the Transportation Research Board offers a benchmark, with generic implications transferable to other cities threatened by climate change.

## 6.4 Adaptation of urban transportation systems

Adaptation of urban transportation systems to the challenges of climate change implies making these systems optimally suited to operate safely; to experience minimal interruptions and losses from the immediate effects of extreme climate events; and to be designed and modified in order to make these adaptations possible over the long term. Urban transport managers need to meet both types of climate challenges – changes in long-term mean trends and short-term extremes – while meeting all the normal challenges of providing transportation that is reliable, accessible, affordable, cost-effective, equitable, and environmentally sound. In addition, mainstreaming adaptation requires attention to existing transportation assets and planned investment (Trilling, 2002).

### 6.4.1 Adaptation planning

Managing climate risks of urban transportation systems requires more than quantitative risk assessment and risk reduction. They require an assessment of the basic mitigation and adaptation options available to the community, as well as their respective costs and benefits, both fiscal and social. When such adaptation measures are planned, the timing as mandated by the changes in hazard levels needs to be considered. So do the hazards' changing spatial distributions as a function of time. These demands may best be met by developing a *climate change adaptation plan* that balances the technical adaptation options and their costs against the benefits they provide to the community in terms of risk reduction. Several examples of such plans that address transportation were given in Section 6.3.3 and they are also covered in the NYC Panel on Climate Change study (NPCC, 2010), and include plans created for London, King County in Washington State, and the State of Maryland. The plan should also serve other objectives such as improving quality of life, infusing economic vitality, and ensuring long-term sustainability. Planning bodies typically set strategies on 20–30 year time frames, and operationalize these with shorter-term, 2–3 year implementation plans that are consistent with long-term goals (Lindquist, 2007). A major challenge is devising clear plans to maintain the basic functionality of urban transport systems in the face of potentially increasing

**[ADAPTATION] Box 6.3 Cities in Climate Change Initiative: Maputo, Mozambique**

**Paulo Junior and Bridget Oballa**

*UN-HABITAT*

The city of Maputo (Mozambique) is one of the four cities around the world where UN-HABITAT is providing capacity building and technical support to the implementation of the pilot phase of the Cities in Climate Change Initiative (CCCI). (The other three cities are Kampala (Uganda), Sorsogon (Philippines), and Esmeralda (Ecuador).) The main focus areas of the CCCI are: (i) awareness, advocacy, and policy dialogue; (ii) tool development and tool application; (iii) piloting climate change mitigation and adaptation measures; and (iv) knowledge management and dissemination.

Maputo is the capital city of Mozambique, it is located at the extreme south of the country, along the coast (Box Figure 6.4). The city is highly vulnerable to the impacts related to climate change since it is facing the Indian Ocean and is the most densely populated urban area in Mozambique. According to the 2007 census (INE, 2007) the city has about 1.1 million inhabitants; however, the metropolitan area Maputo–Matola–Marracuene shows a fluctuating population between 2.5 and 3 million. Maputo, like other African cities, is experiencing rapid population growth causing an increasing demand for housing and infrastructure (UNFCCC, 2006), especially in the peri-urban slum areas. Consequently, the risk of severe impact on the urban poor will increase along with their inability to adapt or relocate to safer areas.

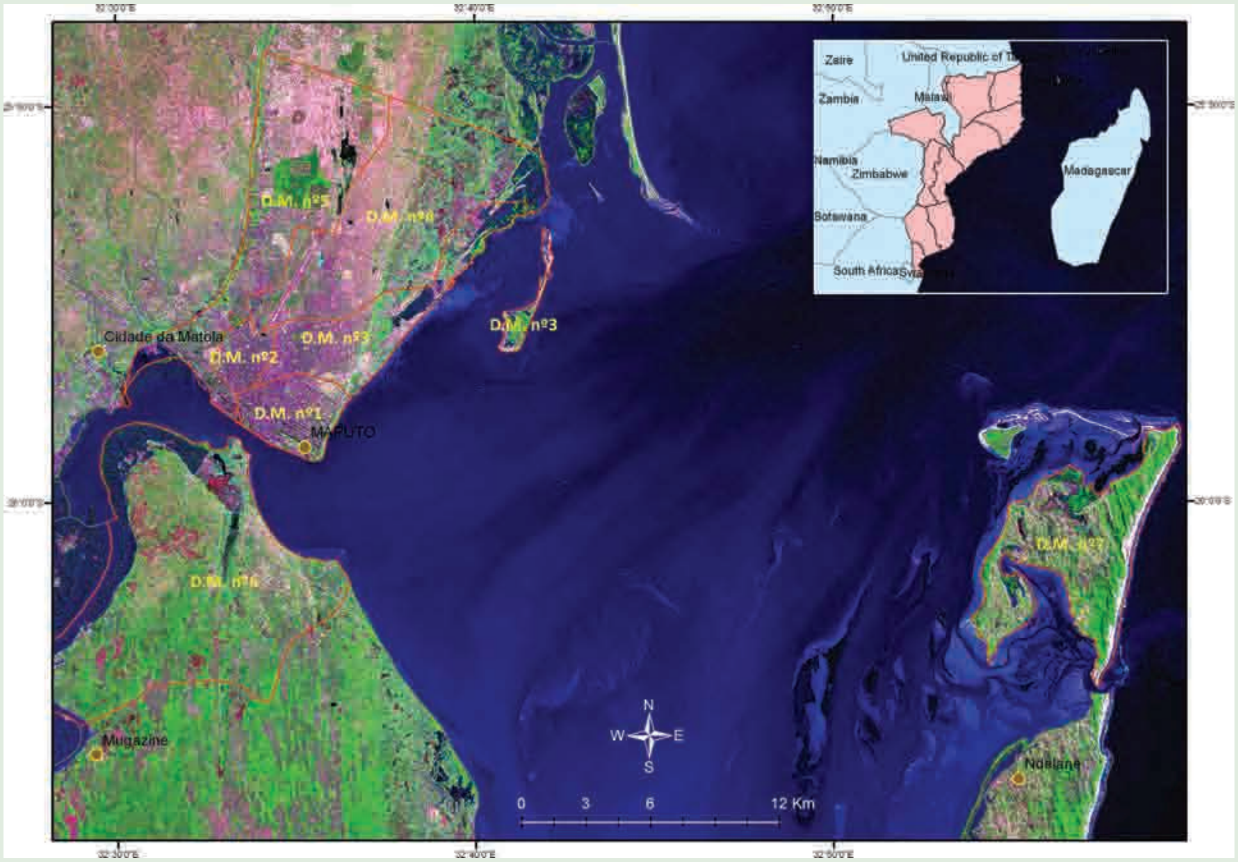
A preliminary assessment on climate change impacts in the urban areas of Maputo city was carried out, and key vulnerable sectors and areas have been identified:

- Coastal zones and ecosystems
- Human settlements and infrastructure
- Health, food security, and waste management
- Transportation system
- Wetlands and urban agriculture

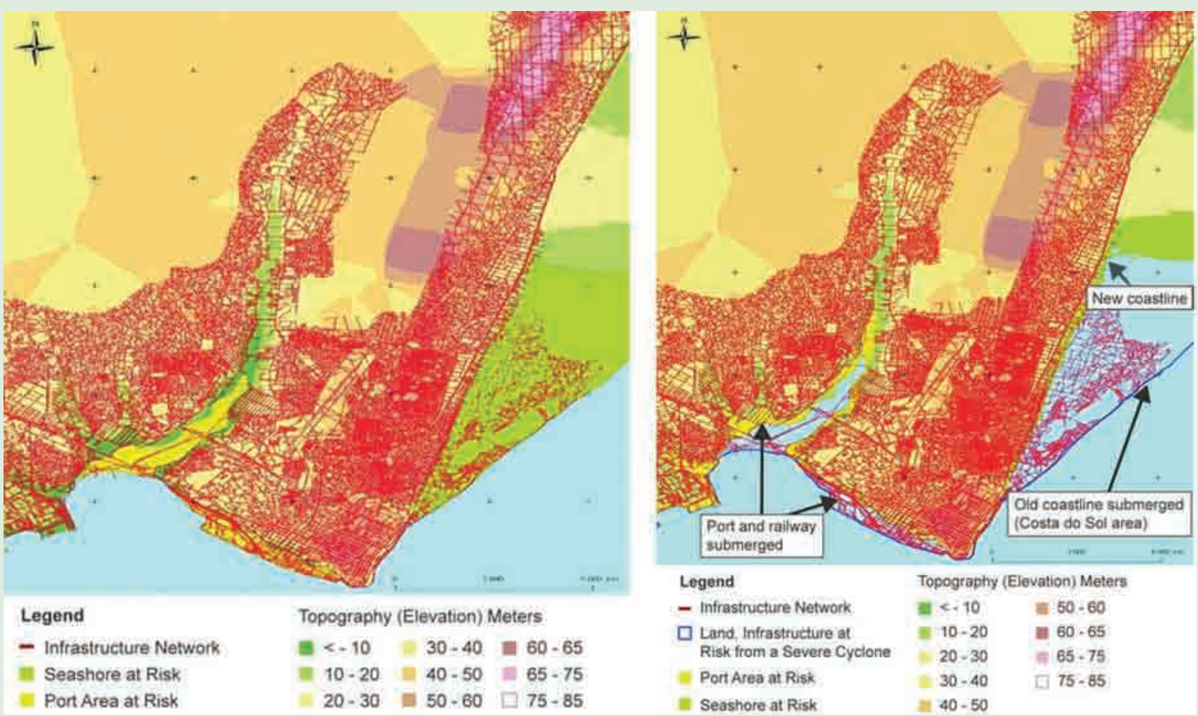
The main climate-related hazards with destructive consequences for these sectors are floods, droughts, rising sea levels, and storms (cyclones).

The predicted sea level rise related to global warming may result in flooding of the lowest topographical areas of Maputo, which are the most populated and where slum dwellers are concentrated. This prediction is also supported by the Mozambique National Adaptation Plan of Action to Climate Change prepared in 2007. The National Institute for Disaster Management's (INGC, 2009) study on the impacts of climate change in Mozambique shows that in the next three decades most of the coastal area of Maputo, including its harbor and other important infrastructure will be affected by sea level rise if no adaptation and mitigation measures are adopted, resulting in high economic and social costs (see Box Figure 6.5).

The assessment identifies the following for establishing a climate change adaptation strategy for Maputo city:




**Box Figure 6.4:** *Maputo City seen from satellite.*




**Box Figure 6.5:** *Map showing areas that can be affected by predicted sea level rise at 5 meters.*

*Source: INGC (2009).*


**Box Figure 6.6:** *Diagram showing the communication mechanism of the CCCI.*

1. Actively involving key stakeholders from the public sector, private sector, academia, civil society, and development partners in the process of raising awareness about the impacts of climate change at all levels.
2. Establishing institutional arrangements between city and central governments through the Ministry of Coordination of Environmental Affairs (MICOA) and the National Institute for Disasters Management (INGC), to ensure effective management and implementation of the climate change risk reduction plans.
3. Establishing communication mechanisms to ensure participatory and inclusive processes in the identification and implementation of sustainable solutions, including the creation of a Natural Disasters Risk Reduction and Climate Change Unit at local level.
4. Preparing an in-depth assessment of the impacts of climate change in Maputo city, in order to determine the required adaptation and mitigation measures to be implemented.
5. Developing methods and tools for the analysis of climate change effects in order to facilitate the financial planning and decision-making and preparation of a Climate Change Adaptation and Mitigation Plan of Maputo city, which identifies priority interventions to be implemented in the short, medium, and long term.
6. Creating synergy and coordination mechanisms with new initiatives, and ongoing projects, to jointly identify potential sources of funding, and ensure continuity of operations.

A CCCI inception workshop was organized in Maputo in May 2009 which was attended by stakeholders dealing with climate change impacts in Maputo: MICOA, INGC, National Institute of Meteorology (INAM), Maputo Municipal Council (MMC), representatives from academia, the private sector, civil society, NGOs, and development partners.

An outcome of the workshop was development of a stakeholder communication mechanism, with the municipal authority taking on the lead role in coordinating projects (see Box Figure 6.6).


**Box Figure 6.7:** *Threatened mangrove areas identified for immediate demonstrative adaptation/mitigation actions under CCCI.*

The threatened mangroves surrounding the Costa do Sol neighborhood (Box Figure 6.7) were identified as a pilot project site for initiating adaptation and mitigation responses. The aim of these immediate interventions is to map the mangrove area, and incorporate responses into the existing Master Plan, which includes special provisions for the protection of endangered species.

*Source: Cities in Climate Change Initiative (CCCI), UN-HABITAT, www.unhabitat.org.*

frequency and strength of storms. Managers can plan in advance to have contingency plans to maintain movement of people and goods in the urban regions when major highways or rail lines become impassable due to climate-related disasters.

### 6.4.2 Specific adaptation measures

The adaptation of transportation systems to climate change is a critical challenge since many of these systems are already in place and are rigid. The exceptions are some of the very large transportation projects underway in the planning stages. Key factors affecting the choice of adaptation measures are whether or not the hazards and threats are intermittent or continuous and whether they are acute or long term. Rosenzweig and Solecki (2001) consider short-term protective measures with local engineering, regional mega-engineering, and long-term land use change. The 2001 study concludes that the most effective and sustainable measures are via land use changes. According to the New York City Panel on Climate Change (2009), adaptation measures may be grouped into three categories: operations and management; capital investment in infrastructure; and policy. Adaptation actions for operations and management of transportation include changing travel routes; altering (reducing) travel behavior to avoid the congestion brought about by altering travel routes; altering repair cycles to anticipate ongoing repairs to damaged infrastructure. Capital investment adaptation consists of measures such as retrofitting existing infrastructure that is susceptible to climate changes – installing pumps to reduce flooding of vulnerable facilities; construction of permanent barriers in the case of water or wind to prevent exposure of transport systems to these forces. Policy oriented adaptation measures may include incorporating climate projections into the siting of transportation projects, e.g., avoiding the construction of roads and rails in areas vulnerable to climate change induced floods or storm surges; or adapting land use to store rain water and reduce wind speed in proximity to transport routes. While impacts vary by location and types of transportation systems, policy measures need to take into account national assessment of the consequences of climate

**Table 6.2:** *Climate change impacts on urban transport and adaptation mechanisms.*

| Climate hazard | Transport system component | Impacts targeted | Adaptation measure |
|---|---|---|---|
| Temperature | Roads, rail, transit vehicles, private vehicles | Adverse effect on speed | Milling out ruts; laying of more heat resistant materials such as asphalt for roads and more heat tolerant metals for rail and rail connections |
| Floods (sea, river, precipitation) | Drainage system; roads, rails, subways; transit vehicles, personal/private vehicles | Congestion, accidents, delays | Use of remote sensing technology to detect damaging water levels and trends<br>Bring in dikes and barriers<br>Better management of drainage system, detours |
| Storms | Roads, bridges, rails, airports, and subways; transit vehicles, personal/private vehicles | Accidents, delays, cancelled trips, limitations of routes | Ability to shelter vehicles by moving them into garages<br>Improving emergency evacuation planning<br>Building protective barriers<br>Higher clearance bridges |
| Sea level | Roads, rails, subways, and airports; transit vehicles, personal/private vehicles | Limits speeds and routes | Bring in dikes and barriers<br>Move vehicles to higher ground<br>Heavier use of pumps<br>Elevation of land and structures to minimize the impacts of flooding |
| Wind | Surface structures and facilities, such as overhead transit electric lines and signaling systems and road support systems such as lighting and traffic lights | Visibility, signaling system | Weighting down of vulnerable structures<br>Readiness in the form of repair equipment and maintaining a replacement inventory |

variability and change. For example, the United States assessments incorporate three types of analysis: regional, sectoral, and national overviews (MacCracken, 2002, p. 60). Table 6.2 provides a brief summary of the impacts of climate change on urban transportation systems and their components and specific adaptation measures. A comprehensive summary is presented in Annex 6.1. The table contains adaptation measures that many different transport systems, modes, and components share in common. For heat resistance, being able to rapidly install structures and facilities with materials to extend the temperature range of tolerance is critical. For water-related impacts from flooding, having barriers, mobile pumps, and drainage facilities that can be deployed quickly to flooded areas will reduce the impacts.

Adaptation measures for urban transportation systems for specific climate hazards are discussed here.

Numerous technologies exist to protect transportation from flooding and have been used routinely. At the extreme, where some roads and rail lines are subject to continuous inundation, some options for operations and management adaptation are: providing alternative travel choices; modifying operational procedures such as reversing the direction of roads and being able to backup trains; avoiding the added congestion on a more limited number of routes due to a shift in travel patterns by encouraging and in some cases mandating other travel choices to reduce the number of trips altogether (which will have mitigation as well as adaptation benefits); and using continuous pumps and drainage technologies (including clearing existing drains) to reroute water. Capital investment adaptation may entail construction of permanent barriers to keep water away from these routes. Policy measures include encouraging land use patterns that complement reduced travel (such as transit oriented development) and modifying land uses to include those that entrain or trap water, relying on porous surfaces and water absorbing uses such as parks.

Potential adaptation actions for transport via rivers might include: additional dredging in shallow areas, limiting the number and weight of barges, releasing more water from upstream sources (recognizing that this can interfere with other water uses such as hydropower generation, ecological resources, agriculture, municipal, industrial, and recreational) and finding alternate navigation routes or modes of transportation (DuVair, *et al.*, 2002, p. 131). For detailed considerations of how transportation systems along the Great Lakes are adapting see Quinn (2002). Additionally, Quinn identifies benefits from climate change to the transportation systems, such as the potential gains from year-round vessel utilization due to decrease in ice cover may exceed the costs imposed by lower water levels in the lakes.

Continuous episodes of high temperatures combined with stress from roadway usage by heavy vehicles can cause deterioration of transportation materials such as steel, concrete, and asphalt. Although the physical and chemical properties of these materials may indicate considerable resilience, the environmental conditions in which they operate, particularly the heat-related effects of climate change, can reduce their resilience. Asphalt can lose its stability in persistent heat. Steel can buckle, and a number of heat-related instances of rail tracks buckling have been documented in the United States and worldwide. Concrete can also buckle above certain temperatures. The adverse impacts of rising temperatures on transportation materials pose operational risks: "Longer periods of extreme heat in summer can damage roads in several ways, including softening of asphalt that leads to rutting from heavy traffic. Sustained air temperature over 90 °F is a significant threshold for such problems. Extreme heat can cause deformities in rail tracks resulting in speed restrictions and, at worst, causing derailments" (Karl *et al*., 2009, p. 65). Adaptation measures require retrofitting of existing assets and incorporation of higher tolerance to heat stress in ongoing and planned transportation investments.

If high wind speeds are intermittent, existing transportation systems can be retrofitted to resist wind damage, and usage during high wind events, when foreseen, can be reduced or eliminated. If high winds are continuous, permanent weighting down of structures may be in order. For example, structural work was added to several bridges in the United States after the Tacoma Narrows bridge collapsed due to high winds that resonated with and amplified the movement (Petroski, 1982 (1992 edition), pp. 164–165). Furthermore, land use can be adapted in a manner to shield transportation systems from high winds, by creating both natural and artificial wind barriers.

Where damage is discrete in space and time, namely it does not extend over large areas, section repairs are possible as an adaptive measure and one that can be programmed institutionally into repair cycles. This approach has been adopted in previous events, such as earthquakes and accidental infrastructure network collapses involving the destruction of bridge, road, and rail segments, providing analogies to what can happen with climate change. However, large-scale damage and complete collapse of structures requires the exploration of revision of design codes as well as, in some cases, relocation of assets. This has been the case in California and Japan for earthquakes, where local authorities in both of those areas have incorporated earthquake resistant structural requirements into construction specifications. Similarly, in areas subject to climate change impacts, equivalent changes in codes and other transportation design standards may be relevant.

### 6.4.3 Policy and economic considerations for adaptation

Adaptation includes modifications of both the transportation system and land use planning changes needed to reduce the vulnerability of urban mobility to climate-induced hazards. Transport infrastructure is capital intensive and has long gestation periods. Therefore, climate adaptation plans need to be coordinated with fiscal planning. Climate adaptation is different for different actors within the urban transportation system. For example, policymakers help adapt a city's infrastructure and its management. While individuals may change their behavior, the role of local authorities is to regulate and coordinate land use and transport systems such that passengers are less vulnerable to the hazards of climate change and therefore do not need to rely solely on expensive personal adaptation. Further, city-specific adaptation assessment of transport systems is essential as the adaptation response will vary. In the case of the Boston Metro Area, Suarez *et al*. (2005) conducted a system-wide analysis of the impacts of climate-induced stress such as riverine and coastal flooding on transportation network performance. Through modeling projected land use changes and demographic shifts and their impacts on transport demand, the study identifies future climate impacts that are likely to cause a "doubling in delays and lost trips." However, the study concludes that system-wide adaptation is not cost effective; instead, adaptation efforts should be limited only to some critical transport segments.

According to the Federal Highway Administration, at present, similar adaptation needs assessments and strategies with regards to transport infrastructure are lacking in most countries. Furthermore, the overall institutional response to the expected impacts of climate change on urban transportation systems is absent, causing most Metropolitan Planning Organizations and Departments of Transportation to withhold adaptation planning until better assessments are conducted.

In the fiscal year 2006–2007, four of the fifty State Departments of Transportation in the United States – California, Oregon, Washington, and Connecticut – and some of the seventy Metropolitan Planning Organizations surveyed mentioned climate change as a consideration. The few departments that were considering climate change focused on mitigation. Counter-intuitively, despite the long-term planning by Metropolitan Planning Organizations and Departments of Transportation, climate impacts on transportation and associated mechanisms for adaptation were neglected (Lindquist, 2007). However, increasingly some sub-national Departments of Transportation in the United States have stressed the need to fill this gap in adaptation assessments and have begun conducting needs assessments of climate impacts and adaptation planning for the shipping industry, such as relocation or protection of ports due to sea level rise, or alterations to transportation planning and management to incorporate climate risk assessments (Lindquist, 2007).

According to the Federal Highway Administration (FHWA, 2008), a growing number of Metropolitan Planning Organizations and Departments of Transportation are participating in or leading inter-agency initiatives on adaptation needs assessments and response planning. By 2008, the number of Departments of Transportation that were working to define transportation policy with regards to adaptation at the state and regional level had more than doubled, from four to ten states of the total fifty states surveyed. New York, Chicago, and San Francisco have initiated research into the effects of sea level changes and storm surges on infrastructure, and thus are establishing partnerships with regional agencies to facilitate coordination among local jurisdictions and establishing protective measures. Despite the lack of analysis, the Federal Highway Administration is encouraging city transportation agencies to take the lead by incorporating adaptation mechanisms into long-range transportation planning (FHWA, 2008).

When it comes to adaptation of urban transport systems to climate-related hazards, mass-transit systems – such as railway tracks, highways, and bridges – face political and fiscal constraints that differ from privately owned individual vehicles. This adaptation handicap is because urban mass-transit systems require lumpy investments – for instance, a subway system or a bus rapid transport system and highways may require hundreds of millions of dollars to initiate adaptation through retrofitting for interventions that have benefits long after the electoral cycle, making such decisions politically challenging, while individuals are free to make personal investments in their own vehicles as each deems appropriate (within the boundaries of regulatory requirements for inspection and maintenance, for example). Furthermore, because climate change impacts have implications in the long term, transport systems such as tunnels, bridges, rights of way, tracks, and roads, which all have long lifespans, are more susceptible to climate-induced risks and uncertainty. The same climate risks are considered to be less of a concern for personal vehicles such as cars and trucks due to the shorter lifespans of these vehicles. Large transit systems, especially low-carbon-emitting rail-based systems, have a greater challenge to adapt to the climate demands over the long term, given the political context in which investments are made. Thus, incremental adaptations as opposed to one-off interventions deserve attention. For instance, when new transportation systems are planned with expected lifespans of up to a hundred years (as is the case for subway systems), adaptation measures may be difficult to introduce quickly. In contrast, cars have a short lifespan of ten years. Therefore, car manufacturers adapt by improving technology with each new generation of cars, yet the design modifications have generally not been in a direction that prevents widespread damage to individual vehicles in disasters that are similar to those expected from climate change. Hence, adaptation in automobiles is occurring in manageable increments at small costs, commensurate with increments in improved climate change projections. In sum, a differentiated and complementary approach to adaptation of individually owned and more flexible transportation systems versus those that are large and lumpy mass transit systems is required.

## 6.5 Mitigation of greenhouse gas emissions due to urban transportation

This section identifies and categorizes mitigation strategies, discusses potential constraints on their effective implementation, and describes relevant policies and financial mechanisms.

### 6.5.1 Mitigation strategies

The transport sector represents around 30 percent of global $CO_2$ emissions, with urban transportation comprising more than half of this amount. This is the type of greenhouse gas emissions "that is expected to grow the fastest in business-as-usual scenarios, increasing at an annual rate of 2–3 percent" (Zegras, 2007, p. 112). The largest part of this growth is expected to happen in developing countries. Price *et al.* (2006, p. 122) forecast a worldwide average annual growth rate between "2.2 and 3.4 percent over the next 30 years.[4] During this 30 year period, the share of developing countries, in world transportation $co_2$ emissions, is projected to grow substantially (Price *et al.*, 2006). However, developing countries account for about five times the population of the developed countries. Thus, per capita urban transportation emissions in developing countries remain many folds lower than developed country cities. The aim of mitigation strategies is to reduce the transport carbon footprint of the city. Because of the complex interrelationships between transport, land use and climate change, reducing greenhouse gas emissions requires a two-pronged approach to tackle urban energy consumption, combining both transportation policy and land use policy. Linkages with other sectoral policies also are critical. For instance, see Chapter 4 on energy. For transportation, motorized vehicles can be made more efficient, carbon content of fuels reduced, use of private vehicles discouraged, and efficient non-motorized and public transport promoted. For land use, urban planning and land use regulation, property taxes need to be adapted to facilitate the concentration of private investment in areas of high accessibility, generated by the implementation of mass transport systems. This will reduce the need for mobility due to higher density and diversity of urban functions. Non-motorized commuting can also be encouraged through appropriate urban design and the articulation of different types of transportation. Table 6.3

**Table 6.3:** *Mitigation strategies for urban transportation systems and related land use.*

| | Demand | Supply |
|---|---|---|
| Transport | Transport demand management; speed limits; congestion pricing; fuel tax; public transport subsidy; promotion of non-motorized transportation; road tolls; parking fees; provision of eco-driving schemes. | Investment in mass transit system.<br><br>Regulation and incentives for improvement of vehicle energy yields or low emission fuels. Facilitate inter-modal linkages application of information technology. |
| Land use | Land use planning; provision of basic services; property tax regimes to discourage sprawl. | Zoning regulation; town planning schemes; incentives for high density urbanization, regulation to discourage sprawl. |

4 In comparison, Price *et al*. (2006) forecast an annual growth of 1.2–1.4 percent for OECD countries.

shows strategies for reducing greenhouse gas emissions in urban transportation systems, through a combination of demand and supply management policies in transportation systems and land use policies.

Regulatory instruments are applied in various forms; for instance, limiting the number of days a vehicle can be on the road, as is the case in Beijing, Bogota, and Mexico City's "hoy no circula" (one day a week, without a car) or quantitative restrictions on ownership, as in Singapore. However, unintended market distortions from such interventions require attention (for details see Bertaud *et al*., 2009). Efficient fuels and technology choices are alternate mechanisms to reduce $CO_2$ emissions. For instance, compressed natural gas (CNG) operated automobiles emit between 20 and 30 percent less $CO_2$ than automobiles operating on a regular gasoline engine (Ministry of Environment, Government of Japan, 2008). In this regard, over the five-year period from 1998 to 2002, in Delhi all public transport buses were converted to CNG operated systems largely due to a verdict by the Supreme Court of India (Mehrotra *et al*., 2009, p. 21, also see Box 6.2). Moreover, the Delhi Metro Rail Corporation introduced measures to reduce greenhouse gas emissions through the use of regenerative braking to capture the energy during deceleration and feed it back into the electrical system. Delhi Metro Rail is considered the first railroad company to obtain carbon credits through such an effort (Mehrotra *et al*., 2009, p. 24).

Pricing instruments (Table 6.4) modify consumer incentives; for instance, relative prices between private vehicles such as cars and mass-transit modes such as commuter rails. Cities around the world deploy different types of pricing instruments – fixed tolls and congestion pricing as in the case of Singapore, London, and Stockholm; fuel tax as in Bogota, Singapore, Chicago; parking charges as in New York, Sheffield, Edinburgh (Bertaud *et al.*, 2009). Some of these pricing efforts aim to reduce market distortions. Pricing congestion and parking, for instance, aims at adjusting the price of using a highway or of a parking space to reflect its economic value, including externalities due to congestion.

Pricing instruments also include subsidies. Subsidies are often aimed at redistribution. For instance, many transit fares are subsidized, as in Los Angeles, San Francisco, Mumbai, Delhi. Transit fare subsidies are aimed at increasing the mobility of low-income households, allowing them to fully participate in

**Table 6.4:** *Environmental benefits of congestion pricing.*

| City | Environmental benefits, including decline in carbon dioxide emission (per year) | Source |
|---|---|---|
| London (2002–2003) | Within the congestion pricing zone: 19.5% carbon dioxide emission reduced; 12% decline in oxides of nitrogen; 12% reduction of suspended particulate matter (PM10, particles <10 micrometers in diameter; 15% drop in vehicle kilometers travelled. | Beevers and Carslaw (2005) |
| | 12% decrease in traffic | Transport for London (2004) |
| | 2.3–2.5 million pounds in savings from carbon dioxide emission reduction; decline of 211–237 million vehicular miles travelled | Evans (2007) |
| | Reduction of 35% in pollution; total environmental benefits: €4.9 million | Prud'homme and Bocarejo (2005) |
| Stockholm (January–July 2006) | 13% carbon dioxide emission reduced (or 36,000 tons in saved emissions); 8.5% decline in oxides of nitrogen; 14% drop in carbon monoxide levels;13% reduction of PM10; avoidance of 27 premature deaths; 22% reduction of vehicle passages in congestion pricing zone. | Johansson *et al*. (2008), Lundqvist (2008) |
| Singapore (1998, 1992, 1975) | 75% reduction of car traffic during morning peak hours; in 1992 car volume was 54% of the pre-1975 level; in modal split, share of cars dropped from 48% to 29% immediately congestion pricing was introduced. | Olszewski (2007) |
| | 1998: Elasticity of passenger cars –0.106 within congestion pricing zone (–0.21 in the short run, –0.30 in the long run); 15% drop in daily traffic volumes. | Olszewski and Xie (2005), Olszewski (2007), Menon (2000) |
| | 1975: Traffic volumes in morning peaks reduced by 45%; car entries decreased by 70% | Willoughby (2000) |
| Milan (2008) | 9% carbon dioxide emission reduction (or 150,000 tons per year reduced); 19% reduction of PM10-emissions; savings of €3.3 million; 37% decline in ammonia ($NH_3$) emissions; 11% drop in oxides of nitrogen emissions; traffic reduced by 14.4% | Milan municipality (2009) |
| Durham | Number of vehicles declined by 50–80% | Santos and Fraser (2005) |

*Source: Adapted from Lefèvre and Renard (2009).*

a unified metropolitan labor market. Transit fare subsidies are also an incentive for car commuters to opt for a modal switch to transit. Although, this is not a very effective manner to increase transit mode share in the long run (Bertaud *et al.*, 2009).

Pay-As-You-Drive (PAYD) programs offer another mechanism to reduce vehicular miles traveled. With encouragement from public authorities, insurance companies are charging insurance premiums based on driving records and other traditional risk factors but are broken down into per-mile charges. Motorists have the opportunity to lower their insurance costs by driving less. When PAYD insurance is offered to a large percentage of California drivers, it may reduce vehicle miles traveled and associated greenhouse gas emissions (Lefèvre and Renard, 2009). Such strategies have limited application in a developing country city context, where car ownership is limited to a small fraction of urban households and most trips are by walking, bicycling, and other two wheelers, complemented by severely constrained mass transit systems. Instead, Perera and Permana (2009) present alternate strategies appropriate for developing countries using the case of Bandung City, Indonesia.

Bicycling is also being encouraged in developed country cities with the aim of reducing automobile dependency and associated greenhouse gas emissions. Strategies take the form of bicycle rental stations, being used in a number of European cities, and provision of bike lanes. On the other hand, while non-motorized transport accounts for a large proportion of commuter trips within the developing country city, the challenge with rising incomes is to facilitate the retention of such low emissions modes as well as complement with demand-responsive mass transit, as opposed to the present trend of low-cost motorized personal transport. Curitiba in Brazil has been a noteworthy example of the use of bus rapid transit in South America, though examples are now widespread throughout the world from Mexico City to recent efforts in Delhi. Shaping land use is also another way to improve accessibility while mitigating emissions; however, the degree of public control on land use varies significantly by jurisdictions and its efficacy remains debatable.

On categorizing energy consumption in urban transport in developing countries by the degree of land use planning: (1) controlled residential and commercial areas, (2) unplanned peri-urban areas, (3) planned satellite towns, Permana *et al*. (2008) find that, in Bandung City, Indonesia, households in "controlled residential and commercial areas" use transport systems – including walking and bicycling – that consume less energy than households in unplanned or planned areas. However, there are several confounding covariates, such as income and type of employment, which correlate with the type of land use (a proxy for house prices) and modal choices, that need to be analyzed further for relevance in alternate geographies.

New York City's mitigation efforts in transportation largely center on some key initiatives within PlaNYC (2007) and the Metropolitan Transport Authority's (MTA, 2009) Blue Ribbon Task Force. PlaNYC and subsequent regulatory and management initiatives to support the plan's goals, including environmental ones, emphasize anti-idling laws and parking restrictions. The city's congestion pricing initiative did not get the support of the New York State legislature. In the area of transit, the MTA, which is the primary provider of transit in the city, has incorporated a strategy of greening its stations and supporting facilities such as maintenance yards.

### 6.5.2 Assessments of mitigation potential and cost

There are some efforts to assess urban transportation sector mitigation potential and cost, but this is still an incipient trend, based on a city-by-city analysis. There is no worldwide urban transportation sector mitigation potential and cost assessment in the literature.

Until now, the issue of cost-effectiveness has been successfully applied to international negotiations, such as the European Emissions Trading Scheme (EU-ETS), and to national policies. Energy-economy or sectoral energy models have made it possible to simulate the economic impact of different policies and especially to build sets of marginal abatement cost curves. These mechanisms are efficient tools for analyzing different aspects of climate policies, particularly seeking to reduce the global cost through a certain leveling of the marginal costs of sectoral initiatives (Lefèvre and Wemaere, 2009). The development of marginal abatement cost curves for urban transportation aims to inform methodological efforts to measure and prioritize the actions to inform policymakers' choices.

For instance, the Siemens study of London's transport system (Siemens, 2008) estimates a reduction in transport emissions "by about one-quarter, from 12.1 million tons of $CO_2$ in 2005 to 9 million tons in 2025". The study identifies better fuel efficiency in cars as a cost-effective means of reducing carbon emissions from transport. In addition, hybrid cars and some biofuels hold abatement potential, albeit at higher costs, given present technology. London could save 0.3 million tons of $CO_2$ by 2025 by switching to hybrid buses and optimizing road traffic management. For similar calculations on how much *becaks* (human powered tricycle transport) and *ojeks* (motorcycle taxis) can contribute to reducing $CO_2$ in Bandung City see Permana *et al.* (2008). Increased use of biofuels could cut emissions by 0.5 million tons – assuming biofuels with low greenhouse gas emissions are used.

As cities are complex, a project-based approach is insufficient to reduce urban transportation carbon emissions. Instead an incremental programmatic approach is more likely to be highly cost-effective such that local climate action plans apply a systemic approach to innovations in spatial organization and transportation planning in the broader context of city development and management. For a case study of such an incremental approach see the case of Bandung City (Perera and Permana, 2009).

### 6.5.3 Constraints to mitigation in urban transportation systems: prospects for green technology diffusion

In the near future, "emergence and large deployment of viable green individual transport technologies is limited" (Pridmore, 2002; Cabal and Gatignol, 2004; Assmann and Sieber, 2005). A study by Heywood *et al.* in 2003, as cited by Zegras (2007), assesses the potential for advancements in passenger vehicle technology "in the United States over a 30-year horizon and concludes that a combination of technological improvements and demand management will be required to reduce transportation energy consumption". Furthermore, according to Assmann and Sieber (2005) the additional time needed for a well-established technology in developed countries to penetrate the market in developing countries is around 10 years. Consequently, according to some estimates a new "green" car, launched today in the developed world, will take 40 to 45 years to reach a significant share of the market in poor countries (Cabal and Gatignol, 2004). However, the pace and scope of global technological diffusion remains a subject of great debate and these estimates need to be revisited as empirical data on technology transfer from developed to developing countries and vice versa becomes available for the urban transport sector.

Mitigation of urban transportation systems requires multilevel-governance arrangements – city level, regional, national, and in some cases global. For instance, while a city can ensure that all vehicles used for city operations are fuel efficient (including taxis), it requires federal legislature to set fuel economy standards and enforce compliance by automakers, as was the case in Santiago (Chile) and Bogota (Colombia). At the national scale, the U.S. has instituted Corporate Average Fuel Economy (CAFE) standards for automobile manufacturers for each model year. (NHTSA 2010). Additionally, measuring carbon emissions at the city scale is challenging for several reasons – the city's jurisdiction does not necessarily overlap with the urban agglomeration, embedded carbon in goods consumed within the city but produced at long distances, or emissions due to transit passengers all pose accounting challenges. In the case of Bandung city, as in many other cities, land use, energy, and transportation policies lack horizontal interagency coordination and vertical intra-sector collaboration (Perera and Permana, 2009).

Public policies that accomplish greenhouse gas reduction in the urban transportation sector are challenging in part because climate change competes with other pressing priorities. Policymakers, especially those in developing countries, face the challenge of ensuring sustainable development of their transportation sector in order to meet the demands of rapid urbanization, economic growth, and global competition. The green agenda is limited to local environmental challenges, especially local air quality, a classic example being Delhi. However, co-benefits from these efforts offer positive externalities in emission reduction as well as capacity-building for institutional response to combat climate change (Mehrotra *et al.*, 2009).

Non-point sources imply diffused emission, making it difficult to collect baseline data for monitoring and evaluation of emissions and their reduction. Additionally, a life-cycle analysis is required if greenhouse gas emissions in the urban transport sector are to be fully accounted. Due to diffuse emission sources it is difficult to involve the key actors necessary to influence the level of greenhouse gas emissions for a given urban transportation system. Finally, due to lack of capacity and willingness of local institutions, enforcement is ineffective.

### 6.5.4 Mitigation policies

Policy objectives for greenhouse gas emission reductions in the urban transportation sector may include both demand-and-supply-side initiatives (see Table 6.3 for example). Demand-side interventions include reducing the need for transportation through land use planning and incentives for decreasing vehicle miles traveled. Some instruments include congestion pricing, charging user fees for parking, and fuel tax to internalize the social cost of the transport sector into pricing to correct for market distortions that presently do not price environmental degradation due to carbon emissions; incentivizing use of clean fuel vehicle technology, and the like. Supply-side interventions include enhancing the provision of energy-efficient mass-transit systems; regulating land use to preserve and enhance carbon sinks (forests, wetlands) when considering locations of new infrastructure facilities as well reducing the need for transit through better land use management; and coordinating land use and transport policies to exploit synergies (Schipper *et al.*, 2000).

The key stakeholders for mitigation response are various levels of government, firms, and households. While the state takes the lead on supply-side initiatives, including regulation and provision of transport systems and providing incentives for behavioral change, private and public vehicle producers respond by supplying various degrees of fuel efficiency in transport modes – cars, rails, and buses. Consumers – both households and firms that consume transport services – lead demand-side initiatives, including consumer choice of transport modes and the like. However, the various levels of government, types of vehicle producers, and consumers of various transport services have a complex set of overlapping and conflicting interests. For instance, while transit-oriented local governments may create incentives for mass-transit systems, state governments with car manufacturing bases may oppose such initiatives. Likewise transit may be welcomed by non-car-dependent urban communities and resisted by car-dependent suburban communities and vice versa. The effectiveness of such mitigation instruments also varies between developed and developing countries. In many developing countries, as car ownership is limited and demand for transportation services is rapidly growing, creating incentives for fuel-efficient private and public transportation systems can yield substantial gains in reduction of the growth of greenhouse gas emissions.

### 6.5.5 Financial tools and incentives

Two key incentive mechanisms for mitigation of greenhouse gas emissions from urban transport systems are intergovernmental transfers and carbon markets. Federal transfers for management of ecological goods and services, which are public goods with positive externalities beyond local jurisdictions, are in practice. For example, since 1996, the "German advisory council on the environment has called for the integration of ecological indicators into intergovernmental fiscal transfers" and performance indicators. For instance, financing is determined partially on the basis of improvements in rural land management and protection of nature reserves (Perner and Thöne, 2005). In India, the thirteenth finance commission advised that 7.5 percent of fiscal transfers to states and union territories be based on percentage of forest cover (Kumar and Managi, 2009). While these environmental grants are performance-based the scope of the projects is limited, but such federal grant conditionals can potentially include broader concerns of climate change, including urban transport mitigation, as in the case of Klimp, a Swedish investment grants scheme targeted at sub-national level governments to address climate change.

Likewise, carbon markets are underutilized for energy-efficient urban transportation. Only two out of twelve hundred clean development mechanism (CDM) projects that have been registered by the UNFCC's Executive Board address urban transportation projects. These two projects are TransMilenio, Bogotá's bus rapid transit, and Delhi subway's regenerative braking system (Mehrotra *et al.*, 2009). Together these two urban transport projects represent less than 0.13 percent of the total CDM project portfolio.

The underutilization of CDMs for urban transport projects is due to three key factors. First, there is a mismatch between the local expertise and global requirements. Local government priorities and associated skills are aimed at developing transport projects to ease severe mobility constraints in developing countries. In contrast, the global institutional requirements of CDMs and the associated standards and fees for screening applications and fulfilling requirements are often beyond the scope and abilities of local governments. Second, due to the diffused emissions in the transportation sector, the cost of aggregating data is high. Thus CDM's "act and gain money" incentive has limited impact. Third, basic CDM project requirements are difficult to fulfill for urban transportation: project boundaries are difficult to define due to up- and down-stream leakages, establishing credible baselines is difficult due to constraints in data collection, and data constraints render monitoring methodologies unreliable.

Enhancing the proportion of urban transport projects within the existing CDM framework may require focusing on short gestation and high-return energy-efficient technologies – technology switch to energy-efficient engines and fuels switch; mass-transit systems; information technology for transport systems optimization, such as smart traffic light systems bundled together for programmatic CDMs. Mehrotra *et al.* (2009) elaborate on the efforts of the city of Delhi, where additional opportunities for utilizing CDM related to urban forestry, street lighting, and landfill are illustrated. These have co-benefits for urban transportation sectors that are yet to be explored. Like the CDMs, the urban transport sector has yet to adequately utilize the Global Environment Facility (GEF), established in 1991 to support developing countries in tackling climate change mitigation and adaptation (Colombier *et al.*, 2007). Thus, project preparation and development support remain a critical gap in linking urban transport to broader climate change and environmental initiatives. In addition to carbon markets, the Partnership on Sustainable Low Carbon Transport, among others, is exploring alternate strategies for financing low-emission urban transport systems through pooling of public and private resources as well as sector-wide approaches to low carbon transport.

**[MITIGATION/ADAPTATION] Box 6.4 A sustainability framework tailored for transportation and applied to Sydney, Australia**

**Ken Doust**

*Asset Management & Sustainability Assessment, Atkins Global*

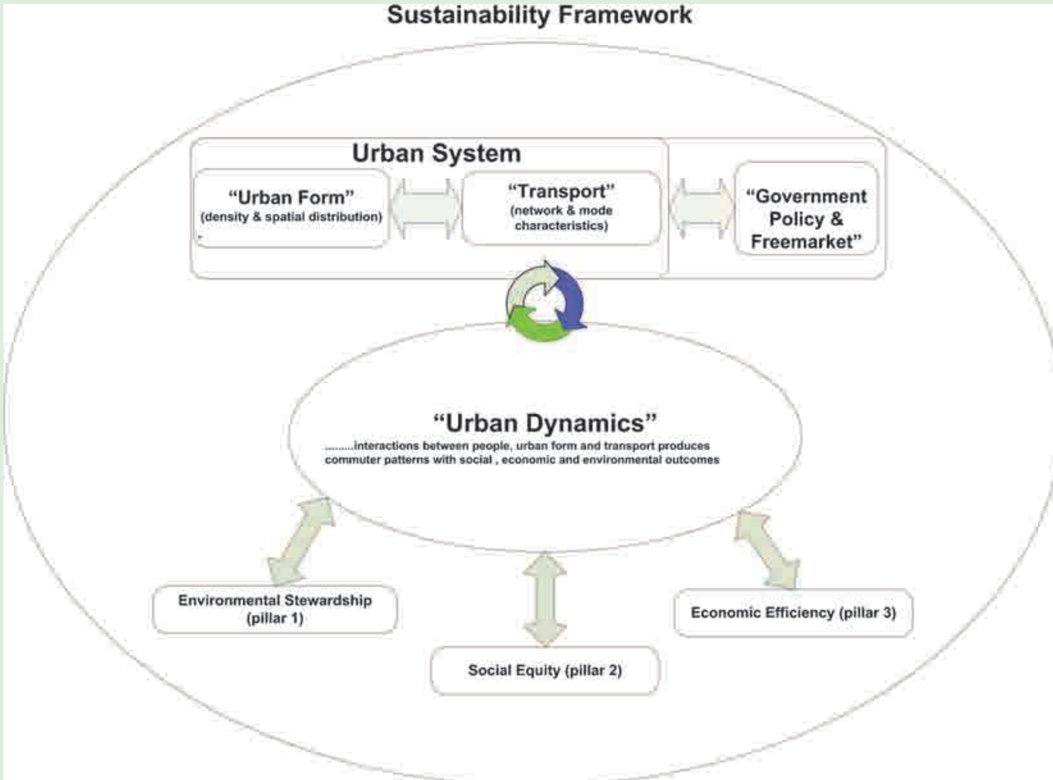
**John Black**

*School of Civil and Environmental Engineering, University of New South Wales*

CUSCCRR (Coalition of Urban Sustainability & Climate Change Response Research) Urban transport system characteristics and system vulnerability provide the basis for a climate change scenario in the context of a sustainability framework as shown in Box Figure 6.8. Climate change impacts are drawn in from physical infrastructure characteristics, network relationships, and behavioral changes, which can vary for different cities. The sustainability metrics incorporate the capability to mitigate and resilience for adapting to climate change impact.

Sydney, Australia, is used to illustrate and visualize the metrics and the environmental sustainability measure (Pillar 1), formulated from known fuel consumption of vehicles (see Cosgrove, 2003, p. 342) with speed and used to calculate carbon dioxide equivalent ($CO_2$-eq) footprints for motor vehicles between each trip origin/destination pair.

Sydney's transport system primarily consists of tolled motorways, arterial roads, and an extensive suburban heavy rail system with a heavy reliance on cars in the suburbs. Estimated annual transport greenhouse gas emissions for Sydney Metropolitan area rose from 9.8 million tons in 1990 to 12.2 million tons in 2001, and emissions are forecast to rise to 16.8 million tons by 2020 on current trends. Car




**Box Figure 6.8:** *A sustainability framework – tailored for transport infrastructure.*

usage contributes 67 percent of these emissions (www.bitre.gov.au/publications/93/Files/r107.pdf, Tables 3.13 and 3.14, accessed August 18, 2009).

A quantifiable measure of greenhouse gas mitigation effectiveness was developed from detailed operational methods, using transport planning building block techniques (Doust, 2008, Chapter 4). The scenario is based on the combination of two concepts, accessibility and environmental sustainability.

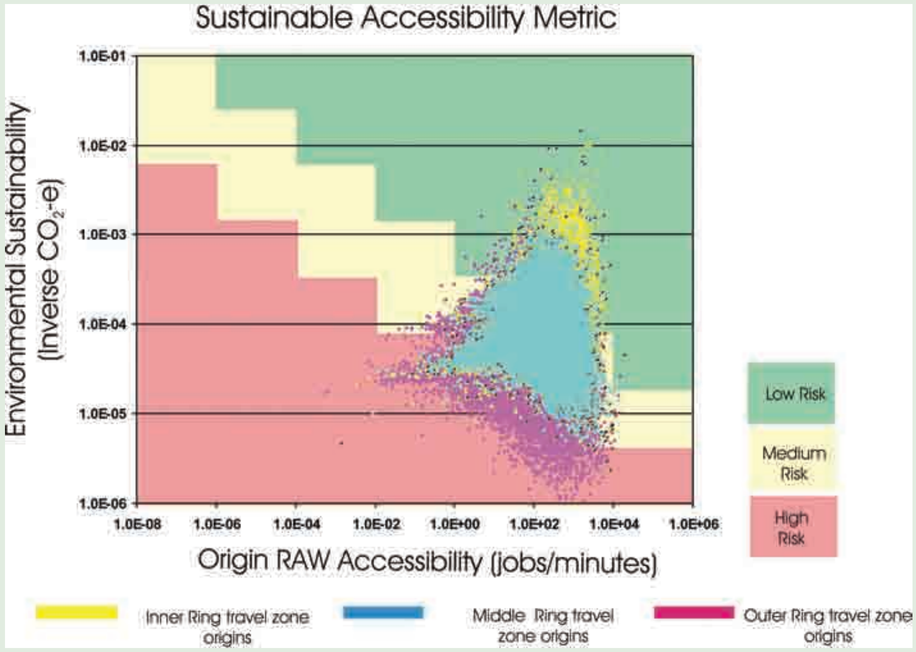
Accessibility has been identified as a useful measure in social and economic aspects of sustainability (see Expert Group on the Urban Environment, 1996; Warren Centre for Advanced Engineering, 2003; Kachi *et al*., 2005, 2007). In the Sydney Case Study, accessibility measures were derived (Doust, 2008, Chapter 4) for each travel zone pair. Separate operational methods were developed to generate worker and employer focused accessibility measures. These are measures that are relatable to social equity (Pillar 2) and economic efficiency (Pillar 3) respectively.

Environmental sustainability measure is defined as the inverse of $CO_2$ emissions from the total Journey to work trips between zone pairs, including an allocation of emissions from manufacture of vehicle and road infrastructure. This is calculated as a sum of the $CO_2$-eq per unit trip km at the average speed with the shortest path trip length and number of trips. The $CO_2$-eq is calculated as the sum of the quantity of greenhouse gas and the Global Warming Potential Index (AGO, 2005, Appendix 3).

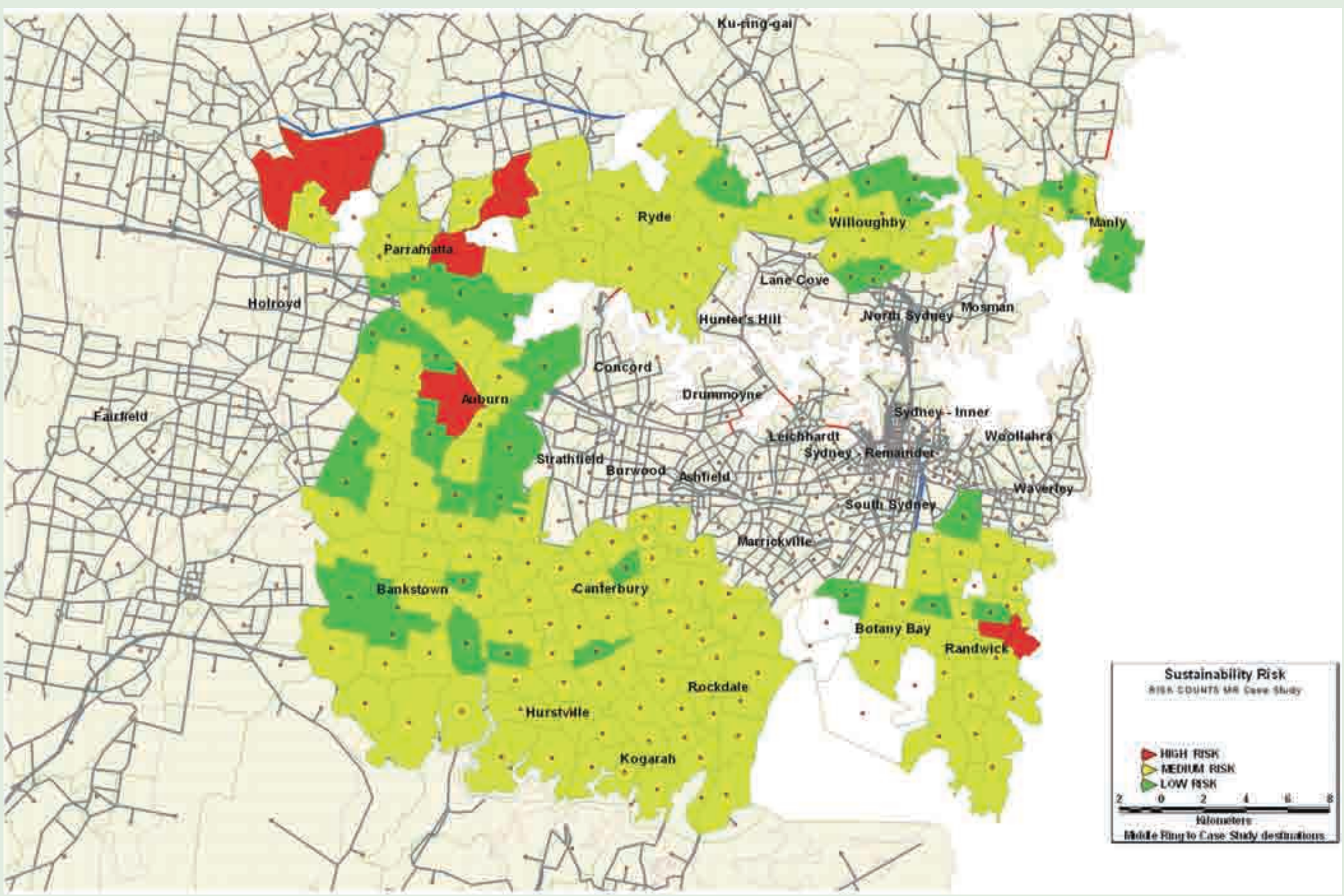
These metrics can also be applied in a way that expresses sustainability performance in terms of sustainability risk. High risk, where sustainability performance is poor, is indicated by low metric values. Low risk, where sustainability performance is satisfactory, is indicated by a higher metric value, above a community accepted minimum target. The grid concept can be likened to a risk matrix allowing each zone pair to be assigned a sustainability risk rating (Box Figure 6.9). The sustainability risk boundaries are specific to each city, and influenced by the population's estimated resilience.

This sustainability risk rating can then be plotted onto geographic space using geographic information system (GIS) thematic mapping. Box Figure 6.10 illustrates such a visualization in geographic space.

Each of these visualizations provides insight into the position, spread, and internal distribution trends for a city's urban sustainability pillars of environmental stewardship, social equity, and economic efficiency. For community and decision-makers these visual differences give a simple snapshot of overall sustainability performance for each scenario being considered. It is straightforward to change the scenario, use the building block techniques, and produce a new metric plot to see the sustainability effect of the policies embedded in the scenario. Stakeholders can see measurable change for their communities in relation to sustainability goals. The process provides another dimension to visioning and sustainability strategy development by adding the means by which a community can measure and judge one infrastructure and urban form scenario with another.




**Box Figure 6.9:** *Sustainability performance risk overlay to Sydney Inner, Middle, and Outer Ring results in 2001.*




**Box Figure 6.10:** *Sustainability risk rating plotted onto geographic space.*

A particular strength of using the sustainability framework, and the metrics demonstrated here, is that they are derived from data sets that have been commonly used by urban and regional planners for many years. Visualizations of this type can be used to inform decision-makers (community and government agencies) in the process of choosing climate change policies and programs for a city.

Under climate change, scenario systems are also at risk of failure. The current process of determining the metrics under an operational system state is to be extended to also estimate the metrics under failed system states due to transport infrastructure system vulnerabilities to climate change impact. The methodology discussed in this case study provides a useful tool for each city beginning to understand how they should respond to climate change. Every city will have its own unique set of urban response scenarios to choose from in mitigating greenhouse gases, and each of these will need to occur in a future that does involve adaptation to climate change impacts of some degree. The more there is understanding of the effectiveness of each of these urban response scenarios, inclusive of the adaptive capability, in balance with other sustainability pillars, the greater the likelihood of real outcomes being realized for each of our cities.

This Case Study is based on the original research titled "Metrics of Environmental Sustainability, Social Equity, and Economic Efficiency in Cities" Doust, K. (2008). Papers from this research have been published in the following peer reviewed journals and conference proceedings: Black and Doust (2008); Black *et al.* (2010); Doust (2010); Doust and Black (2008); Doust and Black (2009); Doust and Parolin (2008); Doust and Parolin (2009); Nakanishi *et al.* (2009).

## 6.6 Key uncertainties, research needs, and information gaps

Many levels of uncertainties drive research needs and define information gaps, these range from the identification and degree of certainty of climatic factors and consequences specific to transportation to the performance of transportation technologies for both mitigation and adaptation and their relationship to other infrastructure.

The IPCC (2007a) has identified three macro-scale uncertainties in assessing transportation adaptation and mitigation potentials for any city. The first uncertainty relates to the international price of oil and associated demand for alternate fossil fuels. The second uncertainty relates to the pace of innovation in alternate energy sources such as biofuels, externalities associated with their large-scale consumption: food prices, water shortages, and the like, and batteries. The third uncertainty is the timeline on which policies on greenhouse gas emissions reduction will be adopted and implemented by developed and developing countries.

Other critical issues pertain to the availability of, and access to, information at the international level. First is the lack of data on transport energy consumption in developing countries now and projected for the future, and thus uncertainties in the magnitude of emissions that will occur as a result of energy consumption overall and the use of alternatives to oil. With a few exceptions, the geographical focus in the present research is on developed country transport systems, especially in the United States and Europe. There is a gap in the literature on the implications of climate change on urban transport policy and planning in developing counties.

Second is the absence of a broad framework to assess global opportunities and costs of reducing greenhouse gas emissions in the transportation sector. Consistency and coordination is needed among international agencies in their support of climate-friendly transportation projects and longer-term goal setting. The availability and distribution of information about adaptation and mitigation vary from local to global levels in both developed and developing countries, and this variability contributes to problems of coordination and consistency.

Potter and Savonis (2003) and Hyman *et al.* (2008) outline some of the important research needs and challenges to prepare transportation system for the impacts of climate change. Regional and local-scale climate projection models that incorporate unique attributes of the urban transportation systems are lacking. But downscaled assessments are a prerequisite for transportation planners to identify facilities and locations that are vulnerable to the impacts of climate-related events. Further, impacts need to be disaggregated into implications for operations, maintenance, and safety of transportation systems for the short- and long-term effects.

City managers require new tools to evaluate the benefits and costs of a range of response options that incorporate future uncertainties into modal choices, siting infrastructure, design and engineering standards, and the like. For example, "[it] is unlikely that infrastructure improvements such as realignment of roadways, many of which run through river valleys, can be justified on a cost-benefit basis" in the Boston area (Tufts University, 2004, p.155). Additionally, there is a need for improved techniques for assessing risk and integrating climate information into transportation planning and management within the broader context of city planning and management.

On top of these uncertainties and gaps in knowledge are those within climate science itself, discussed extensively in other chapters. One example is the extent of ice melting and its impact on sea level rise at specific geographic locations. Another is the intensity and frequency of storms in light of the difficulty of predicting cloud formation and, more recently, the influence of changes in monitoring protocols of storm frequency and intensity. These climate uncertainties combine with uncertainties associated with the consequences of climate conditions specifically for transportation at any given place and time. Finally, the performance of technologies in reducing the adverse consequences adds another layer of uncertainties which reflects gaps in knowledge. For example, construction standards and the designs of transportation infrastructure will adapt to climate change impacts depending on environmental factors that affect the strength of the new systems.

Research gaps for adaptation include the need for knowledge on how climate hazards will affect transport infrastructure, including the engineering design and performance standards for urban transport systems and associated infrastructure assets. Furthermore, research on relationships between climate hazards and social and economic impacts related to urban transport systems is much needed. For instance, research on quantifying the expected impacts of climate change on types of transport systems and their users is lacking. Further, there is need for research analyzing climate impacts on planned investments in the transport sector, as most research focuses on climate impacts on existing transportation systems. Finally, intra-and-inter sectoral co-benefits of adaptation and mitigation need attention (Lindquist, 2007). For example, transportation is dependent on electric power and telecommunications as well as water and environmental services and will be affected by adaptation and mitigation efforts in these sectors. Likewise, changes in the the delivery of goods and services for transportation industry supply chains will affect the transportation systems as well.

Research needs and information gaps for mitigation include the evaluation of specific mitigation policies for effectiveness in reducing greenhouse gas emissions from transport in a city; and economic costs of mitigation in the urban transport sector with careful consideration of areas in which mitigation measures for transport might conflict with others and actually contribute to greenhouse gas rather than reducing it. For instance, there is a need for comparative studies on the cost of producing and switching to clean fuels and new vehicle technology so as to allow urban transport planners and stakeholders to make informed choices on new technology options for low-emission transportation systems. Finally, as with adaptation, the feasibility for mitigation of various options in light of the extent and role of the interdependencies within various transportation sectors (Lindquist, 2007) and between the transportation sectors and other sectors and activities with which transportation interacts or affects must be studied. For instance, there is a need for further research on methodologies for standardizing inventories from transportation emissions and criteria for including emissions from national, regional, and local transport systems that extend beyond the jurisdiction of cities and are interconnected with other sectors such as telecommunications, energy, and water. There is also a need to explore the interaction between the energy intensity resulting from modal choices and their interaction with types of land uses and other urban infrastructure systems.

Thus, large uncertainties will continue to exist and new ones will continue to emerge as summarized above in the science and technology that justify and support moving forward on both adaptation and mitigation. In light of this, some have argued that the key strategy is to move forward on reasonably robust measures and to evaluate the performance of those measures over time, rather than to await the resolution of uncertainties before acting (Dessai *et al*., 2009). For transportation, adopting such a policy with its accompanying strategy suggests moving ahead with a multi-pronged approach that emphasizes the availability and use of multiple modes of travel that avoid greenhouse gas emissions and at the same time are flexible and resilient to the impacts of climate change, that is, made of more resistant materials and able to withstand potentially prolonged flooding and the intensity of storms.

## 6.7 Conclusions

Generally, public actions aim to anticipate and frame market-based urban development toward a more energy-efficient city. That can involve analyzing market dynamics – transport markets, real-estate markets, and housing markets – and integrating them in local urban planning. A challenge is to adopt a planning model that works to create dynamic middle- and long-term urban development trajectories, rather than static or “one-off” systems.

The combination of adaptation and mitigation policy instruments to be implemented for the urban transportation system is a city-specific issue combined with overarching global policies as a guide. Transport policies are easier to implement, but their potential to reduce greenhouse gases may be lower than for other activities. Land use policies can be stronger levers of action to reduce greenhouse gas emissions due to urban transportation, but they may be harder to implement.

For cities in developing countries, the challenge is more to keep their mixed land use and high-density settlements, and transport systems in which low-emission modes are still dominant, without compromising efforts for future economic development and urban poverty reduction, both of which rely on expanding effective and efficient transportation systems and associated modal choices.

Public education and effective communication on policies that aim to reduce greenhouse gas emissions are important aspects for successful promulgation of adaptation and mitigation policies in urban transportation systems. These efforts can emphasize local co-benefits in and seek to gain – and secure over the long-term – public support for these measures.

Finally, several elements have emerged for climate change adaptation and mitigation policies to be successful for urban transport planning and management. These include strong leadership and even championing climate change mitigation; an effective outreach and public education campaign; risk assessment, benefit-cost analysis, and management – particularly for adaptation; mainstreaming of climate concerns in transport planning and policymaking; higher-level government or international community provision of incentives to mainstream climate – not only through funding, but through international recognition as well; technology transfer; regional–local governance coordination; assessment of the capacity to act among all actors – all levels of government, private sector and individuals; and overall, attention to reduction in vehicle miles traveled through land use and other strategies that may accomplish this. Science-based policy is crucial.

## Annex

**Annex Table 6.1:** *Impacts of climate change on transportation.*

| Climate change | Infrastructure impact | Operations impact | Adaptation measures | Sources |
|---|---|---|---|---|
| **Temperature-related** | | | | |
| Temperature increase | Pavement damage; asphalt rutting | Traffic speed | Frequent maintenance; milling out ruts; laying of more heat-resistant asphalt | Andrey and Mills., 2003 (Canada); Wooler, 2004 (United Kingdom); Soo Hoo, 2005 (Seattle) |
| | Deformation and "deterioration of road and rail infrastructure from buckling and expansion" (CRI, p. 59) | Potential for derailment of trains; decreased travel speed | Improved monitoring of rail temperatures and more frequent maintenance track; speed restrictions | OFCM, 2002 (Mid-Atlantic, U.S. Amtrak derailment incidence 2002, pp.1–7); Caldwell *et al.*, 2002 (p. 11); Wooler, 2004 (United Kingdom) |
| | | Heating of underground cars and lack of ventilation. | | Wooler, 2004 (London) |
| Extended period of growing season for trees and vegetation | Obscuring signs; slipperiness (by fallen leaves) on roads<br>Potential for derailment of trains; decreased travel speed | Better management of foliage; better management of trees that grow alongside the transportation corridors; planting slower growing plants to reduce leaf fall | | Wooler, 2004 |
| Temperature increase in winter | New passages for marine transportation (Northwest Passage) | Less spending on winter maintenance for snow and ice control; less pavement damage from frost | | Andrey and Mills, 2003 (Canada); Kinsella and McGuire, 2005 (New Zealand); Infrastructure Canada, 2006 |
| Freeze–thaw cycle frequency increase | Premature damage of pavement, roads, runways, railroads and pipelines. | | | Caldwell *et al.*, 2002 (p.11); Mills and Andrey, 2002 (p. 79) |
| Thawing of permafrost | Damage to roads, rail lines, pipelines, and bridges; affect northern latitude (Alaska) more severely because it depends more heavily on frozen roads for freight movements | Road capacity to sustain transportation is reduced | Need for different construction methods, such as installment of cooling machineries | Caldwell *et al.*, 2002 (Alaska region, p. 10); Infrastructure Canada, 2006 (Manitoba region, p. 13) |
| Other | Reduction in ice loads on structures (bridges and piers) | Extended transport-related construction season due to warmer temperature | | Andrey and Mills, 2003 (p. 246); Lockwood, 2006. |

**Annex Table 6.1:** (*continued*)

| Climate change | Infrastructure impact | Operations impact | Adaptation measures | Sources |
|---|---|---|---|---|
| **Water-related** | | | | |
| Increase in precipitation amount and frequency | Erosion and decay of the physical structure in the track subgrade. | Instability of the tracks for the transit of heavy engines. | Improvement of remote sensing technology that allows detection of water bodies and air pockets | Wooler, 2004 (London, Liverpool); Kinsella and McGuire, 2005 (Western half of New Zealand, p. 6); Kafalenos, 2008 (pp. 4–20) (Gulf coast region); CRI, 2009 (New York City) |
| | | Flooding of roads, basement and sewer will overload drainage systems more frequently, resulting in more wear and tear on equipment and infrastructure | Increased congestion, accidents, and delays | Better management of drainage system, detours |
| | | Snow accumulation on roadways | Disrupts traction control, visibility, and increases crash risks | Improve advisory system and perform pretreatments on roadways |
| Decrease in precipitation amount and frequency | Likelihood of drought which affects growth of roadside vegetation. | Less disruption to construction and maintenance activities; mobility benefit | | Mills and Andrey, 2002; Kinsella and McGuire, 2005 (Eastern half of New Zealand, p. 6) |
| Sea level rise | Progressive damage caused by flooding to the infrastructure that lacks a fouling-resistant design against salt water. | Limits speeds and routes | Frequent maintenance, relocation, construction of flood-defense mechanisms, such as dikes; elevation of land and structures to minimize the impacts of flooding; heavier use of pumps; | Titus, 2002; Wooler, 2004 (London, Liverpool); Kinsella and McGuire, 2005 (New Zealand coastal highway); Infrastructure Canada, 2006; Kafalenos, 2008 (Gulf coast, New Orleans buses and streetcar, pp. 4–17); CRI, 2009 (New York City) |
| Increase in the frequency or intensity of extreme weather events | Storm surge (and/or wave crests) – damaging roadways, bridges, rails, airports, and subways; structural damage to street, basement and sewer infrastructure due to wave action; degradation of road platform | The reduction in routes caused by the power outage increases the need for the implementation of emergency plans, to reduce traffic delays and travel rescheduling. | Preventive design of emergency systems (as well as evacuation plans) include protective barriers, relocation of physical supplies, ability to generate alternative road routes and higher bridgesover water surface. | Mills and Andrey, 2002; Tufts, 2004 (Boston); Kinsella and McGuire, 2005 (New Zealand); Jacob *et al.*, 2007 (New York City); Kafalenos, 2008 (pp. 4–15, Gulf coast); Meyer, 2008 (p.6, Gulf coast, bridges); CRI, 2009; Zimmerman and Faris, 2009 |
| | | High winds and lightning could damage overhead cables, vehicles, trees, signs, etc. | Debris blown onto the roadway impacts visibility; produces power outage, fires, and disrupts signaling system | Adapt transportation systems to defy wind damage (as was done by appliying a second layer to several bridges after the Tacoma Narrows bridge collapse) |
| Decrease in storm frequency or intensity during winter | | Facilities of transportation for operators and users | | Mills and Andrey, 2002 (p.77) |
| **Other** | | | | |
| Humidity increase (fog) | | Reduces visibility and increases crash risks | Signs, speed control, monitor | Lockwood, 2006 (Annex A) |

*Source: Mehrotra and Kang (2009) with inputs from Hyman et al. (2008) and Lockwood (2006).*

**Annex Table 6.2:** *Indirect impacts of climate change as a result of direct impacts outlined in Annex Table 6.1.*

| **Economic impacts** | |
|---|---|
| Increased temperature | "Increase energy demand, resulting in more frequent power outages and requiring energy restrictions on use of HVAC and other systems." CRI, 2009 (New York City); "Increase the number of passengers overheating while waiting for trains" CRI, 2009 (New York City); "This is a public health concern, but this could also lead to decreased demand for trains, sales of all the railway-related goods and services. Possible adaptation measures include installing air conditioners" (Wooler, 2004) |
| Increasing temperatures in northern regions | Northern ice roads may thaw earlier than usual and trucks may have to reduce their loads |
| Decreasing inland waterway levels | "Milder winters could lengthen the ice-free shipping season by several weeks, increasing vessel utilization and reducing the costs of icebreaking" (Caldwell, 2002, p.10); "Falling water levels on the lakes will decrease water depths, necessitating shallower draft vessels, and therefore less tonnage capacity per trip. … Past instances of low water levels on the Great Lakes hint at the seriousness of the problem. Most recently, in 2000, low water levels forced carriers into 'light loading,' reducing their cargo tonnage by five to eight percent" (Caldwell, 2002, p.10); Similar study by Quinn (2002, p. 120) was cited in Hyman *et al*. (2008); St. Lawrence Seaway and the Great Lakes are good examples |
| All adverse weather impacts on roadways that lead to traffic delays | As of 2002, congestion costs Americans $78 billion a year in wasted fuel and lost time – up 39 percent since 1990. In Houston, traffic jams cost commuters on the Southwest Freeway and West Loop 610 an average of $954 a year in wasted fuel and time. In New Jersey's Somerset County, congestion costs the average licensed driver $2,110 a year (US News and World Report, 2001); The Federal Highway Administration projects that, over the next 10 years, the number of vehicle-miles traveled is estimated to increase by 24 percent. In 20 years, it is expected to increase by 53 percent (FHWA, 2002a)*; |
| **Environmental impacts** | |
| Reduced winter maintenance | Reduced use of road salt (and other de-icing chemicals) will lead to less salt corrosion of vehicles and salt loadings in waterways, which in turn will positively impact the environment (Warren *et al.*, 2004, p. 139) |
| Air condition | "Transportation-related activities are major sources of NOx, VOCs, CO, and particulate matter. The surface and upper air conditions (warm temperatures; stagnant anticyclonic air masses) that promote the occurrence of high concentrations of these pollutants may become more frequent and of longer duration under certain climate change scenarios" (Mills and Andrey, 2002, p. 82) |
| Increased marine transportation in the Arctic region | Increase the probability of hazardous spills (Mills and Andrey, 2002, p. 82) |
| Dredging | "Dredging of waterways – in response to falling water levels – could have unintended, harmful environmental impacts." (Hyman *et al.*, 2008, p. 16) – Great lakes study Sousounis (2000) was cited |
| **Demographic impacts** | |
| UK Climate Impacts Programme Report on the West Midlands noted, "higher temperatures and reduced summer cloud cover could increase the number of leisure journeys by road." (Entec UK Ltd, 2004) | |
| **Security impacts** | |
| Increased shipping activities will raise security, ownership, maintenance, and safety concerns | |

*Source: Mehrotra and Kang (2009) with inputs from Hyman* et al. *(2008) and Lockwood (2006).*

## REFERENCES


Aerts, J., D. C. Major, M. J. Bowman, P. Dircke, and M. F. Marfai (2009). *Connecting Delta Cities*, Amsterdam, the Netherlands:VU University Press.

AGO (2005). *AGO Factors and Methods Workbook*, Australian Greenhouse Office, Australian Government, Canberra.

Andrey, J. and B. N. Mills (2003). Climate change and the Canadian transportation system: vulnerabilities and adaptations. In J. Andrey and C. Knapper (Eds.), *Weather and Transportation in Canada*, Department of Geography, University of Waterloo, Ontario, Canada.

Assmann, D. and N. Sieber (2005). Transport in developing countries: Renewable energy versus energy reduction? *Transport Reviews*, **25**(6), 719–738.

Beevers, S. and D. Carslaw (2005). The impact of congestion charging on vehicle emissions in London. *Atmospheric Environment*, **39**, 1–5

Bertaud, A., B. Lefèvre, and B. Yuen (2009). *Greenhouse Gas Emissions, Urban Mobility and Efficiency of Urban Morphology: A Hypothesis*, World Bank Commissioned paper, Marseille Symposium, July 2009.

Bhattacharya, S., C. Sharma, R. C. Dhiman, and A. P. Mitra (2006). Climate change and malaria in India. *Current Science* **90**(3), 369–375.

Birkmann, J. (Ed.) (2006). *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies*, Tokyo, Japan, and New York, USA: United Nations University Press.

Black, J. and Doust, K. (2008). Metrics of environmental sustainability, social equity and economic efficiency for employment location and commuting. In T. Gilmour, E. J. Blakely and R. E. Pizarro (eds), *Dialogues in Urban Planning: Towards Sustainable Regions*. Sydney: University of Sydney Press, Chapter 2.

Black, J., Cheung, C., Doust, K. and Masuya, Y. (2010) *Land-Use/Transport Scenario Assessment Model: Optimization Algorithms and Preference Functions, Accessibility and Green House Gas Trade-offs*. 12th WCTR, Lisbon.

Bradley, R., K. A. Baumert, B. C. Staley, T. Herzog, and J. Pershing (2007). *Slicing the Pie: Sector Based Approaches to International Climate Agreements*, Washington, DC, USA: World Resources Institute.

Brandon, C. and K. Hommann (1995). *The Cost of Inaction: Valuing the Economy-wide Cost of Environmental Degradation in India*. Washington, DC, USA: World Bank.

Cabal, C. and C. Gatignol (2004). *Rapport sur la définition et le simplications du concept de voiture propre*, Office parlementaire d'évaluation des choix scientifiques et technologiques.

Caldwell, K., H. Quinn, J. Meunier, J. Suhrbier, and L. Grenzeback (2002). Potential impacts of climate change on freight transport. In *The Potential Impacts of Climate Change on Transportation Workshop, October 1–2, 2002*, Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA.

Census of India. http://censusindia.gov.in/.

Chomitz, K. M. and D. A. Gray (1996). Roads, land-use, and deforestation: a spatial model applied to Belize. *World Bank Economic Review*, **10**(3), 487–512.

Colombier, M., H. Kieken, and M. Kleiche (2007). From Rio to Marrakech: development in climate negotiations. In *Energy and Climate Change: the Main Analyses of Regard sur la Terre*. IDDRI-AFD, pp. 53–62.

Cosgrove, D. (2003). *Urban Pollutant Emissions from Motor Vehicles: Australian Trends to 2020*, Final Draft Report for Environment Australia, Bureau of Transport and Regional Economics (BTRE), Australian Government, Canberra.

Cropper, M. L., N. B. Simon, A. Alberini, and P. K. Sharma (1997). *The Health Effects of Air Pollution in Delhi, India*, World Bank Policy Research Working Paper No. 1860. Retrieved from http://ssrn.com/abstract=604994.

Dessai, S., M. Hulme, R. Lempert, and R. Pielke, Jr. (2009). Do we need better predictions to adapt to a changing climate? *Eos*, **90**(13), 111–112. Accessed August 25, 2009, http://sciencepolicy.colorado.edu/admin/publication_files/resource-2720–2009.08.pdf.

Doust, K. (2008). Metrics of environmental sustainability, social equity, and economic efficiency in cities. Unpublished Ph.D. thesis, University of New South Wales.

Doust, K. (2010) *Responding to Climate Change in Cities: Techniques for Minimising Risk through Transport System and Urban Form Planning and Asset Management.* HKIE Civil Conference 2010 Infrastructure Solutions for Tomorrow, Hong Kong

Doust, K. and Black, J. (2008). *Visual Sustainability Metrics : A Community Discussion and Decision Making Tool*. 2nd Sustainable Development Conference: Making Tommorrow Today, Milan.

Doust, K. and Black, J. (2009). A Holistic Assessment Framework for Urban Development and Transportation with Innovative Triple Bottom Line Sustainability Metrics. In Eva Kassens (ed.) *Sustainable Transportation – An International Perspective*. MIT Journal of Planning, vol. 9, pp. 10 – 27.

Doust, K. and Parolin, B. (2008). *Performance Metrics for Sustainable Urban Transport: Accessibility and Greenhouse Gas Emissions*. 31st Australasian Transport Research Forum, Gold Coast.

Doust, K. and Parolin, B. (2009). *Enabling city sustainability through transport systems: moving from vision to reality*. State of Australian Cities National Conference, Perth

DuVair, P., D. Wickizer, and M. J. Burer (2002). Climate change and the potential implications for California's transportation system. In *The Potential Impacts of Climate Change on Transportation Workshop, October 1–2, 2002*, Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA, pp. 125–134.

Entec UK Ltd (2004). *The Potential Impacts of Climate Change in the West Midlands*, Sustainability West Midlands, UK, January.

Evans, R. (2007). *Central London Congestion Charging Scheme: Ex-post Evaluation of the Quantified Impacts of the Original Scheme*, Prepared for London Congestion Charging Modelling and Evaluation Team, Transport for London. Accessed August 31, 2009, www.tfl.gov.uk/roadusers/congestioncharging/6722.aspx.

Expert Group on the Urban Environment (1996). *European Sustainable Cities Report*. Brussels, Belgium: European Commission.

FEMA (2009). *HAZUS Overview*. Accessed August 25, 2009, www.fema.gov/plan/prevent/hazus/hz_overview.shtm.

FHWA (2002). *Federal Highway Administration FY2002 Performance Plan and FY2000 Performance Report*, Budget Submission Draft, Washington, DC, USA: US Department of Transportation. Accessed August 28, 2009, www.fhwa.dot.gov/reports/2002plan/index.htm.

FHWA (2008). *Federal Highway Administration: Integrating Climate Change into the Transportation Planning Process*, Final Report, July 2008. Accessed August 25, 2009, www.fhwa.dot.gov/HEP/climatechange/climatechange.pdf.

Forrester, J. W. (1969). *Urban Dynamics*. Portland, OR, USA: Productivity Press.

Geurs, K. T. and B. van Wee (2006). Ex-post evaluation of thirty years of compact urban development in the Netherlands. *Urban Studies*, **43**(1), 139–160.

GHMC (Greater Hyderabad Municipal Corporation) (2007). *City Development Plan*, Hyderabad: GHMC.

Greater London Authority (2005). *Climate Change and London's Transport Systems*, Summary report prepared by Mayor of London with the London Climate Partnership, September 2005. Accessed December 11, 2009,www.london.gov.uk/lccp/publications/docs/climatetransport-sept05.pdf.

Hyman, R. C., J. R. Potter, M. J. Savonis, V. R. Burkett, and J. E. Tump (2008). *Why Study Climate Change Impacts on Transportation*? In M. J. Savonis, V. R. Burkett, and J. R. Potter (Eds.), *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*, A Report by the US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Transportation, Washington, DC, USA.

Hunt, A. and P. Watkiss (2007). *Literature Review on Climate Change Impacts on Urban City Centres: Initial Findings*, OECD, Paris.

Iacono, M. and D. Levinson (2008). *Predicting Land-use Change: How Much Does Transportation Matter?* Working Papers 000045, University of Minnesota, Nexus Research Group, http://ideas.repec.org/p/nex/wpaper/predictinglandusechange.html.

Infrastructure Canada (2006). *Adapting Infrastructure to Climate Change in Canada's Cities and Communities*. Accessed August 23, 2009, www.infc.gc.ca/altformats/pdf/rs-rr-2006–12_02-eng.pdf.

INE (National Statistics Institute) (2007). www.ine.gov.mz/censo2007.

INGC (2009). *Study on the Impact of Climate Change on Disaster Risk in Mozambique*, INGC Climate Change Report, K. Asante, R. Brito, G. Brundrit, *et al.* (Eds.), INGC, Mozambique.

IPCC (2007a). *Climate Change 2007, Synthesis Report, An Assessment of The Intergovernmental Panel on Climate Change*. Accessed August 25, 2009, www.ipcc.ch/.

IPCC (2007b). *WG II Glossary*, Accessed August 25, 2009, www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-app.pdf, also see www.ipcc.ch/.

Jacob, K. H., N. Edelblum, and J. Arnold (2000). Risk increase to infrastructure due to sea level rise: sector report. In *Infrastructure for Climate Change and a Global City: An Assessment of the Metropolitan East*

*Coast (MEC) Region*. http://metroeast_climate.ciesin.columbia.edu/reports/infrastructure.pdf. A shortened version of this report is included in Rosenzweig and Solecki (2001).

Jacob, K. H., V. Gornitz and C. Rosenzweig (2007). Vulnerability of the New York City metropolitan area to coastal hazards, including sea level rise: inferences for urban coastal risk management and adaptation policies. Chap. 9, In L. McFadden, *et al.*( Eds.), *Managing Coastal Vulnerability: Global, Regional, Local*, Amsterdam, London and New York: Elsevier, pp. 141–158. Accessed August 25 2009, http://pubs.giss.nasa.gov/abstracts/2007/Jacob_etal.html and http://pubs.giss.nasa.gov/docs/2007/2007_Jacob_etal.pdf.

Jacob, K. H., C. Rosenzweig, R. Horton, D. Major, and V. Gornitz (2008). *MTA Adaptations to Climate Change: A Categorical Imperative*, White paper for the MTA BRCS. Accessed August 25, 2009, www.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf.

Johansson, C., L. Burman, and B. Forsberg (2008). The effects of congestions tax on air quality and health. *Atmospheric Environment*, **42**, 1–12.

Kachi, N., Kato, H., Hayashi, Y., and Black, J. (2005). Making cities more compact by improving transport and amenity and reducing hazard risk. *Journal of the Eastern Asia Society for Transportation Studies*, **6**, 3819–3834.

Kachi, N., Hayashi, Y., and Kato, H. (2007). A computable model for optimizing residential relocation based on quality of life and social cost in built-up areas. *Journal of the Eastern Asia Society for Transportation Studies*, **7**, 1460–1474.

Kafalenos, R. S., K. J. Leonard, D. M. Beagan, *et al.* (2008). What are the implications of climate change and variability for Gulf Coast transportation? In M. J. Savonis, V. R. Burkett, and J. R. Potter (Eds.), *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*, Report by US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Transportation, Washington, DC, USA.

Kahn-Ribeiro, S., S. Kobayashi, M. Beuthe, *et al.* (2007). Mitigation. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer (Eds.), *Climate Change 2007. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York, USA: Cambridge University Press.

Karl, T. R., J. M. Milillo, and T. C. Peterson (Eds.) (2009). *Global Climate Change Impacts in the United States*. Cambridge, UK: Cambridge University Press.

Kinney, P. L. (2008). Climate change, air quality, and human health. *American Journal of Preventive Medicine*, **35**(5), 459–467.

Kinsella, Y. and F. McGuire (2005). *Climate Change Uncertainty and the State Highway Network: A Moving Target*, Transit New Zealand, Auckland, New Zealand.

Kovats, S. and Akhtar, R. (2008). Climate, climate change and human health in Asian cities. *Environment and Urbanization*, **29**(1), 165–175.

Kumar, S. and S. Managi (2009). Compensation for environmental services and intergovernmental fiscal transfers: the case of India. *Ecological Economics*, **68**(12), 3052–3059.

Lefèvre, B. and V. Renard (2009). *Financing Sustainable Urban Policies*, OCDE Background Paper.

Lefèvre, B. and M. Wemaere (2009). *Fitting Commitments by Cities into a Post-2012 Climate Change Agreement: Political, Economic, Technical and Legal Aspects*, Ideas Iddri.

Leonard, K. J., J. H. Suhrbier, E. Lindquist, *et al.* (2008). How can transportation professionals incorporate climate change in transportation decisions? In M. J. Savonis, V. R. Burkett, and J. R. Potter (Eds.), *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*, Report by US Climate Change Science Program and Subcommittee on Global Change Research, Department of Transportation, Washington, DC, USA, pp. 5–1–5F-5.

Lindquist, E. (2007). *Climate Change and Adaptive Strategies in Subnational Transportation Planning Agencies in the United States*, Institute for Science, Technology and Public Policy. Accessed on August 25, 2009, www.2007amsterdamconference.org/Downloads/AC2007_Lindquist.pdf.

Lockwood, S. A. (2006). *Operational Responses to Climate Change Impacts.* PB Consult, December 29. Accessed August 19, 2009, http://onlinepubs.trb.org/onlinepubs/sr/sr290Lockwood.pdf.

Lundqvist, L. (2008). Can congestion charging support sustainable development of metropolitan areas? The Case of the Stockholm trial on congestion charging, Paper presented at *47th Annual Meeting of the Western Regional Science Association*, Hawaii.

MacCracken, M. C. (2002). National assessment of the consequences of climate variability and change for the United States. In *The Potential Impacts of Climate Change on Transportation Workshop*, October 1–2, 2002 Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA, pp. 65–76.

Manheim, M. L. (1979). *Fundamentals of Transportation Systems Analysis, Volume 1, Basic Concepts*, Cambridge, MA, USA: MIT Press.

Mehrotra, S. and Y. J. Kang (2009). *Impacts of Climate Change on Transportation*. New York, USA: Columbia University.

Mehrotra, S., C. E. Natenzon, A. Omojola, *et al.* (2009). *Framework for City Climate Risk Assessment*, Commissioned research, World Bank Fifth Urban Research Symposium, Marseille.

Menon, A. (2000). ERP in Singapore: A perspective one year on. *Traffic Engineering and Control*, **41**, 40–45.

Meyer, M. D. (2008). Design standards for U.S. transportation infrastructure: the implications of climate change. In *The Potential Impacts of Climate Change on U.S. Transportation*, National Research Council, National Academy of Science, Transportation Research Board and Department of Earth and Life Sciences, Washington, DC, USA.

Milan Municipality (2009), in *Milan Today Newsletter*, www.apcom.net/milano_today/latestnewsmilan.

Mills, B. and J. Andrey (2002). Climate change and transportation: potential interactions and impacts. In *Potential Impacts of Climate Change on Transportation*, Proceedings of the U.S. Department of Transportation Research Workshop, Washington, DC, USA, October 1–2.

Ministry of Environment Government of Japan (2008). *Teikogaisha Guidebook 2008* [*Less-emission Vehicle Guidebook 2008*].

MTA [Metropolitan Transportation Authority] (2007). *Report to the NYS Governor and NYC Mayor*, Appendix 2: Climate Component, 8.8.07 MTA Task Force Report, prepared by C. Rosenzweig, R. Horton, D. C. Major, V. Gornitz, and K. Jacob, Columbia Center for Climate Systems Research. Accessed August 25, 2009, http://www.mta.info/mta/pdf/storm_report_2007.pdf.

MTA [Metropolitan Transportation Authority] (2009). *Greening Mass Transit & Metro Regions: The Final Report of the Blue Ribbon Commission on Sustainability and the MTA*, New York, NY, USA. Accessed August 25, 2009, http://mta.info/environment/pdf/SustRpt Final.pdf.

Nakanishi, H., Black, J. and Doust, K. (2009). *Metrics of Environmental Sustainability, Social Equity and Economic Efficiency*. IHDP 7th Open Meeting, 7th International Science Conference on the Human Dimensions of Global Environmental Change, 26-30 April 2009, Bonn, Germany.

Newman, P. and J. Kenworthy (1989). *Cities and Automobile Dependence: An International Sourcebook*, London, UK: Gower.

Nicholls, R. J., S. Hanson, C. Herweijer, *et al.* (2008). *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates*, OECD Environment Working Papers, No. 1, OECD. Accessed August 25, 2009, http://lysander.sourceoecd.org/vl=8846437/cl=26/nw=1/rpsv/workingpapers/19970900/wp_5kzssgshj742_long_en.htm.

NPCC (2009). *Climate Risk Information*, New York, NY: City of New York, February 17. Accessed August 25, 2009, http://www.nyc.gov/html/planyc2030/downloads/pdf/nyc_climate_change_report.pdf.

NPCC (2010). Climate change adaptation in New York City: building a risk management response. *Annals of the New York Academy* **1183**, in press. Accessed December 11, 2009, www.nyas.org/Publications/Annals/Detail.aspx?cid=ab9d0f9f-1cb1–4f21-b0c8–7607daa5dfcc.

OFCM (2002). *Weather Information for Surface Transportation: National Needs Assessment Report*. Office of the Federal Coordinator for Meteorological Services and Supporting Research. Accessed August 28, 2009, www.ofcm.gov/wist_report/wist-report.htm.

Olszewski, P. (2007). Singapore motorisation restraint and its implications on travel behaviour and urban sustainability. *Transportation*, **34**, 319–335.

Olszewski, P. and Xie, L. (2005). Modelling the effects of road pricing on traffic in Singapore. *Transportation Research Part A: Policy and Practice*, **39**, 755–772.

Perera, R. and Permana, A. (2009). The nexus of land use, transport, energy and environment as a workable policy arena to synergize co-benefits: evidence from Bandung City, Indonesia. In E. Zusman, A. Srinivasan, and S. Dhakal (Eds.), *Low Carbon Transport in Asia: Strategies for Optimizing Co-benefits*, London, UK: Earthscan.

Permana, A. S., R. Perera, and S. Kumar (2008). Understanding energy consumption pattern of households in different urban development forms: a comparative study in Bandung City, Indonesia, *Energy Policy*, **36**, 4287–4297.

Perner, A. and M. Thöne (2005). *Naturschutz im Finanzausgleich; Erweiterung des naturschutzpolitischen Instrumentariums um finanzielle Anreize für Gebietskörperschaften*, FiFo-Reports, No.3, University of Köln.

Petroski, H. (1982) *To Engineer is Human*. New York, NY, USA: Vintage Books, a division of Random House, Inc. [1992 edition].

PlaNYC (2007). *A Greener, Greater, NY.* Transportation. Accessed August 25, 2009, www.nyc.gov/html/planyc2030/downloads/pdf/report_transportation.pdf.

Potter, J. R. and M. J. Savonis (2003). Transportation in an age of climate change. *TR News*, **227**, July–August 2003, 26–31.

Price, L., S. de la rue du Canm, J. Sinton, *et al.* (2006). *Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions*, LBNL-561444, Ernets Orlando Berkeley National Laboratory, Environmental Energy Technologies Division, Berkeley, CA, USA.

Pridmore, B. (2002). *The Role of Hydrogen in Powering Road Transport*, Tyndall Centre for Climate Research, Working Paper.

Prud'homme, R. and J. Bocarejo (2005). The London Congestion Charge: A Tentative Economic Appraisal. *Transport Policy*, **12**, 279–288.

Quinn, F. H. (2002). The potential impacts of climate change on Great Lakes transportation. In *The Potential Impacts of Climate Change on Transportation Workshop*, October 1–2, 2002. Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA, pp.115–124.

Revi, A. (2008). Climate change risk: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, **20**(1), 207–229.

Rogers, P. and S. Srinivasan (2008). Comparing sustainable cities: examples from China, India and the USA. In M. Keiner (Ed)., *Sustainable Urban Development in China: Wishful Thinking or Reality*?, Munster, Germany: Verlagshaus Monsenstein und Vannerdat OHG.

Rosenzweig, C. and W. D. Solecki (Eds.) (2001). *Climate Change and a Global City: the Potential Consequences of Climate Variability and Change – Metro East Coast*. Report for the US Global Change Research Program, National Assessment of the Potential Consequences of Climate Variability and Change for the United States, Columbia Earth Institute, New York. Accessed August 25, 2009, http://ccsr.columbia.edu/cig/mec/index.html.

Rossetti, M. A. (2002). Potential impacts of climate change on railroads. In *The Potential Impacts of Climate Change on Transportation Workshop*, October 1–2, 2002. Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA, pp209–221.

Santos, G. and G. Fraser (2005). *Road Pricing: Lessons from London*, Paper for the October 2005 Panel Meeting of Economic Policy, London.

Schipper, L., C. Marie-Lilliu, and R. Gorham (2000). *Flexing the Link Between Transport and Greenhouse Gas Emissions: A Path for the World Bank*. International Energy Agency.

Shukla, P. R., S. K. Sharma, N. H. Ravindranath, A. Garg, and S. Bhattacharya (Eds.) (2003).*Climate Change and India. Vulnerability Assessment and Adaptation.* Hyderabad: Universities Press.

Siemens (2008). *Sustainable Urban Infrastructure, London Edition: A View to 2025*. w1.siemens.com/entry/cc/features/urbanization…/study_london_en.pdf.

Sivak, M. (2009). Potential energy demand for cooling in the 50 largest metropolitan areas of the world: implications for developing countries. *Energy Policy*, **37**(4), 1382–1384.

Smith, N., J. Garrett, and V. Vardhan (2007). *Food and Nutrition in Hyderabad, Current Knowledge and Priorities for Action in an Urban Setting. Research Report 1, Sustainable Hyderabad Project.* www.nexusberlin.com/megacity/uploads/documents/Microsoft+Word+Megacity+Report-1.pdf.

Soo Hoo, W., M. Sumitani, and S. Cohen (2005). *Climate Change Will Impact the Seattle Department of Transportation*, Office of City Auditor, Seattle.

Stone Jr., B., A. C. Mednick, T. Holloway, and S. N. Spak (2007). Is compact growth good for air quality? *Journal of the American Planning Association*, **73**(4), 404–418.

Suarez, P., W. Anderson, M. Vijay, and Lakshmanan T. R. (2005). Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D*, **10**(3), 231–244.

Titus, J. (2002). Does sea-level rise matter to transportation along the Atlantic coast? In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, US Department of Transportation, Workshop, 1–2 October. Accessed August 28, 2009, http://climate.volpe.dot.gov/workshop1002/.

Transport for London (2004). *Congestion Charging Central London: Impacts Monitoring: Second Annual Report*, London, UK.

Transportation Research Board (2008). *Potential Impacts of Climate Change on U.S. Transportation*, TRB Special Report 290, Washington, DC, USA: National Academy of Sciences. Accessed August 25, 2009, http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf.

Trilling, D. R. (2002). Notes on transportation into the year 2025. In *The Potential Impacts of Climate Change on Transportation Workshop*, October 1–2, 2002, Center for Climate Change and Environmental Forecasting, US Department of Transportation, Washington, DC, USA, pp. 65–76.

Tufts University (2004). *Climate's Long-Term Impacts on Metro Boston: Final Report*. Environmental Protection Agency, EPA Grant Number: R.827450–01. Accessed August 28, 2009, www.tufts.edu/tie/climb/.

UNFCCC [United Nations Framework Convention on Climate Change] (2006). Impacts, vulnerability and adaptation to climate change in Africa. Background paper for *African Workshop on Adaptation Implementation of Decision 1/CP.10 of the UNFCCC Convention*, Accra, Ghana, 21–23 September.

UNFPA (2007). *State of World Population 2007: Unleashing the Potential of Urban Growth*. Accessed August 25, 2009, http://www.unfpa.org/webdav/site/global/shared/documents/publications/2007/695_filename_sowp2007_eng.pdf.

UN-HABITAT (2008). *State of the World's Cities 2008/2009: Harmonious Cities*, United Nations Human Settlements Programme, Nairobi, Kenya.

USACE [United States Army Corps of Engineers] (1995). *Metro NY Hurricane Transportation Study*, Interim Technical Data Report, New York: Federal Emergency Management Agency, National Weather Service, NY/NJ/CT State Emergency Management.

USDOT (United States Department of Transportation), NHTSA (National Highway Traffic Safety Administration) (2010) "CAFE Standards - Frequently Asked Questions," Accessed Nov. 28, 2010, http://www.nhtsa.gov/cars/rules/cafe/overview.htm

Vairavamoorthy, K., S. D. Gorantiwar, and A. Pathirana (2008). Managing urban water supplies in developing countries: climate change and water scarcity scenarios. *Physics and Chemistry of the Earth*, **33**, 330–339.

van Rooijen, D. J., H. Turral, T. W. Biggs (2005). Sponge city: water balance, mega-city water use and wastewater use in Hyderabad, India. *Irrigation and Drainage*, **54**, 581–591.

Warren Centre for Advanced Engineering (2003). *The Sustainable Transport in Sustainable Cities Project*, University of Sydney, CD-ROM.

WBCSD (World Business Council for Sustainable Development) (2004). *Mobility 2030: Meeting the Challenges to Sustainability*, The

Sustainable Mobility Project, World Business Council for Sustainable Development. Accessed Nov. 28, 2010, http://www.wbcsd.org/web/publications/mobility/mobility-full.pdf.

Wegener, M. (2009). Possible future transport and land-use strategies for sustainable urban development in European cities. *Proceedings of the CIB-W 101 & GCOE Workshop Urban Infrastructure and Land-use Control*, University of Tokyo, 13 June 2009. Accessed September 2009, www.spiekermann-wegener.de/pub/pdf/MW_Tokyo_130609.pdf.

Willoughby, C. (2000). *Singapore's Experience in Managing Motorization and Its Relevance to Other Countries*, World Bank Discussion Paper TWU-43, Washington, DC, USA.

Wisner, B., P. Blaikie, T. Cannon, and I. Davis (2004). *At Risk: Natural Hazards, People's Vulnerability, and Disasters*. London, UK: Routledge. Wooler, S. (2004). *The Changing Climate: Impact on the Department for Transport*, London, UK: Department for Transport.

Young, S., L. Balluz, J. Malilay (2004). Natural and technologic hazardous material releases during and after natural disasters: a review. *Science of the Total Environment*, **322**, 3–20. Zegras, C. (2007). As if Kyoto mattered: The clean development mechanism and transportation. *Energy Policy*, **35**.

Zimmerman, R. and M. Cusker (2001) Institutional decision-making. In C. Rosenzweig and W. D. Solecki (Eds.), *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change – Metro East Coast*, New York, USA: Columbia Earth Institute and Goddard Institute of Space Studies, pp. 9–1 to 9–25 and A11–A17.

Zimmerman, R. and C. Faris (2010). Infrastructure impacts and adaptation challenges. In *Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change 2010 Report*, edited by C. Rosenzweig and W. Solecki. Annals of the New York Academy of Sciences, **1196**, New York, NY, NY Academy of Sciences, 63–85.