Transportation Sustainability in the Urban Context: A Comprehensive Review

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Abstract:

Although the term "sustainability" did not gain traction until the 1980s, concerns about the consequences of transportation technology started long before. This paper reviews the literature on urban transportation sustainability using three frameworks. First, urban transportation can be unsustainable environmentally, economically, and socially (the three pillars of sustainability). Second, sustainable strategies tend to fall into two paradigms. Sustainable Transport Technology improves current patterns of modes and trips by consuming less resources and generating less waste. Sustainable Travel Behavior and Built Environment takes a more holistic approach that targets more sustainable travel choices, recognizing that changes in the built environment that currently constrains those choices are also essential. Third, the Planner's Triangle helps explain commonly encountered situations where inherent tradeoffs can impede win-win-win strategies across environmental, economic, and social domains. The paper concludes with future research directions and concluding thoughts about urban transportation and sustainability.

Keywords: Cities | sustainability | urban transportation | travel behavior | built environment | technology

Article:

Introduction

The focus of this review is the sustainability of transportation in the urban context. Transportation is intertwined with many aspects of urban geography and planning, especially when considering sustainability. The Brundtland Commission (1987) defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." (p. 8). Although the term "sustainability" was rarely used in urban transportation and urban geography until the early 1990s (Purvis & Grainger, 2004), concerns over the development of transportation systems and their associated impacts on urban form, air quality, and society go back over a century (Alonso, Monzón, & Cascajo, 2015; Carroll & Bovls, 1957; Dickinson, 1949; Kidd, 1992; Marble, 1959; Pratt, 1911; Stradling & Thorsheim, 1999; Taylor, 1915).

Urban transport systems today are largely motorized, dependent on nonrenewable fossil fuels (Black, 2010). Emissions from vehicles contribute significantly to both climate change and the degradation of urban air quality (Chapman, 2007; U.N. Habitat, 2016). Traffic congestion causes substantial economic losses in wasted time and fuel (Downs, 2005). The geographic organization of land use and transport infrastructure in our cities can promote social equity (Curtis, 2008; Van Wee & Handy, 2016) or lead to social exclusion for disadvantaged groups (El-Geneidy et al., 2016; Lucas, Van Wee, & Maat, 2016; Manaugh & El-Geneidy, 2012). New research has begun to show that transport systems affect our happiness (Pfeiffer & Cloutier, 2016) and overall quality of life (Bäckström, Sandow, & Westerlund, 2016; Bergstad et al., 2011; Friman, Fujii, Ettema, Gärling, & Olsson, 2013).

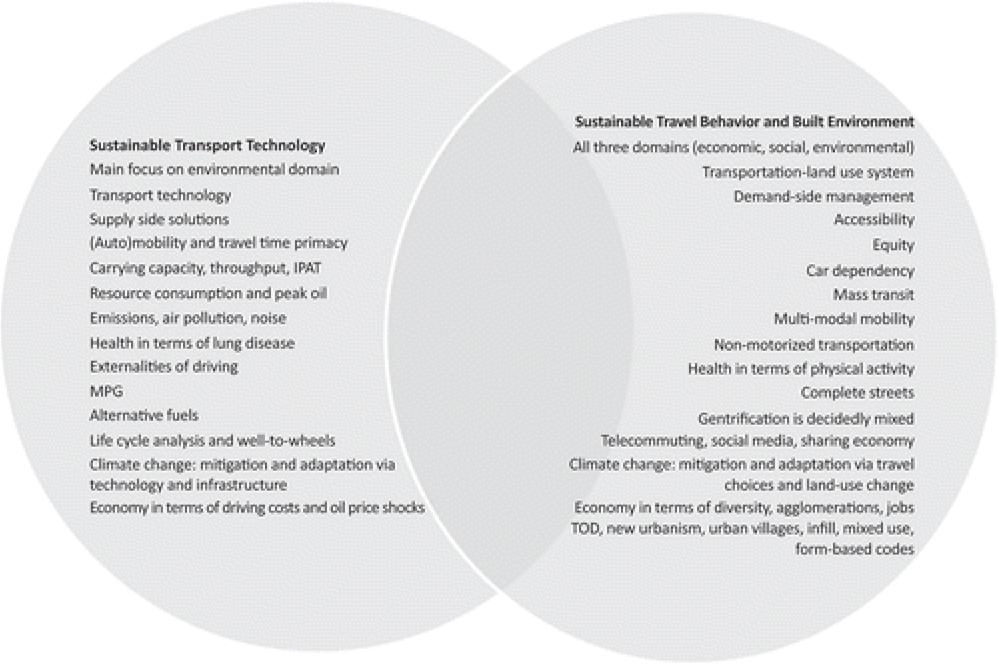

Figure 1. Two main approaches to urban transportation sustainability.

This paper reviews the literature on urban transportation sustainability using three frameworks. First, the goals of transportation sustainability are summarized in three fundamental "pillars" of environmental, social, and economic quality (Gudmundsson, Hall, Marsden, & Zietsman, 2016). The unsustainability of urban transportation systems can also be understood via these three pillars. Second, the literature on sustainable transport solutions is often divided into narrow and broad approaches (Litman & Burwell, 2006), as summarized in Figure 1. The narrower Sustainable Transportation Technology approach focuses on making each form of mobility more sustainable by reducing its resource use and pollution. The broader Sustainable Travel Behavior and Land Use approach is more holistic. It recognizes that moving people and goods more sustainably will require a reconfiguration of urban form to improve accessibility for more sustainable transport modes. While both approaches address concerns about the unsustainability of our current transportation system, they emphasize different solutions.

The third framework is based on Campbell's Planner's Triangle (1996, 2016), which emphasizes the sometimes inherent conflicts and tradeoffs between economic, social, and environmental goals (the three pillars of sustainability). Win-win-win solutions are elusive; efforts to promote one or two pillars of sustainability often conflict with the third. We offer hopefully thought-provoking examples of typical and often inevitable conflicts between sustainability goals. Our contribution is an up-to-date, comprehensive review of the literature on urban transportation sustainability. We use three distinct frameworks to organize this literature, provide numerous examples of the challenges of urban transportation sustainability, and conclude with a long list of promising future research directions.

Unsustainability of urban transportation

The study of urban transport sustainability starts by identifying what makes urban transport *un*sustainable. We present a brief overview of the main problems, each of which impacts the three pillars of sustainability differently (see Table 1 for a summary). Due to space limitations, concerns such as noise, wetlands, water pollution, wildlife, agriculture, land-surface modification, and archaeological resources are not covered.

Table 1. Sustainability impacts of urban transportation.

	Pillars of Sustainability		
Unsustainable Transportation-Related Problem	**Economic**	**Social**	**Environmental**
Material throughput and carrying capacity	Primary – see oil supply, reserves, and prices	Primary – see air pollution and climate change	Primary – see air pollution and climate change
Oil supply, reserves, and prices	Primary – oil prices	Secondary – price effects on families and communities	Secondary – drilling in sensitive ecoregions
Air pollution	Secondary – health care and other costs	Primary – health	Primary – air quality
Climate change	Primary – impacts on all economic sectors	Primary – e.g., health, occupations, food, safety, water, migration, conflict	Primary – e.g., biodiversity, precipitation, extreme weather
Traffic congestion	Primary – time costs	Secondary – time constraints on households	Secondary – increased emissions
Road safety	Primary – accident costs	Primary – injuries and deaths	Secondary – resources used in repairing and replacing
Transportation affordability	Primary – accessibility to jobs, school, etc.	Primary – household budgets	Secondary – higher emissions of older cars
Equity	Secondary – exclusion of potential consumers and workers	Primary – accessibility to jobs, school, etc.	Secondary – equal access to alternatives to driving will improve environmental quality
Physical activity and health	Secondary – medical costs	Primary – health	Secondary – zero emissions of non-motorized modes

Material throughput and carrying capacity

The term “sustainability” has been credited to Meadows, Meadows, Randers, and Behrens (1972) global simulation classic, *The Limits to Growth*. Accordingly, sustainability in transportation was initially viewed from the principles of environmental carrying capacity (Black, 1997a). Three conditions were identified for meeting the transport needs of future generations (Black, 1997b): 1) renewable resource use not exceed their rates of regeneration; 2) non-renewable resource use not exceed the rate at which sustainable renewable substitutes are developed; and, 3) pollution emissions not exceed the assimilative capacity of the environment. The IPAT identity was an early organizing principle for understanding the driving forces of population (P), affluence (A), and technology (T) that lie behind the activities that generate the material throughput (I) that causes environmental impacts (Chertow, 2000). In the transportation context, an example might be:

$$\mathrm{I(barrels\ of\ oil\ consumption)} = \mathrm{P(persons)} \times \mathrm{A(\$GDP/person)} \times \mathrm{T(barrels/\$GDP)}$$

In a similar vein, the transport-specific ASIF framework (Schipper, 2011) estimates transport sector carbon emissions as a function of A (volume of transport activity), S (mode share), I (energy per ton-mile or passenger-mile), and F (carbon content of the fuel). Since material throughput includes both resource inputs and waste outputs, its impacts listed in Table 1 include the primary effects of the next three categories: oil supply, air pollution, and climate change.

Oil supply, reserves, and prices

The oil crises of the 1970s were seminal events in transportation sustainability. Precipitated by geopolitical events in the Middle East and the formation of OPEC, inflation-adjusted crude oil prices increased 10-fold (British Petroleum, 2017). From the 1970s to the 2008 financial crisis, the problems associated with finite oil reserves returned in repeated cycles: the volatility of oil prices, the vulnerability of the economy to recession and inflation, the inelasticity of oil demand, the boom and bust of oil exploration and production, the military costs of keeping oil shipping lanes open, and the pressure to drill in sensitive offshore and wilderness locations. In the 2000s, these concerns were joined by the rapid motorization of newly industrializing countries, especially China (Sperling & Gordon, 2009). By the mid-2010s, however, the fears of permanent $150 per barrel crude prices and $5 per gallon gasoline prices in the United States (Mann, 2013; White, 2011) had receded into the future due in part to the invention of hydraulic fracturing (“fracking”) technology.

Air pollution

In the U.S., transportation is responsible for over 20% of ultrafine particulate matter, over 30% of volatile organic compounds, and over 50% of nitrogen oxide emissions (USEPA, 2016 U). Concentrations of these pollutants are substantially elevated near major roads (Karner, Eisinger, & Niemeier, 2010). In the U.S. alone, air pollution from transportation causes hundreds of thousands of early deaths (Caiazzo, Ashok, Waitz, Yim, & Barrett, 2013). U.S. air quality regulations that reduce this exposure are estimated to account for 61–80% of the monetized benefits of all federal regulations (USOMB, 2016).

Climate change

Transportation both impacts, and is impacted by, climate change. In March 2016, transportation eclipsed power generation as the leading source of CO_2 emissions in the United States, and is the only energy-use sector with increasing emissions (USDOE, 2016). The effects of climate change – extreme storms and associated flooding, sea-level rise combined with storm surges, higher temperatures, melting permafrost, and wildfires – will directly affect transportation infrastructure and vehicles and indirectly affect traveler behavior, population shifts, and supply and demand for freight (National Research Council, 2008). The Third National Climate Assessment adopted a risk-management approach to assess the risks in terms of (a) likelihood of occurrence and (b) magnitude of impact (McLaughlin, Murrell, & DesRoches, 2011; Schwartz et al., 2014). For instance, inundation of coastal roads, rail, and airports is considered (a) virtually certain to occur and (b) highly disruptive.

Traffic congestion

Delay from traffic congestion is a large external cost to our urban transport system. The total cost of this delay includes the cost of fuel, added pollution, and time wasted by commuters and freight stuck in traffic. A recent report by the Centre for Economics and Business Research (2014) estimated that the total cost of traffic congestion in the United States reached $124 billion in 2013, and projected that traffic congestion costs would increase an additional 50% by 2030. By many accounts, congestion is the single largest external cost of our transport system (e.g. Parry, Walls, & Harrington, 2007).

Road safety

Annually, 1.25 million people die in crashes on the world's roads (World Health Organization, 2016). Traffic-related deaths are the leading cause of mortality for 15–29 year-olds worldwide (World Health Organization, 2016). In U.S. cities, bicyclists are 12 times more likely to be killed than drivers (Brustman, 1999; Buehler & Pucher, 2017). Even though bicycle and pedestrian deaths have declined since 1975, each year bicyclists account for 2% of deaths and pedestrians for 15% (IIHSLDI, 2016). The U.S. has much higher fatality and serious injury rates per kilometer driven than other developed countries (Buehler & Pucher, 2017). Urban fatality rates per million VMT are 62% lower than rural rates (NHTSA, 2017). Many cities worldwide have adopted Vision Zero with the goal of eliminating traffic deaths altogether (Vision Zero, 2017).

Transportation affordability

Transport affordability is a substantial challenge for many urban residents in both the developed and developing worlds. In the U.S., transportation is the second highest expenditure category after housing (BLS, 2015). Low-income households choose between struggling to pay for vehicle ownership (e.g., Puentes & Roberto, 2008) and struggling to access jobs and services without a car (e.g., Kawabata & Shen, 2007). In much of the developing world, urban residents choose between struggling to pay transit fares and traveling on foot (e.g., Salon & Gulyani, 2010).

There is an important spatial tradeoff at work here for urban residents. As predicted by economic theory (Alonso, 1964), housing costs generally increase with accessibility. All else equal, housing and transport costs move in opposing directions across space in a metropolitan area. Lower-income households may choose to live on the urban fringe in order to be able to afford housing – especially if they are interested in home ownership – and then be stuck with high transportation costs (Haas, Newmark, & Morrison, 2016; Kane, York, Tuccillo, Gentile, & Ouyang, 2014; Mattingly & Morrissey, 2014).

Equity

Transport equity is the fairness with which benefits and costs of transportation are distributed (Litman, 2016). Transport inequity results when costs paid are not proportional to benefits received (Taylor, 2017). Looking at benefits only, transport inequity occurs when a city's transportation-land use system affords different levels of access to different groups. Transport inequity can lead to social exclusion (Lucas, 2012), which results in the inability of certain groups to fully participate in the economic and social life of their city.

Equitable transportation systems need not provide equal services to all areas and socioeconomic groups. Indeed, the greatest benefits for certain transport investments can go to the least-advantaged areas and groups based on need. For instance, greater investment in public transit, pedestrian, and bicycle facilities in lower-income communities is warranted because residents of these areas own fewer cars.

While much has been written about social equity and urban transport (Curtis & Low, 2016; Preston, 2009), integrating equity into transportation planning practice remains rare (Manaugh, Badami, & El-Geneidy, 2015). Since transportation investments historically created spatio-temporal disparities in access to opportunities (Lucas, 2012), remedying this should be a high priority.

Physical activity and health

Active transportation promotes health (Bertolini, Le Clercq, & Kapoen, 2005; Sallis et al., 2016). Physical inactivity is the fourth leading risk factor of chronic diseases such as cancer, heart disease, and type-2 diabetes (WHO, 2010). Inactivity accounts for 3.2 million deaths each year (Pratt, Norris, Lobelo, Roux, & Wang, 2014) and over $50 billion in health-care costs worldwide (Ding et al.,). In the U.S., 8.7% of health care costs are for treating diseases associated with physical inactivity (Carlson, Fulton, Pratt, Yang, & Adams, 2015). By almost any measure, however, active transportation represents a small fraction of all travel – at least in the U.S. Less than 4% of Americans walk or bike to work (Sultana, 2014). The National Household Travel Survey (2009) reports less than 35% of Americans walked at all in the previous week.

Sustainable transportation technology

The most direct approach to improving transport sustainability, but also the most narrowly defined, is to make the same trips on the same modes more sustainable (Black, 1997b). Technocentric approaches recognize that American cities and lifestyles have evolved to the point that they revolve around the automobile and view this dependency as extremely difficult to change in the short or medium term (Sperling & Gordon, 2009). Sustainable Transportation Technology solutions include policies that address innovation, infrastructure investment, energy efficiency, alternative fuels, pollution control, and intelligent transportation systems (Huang, Kuby, & Chow, 2017). Additional emerging technologies are discussed later as promising research directions.

Cleaner petroleum-powered cars

To the driving public, transportation sustainability is mainly about fuel-efficient cars. In the U.S., the Corporate Average Fuel Economy (CAFE) standards are the primary policy to increase fuel economy (Greene, 1998). In other countries, high fuel taxes play a much larger role in encouraging efficient cars (and fewer and shorter car trips). Regulatory mechanisms requiring pollution-control equipment have dramatically reduced emissions of harmful pollutants from vehicles – although these technologies do not reduce CO_2 emissions (Godish, Davis, & Fu, 2014). A major advantage of focusing on cleaner and more efficient petroleum-powered cars is that it requires no revolutionary changes in travel behavior, urban form, technology, or infrastructure.

Alternative fuels, stations, and vehicles

The U.S. relies on oil for over 92% of its transportation energy. To reduce oil dependence and meet the Paris Agreement's goal of 80% reduction of greenhouse gas (GHG) emissions from 2005 levels by 2050, greener alternatives to petroleum are needed for motor vehicles. Petroleum, however, enjoys major advantages over alternatives, including energy density, economies of scale, familiarity, and nearly ubiquitous refueling stations. For biofuels, natural gas, electricity, and hydrogen to compete, multiple industries must develop simultaneously, including vehicle and fuel production, fuel retailing, repair, and insurance (Farrell, Keith, & Corbett, 2003; Lu, Rong, You, & Shi, 2014; Melendez, 2006).

A sophisticated literature simulates the roll-out, competition, coordination, economies of scale, learning, and incentives required to transition to greener sources of transportation energy (Fan et al., 2017; Greene, Leiby, & Bowman, 2007; Ogden, Fulton, & Sperling, 2016; Struben & Sterman, 2008). How many stations and where to locate them is an inherently geographical question (Agnolucci & McDowall, 2013; Kuby & Lim, 2005; Melaina & Bremson, 2008), as is the revealed behavior of drivers choosing where to refuel in the face of a scarcity of stations (Kelley & Kuby, 2013; Sperling & Kitamura, 1986). Driving range is a critical constraint to adoption of electric vehicles in particular (Pearre, Kempton, Guensler, & Elango, 2011). Finally, all alternatives to petroleum are not equally economical or sustainable: well-to-wheels and life-cycle analysis evaluate the potential of different energy source-carrier-propulsion pathways (Edwards, Mahieu, Griesemann, Larivé, & Rickeard, 2004; Von Blottnitz & Curran, 2007).

Intelligent transportation systems

Table 2. How transport/land-use system changes impact travel demand.

System Change	**Policy/Investment Actions (examples)**	**Trip Distance**	**Trip Frequency**	**Carpooling (vehicle occupancy)**	**Non-Auto Mode**
Increase density	• Multifamily housing development • Increase housing unit density • Urban infill development	-	+	+	
Mix land uses	• Mixed-use zoning • Vertically mix buildings	-	±	+	+
Increase local access to jobs	• Jobs-housing balance • Mixed-use zoning • Higher floor-area ratio • Reduce parking requirements	-	+		+
Increase regional access to jobs	• Economic development strategies such as small business incentives and support services, and business-enabling zoning changes	+/-			
Improve network connectivity	• Reduce block length • Grid network design • Cut-through streets and paths	-	+		+
Improve public transport access	• Add transit routes • Increase service frequency • Transit-oriented development • Intermodal infrastructure (e.g. bikeshare, bike racks)				+
Improve public transport service	• Real-time arrival information to stations and stops • Premium (e.g., faster, more comfortable) service for an additional charge • Additional amenities on transit vehicles and at transfer hubs (e.g., wi-fi)				+
Improve walkability	• Complete streets • Sidewalks and paths • Road diets • Traffic calming • Safer crossings				+
Improve bikeability	• Complete streets • Bicycle lanes, paths, and boxes • Bicycle boulevards • Road diets • Traffic calming • Bicycle parking				+
Reduce parking supply	• Modify off-street parking minimums and maximums • Convert on-street parking to BRT, streetcar, or bike lanes		-	+	+
Increase prices	• Raise fuel taxes • Raise parking fees • Raise licensing and registration fees • Road user fees • Congestion pricing • Carbon tax	+	+	-	-
Increase highway capacity	• Build new roads or widen existing ones • Traffic management	+	+	-	-

Intelligent transportation systems (ITS) include a variety of technologies to manage congestion, including lane sensors, ramp metering, dynamic messaging, and emergency dispatching (Zhang et al., 2011). Recurrent bottlenecks driven by a systemic imbalance of vehicles and road space account for 40%, crashes and disabled vehicles for 25%, weather for 15%, construction for 10%, poor signal timing for 5%, and special events for 5% of congestion (Cambridge Systematics, 2005). Different ITS technologies address each of these. While ITS is generally the province of traffic engineers, it is important for transport and urban geographers to understand because it represents an attractive option for moving more vehicles faster without new road construction or lane expansion.

Sustainable travel behavior and the built environment

Policies, transportation investments, and the built environment affect the demand side of travel by changing the underlying price, time, comfort, and convenience of transport alternatives. Built environment and transport investment strategies can affect transport sustainability through (1) reducing trip distances, (2) reducing trip frequencies, (3) increasing vehicle occupancy, or (4) shifting travel to non-car modes. Table 2 presents a matrix illustrating how a variety of policy and investment strategies lead to changes in the transportation and built environment system that affect travel behavior in each of these four ways. Plus and minus signs indicate the expected directions of the effects. Notice that some changes may have conflicting effects on sustainability. This list is not comprehensive: we do not cover carpooling, telecommuting, online shopping and education, social media, and behavioral-change programs.

Pricing

One of the most powerful tools to encourage behavior change is pricing. When goods are more expensive, people voluntarily consume less of them, and transportation is no exception. The literature is clear on this. The price of fuel affects both the fuel efficiency of the vehicles purchased (Busse, Knittel, & Zettelmeyer, 2013) and how much people drive (Gillingham, 2014; Goodwin, Dargay, & Hanly, 2004; Graham & Glaister, 2004; Lane, 2010). Road pricing – or its more sophisticated cousin, congestion pricing – is identified as possibly the only policy tool that can substantially reduce traffic congestion (Downs, 1992, 2004, 2005). Transit fares impact ridership (Taylor, Miller, Iseki, & Fink, 2009). Raising parking prices reduces parking occupancy (Ottosson, Chen, Wang, & Lin, 2013; Pierce & Shoup, 2013).

Modes

An essential part of making urban systems more sustainable is providing viable alternatives to cars. Historically, the primary alternatives included transit, walking, and bicycling. Transit provision both reduces car dependence (Spears, Boarnet, & Houston, 2016) and increases transit use (Taylor et al., 2009). Pedestrian-friendly neighborhoods encourage walking (Saelens & Handy, 2008) and bicycle facilities strongly encourage biking (Dill & Carr, 2003; Pucher, Dill, & Handy, 2010). Evidence on the extent to which active travel reduces car use, however, is weaker (Piatkowski, Krizek, & Handy, 2015).

The “alternatives” to cars have recently expanded to include ways of accessing cars without owning them, such as car-sharing organizations (e.g., Zipcar) and ride-sourcing smartphone apps (e.g., Uber, Lyft). While trips made using these services are car trips, the sustainability advantage is that they allow households to own fewer cars and make more of their other trips using alternative modes. There is convincing evidence that car-sharing organizations measurably reduce car ownership (Martin, Shaheen, & Lidicker, 2010). The evidence on ride-sourcing is less well-developed, but early studies suggest ride-sourcing may improve urban transport sustainability (e.g., Li, Hong, & Zhang, 2016; Rayle, Dai, Chan, Cervero, & Shaheen, 2016).

Land use

Land-use strategies ranging from leapfrog, beltway, and exurban development at one end of the spectrum to infill, urban villages, smart growth, and new urbanism at the other can affect transport system sustainability in either direction. They do so by bringing trip origins and destinations closer together (e.g., jobs/housing balance, density), forcing them farther apart (e.g., large lot zoning), diversifying neighborhoods (e.g., mixed-use development), improving transit access (e.g., transit-oriented development), and setting minimum or maximum off-street parking requirements.

There are large differences in car dependence across built environment typologies, regardless of scale. At the metropolitan scale, average car use in 13 major U.S. cities was 7.5 times greater than in Singapore, Tokyo, and Hong Kong (Kenworthy & Laube, 1999). Using a neighborhood typology approach, Salon (2015) demonstrated that car dependence differs by a factor of two across neighborhood types in California. Across neighborhoods in San Francisco, car mode share ranged from 60% to 90% (Kitamura, Mokhtarian, & Laidet, 1997).

This evidence, however, does not conclusively show that the built environment has a strong effect on travel behavior. There is the distinct possibility that households that prefer not to drive self-select into neighborhoods and cities that provide good alternatives to driving, and vice versa. A substantial literature (including Kitamura et al., 1997; Salon, 2015) attempts to control for residential self-selection and focuses attention on the direct effect of built environment characteristics on travel behavior.

Reviews of this literature suggest that the built environment does impact travel choices, but that socioeconomic factors are probably more important than built environment characteristics (e.g., Ewing & Cervero, 2010; Salon, Boarnet, Handy, Spears, & Tal, 2012; Sultana, 2015; Sultana & Weber, 2007). Built environment characteristics such as population density, accessibility of employment and other destinations, and land-use diversity are important determinants of travel choices in at least some published studies, and the relationships are in the expected direction (Table 2). A separate literature investigates the effect of parking supply on car dependence, finding strong evidence that more parking spaces lead to more driving (Chester, Fraser, Matute, Flower, & Pendyala, 2015; Guo & Ren, 2013; Sultana, 2015).

Networks

Connectivity and design are the main network features that influence urban sustainability. Connectivity is a distinct concept from accessibility, which factors in the destinations within reach. Connectivity refers to the ability of the network configuration to provide direct routes and options for alternative routes (Berrigan, Pickle, & Dill, 2010). Route-directness (Stangl, 2012) measures the detour required for a particular O-D pair, while aggregate measures such as link-node ratio, intersection density, and block length estimate the general ability to connect origins and destinations (Tal & Handy, 2012). Grid networks generally connect better than post-war suburban networks (Randall & Baetz, 2001), and are strongly associated with more walking and biking (Ewing & Cervero, 2010). Design refers to qualitative aspects of networks, such as wide sidewalks, painted bike lanes, plazas, shade, landscaping, lighting, cleanliness, and amenities, which make each unit of distance travelled safer and more pleasant (Cervero & Kockelman, 1997). The Complete Streets movement emphasizes sustainable design, with over 1,000 local and state agency adoptees (Smart Growth America, 2017).

Conflicting goals: win-win-win solutions are elusive

> "In a world in which the distribution of mobility is enormously unequal, it is inevitable that competing imperatives of reducing greenhouse gas emissions and improving mobility will come into conflict." (Wachs, 2010, p. 9)

It is often difficult to find solutions that simultaneously advance all tenets of sustainability: environmental, economic, and social. Urban planners have long recognized this tension, depicting it graphically as "The Planner's Triangle" (Figure 2) (Campbell, 1996). The triangle highlights the often necessary choice between investing scarce resources toward one sustainability goal at the expense of another. Campbell's 1996 paper was revisited in a series of articles in the *Journal of the American Planning Association* on its 20th anniversary (e.g., Campbell, 2016; Hirt, 2016).

Figure 2. Planners triangle, adapted from Campbell (1996).

Here, we illustrate some of the challenges outlined by Campbell and others using commonly encountered situations faced by urban decision makers at the intersection of urban sustainability and transport sustainability. These are not case studies per se, but rather are illustrative scenarios intended to inspire creative thinking about controversial urban transport sustainability solutions.

Transit-oriented development and gentrification

Transit-oriented development (TOD) is heralded by many as an important part of the solution to our urban sustainability challenge, improving accessibility and reducing car dependence. TOD is defined as “compact, walkable, pedestrian-oriented, mixed-use communities centered around high quality train systems” (Transit Oriented Development Institute, 2017), and is being built in central urban neighborhoods all over the U.S.

Accessible urban forms, however, attract higher income residents and increase land and housing costs, which can lead to frustration and relocation of low-income renters (Koschinsky & Talen, 2016). Despite the goal of income diversity in these neighborhoods, TOD often worsens social exclusion by displacing the low-income population to neighborhoods that have less walkable access to activities (Pollack, Bluestone, & Billingham, 2010). If affordability is prioritized, there is a potential to reduce social inequality in highly accessible neighborhoods. Unfortunately, prioritizing affordability reduces developer profit and is therefore not simple. Using the terminology of the Planner’s Triangle, TOD investments are consistent with both economic and environmental goals, but sometimes will reduce social equity, thereby creating both property and development conflicts.

Infill development and affordable housing provision

Infill development (including most TOD) is both riskier and more expensive than greenfield development on the urban fringe. First, multifamily housing development is inherently riskier than single-family tract development. In single-family developments, homes are sold individually as completed; if demand drops, construction can pause. Multifamily housing developers, however, must invest in entire buildings before any units can be sold or leased; if demand drops, the developer risks substantial losses. Further, developing in central areas requires difficult parcel assembly (Brooks & Lutz, 2016; Terrence, 2001), the possibility of brownfield cleanup requirements (Terrence, 2001), and facing neighborhood opposition (Cervero et al., 2004; McConnell & Wiley, 2010; Terrence, 2001). For these reasons, financing infill development can be challenging and expensive (Venner & Ecola, 2007). In addition, cities often want affordable housing included in infill projects to fulfill social equity goals. However, requiring affordable housing reduces the profit margins on already risky projects, making this type of (more) sustainable development less financially feasible. In Planner’s Triangle terms, there is a tradeoff between social equity and the profitability of infill development, creating a property conflict. In addition, infill development is economically riskier than greenfield development, creating a potential resource conflict with infill’s clear environmental benefits.

Transit’s multiple purposes

Transit provides a more sustainable alternative to the private car, allowing large numbers of people to move through the city without the substantial internal and external costs of driving. Transit – especially rail – can play an important role in channeling economic growth to station neighborhoods (e.g., Mohammad, Graham, Melo, & Anderson, 2013). Transit also provides vital mobility and access services for the urban poor and carless (Giuliano, 2005). Thus, it appears that perhaps public transport investment is a win-win-win solution, improving environmental performance, local economies, and social equity.

The challenge arises when geography is introduced. Transit serves low-income people, aims to get wealthier people out of their cars, and aims to spur local economic development. Giuliano (2012) identified that not only are the poor located in different neighborhoods from the wealthy, but they also have different transportation needs: "Every investment represents a choice of what transit market is to be served" (576). Indeed, some of the most well-known environmental justice lawsuits have centered on the choice of technology (bus vs. rail) and corridor (e.g., Golub, Marcantonio, & Sanchez, 2013; Grengs, 2002). In terms of the Planner's Triangle, this scenario differs from the other examples, in that transit investments generally advance all three goals, but depending on which technology is built in which corridor, one of the goals may lag behind the others, creating property, development, or resource tensions.

Alt-fuel vehicle costs and subsidies

Alternative-fuel vehicles (AFV) are more expensive than their conventional equivalents and are marketed to wealthier, more highly educated, multi-car households, creating tension with equity goals. The success of the AFV industry depends on early adopters to purchase new vehicles and help the industry get up to scale, which will make the vehicles and fuel more affordable to later adopters. For this reason, many governments subsidize early adopters through tax credits, reduced registration fees, and HOV lane access (Alternative Fuels Data Center, 2017), and cluster stations in wealthier target neighborhoods (Ogden & Nicholas, 2011). Some politicians have critiqued EV incentives as poorer citizens subsidizing the wealthy – an argument that is also used against rooftop solar, bicycle infrastructure, and high-speed rail. Recently, some states have not only eliminated subsidies for EV buyers but also raised EV registration fees to compensate for the fact that they do not pay their fair share of road maintenance costs through fuel taxes (Spector & Pyper, 2017). With positive effects on the environment and the economy and negative effects on social equity, subsidizing AFVs creates both property and development conflicts.

Promising research directions

In light of the recent discourse about transport sustainability within the urban context, we now turn to considering what usefully comes next. This penultimate section suggests promising directions for research. These suggestions are not entirely novel; the contribution here is to put them in one place.

Natural and policy experiments to study land use effects on travel behavior

Despite a sizable literature, evidence on the relationship between land-use policy and travel behavior remains weak. Much of the uncertainty stems from the fact that most studies are based on cross-sectional data, collected from many people, but only at one point in time. Although we can and do try to use these data to shed light on the likely effect of changes in Table 2 strategies on car dependence and urban sustainability, there simply is no way for even the most sophisticated statistical methods to fully overcome both the challenges of correlation between variables and to control for neighborhood self-selection. To measure the effects of a change in policy, we need to collect data on travel choices before and after real changes happen, and compare them to estimate the effect. This suggestion is not new (e.g., Boarnet, 2011; Salon et al., 2012), but research employing this evaluation model remains uncommon in the transportation sustainability literature. Recent examples include Spears et al. (2016), Brown et al. (2016), Ye, Mokhtarian, and Circella (2012), and Lovejoy, Sciara, Salon, Handy, and Mokhtarian (2013). Not every land-use change can be studied this way – some effects occur over long periods of time, making this approach infeasible. However, in cases that can be evaluated over a short time horizon, before-after data collection and analysis is a promising avenue for research.

Effects of urban and transportation policy packages

Policymakers often consider policy and investment *packages* rather than actions in isolation. The importance of integrated transport sustainability strategies is acknowledged by the research community (May, Kelly, & Shepherd, 2006), but few studies have quantified the interaction effects. Rare examples include Lee and Lee (2013) and Guo, Agrawal, and Dill (2011). Most quantitative studies have focused almost exclusively on the effects of each strategy individually.

Understanding heterogeneity

Much of the empirical work on travel behavior presents results as though the relationships of interest – for instance the price elasticity of gasoline or the effect of improved employment access on travel – are constant across people and space. These relationships are not constant, however, and understanding the heterogeneity in these relationships will better inform decision makers about how their actions may yield different results for different categories of people, places, and trips. A few recent studies have begun to explore this heterogeneity (e.g., Boarnet, Houston, Ferguson, & Spears, 2011; Salon, 2015), but more work is needed.

Include preferences, experiences, and attitudes in behavioral analysis

How do preferences, past experiences, and attitudes affect travel and related choices? Evidence to date suggests that these factors can add substantial explanatory power to travel behavior models (Sultana, 2015). Parkany, Gallagher, and Viveiros (2004) provide an early review of this literature; Van Acker, Van Wee, and Witlox (2010) provide a conceptual framework for this research area. However, because most surveys do not include questions about preferences, experiences, and attitudes, most analyses do not include them.

Urban freight

Understanding the sustainability implications of urban freight movement in the e-shopping era is an emerging and important area of study. Brick-and-mortar stores are shutting their doors as retail moves online. Research has shown that the environmental impacts of this change in last-mile goods movement are surprisingly ambiguous, and depend critically on the spatial configuration of both the urban environment and the goods distribution network (Wygonik & Goodchild, 2016). At the same time, urban streets and neighborhoods are not built to accommodate large trucks, and "complete streets" designers often neglect to include freight movement in sustainable urban plans (Smart Growth America, 2017; Zavestoski & Agyeman, 2014). Enterprising companies are experimenting with a variety of delivery modes (e.g., bicycles, robots, and drones) and options (e.g., differential pricing by delivery speed, delivery to lockers instead of individual homes) – all of which are ripe areas for research.

Cultural and development-level differences

Research in different cultural and developmental contexts offers opportunities to learn how sustainability policies translate between more- and less-developed countries. There are at least three frames for this topic, all understudied. First, movement toward sustainability means different changes in different contexts. For instance, most megacity dwellers in developing countries would likely view densification as less sustainable and desirable, while the opposite would be true for most U.S. cities (McFarlane, 2016; Moroni, 2016). Second, little is known about the diffusion of transportation technologies from less- to more-developed cities. While cars, trucks, planes, and trains originated in the industrial north, the Global South has led the way with flexible, lower-investment options, such as electric bicycles, bus rapid transit, and informal jitney services. Third, many have urged the developing world to learn from the unsustainable mistakes of the north and "leapfrog" ahead with locally appropriate sustainable land-use policies and infrastructure investments. It is crucial to investigate these successes and failures.

Disadvantaged neighborhoods

Much equity research has compared transportation behavior and service between lower and higher income neighborhoods, but there is a need for in-depth studies of how to better serve the most disadvantaged neighborhoods. It is important to identify particular at-risk groups in close collaboration with the intended population, local policymakers and key stakeholders (Lucas et al., 2016). Some research has explored independent transportation for disadvantaged children (Veitch et al., 2017) and accessibility in disadvantaged neighborhoods (El-Geneidy et al., 2016; Pyrialakou, Gkritza, & Fricker, 2016), but more work is needed.

Equity

Measuring social equity will also require creating novel methodologies by adopting quantitative, qualitative, and participatory approaches (Pereira, Schwanen, & Banister, 2017). Analyses of the distributive effects of transit service changes, for instance, usually relies on the demographics of the service area, with the assumption that the demographics of the ridership is similar, which may not be the case (Karner, Kuby, & Golub, 2017).

High speed rail and hyperloop

Long-distance, high-speed, low-carbon transportation modes have excellent potential for win-win-win outcomes. High-speed rail (HSR) with typical speeds of 250–350 km/h are much faster than automobile and conventional rail and are competitive with airlines over distances from 400–

2000 km (Kim, 2016; Li & Loo, 2016). Though still in its conceptual and developmental stage, Elon Musk's idea for a long-distance Hyperloop using vacuum tube technology and small pods is being taken seriously in many circles, including by USDOT (Taylor, Hyde, & Barr, 2016). Both HSR and Hyperloop stations can be located in central business districts, where they will enjoy a large door-to-door travel time advantage over air travel and reinforce the economic vibrancy of central cities (Kim & Sultana, 2017; Vickerman, 2015). Analysis of corridor suitability, direct vs. indirect connectivity, and comparison of door-to-door travel times among long-distance modes for different regions of the city are promising areas for geographical research.

Psychological well-being and happiness

Much attention has been given to the relationship between the built environment and physical health, but more research is needed on its effect on psychological well-being (Galea, Ahern, Rudenstine, Wallace, & Vlahov, 2005). A few studies have focused on built and social environments and their relationship with older adult mental health (Galea et al., 2005) and young adults' quality of life (Xiong & Zhang, 2016). This is an area of research where heterogeneity across socio-economic groups, gender, race, ethnicity, age and place may be especially important.

Alternative-fuel vehicle adoption and station arrangement

Consumer decision-making about AFV purchasing is most often studied using stated preference surveys and experiments (e.g., Bunch, Bradley, Golob, Kitamura, & Occhiuzzo, 1993; Potoglou & Kanaroglou, 2007). Because fuel station availability is but one factor of many, surveys usually present it to respondents in a simplified way in terms of a single station either close to home or along a commuting route, or as a percentage of existing stations offering the fuel. Research is needed on how potential early adopters evaluate the geographic arrangement of *multiple* stations to provide an improved behavioral basis for station planning.

Non-electric AFVs

Most AFV research to date has focused on the arrival of EVs and the potential of fuel-cell vehicles. More research is needed on the purchase and fueling of propane, natural gas, and biofuel vehicles. Millions of Americans own flex-fuel vehicles they can fill with either gasoline or E85 (85% ethanol, 15% gasoline), but little is known about who actually fills them with E85, and when, where, and why. In addition, most AFV research focuses on consumers, but for these fossil and bio alt-fuels, commercial and government fleets are often the early adopters, and fleet vehicles drive more miles per year and use more fuel per mile (Nesbitt & Sperling, 1998).

Connected and autonomous vehicles (CAVs)

Research directions abound as to how CAVs will affect urban sustainability. The primary driving force behind the push for CAVs is increased safety (Anderson et al., 2016), but questions remain about how CAVs will interact with human drivers and whether improved safety will encourage more bicycle riders. In terms of land use, what will be the effect on residential choices and sprawl? Which ownership model (shared vs. private) will dominate, and if shared, which kinds of companies will emerge as the leaders? The contenders include legacy taxi companies; ride-hailing companies like Uber and Lyft; IT companies like Google or Apple; car manufacturers like GM or Tesla; or possibly even electric utilities, which could use autonomous EVs to store and release excess renewable energy to improve grid stability and operate the transport system under a public-utility model. If one of the shared ownership models wins out, will developers planning new and supposedly more sustainable multi-family housing today find that they were required by outdated code to overbuild their off-street parking by a wide margin? Finally, how will CAVs impact public transportation? Will they help solve the first/last mile problem, or will they replace transit with their faster door-to-door service? In a CAV society, will we still need transit – and in what ways would these vehicles make cities more or less sustainable?

Adaptation to climate change

With each passing year, it is becoming more urgent to develop robust climate change adaptation strategies for transportation systems. The most recent National Climate Assessment (Schwartz et al., 2014) provides a useful framework for this task, identifying two forms of adaptation (Figure 3). The first aims to reduce, to the extent possible, the impacts of climate change on transport systems, mostly by infrastructure investment. The second aims to reduce the consequences of unavoidable impacts, mostly through strategic resilience planning for transport system disruption.

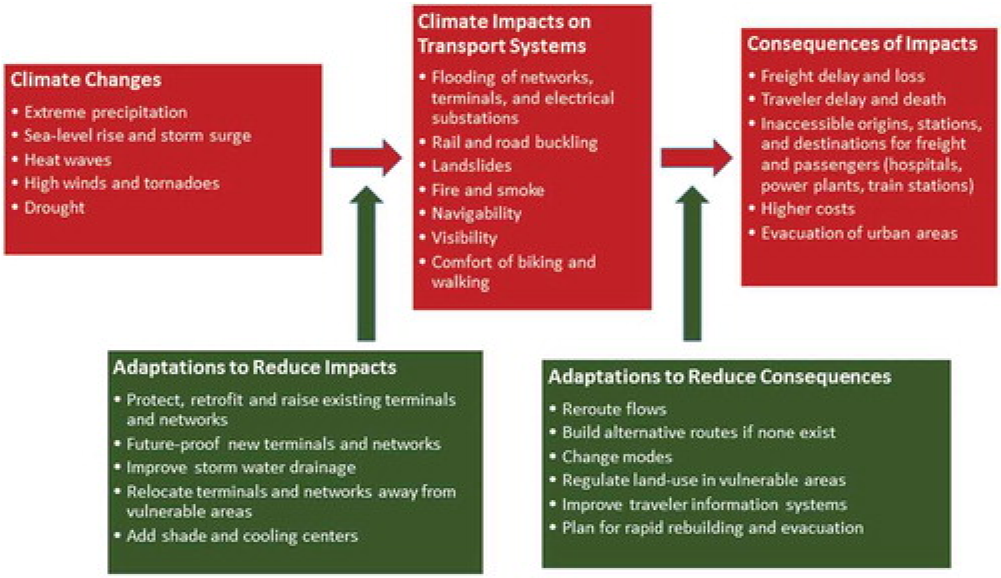

Figure 3. Adaptive strategies to reduce climate change impacts on transportation systems and resulting consequences. Based on Third National Climate Assessment, Transportation chapter (Schwartz et al., 2014).

Equally important for cities is the effect of climate change on travel behavior. There is a growing literature on how weather affects travel choices, but many of the findings in one climate or culture are contradicted in another (Böcker, Dijst, & Prillwitz, 2013). Climate changes are likely to be felt most keenly by travelers exposed to the weather, which are precisely those using the modes that are considered more sustainable: walking, biking, and mass transit.

Concluding remarks

Substantial progress has been made in advancing urban transport sustainability. AFVs are finally out of the laboratory and on the streets. Built environment concepts such as TOD and complete streets have become mainstream. Cities across the globe are implementing Vision Zero policies to reduce traffic deaths. Urban air quality in the U.S. is far better than a generation ago. Despite these gains, GHGs from transportation are the fastest growing of any energy use, congestion continues to grow, and transport equity, affordability, safety, and health challenges remain.

If we agree that cars with current technology and fuels are a big part of the problem, should we invest our limited resources more heavily in making cars more sustainable or in getting people out of cars? The literature recognizes many co-benefits of sustainable travel behavior and land use solutions, but can we realistically expect societal behavior change to reduce car usage sufficiently and rapidly enough to address the challenge of climate change and reach our sustainability goals? Ultimately, this is the $64 billion (trillion?) question.

Organizations such as C40 Cities (2017, p. 1) tout that “cities have the power to change the world.” Cities have the ability to implement bolder strategies faster than states, provinces, or countries, with their more diverse stakeholders (Rosenzweig, Solecki, Hammer, & Mehrotra, 2010). Preemption of urban sustainability initiatives by higher-level governments, however, has emerged as a political and legal battleground between cities, states, and the federal government (Burger, 2009; Graham, 2017).

Cities have nearly full control of their land use, but less control over their transport systems. An important takeaway from this paper is the overriding importance of integrated transportation and land use planning. This is not a new conclusion. Tight integration of land-use and transport systems has been an aspiration for 60 years (e.g., Clark, 1958; Wheeler, 1967). Some progress has been made (California’s SB 375), but true solutions are elusive.

After a half century of mostly incremental change in our motorized transportation systems, we are now in the midst of a “disruption” or “transport revolution” (Gilbert & Perl, 2013), the implications of which will engage scholars of sustainable urban transportation for the (un)foreseeable future. It is worth remembering, however, that concerns about the sustainability of urban transportation once focused on depletion of grazing commons and emissions of horse manure. The quest for mobility has led humanity from non-human animate energy to motorized vehicles and inanimate energy, but each technological era has had its own issues with material throughput from finite resources to limited environmental capacity to absorb waste, and its own problems with spatial reorganization and economic, equity, and health consequences. If and when we succeed in replacing the automobile, it would be naïve to think that our urban transportation system will finally be environmentally, economically, and socially sustainable.

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