

Quality of Life, Sustainable Civil Infrastructure, and Sustainable Development: Strategically Expanding Choice

Jamie Montague Fischer¹ and Adjo Amekudzi, Ph.D., M.ASCE²

Abstract: As sustainable development becomes a more important objective in civil infrastructure planning and policymaking, quality of life (QOL) is an increasingly important measure to understand, characterize, and apply effectively in the search for and development of appropriate infrastructure solutions for sustainable development. This paper reviews the role of QOL in civil infrastructure decision making. It provides an overview and critique of methodological approaches to defining QOL and explains the significance of QOL in infrastructure decision making for sustainable development. Examples are used to demonstrate how infrastructure can be strategically developed or redeveloped to improve regional QOL and economic competitiveness while preserving or enhancing the natural environment. Based on the theoretical review and examination of infrastructure development examples, the writers suggest that a new paradigm that views infrastructure development as part of a sociotechnical system be considered. Such a paradigm would encourage strategic infrastructure designs and policies that expand choice and achieve multiple objectives for sustainable development. DOI: 10.1061/(ASCE)UP.1943-5444.0000039. © 2011 American Society of Civil Engineers.

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Sustainable Development and Sustainability

Nearly every aspect of human endeavor has been touched in recent years by the emerging concept of sustainable development. The most common and widely used definition of sustainable development comes from the United Nations Brundtland Commission: "Development that meets the needs of the current generation without compromising the ability of future generations to meet their own needs" [World Commission on Environment and Development (WCED) 1987]. In general, it is also understood that the achievement of sustainability entails development that is sustainable in three areas, also called the pillars of sustainability: the environment, the economy, and society. Environmentally, sustainable development requires that natural assets are preserved and are not consumed more quickly than they are replenished (through natural or technological means). Economically, sustainable development requires the maintenance of healthy markets through which financial means are leveraged to produce and maintain capital assets. Capital assets include goods that are consumed, as well as more permanent goods such as infrastructure systems. Finally, socially sustainable development involves the development and maintenance of quality of life (QOL) for human beings and communities. As pointed out in a literature review by Boschmann

and Kwann (2008), this third pillar has been the most ambiguous and enigmatic of the three, but it includes at least two components: the improvement of living standards for people on average and the equitable distribution of both the benefits and burdens of development.

The process of sustainable development may be summarily understood as a process that provides an acceptable or improving quality of life for individuals and communities while preserving those assets that enable such provision to continue. Here, quality of life and preservation of assets can be understood to incorporate all three elements of sustainable development. Sustainability, then, can be viewed as a state where the key goals of sustainable development are satisfied, a high quality of life is achieved, and the environment is preserved.

Chambers et al. (2000) offer an enlightening discussion differentiating sustainable development from sustainability. They present four scenarios, or states in which a community may exist relative to meeting needs and preserving the environment. Fig. 1 summarizes these scenarios, with the quadrant of sustainability in zone D. The figure also illustrates possible development trends. Unsustainable development, which is a common response to increased demand for natural resources due to increased expectations for standard of living, increasing population, and an expanding economy, is represented by broken pathways. Sustainable development, which communities in Zones A, B, and C would engage in to move to Zone D, is represented by the solid pathways in Fig. 1. The cycle shown in Zone D represents a continuation of sustainable development through which communities may improve their relative levels of sustainability by achieving a higher QOL, improving equity, and decreasing natural resource and waste footprints.

A look at historical civilizations such as Easter Island, the Maya, and the Tokugawa (Japan) reinforces the idea that communities tend to be most concerned about the issues that threaten their survival or quality of life (Diamond 2005). For example, several ancient civilizations were typically concerned about maintaining

¹Graduate Research Assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355. E-mail: jm.fischer@gatech.edu

²Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355. E-mail: adjo.amekudzi@ce.gatech.edu

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Models that use objective indicators alone may be better described as capturing a standard of living, not QOL. Standard of living may be defined as encompassing the externally observable conditions that contribute to the well-being of an individual or community. Models that capture standard of living make assumptions about the relative importance of amenities based on some valuation scale that is external (exogenous) to the person. For instance, the compensating differentials model, which has been developed by various researchers since the late 1970s (see for instance Rosen 1979; Roback 1982; Greenwood 1991; Gabriel et al. 2003), assumes that all amenities that a community has access to have implicit price. In other words, high wage rates or low housing prices should offset any undesirable noneconomic characteristics of a location.

In the earlier discussion of sustainable development and sustainability, three pillars were mentioned: environmental, economic, and social. The achievement of acceptable and equitable levels of QOL was presented as the primary measure for the social aspect of sustainability. By attempting to describe QOL in purely economic terms, models such as compensating differentials effectively equate social value with economic value. This equation ignores social values that cannot be economized and it treats phenomena such as economic stratification as socially insignificant. For these reasons, compensating differentials and similarly based models fail to serve the purposes of QOL as a performance measure for sustainable development because they ignore the equity and social justice components to sustainability that were acknowledged in the original Brundtland report.

Revealed preference models for QOL introduce an element of endogenous valuation. The central assumption of the revealed preference concept is that people and businesses choose locations or activities which will provide them with the highest benefit, in this case the highest QOL. Thus, Jensen and Leven (1997) formulated QOL as an indirect utility function of housing supply and labor supply, assuming that trends of emigration and immigration reveal popularly perceived differences between the levels of QOL provided in different places. This is similar to the compensating differentials model in that locations are seen in competition, but revealed preference introduces endogeneity through the recognition that QOL may be defined and revealed by the choices people make.

Despite its leap forward from purely objective formulations of QOL, the revealed preference paradigm is inadequate as a performance measure for sustainable development. It ignores those people who cannot make choices based on preference, for instance, due to economic disadvantage or disability, effectively ignoring any role for social equity. Also, revealed preference methodologies do not provide for the occasion when an ideally preferred option, one that is truly in line with personal values, is unavailable. In such a case, choices reveal the option that is seen as relatively better but not necessarily best. Doi et al. (2008) helpfully differentiate between preferences, which are always limited by specific situations, and values, which transcend the moment and “are underlying personal or societal principles, standards, goals, or ideals.”

The most clearly endogenous of QOL measures are based on *stated preference*, usually using survey tools. Stated preference methods have been widely used in transportation planning since the 1980s and can be applied to several research questions (Loo 2002). For instance, De Groot and Steg (2006) asked respondents from five European countries to indicate their expectation of how a proposed transport pricing policy would affect their QOL, relative to seven broadly defined indicators. In another application, Doi et al. (2008) formulated a multiattribute utility function and then operationalized it “by means of a questionnaire survey,” in order to endogenously weight the relative importance of relevant indicators.

Surveys are useful for understanding the values and attitudes held by a community and for capturing differences between the values held by different communities. Loo (2002) calls the data collected by surveys “soft... disaggregate data,” which is “essential for the planning of a sustainable transportation system.” However, models based solely on stated preference cannot provide QOL-based performance measures for sustainable development because they do not capture the objective and exterior conditions that constrain choice, such as characteristics of the natural and built environments or prevailing societal trends. As Felce and Perry (1995) point out, “high satisfaction” cannot be equated with “maximized welfare” when it does not represent “the expression of preference under the conditions of free choice.”

Depending on the priorities of a person or population, QOL may be defined differently from one context to another. For instance, De Groot and Steg’s (2006) study revealed that five national cultures expected certain indicators to be negatively affected by an increase in transport pricing (comfort, money, change, and work), and others to be positively affected (environment, nature, and safety). However, some cultures showed more optimism about the change, expecting greater positive effects than negative, while others expected the opposite. Furthermore QOL may be temporally relative, with people assessing the quality of current conditions with respect to past conditions, as shown by Gabriel et al. (2003). Finally, people may perceive QOL as spatially relative, migrating from areas of perceived lower QOL to those with perceived higher QOL (Jensen and Leven 1997).

To gauge progress toward sustainable development, a model for QOL should include objectively gathered information regarding standards of living as well as information about the endogenous values of the community whose QOL is being evaluated. Such a model should be contextually flexible, and it should meet the same requirements set by Papageorgiou (1976): enabling comparisons at different spatial levels and capturing changes over time. To effectively proxy social sustainability and then integrate it with an overarching model for sustainable development, the model should include information about social equity, at least as far as choice is concerned.

Sustainable Infrastructure Development for Quality of Life

The role of infrastructure in advancing sustainable development was recognized early, but the discussion was mostly limited to the sphere of environmental stewardship. It was recognized that infrastructure designs should “enhance the natural environment, protect natural resources, and restore natural systems,” and through this stewardship engineers would provide for the “health, safety and general welfare not only of the present generation, but also of those who follow (Wright 1996).” This concept of influencing QOL through environmental stewardship is still relevant to the sustainability discourse (see for instance Amekudzi and Meyer 2006); however, the evolved definition of QOL above implies that infrastructure can make a more direct impact through social considerations. Thus, a sustainable infrastructure system will support and enhance QOL for communities that use or are otherwise impacted by the system, while preserving the natural and man-made assets that enable such communities to pursue their economic and social development in a sustainable manner. This paper uses the terms “infrastructure sustainability,” “sustainable infrastructure” and “sustainable infrastructure systems” interchangeably.

Drawing on the conceptual definition of QOL above, it may be said that sustainable infrastructure systems will provide a wide

range of choices to a community, such that the values held by any person within the community are more likely to be expressed in the system. “The process of enlarging people’s choices,” specifically referring to those choices required to “lead a long and healthy life, to acquire knowledge, and to have access to the resources needed for a decent standard of living,” is what the United Nations Development Programme (UNDP) calls “human development” (UNDP 1990). Because (first) material development is both dependent on and subservient to human resources, and (second) human beings are more equipped to promote the progress of civilization when they are happy and healthy, sustainable infrastructure will promote human development, and it will thereby promote improvements in QOL.

Fig. 2 illustrates the “dynamic interchange” (Krupat 1985) between the human experience and the external environment, through decision making. As discussed above, QOL is shaped by external physical conditions, held attitudes and values, and the exercise of personal choice or preference. The external environment is important because of its effects on human health and well-being. Lifestyle choices are both constrained by the external environment and informed by held values. Constraints on personal choices are determined by institutional choices such as policy-making, planning, and project development and management.

The pathways indicated by arrows in Fig. 2 are *probabilistic*, coming about because humans are rational, creative, and physical beings. As Gellert and Lynch (2003) point out, “Those who imagine, define and transform landscapes bring about material changes in the biogeophysical environment, which in turn influence social organization, values, understandings and actions.” Probabilism (as differentiated from *possibilism* or *determinism*) asserts that the external environment “supports rather than requires; discourages rather than prohibits” certain choices and behaviors (Krupat 1985). For example, it is being increasingly documented and acknowledged that land-use and transportation-infrastructure patterns can either encourage or discourage certain transportation choices (Soltani et al. 2006; Shay and Khattak 2009; Frank et al. 2006; Boschmann and Kwan 2008). In this way, any development decision in design or policy can either facilitate or impede progress toward sustainability. Therefore, it is critical that decision makers

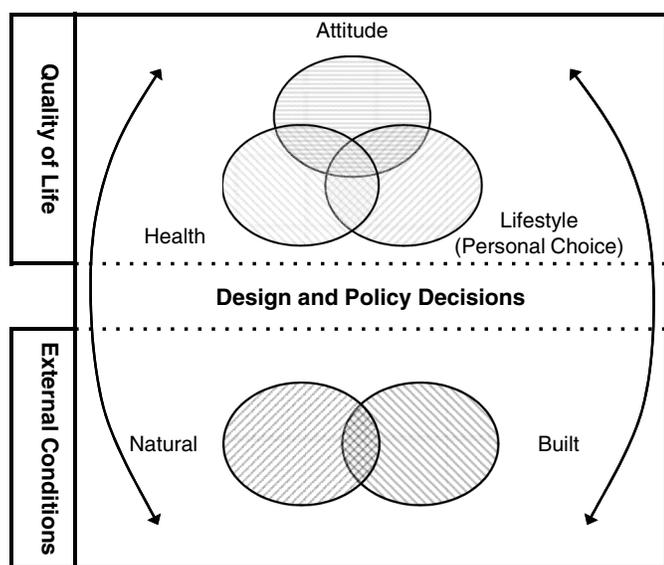


Fig. 2. Interaction between quality of life and external conditions through choice (adapted from Mani et al. 2005; Frank et al. 2006; NCUE 1975; Krupat 1985)

are familiar with the prevailing values and associated lifestyle preferences in the communities that they serve. This will help with the development of infrastructure solutions in at least two ways: enabling the decision makers to provide systems that reflect local values and lifestyles, and enabling stakeholder buy-in for the system. As Amekudzi et al. (2009) point out, “It is not unreasonable that stakeholders would not wish to commit themselves to plans that do not explicitly support their priorities or accommodate their constraints.”

Pathways from Infrastructure Planning to QOL

Depending on the level of development of a region, different development concerns may take priority. In less developed regions, for example, issues of survivability such as access to food, clean drinking water supplies, sanitation, and health care are of primary concern before other human development concerns can be addressed, such as access to education and commerce (UNDP 1990). No matter the level of development, however, it is usually *access* that is the issue. Whether or not resources are available is irrelevant if access to resources is lacking; that is, the ability to transport resources to people or vice versa. Therefore, it makes sense that much of the recent literature on how infrastructure affects QOL has emerged from the transportation planning field.

In more developed regions where survivability is no longer a question, the *quality of access* provided by transport infrastructure can significantly affect QOL. This is true through both direct and indirect pathways. In urban areas, where fast-growing populations require access to an ever-expanding pool of amenities, congested transportation systems can directly affect QOL through time delays, which lead to loss of money and time. For example, the cost of traffic congestion in the United States was estimated at 3.7 billion hours with delays costing \$63 billion in 2003 (Schrank and Lomax 2005). Frank et al. (2006) linked suburban sprawl to health through the impact on transportation choices of residents. The degree of *walkability* of a region, which takes into account residential density, street connectivity, land use mix, and retail floor area, is strongly related to the likelihood of people choosing active transportation methods such as walking or biking instead of driving, according to a study (Frank 2006) in King County, Washington. In the study, the walkability index was shown to be five times more significant than six other demographic and socioeconomic factors combined in explaining transportation habits. Consequently, regions with lower walkability statistically show higher vehicle miles traveled per person, contributing to both higher rates of vehicle emissions per person (increased nitrogen oxides and volatile organic compounds in the atmosphere) and fewer hours of weekly exercise per person. Both impacts contribute to health problems. On the other hand, Frank et al. (2006) also note that areas with increased walkability show increased concentrations of small particulate matter in the air, perhaps because of kicked-up dust, outdoor smoking, or other factors, which have been linked to cardiovascular disease. Thus, it is important for planners to consider various pathways through which development decisions may affect QOL and attempt to balance them. Gabriel et al. (2003) corroborate that managing transportation patterns, as “management of population growth,” is integral to QOL development, more so than population growth itself. Gabriel et al. (2003) found governmental spending on highways and transportation infrastructure, followed closely by commute times, to be the most influential factors in changing the QOL rankings of U.S. states over time.

Modeling Infrastructure Impacts

The studies cited above (Gabriel et al. 2003; Frank et al. 2006; Schrank and Lomax 2005) describe the transportation choices of

a population as occurring within and influenced by the larger context of land-use and infrastructure-planning patterns. They also show that transport choices can influence the health of a population, limit its access to amenities such as free time, and mean the difference between billions of dollars wasted or saved. It therefore follows that, as Feng and Hsieh (2009) describe, transport diversity can be used as an effective QOL indicator to “assess whether ...important needs are satisfied equitably, and monitor whether the transportation system is moving toward sustainability.” This is because diversifying the transport options is an example of expanding the choices available to people.

In order to assess the sustainable development impact of an infrastructure project or system, such an indicator as transport diversity should be linked to environmental indicators in an overarching model for sustainable development. In an example application of the *sustainability footprint* model, Amekudzi et al. (2009) choose a QOL-related indicator of “% daily congested travel,” with natural resource and waste indicators of “gas consumption” and “emissions” respectively. The sustainability footprint model is meant to capture the relative efficiency of a development decision within a community framework, assessing “how much of ‘well-being’ (QOL) is being purchased by any given ecological footprint as a community develops over time.” The method calls for multiple data points in time, in order to compare the relative progress of different communities. In other words, “entities that increase their quality of life significantly with little or no change in their ecological footprint (or even a reduction in their ecological footprint) can be said to be making better progress toward sustainability.”

The choice of congestion delay as a QOL indicator is directly relevant to the discussion of QOL indicators and modeling above because congestion reduces freedom of choice for the traveler. Congestion restricts the choices of how fast or slow to travel, and at what spacing, and the associated choice of how leisurely or rushed a trip should seem. The environmental impacts of congestion also indirectly affect QOL through health impacts, which can also be conceptualized as choices. For instance, travelers sitting in congestion are restricted to either breathing exhaust fumes or keeping their windows closed. In any infrastructure problem that might be solved through modeling, it is important to consider both direct and indirect impacts on freedom of choice. The following examples briefly illustrate other ways in which infrastructure development can expand choice within the context of sustainable infrastructure development.

Applying the Concept of Expanding Choice to Promote Sustainable Development: Three Case Studies

While transportation infrastructure primarily aims to improve mobility, the three transportation projects examined below, The Dallas/Fort Worth International Airport (DFW) in the United States, the Millau Viaduct in France, and the Öresund Fixed Link bridge in Sweden/Denmark have also functioned to expand choice and to improve environmental stewardship in their regions. These examples are used more to illustrate ways in which infrastructure can contribute to sustainable development, rather than to represent sustainable infrastructures in the ideal sense. In fact, some of the lifestyles that are enabled by these infrastructures are still markedly unsustainable from an environmental perspective because they rely on fossil fuel use and emit greenhouse gases. Nonetheless, it is useful to examine these projects as state-of-the-field examples in the process of advancing environmentally sustainable infrastructure development and as systems which invigorate socially sustainable

development by increasing access to economic, educational, and cultural amenities in the regions that they serve.

Dallas/Fort Worth International Airport

Social and Economic Impacts: Expanding Choice

The Dallas/Fort Worth International Airport (see Fig. 3) has operated since 1974 and now serves as a major economic engine for North Texas, stimulating the regional economy with more than \$16 billion annually (DFW 2008). Changes to the Dallas/Fort Worth Metropolitan Area (also known as the Metroplex) since the opening of the airport can be described by the “aerotropolis” phenomenon—a city evolving around its airport. As Kasarda (2008) puts it, “...just as urban development did not stop at the political boundaries of metropolitan area central cities, so airport-dependent development will not stop at the formal boundaries of airports.” An aerotropolis emerges as the central airport diversifies its business into nonaeronautical activities, and, in fact, two-thirds of DFW revenues are not airline related. DFW has especially invested in the hospitality and shipping industries (DFW 2006), and the airport provides approximately 305,000 jobs to the region (DFW 2008). Thus, the existence and management of DFW has expanded Metroplex resident choices for employment opportunities; by providing jobs, the airport has broadened economic access to improve equity in the region, and ultimately the attractiveness and economic competitiveness of the Metroplex have increased.

Aerotropolis development is also spurred by the revitalization of previously undesirable land around the airport. The commercial sector has taken advantage of inexpensive land values near DFW since the airport opened, and the Metroplex has come to accommodate the headquarters of 24 of the largest U.S. companies. Many of these firms are in the knowledge industries, such as consulting, information technology, accounting, communications, and management. Workers in knowledge industries travel by air 400% more frequently than workers on average (Kasarda 2008), so they value proximity to an airport both at home and at work. Under some of the DFW quieter flight paths, the nearby communities of Southlake and Colleyville have experienced considerable increases in both size and property value, now housing frequent-flying professionals in million dollar homes (Byrnes 2007). While most regular air travelers collect incomes three to five times higher than the national average (Kasarda 2008), in the Metroplex they also

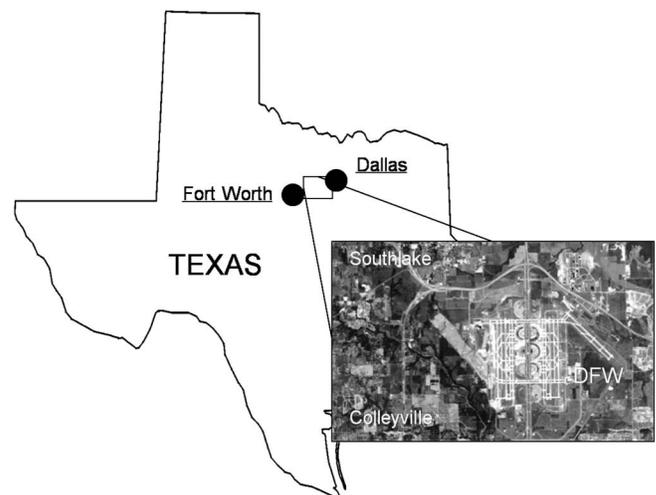


Fig. 3. Illustrative map for DFW airport, Texas [aerial image courtesy NASA Earth Observatory (1984)]

demonstrate a high willingness to pay for proximity to the airport. One such resident chose the area for its school district, but still works in Canada. He recognizes 10 or 15 people on his weekly round trip between DFW and Toronto. For him and others, living near the airport maximizes the choice of where to live and work, expanding that choice to the global network of airport cities (Byrnes 2007).

While celebrating DFW's impacts in terms of employment choice and economic vitality, it is important to note that the region has not achieved social sustainability in the ideal. To determine precisely how much the airport has contributed to socially sustainable development, more in-depth QOL analysis would be needed. For instance, as shown in Fig. 3, both of the high-income communities mentioned by Byrnes (2007) are to the west of the airport. This observation begs a question regarding social equity and what kind of noise pollution might be suffered by Metroplex residents to the east. Also, any benefits contributed by DFW cannot be divorced from their context, for instance the proximity of other airports, or the cultural dynamics of the Metroplex.

Environmental Impacts: Preserving Natural Capital

Although the airport catalyzed much economic development and social reorganization in formerly agrarian North Texas, DFW was not originally an environmental champion. An investigation launched against the airport in 2000, regarding violations of the clean water act, has resulted in several improvements. In response to the investigation, the airport developed an Environmental Management System (EMS) that gained DFW entry into the EPA National Environmental Performance Track Program, which recognizes environmental leadership at public and private facilities. The system has since also received an award from the North Central Texas Council of Governments (NCTCOG) for "leadership in development excellence" (NCTCOG 2004).

An EMS organizes the integration of environmental stewardship into everyday business operations. The airport has identified several internal and external benefits of its system, including greater trust and transparency between the airport, regulating agencies, and the public, and an emerging corporate culture that promotes environmental sustainability. Some concrete results of the EMS include:

- Reduced air emissions by 95% through a runway extension that reduced aircraft taxi time, the installation of delay-reduction technologies, increased use of an alternate fueled vehicle (AFV) fleet, and the replacement of aged boilers and chillers.
- The creation of a Watershed Drainage Map and the establishment of a Watershed Management Program which prevents discharge of aircraft fluids into surrounding waterways and uses aerators to maintain appropriate dissolved oxygen levels in an on-campus lake.
- Extensive recycling of demolition debris, white paper, cardboard, spent fluorescent light bulbs, used oil, and spent oil filters.
- A reduced energy footprint by 25 MMBTUs (Bergman 2007).

Öresund Fixed Link

Social and Economic Impacts: Expanding Choice

The Öresund Fixed Link (Fig. 4) is a bridge and tunnel complex that connects the Malmö-Lund region of Sweden to the Danish capital of Copenhagen across the Öresund Sound. It was motivated by a mutually agreed upon need "to create improved road and rail communications between the two countries and thus create conditions necessary for improved and extended cultural and economic exchange, and for the development of common labor and housing

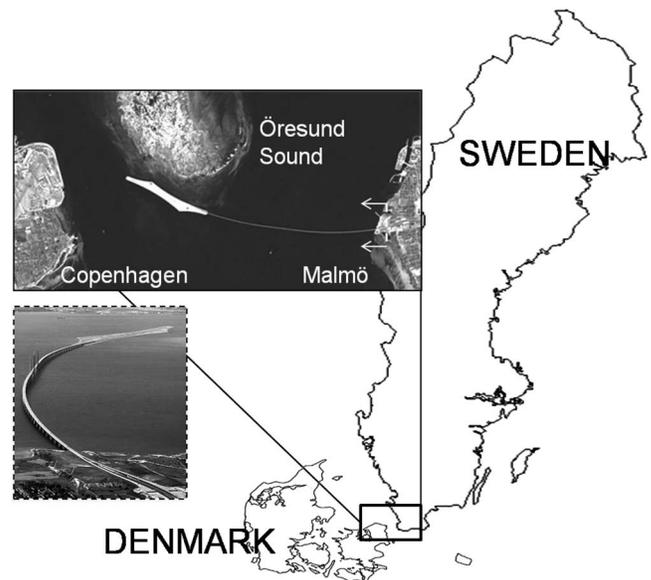


Fig. 4. Illustrative map for Öresund Fixed Link, Scandinavia [aerial image courtesy NASA Earth Observatory (2006); view of Malmö courtesy Travel On The Dollar (2009), with permission]

markets in the Öresund Region" (quoted in Matthiessen 2004). Since opening, the more than 10-mile link has decreased travel time across the sound considerably: from an hour and a half by ferry (or up to three hours when dealing with winter ice flows) to less than half an hour by train or personal vehicle. What has resulted is a binational metropolitan region developing its own distinct character. (Bjorken 1994; Zeyher 2001; Wolff 2003; MacCarthy 1998).

Since the link opened in 2001, previously depressed areas have begun to flourish, and both cross-border shopping and employment have increased (Bygva and Westlund 2004). Malmö, previously with the sixth highest crime rates in Sweden, is now one of the fastest growing cities in the country due to the jobs created by large and small companies relocated to the area (Sains 1999). According to the Öresund Job Center, there was a 50% increase in the number of job applications at its Malmö office immediately after the link opened. As for the Danish side, there also was a 40% increase in Danes applying for work in Sweden (Zeyher 2001).

The most notable development has been the emergence of what has been nicknamed a "Medicon Valley" in the region. There are now more than 500 companies involved in life science, in addition to 11 research universities with 140,000 students and 10,000 researchers. Since the opening of the link, the opportunity for corporate executives and scientists to meet more frequently face-to-face and on shorter notice has invigorated research and development. The vice chairman of the nonprofit group Medicon Valley Academy said that "the region benefits from diversity and pluralism; we have a dialogue between equal scientists in terms of country-to-country situations" (quoted in Wolff 2003). A similar effect is provided by cross-border cross-enrollment between universities, which has similarly increased (Wolff 2003).

Paradoxically, link operation has both contributed toward regional integration and impeded it (Mudd 2001). Since the link opened, the Öresund can be crossed by road at any time and by train at frequent and regular intervals. However, with car tolls corresponding to the cost of the ferry, the cost still deters some travelers. Models have predicted that decreasing the tolls by 50 or 75% could result in quadrupling link traffic and accelerating the integration process (Matthiessen 2004). While this would actually increase revenues, both directly through tolls and indirectly through industry

and taxes, as well as decrease the payback time for the link, it would also increase congestion on the link (Matthiessen 2004; DenmarkFacts.com 2008). Thus, slow integration may be preferable to rapid integration of the Öresund region from sustainability and QOL standpoints. In support of the “Slow City” movement, Mayer and Knox (2006) advise that slower growth is more conducive to preserving and developing cultural distinctiveness, local markets, and equity, which are all important for social sustainability.

Environmental Impacts: Preserving Natural Capital

Water transported through the Öresund Sound accounts for approximately 3/11 of the total water transported between the North Sea and the Baltic Sea. Therefore, any disturbance to the Öresund waters could have significant impacts both locally and across the Baltic region. International environmental laws existed when the link project began, based on the common law principle of “sic utereor” or good neighborliness, but the legislation lacked enforceability because of the legal challenges in demonstrating liability. However, Denmark and Sweden have advanced environmental practices and, as is common in Scandinavia, watchful and environmentally conscious citizens. From the beginning of the link development, the two nations launched a multinational collaboration with environmental accountability as a top priority. In a 1991 treaty, the Danish and Swedish governments agreed that, “the final characteristics of the Fixed Link... shall be executed with due consideration of what is ecologically motivated, technically feasible and financially reasonable in order to prevent any detrimental effects on the environment” (quoted in Gullett 2000).

In 1992, they formed an International Expert Panel (IEP) to investigate the potential impacts of the proposed link. The panel included 10 European scientists, none from either of the sponsoring nations. The IEP goal was to oversee a “zero solution”: a design that ensured unchanged water flows, and particularly unchanged dissolved oxygen and salt concentrations passing through the Öresund to the Baltic Sea (Gullett 2000). These factors are critical for the health of fish populations, especially cod, which are harvested in Sweden, Denmark, Germany, Poland, Lithuania, Latvia, Estonia, Russia, and Finland. Also, construction methods were designed to safeguard sensitive eelgrass habitats and the feeding needs of coastal birds. This required extensive modeling and testing of turbidity, which can affect fish migration and the photosynthesis of water plants (Valeur and Jensen 2001). Major changes were made throughout the link planning process, often trading considerable cost for environmental benefit; for instance the IEP chairperson describes the redesign of an artificial island, which had been originally placed to optimize the length of the tunnel, to a location that would not disrupt water flows (Gray 1999).

In addition to achieving the zero solution through design and construction methods, Sweden and Denmark have extended the high environmental achievements of the link into operations through transport pricing. That is, tolls for crossing the link by auto, about 35 Euros one way for cars, are much higher than crossing by rail, about 16 Euros, giving travelers a cost incentive to conserve fossil fuels and prevent congestion. Also, roadway tolls increase by vehicle weight, ranging from about 20 Euros for motorcycles (one way) to more than 100 Euros for trucks, reflecting the simultaneous increase in vehicle emissions (Matthiessen 2004; DenmarkFacts.com 2008).

It is important to note the linkages between the environmental and socioeconomic impacts of the link. Many of the link’s design aspects directly affect the natural environment but indirectly affect society. A prime example is the consideration of international equity in the protection of fishing communities. With this in mind,

the concept of a zero solution takes on very specific meaning. It does not mean the absolute absence of environmental impact, or even of social displacement, which Gellert and Lynch (2003) argue is impossible with any megaproject. Rather, a zero solution entails the responsible, sustainability-minded management of impacts such that assets are preserved rather than degraded and livelihoods may continue to develop.

Millau Viaduct

Social and Economic Impacts: Expanding Choice

Opened in 2004, the Millau Viaduct (Fig. 5) spans the Tarn River Valley, in the department of Aveyron, in southern France. It is the tallest road traffic bridge in the world, 343 m (1,125 ft) high at its tallest point, and the longest multispan cable-stayed bridge at more than 2.4 km (1.5 miles). The French highway department SETRA initiated studies for the viaduct in 1988 in order to solve severe holiday congestion on route A75 through Millau. Traffic queues frequently stretched back 19 km (12 miles) for travelers between Paris and Barcelona. Now with an estimated 10,000–25,000 vehicles crossing it daily, the viaduct has shortened travel time between Paris and Barcelona by to 4 hours during the holiday season. The viaduct allows travelers to bypass the town if they choose, but it also has unleashed an economic boom in Millau. (Brown 2002; Harris 2005; Saxton 2007).

The bridge attracted more than 400,000 visitors before it even opened. Its aesthetic appeal was described by its designers from Foster and Partners in London:

“[The] architecture of infrastructure has a powerful impact on the environment... A cable-stayed, masted structure, the bridge is delicate, transparent, has the optimum span between columns... The bridge not only has a dramatic silhouette, but crucially, it also makes the minimum intervention in the landscape. Lit at night, it will trace a slender ribbon of light across the valley” (Foster and Partners 2008).

Once the bridge opened, not surprisingly, Millau experienced rapid growth in tourism, as well as other industries. More than 100 building permits were issued for new businesses in 18 months, three of which allowed the construction of new hotels. The official tourism website for the viaduct (Eiffage 2008) directs tourists to Roquefort for ewe cheese and to Laguiole for knives. It describes the leatherworking, winemaking, and local market traditions of the Millau region. Furthermore, it highlights historic and preserved features of the built and natural environments around Millau: Gorges on the Tarn and Jonte Rivers, Roman ruins, a Cistercian abbey, and Micropolis, the “insect city” museum. These directions illustrate the multidimensional intentions of the viaduct, which have benefited the surrounding region both culturally and economically.

Although the viaduct is usually closed to pedestrians, it has twice hosted walkers and runners from the region. In December 2004, 19,000 participants in the Three Bridge Walk were privileged to go out to the first pier before the bridge was even open to cars. Later, in May 2007, racers began in the center of Millau and crossed to the southern side of the viaduct and back, displacing auto traffic for a day. These cultural events can only take place in off-peak travel seasons, but they represent another way in which the viaduct has attracted regional attention to Millau and the Tarn Valley (Eiffage 2008).

In addition to its tourism impacts, the viaduct has directly affected the shipping and logistics industry. By providing the “missing link” (Aveyron Expansion 2008) of route A75, it created a new alternative trans-European route which saves time and money for shippers; Aveyron Expansion (2008) reports an equivalent savings of 74 km (46 mi), 1.25 h, 22.7 L (6 gal.) of fuel, and \$31 US for trucks over 12 tons traveling between Paris and Perpignan. The sav-

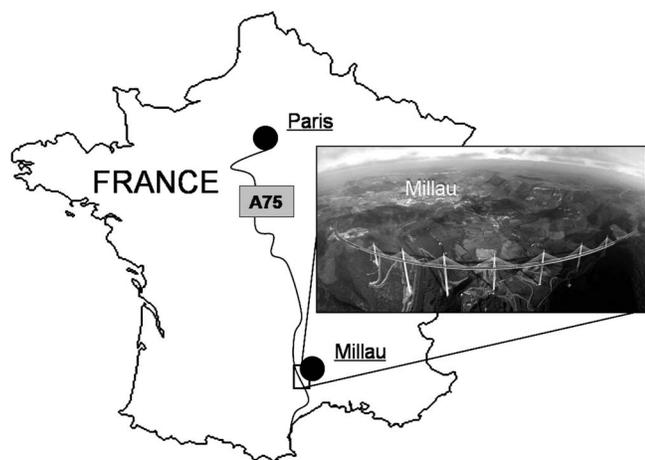


Fig. 5. Illustrative map for Millau Viaduct, France (aerial image courtesy of Foster + Partners, architects)

ings can benefit all of Europe, but have spurred the expansion of the logistics industry in Aveyron specifically. Other industries spurred by the viaduct include information technology, mechanical engineering and construction.

Environmental Impacts: Preserving Natural Capital

The designers and constructors of the Millau Viaduct took several steps to preserve natural capital in the Tarn Valley. As Saxton (2007) reported, the cable-stayed bridge design avoided the need for a tunnel, which was one of the alternatives considered by SETRA that would have caused much greater environmental disturbance. The high CO₂ emissions associated with concrete use (both production and transport) were partially reduced by building on-site batch plants for the piers and by constructing the deck out of steel instead of concrete. Although emissions were associated with transporting the prefabricated steel sections from off-site, overall emissions savings were made considering the amount of concrete that would have been required for structural integrity. Also, steel could better conform to the architectural vision of a “slender ribbon” (Foster and Partners 2008). In order to construct the massive bridge with minimal disturbance to the valley bottom, innovative methods using hydraulic technology were used to launch the deck across the valley, advancing one pier at a time (Saxton 2007).

In operation, the viaduct has relieved air and noise pollution due to heavy congestion through Millau. In order to manage congestion levels on the bridge and to prevent traffic convergence, tolls are higher during the summer holiday months. Permanent surveillance from sensors along the bridge and a control tower, as well as emergency telephones placed regularly along the shoulder, allow for fast intervention and management of incidents to ensure that traffic flows at its optimum (Eiffage 2008). These measures, while they do not solve the problem of fossil fuel use, significantly increase the viaduct’s environmental efficiency as well as social sustainability.

Concluding Remarks

The theoretical discussion and case studies above show how infrastructure may be viewed as part of a socio-technical system, in continuous relationship with the human and natural environments. Sustainable infrastructure development will help communities to bypass typical development pathways to achieve sustainability in shorter time frames than the status quo indicates is possible. In Fig. 1, this is represented by a paradigm shift from following the broken pathways to following the solid pathways. Fig. 2 illus-

trates the mechanism for this achievement: infrastructure designs and policies that lessen environmental impacts and their associated health linkages, while simultaneously expanding the lifestyle choices available to users. Like all megaprojects, the Dallas/Fort Worth International Airport, Öresund Fixed Link, and Millau Viaduct are large and have far-reaching influence. Unlike projects that ignore the requirements of sustainability, each of these has expanded the opportunities and choices available to residents in their respective regions, resulting in an improved quality of life for many people. They have also spurred the evolution of distinctive communities: some that could not have existed without them and others that could not have been appreciated. Moreover, each of these projects has to one degree or another addressed the issues of conserving natural capital.

Considered as a solution to congestion, the Millau Viaduct exemplifies the use of a drastically bold and creative idea or initiative to fully eliminate an existing problem, i.e., congestion and travel delay. It significantly transformed the community of Millau and is in stark contrast with proposals that only attempt to incrementally chip away at an existing problem without the intent to eliminate it once and for all, but to temporarily alleviate it—usually resulting in a long period of a community fraternizing with the problem and perhaps even lowering their QOL expectations. This example demonstrates how sustainable infrastructures tend to be multiple-objective infrastructures, not designed to solely execute their primary function effectively, but simultaneously to be a force for economic and social development and environmental preservation.

The Öresund Link also demonstrates various characteristics of sustainable infrastructures. It exemplifies the role of infrastructure as a regional integration tool, creating economies of scale, expanding choices and generating new value among the communities it integrates—all with zero or near-zero degradation of the natural environment. In particular, the link highlights the value of seeking opportunities to create more sustainable societies through infrastructure development. No problem in particular dictated the need for the link but, rather, an opportunity was seen to use infrastructure creatively to generate added value through increased choices and to foster new reputations that promote economic value. The zero solution of the Öresund Link also sets a standard for sustainable infrastructures: the strategic and sensitive protection of environmental, social, and economic assets.

Likewise, the Dallas/Fort Worth International Airport is a good example of an infrastructure facility that is multipurpose or multifunctional in nature, taking advantage of opportunities to create value beyond the primary function of the facility. Through its local and regional economic impact on industry expansion, job growth, and property value increase DFW has expanded the choices available to Metroplex residents. Furthermore, DFW shows how physical and procedural changes can be made to an existing system in order to drastically improve sustainability. Although the frequent-flyer lifestyle enabled by aerotropolis-type development is heavily reliant on fossil fuels, through its award-winning EMS the airport has shrunk the natural resource footprint associated with frequent-flying.

Future Research

The examination of these three transportation megaprojects is rooted in the concept of sustainable infrastructure development as promoting the goals of sustainability: to provide an acceptable or improving QOL while preserving natural assets. Existing quantitative methods for defining QOL are inadequate as performance measures for sustainable development, and there is a research need to advance new methodologies. However, evolution in the theoretic-

cal definitions of QOL that underlie the existing models has demonstrated the importance of choice and preference. New QOL measures should link community priorities and values to objectively measurable indicators for living standards, thereby capturing the interaction between external conditions, institutional decisions, and the expansion or restriction of choice.

Infrastructure design, planning, and policy decisions can profoundly affect QOL, either positively or negatively. In turn, values, perceptions, attitudes, and lifestyles affect the development of infrastructure and how it is used. Further research should explore how even small-scale infrastructure development can advance sustainability in innovative ways. For instance, what does a zero solution look like in different contexts and at different scales? Also, infrastructure development does not equate with infrastructure expansion, but it could include innovative solutions in institutions, management, and operations, or even nonengineering solutions, such as public outreach, to change the way that a system is understood and used.

QOL-based methodologies for infrastructure development can lead to tangible engineering targets for socially sustainable development. If implemented in several localities, QOL-based methodologies will provide information about how appropriate operational definitions of sustainable infrastructure development may vary depending on context. Although operational definitions will vary because different communities have different development needs, values, and habits, the fundamental concept is the same temporally and spatially: sustainable infrastructure development will improve QOL by expanding or protecting powers of choice. In other words, it will advance the process of *human development*, as defined by the United Nations.

In order to comprehensively advance the sustainability discourse, methods should be developed for linking social, economic, and environmental impact analyses. Approaches that credibly capture contextually relevant QOL aspects will be able to support robust analyses of social costs and benefits, decreasing ambiguity in this area. Thus, infrastructure development decisions will be enabled that advance sustainable development, broadening the focus from achieving functional efficiency to include far-reaching influences on the economy, natural environment, and social quality of life.

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