Energy for Transport

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Abstract

Global transportation energy use is steeply rising, mainly as a result of increasing population and economic activity. Petroleum fuels remain the dominant energy source, reflecting advantages such as high energy density, low cost, and market availability. The movement of people and freight makes a major contribution to economic development and social well-being, but it also negatively impacts climate change, air quality, health, social cohesion, and safety. Following a review published 20 years ago in the *Annual Review of Environment and Resources* (then named the *Annual Review of Energy and the Environment*) by Lee Schipper, we examine current trends and potential futures, revising several major global transport/energy reports. There are significant opportunities to slow travel growth and improve efficiency. Alternatives to petroleum exist but have different characteristics in terms of availability, cost, distribution, infrastructure, storage, and public acceptability. The transition to low-carbon equitable and sustainable transport will take time but can be fostered by numerous short- and medium-term strategies that would benefit energy security, health, productivity, and sustainability.

Contents

1. INTRODUCTION

Energy for transport encompasses an area of research and policy debate with many issues of high significance. Recent years have seen the publication of several major global reports investigating potential alternative energy futures for transport (1–4). This review builds on findings from these reports and is inspired by a seminal article by Lee Schipper (5) that discusses the roles of key determinants of energy use in transport and how policy changes could affect these variables in the future. This article reviews and expands this early approach. We address key questions that have arisen from recent events and academic research and synthesize scholarly work on the transformation of energy use in transport and its potential to shift the sector onto a more sustainable pathway.

Transport plays an important role in total global energy demand. It is the second largest and the fastest growing energy end-use sector and accounts for 28% of total final energy demand (1, 2, 6). The vast majority (94%) of the energy used in transport comes from fossil fuels, which is responsible for emissions of 6.9 Gt CO_{2-eq} carbon dioxide (CO_2) and other greenhouse gases (GHGs) whose increasing concentration in the atmosphere is the dominant factor in the warming of the climate (6). The near complete dependency of transport on energy from fossil fuels poses major challenges for the transport sector, which are severe in certain regions—particularly challenges related to air pollution, environmental degradation, energy security, economic efficiency, and sustainable development.

Even with a breakthrough in low-carbon fuels and technologies and their immediate uptake, the inertia of the transport sector means that achieving a significant global transition will take time. Fossil fuels are likely to continue to dominate energy use in transport for decades to come, but there are proven strategies, economically viable technologies, operational measures, and tools that hold enormous potential as alternatives to fossil-fuel-based transport.

The research and practices reviewed in this article indicate that countries at all levels of economic development can take advantage of the variety of available strategies, technology options, and measures to galvanize transformative action for low-carbon energy-efficient mobility without delay. We discuss trends and scenarios across different world regions, uncovering possibilities, barriers, and challenges. Sections 2, 3, and 4 examine the roles of the available policy options, highlighting their transformative potential and cobenefits with sustainability and energy security goals. Sections 5 and 6 discuss data and research needs and provide overall conclusions.

2. ENERGY USE IN TRANSPORT: DRIVERS AND TRENDS

The expansion of population, economic development, urbanization, growing wealth, and motorization are major drivers in global transport energy use. Increasing incomes have historically been translated into higher demand for faster, more energy-intensive modes of transport (3, 7, 8). Regionally, the modal composition, per-capita activity level, and pace of activity growth varies widely, but everywhere, transport energy use is dominated by the growing movement of vehicles on roads (6). Transportation accounted for 28% of total final energy demand worldwide in 2012 and is set to grow at a faster pace than other final energy-consuming sectors such as buildings and industry (1). Only recently has this fast trend of the rate of per-capita car travel growth begun to show signs of slowing down in some industrialized countries (9, 10). However, growth remains strong in most developing and emerging countries. This section reviews trends in energy consumption globally, by region, and across modes. It discusses contributions ranging from key driving factors to the increase of transport energy use.

According to the methodology presented by Schipper (5), the study of transport and energy use can be usefully broken into four components that constitute the ASIF framework: the level of aggregate activity (A) measured in passenger-kilometers and freight-kilometers, the share of activity accounted for by each mode of transport or structure (S), the energy intensity (I) of the vehicles that move passengers or goods, and the types of fuels (F) used to power this movement. Whereas the number of studies analyzing trends on energy for transport over the past 20 years has multiplied, including the publication of several major global reports, this review preserves the discussion of factors affecting energy use in transport using the ASIF framework as guidance. The framework is extended to contrast regional and global trends and to include research findings on trends in both freight and passenger transport.

2.1. Discussion of Key Drivers and Trends

Transport energy use has more than doubled since 1970, with a sharp increase in non-OECD growth after 2000 and a recent pronounced decline in countries in the Organisation for Economic Co-operation and Development (OECD) (**Figure 1**) (1, 3). Per-capita transport energy use remains substantially higher in OECD countries, reflecting income differences and the persistence of a sizable gap in the delivery of transportation services between countries and regions. Global trade supply chains have allowed businesses to access cheaper sources of supply but, in the process, have greatly lengthened transport distances and increased energy use in the freight transport system (11). Following a policy of open skies, air travel is experiencing fast growth worldwide (12).

The large regional differences in total transport energy use can also be seen in terms of GHG emissions (**Figure 2**). In OECD countries, passenger transport activity is dominated by private car use; in non-OECD countries, public transport, informal public modes, motorized two-wheelers, and nonmotorized modes are prevalent (1, 13). The car-dominated nature of transport in North America also largely explains the high contribution of transport to GHG emissions (see **Figure 2**).

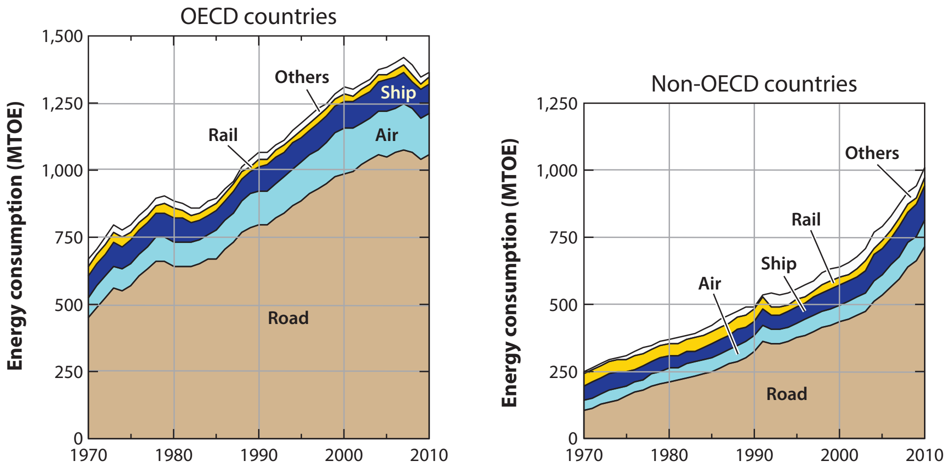


Figure 1

Final energy use by mode and region, 1970–2010. Figure modified from Reference 13 with permission. Abbreviations: MTOE, million tonnes of oil equivalent; OECD, Organisation for Economic Co-operation and Development.

2.2. People and Goods on the Move: Regional Differences and Common Challenges

The elements of the ASIF framework—transport activity (A), structure (S), intensity (I), and fuel availability (F), as discussed above—are influenced by a variety of factors (drivers) and conditions. The understanding of these drivers is the subject of extensive academic research anchored in different theories, methodologies, and reference literature. This subsection reviews drivers of transport demand that are most prominently discussed in academic studies; the aim is to present a balanced overview of regional circumstances and of significant distinctions between more and less developed regions. A group of several drivers—population, economic growth, and urban expansion and travel cost—are covered (Section 2.2.1), and then effects on passenger (Section 2.2.2) and freight transport (Section 2.2.3) are discussed. This is followed by discussions on technology and the built infrastructure (Section 2.2.4) and on demographics, lifestyle, and motorization (Section 2.2.5).

2.2.1. Population, economic growth, and urbanization. In most of the world's regions, population growth rates are declining as the world is becoming increasingly urban (14). More than half of the global population is now urban, although the urban growth processes vary: Some cities are experiencing rapid population growth, some are experiencing slower growth, and some are even declining (15). Trade, economic development, and population are unequally distributed among regions and within countries and urban areas (16). Persistent population growth is expected to continue at a fast pace in Asia, the Middle East, and Africa and at a slower pace in Latin America and the Caribbean; slow growth or even declining populations are projected for most developed countries (14). Urban areas will absorb most of the population growth up to 2050 along with a continued migration flow from rural areas. The United Nations projects that total urban population will increase from 3.6 billion people in 2011 to 6.3 billion by 2050, approaching 70% of the total projected world population of 9.3 billion. Furthermore, virtually all of the expected growth in the world population will be concentrated in the urban areas of the less developed regions, whose

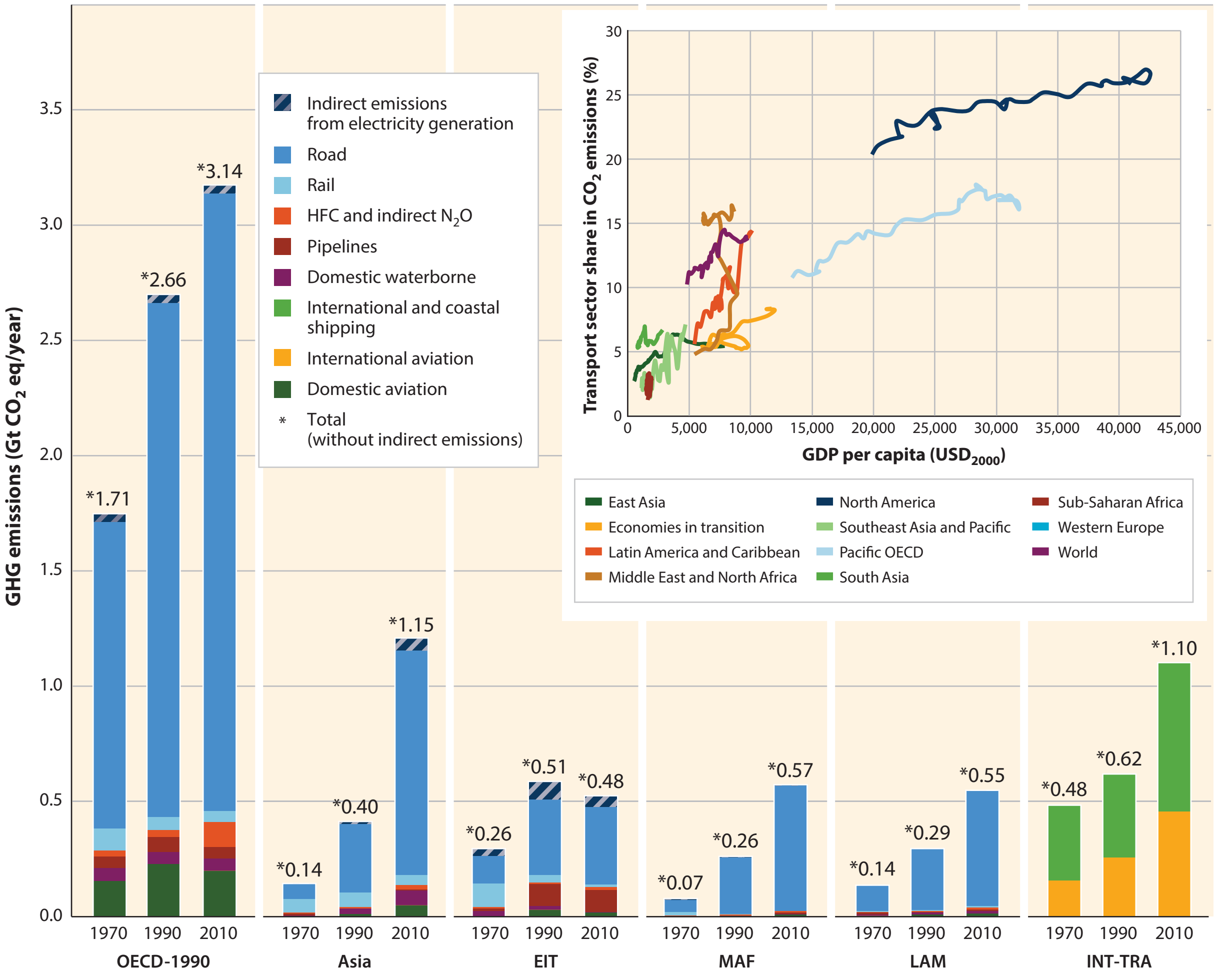


Figure 2

GHG emissions from transport modes by region in 1970, 1990, and 2010. Figure modified from Reference 6 with permission. Abbreviations: EIT, economies in transition; HFC, hydrofluorocarbon; GHG, greenhouse gas; Gt, gigaton; INT-TRA, international transport; LAM, Latin America and Caribbean; MAF, Middle East and North Africa; OECD, Organisation for Economic Co-operation and Development.

combined populations are projected to increase from 2.7 billion in 2011 to 5.1 billion in 2050 (15). The implication is that most of the growth in travel demand and its corresponding energy use will have to be approached as an urban phenomenon. In industrialized countries, high demand levels that accompany slow growth will need to be addressed, as will fast growth, albeit from low present levels, in developing world cities. In addition, rapid increases in long-distance national and international travel will continue as incomes rise and more urban dwellers and products move between cities and countries. These population and income trends are a major influence on three high-energy-intensity modes of transport: passenger cars, freight trucks, and planes. Rural travel will remain important from a sustainable development viewpoint and is critically linked to the fulfilment of international agreements and objectives such as the Millennium Development Goals (17).

Rapid urbanization creates enormous challenges because an increasing share of the expected growth will take place in the world's poorest regions (18) and will take place predominantly in cities smaller than those currently functioning as megacities (more than 10 million inhabitants) (15). The fast rates of migration from rural areas in developing countries are running ahead of capital formation, creating serious deficits of energy access and infrastructure development (15). In this evolving urban transition, there are still numerous opportunities for adopting city planning and sustainable mobility principles.

The transport-planning academic research emphasizes the importance of urban form and location as determinants of accessibility and energy demand for transport (19, 20). Travel can be impacted by location characteristics, such as the dominance of a major central city, usually the capital within a country, versus a polycentric structure where an urban region has multiple activity centers that attract business and provide essential services. Within different urban configurations, there are in addition structural conditions such as density, design, distance, jobs distribution, diversity, and access to retail and service nodes that affect the amount of travel, and also the speed, quality, and total distance traveled by persons and goods. The effects are typically discussed in comprehensive but separate bodies of research and findings for passenger and freight transport (21–23).

2.2.2. Passenger transport. High urban density levels are correlated with lower car ownership rates, less road space per capita, economic parking shortages, and higher availability of public transport services, all of which combined can moderate private car use and fuel consumption (18). In developing countries, urban population densities tend to be higher, and a significant proportion of city dwellers reside in peripheral and slum areas, often located far outside the city, where mostly public and informal means of transport are available (24). In these areas, travel time and cost are major barriers to economic growth and development (25). In African and Asian countries with significant rural population share, walking and bicycling are the two most dominant modes of travel; other nonmotorized modes include cycle rickshaws and animal carts (26, 27). With increasing urbanization, higher incomes, and the spatially dispersed distribution of activities and population groups, the distances that passengers travel have also increased, and accompanying this increase is the use of energy-intensive transport modes (8, 28).

Schipper's observations 20 years ago in the *Annual Review of Environment and Resources* (then named the *Annual Review of Energy and the Environment*) (5) are still valid today. Rising per-capita transport energy use reflects several key factors: rising incomes, greater availability of private modes (cars, two-wheelers), and the ability to use better regional accessibility and faster speeds to make more trips and cover longer distances on those trips. Improved modal efficiencies have not kept up with these trends, particularly in the developing world (3, 4). Automobile traffic tends to capture a high share of total mobility in industrialized nations and within most countries' higher-income population segments (**Figure 3**) (3). Moreover, at very high mobility levels [above 20,000 passenger-kilometers (p-km) per capita per year, e.g., the annual average in the United States in 2012 (29)], the evidence indicates a saturation in the use of private automobiles with growth shifting to faster modes—aircraft and (in Europe and Asia) high-speed trains (30). In lower-income countries, instead, the effect of rapid migration to cities, higher population density, lower incomes, and frequent inadequacy of transport infrastructure can combine in ways that limit the growth in private vehicle use and other fast modes of travel (31).

2.2.3. Freight transport. With economic development and associated improvements in infrastructure, production and distribution operations tend to become more centralized (32). The reconfiguration of logistical systems and supply chains over the past few decades has led to

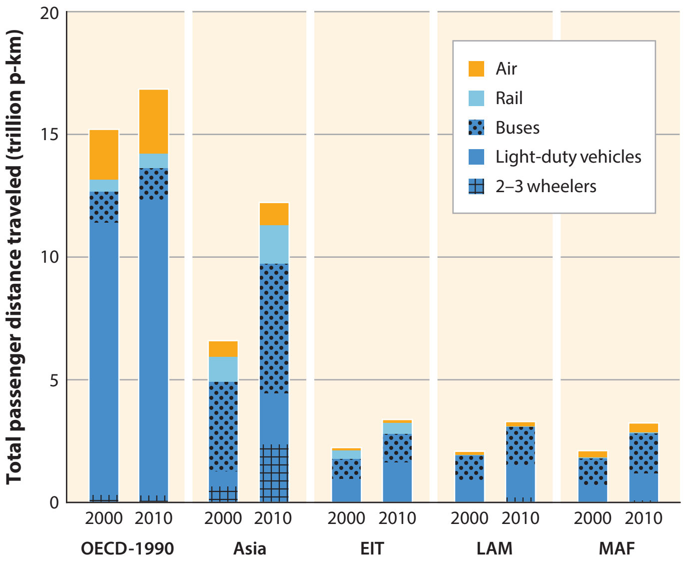


Figure 3

Total passenger distance traveled by mode and region in 2000 and 2010. Figure modified from Reference 6 with permission. Abbreviations: EIT, economies in transition; LAM, Latin America and Caribbean; MAF, Middle East and Africa; OECD, Organisation for Economic Co-operation and Development; p-km, passenger-kilometer.

increasing average distance of freight hauls. In many developed economies, this extenuation of supply lines has become the main driver of freight traffic growth (33). As supply links lengthen and trucks capture more of the freight market, freight-related energy use rises—a process that is difficult to reverse in the short term. At a macro level for freight, Kamakaté & Schipper (34) and Eom et al. (35) found widely varying trends in megajoules per tonne-kilometer (MJ/tonne-km) for trucking over the period 1970–2008 in a sample of OECD countries. The authors attributed the observed variations to a complex interaction among trends in macro variables: economic development, industrial structure, infrastructure investment, fiscal policy, and inventory levels. Eom et al. (35) also discovered mixed trends in the overall energy intensity of domestic freight movements by road, rail, and water in the OECD countries.

In most developed countries, trucking has been increasing its share of the freight market at the expense of rail and waterborne services (36). This modal shift to the most energy-intensive of the surface freight modes has tended to offset the mode-specific improvements in energy efficiency. For example, the energy efficiency of rail freight operations per tonne-kilometer improved by 52% between 1975 and 2010 and by 18% between 2000 and 2010 (37), but, despite this favorable trend, rail's relative share of the global freight market has significantly declined. Increasing distance and an ongoing shift toward energy-intensive modes have remained the most influential factors in rising energy use for freight transport, despite the technological advances discussed in the next subsection.

2.2.4. Technology and the built infrastructure. Over time, technological change has been a key driver transforming the manner, convenience, and speed of transport, along with the energy used. This development can be seen in faster road vehicles (on better roads and more highways), high-speed rail, and aviation. Technological improvements in vehicles along with increasing scale and improvements in system efficiencies have also lowered the cost per kilometer of transport in many cases. Faster speeds, particularly possible on highways, by rail, and in air travel, have made taking longer trips more feasible and convenient. The expansion of air travel to farther and remote destinations facilitated the tendency to make longer trips possible for more purposes (38). Airfreight currently accounts for 35% of the transport of world trade by value (39).

The expansion of infrastructure (roads, airports, ports, and rail systems) that supports transportation and hence the planning and decisions regarding which infrastructure to build are among the structural drivers of energy for transport that can influence the options available for travel choices and can result in differences in energy intensity and use. In rapidly growing urban regions where new infrastructure is being planned, investments in efficient, high-capacity, and high-speed public transport can therefore be considered an important mechanism for improving the energy efficiency of the land transport system (6). In car-dominated urban environments, spatial and infrastructure "lock-in" may limit this potential, although new technology deployment such as "on-demand" transport services and electronic road and parking pricing can help partially overcome such barriers.

Among the new technologies, online retailing and the development of new fulfilment systems for online orders create opportunities to rationalize both freight and passenger transport in urban areas. The replacement of car shopping trips with van deliveries with high load factors to the home could cut energy use and emissions provided they actually replace individual car trips (40–42). These savings can be augmented if the deliveries are made to a consumer's reception box that permits unattended delivery at any time of the day or night (43) or if they are distributed to local collection points from which the consumer can pick up consignments on foot or by bicycle (44). More radical changes to the pattern of last-mile delivery have been proposed, such as the use of drones for home delivery, but, for a number of economic, logistical, and safety reasons, this method is unlikely to prove workable on a large scale (45). Claims that 3D printing will transform the supply chain are also likely to exaggerate its impact, at least over the next 5–10 years. For the vast majority of consumer products, mass production in factories is likely to command a substantial price advantage over 3D-printed products for the foreseeable future. At the consumer level, 3D printing is likely to be confined to niche applications, for which the value attached to customization exceeds the relatively high printing costs (46).

2.2.5. Lifestyle and motorization. In most societies, higher incomes increase the demand for faster, private, and energy-intensive transport modes that directly influence energy for transport (47, 48). Combined with trends toward smaller household sizes worldwide (49), increasing incomes can be linked to higher per-capita transport energy use and higher per-capita vehicle travel as people transition to using faster modes and options when and as much as income allows (28, 50). Recently, in several industrialized countries, reductions in per-capita, per-vehicle, and per-household travel (distances) are combining with improvements in vehicle efficiency to show signs of a shift toward a reduction in private car fuel consumption (9). The character of this trend, whether signaling saturation (10) or a "peak" followed by a decline, is still uncertain. With the observable trend approaching a decade, by some accounts (51, 52), researchers are considering whether per-capita car travel growth in developed nations has indeed undergone a lasting shift (53).

The case for developing countries is evolving on a different trajectory, whereby the influence of drivers such as economic growth, urbanization, motorization, income and lifestyle changes, and the use of communication technology is expected to result in rapid travel growth through 2030 and beyond. For some countries, such as China, fast growth has already been occurring for a decade or more. China has experienced a doubling of per-capita incomes and nearly a tripling of car ownership between 2002 and 2007 (54).

Car ownership and per-capita levels of transport energy use can differ widely, even for regions with similar per-capita incomes. For example, the United States has a per-capita transport energy use that is three times higher than that of the European Union or Japan, and a per-capita level of transport-related CO_2 emissions that is two-and-a-half times higher (55). In part, this difference is attributed to the role played by land-use development practices and to planning policies in historical development processes. The challenge of developing functional urban areas of higher densities and compact built environments makes land-use-based urban transport planning potentially even more important in developing countries (18, 56).

3. TRANSPORT FUTURES IN A CARBON-CONSTRAINED WORLD

What are the likely future directions that transport energy use will take? A number of major recent studies have assessed potential pathways for transport growth and energy demand, including studies by the International Energy Agency (IEA) [e.g., *World Energy Outlook* (57) and *Energy Technology Perspectives* (1)], the Global Energy Assessment (GEA) by the International Institute for Applied Systems Analysis (IIASA) (2), studies by the United States Energy Information Administration (58), and publications by companies such as Shell (59). This section considers recent reference-case or business-as-usual-type projections. Alternative low-carbon futures are considered in Section 4.

Comparing the various transport studies and global scenarios is complicated by the fact that they are often done for different reasons, with widely varying assumptions. Some are based on the paradigm of a reference-case future, perhaps a business-as-usual scenario unaffected by significant changes in policy. Others describe different possible futures that mix changing economic, social, and technological assumptions without referring to policies (such as the Shell scenarios) or exploring what changes in the supply and demand of energy can lead to the concurrent meeting of energy, climate, and sustainable development objectives (such as the GEA scenarios). Others belong to the backcast scenario work typology, showing pathways to meet specific targets in the future [such as the IEA Energy Technology Perspectives (ETP) scenarios]. Finally, some are policy based, showing how different policies or policy packages would likely influence future trends [such as the IEA *World Energy Outlook* 450-ppm scenario (57)].

Here we focus the comparison on projections from different studies that are approximately designed as reference-case projections, indicating where transportation energy use may be headed without significant policy intervention. We caution, however, that a wide range of assumptions have been used and not all of these are pure reference-case projections. **Figure 4** compares projections of transport energy use in 2040 from a range of studies including those using the following models: the Global Change Assessment Model (GCAM) (60–62); IIASA's MESSAGE model (63, 64); the IEA Mobility Model (MoMo) (1, 65, 66); the US Energy Information Administration (EIA) *International Energy Outlook* model (58); the International Council on Clean Transportation's ROADMAP model (67); and the Shell Mountain and Ocean models (59).

There is approximately a 25% range in energy use in 2040 across these different studies, although several are quite close together and all are projected to be at least 45% higher in 2040 than the 2010 global transport energy use level of approximately 103 exajoules. Nearly all the studies estimate that fossil liquids will represent 90% or more of transport fuel (Shell does not report the fuel type breakout for transport). The Shell Mountain and Ocean scenarios are a bit different from the others in that they reflect two possible futures with a range of assumptions, such as more influence by the status quo stakeholders (governments and industries) in mountains

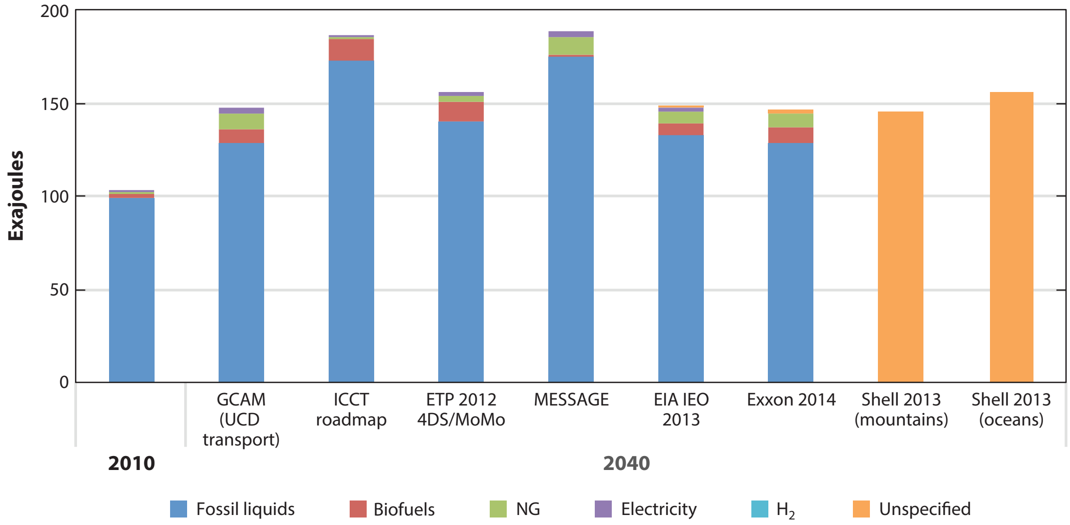


Figure 4

Comparison of projected transport energy use in 2040. Abbreviations: 4DS, four-degree scenario; EIA, US Energy Information Administration; ETP, Energy Technology Perspectives; GCAM, Global Change Assessment Model; ICCT, International Council on Clean Transportation; IEO, International Energy Outlook; MoMo, International Energy Agency Mobility Model; NG, natural gas; UCD, University of California, Davis.

and more dispersed influence in oceans. Despite the differences, the two scenarios result in similar total transport energy use by 2040 (59).

In all of these projections, this strong increase in energy use derives from strong growth in both passenger and freight travel around the world, which is only partially offset by improvements in vehicle efficiency. Although not shown in **Figure 4**, the GHG implications of these projections are typically similar because little fuel switching occurs.

However, when one considers some of the underlying drivers of these scenarios, bigger differences can be seen. **Table 1** compares the reference-case projections for the GEA (2), those from the IEA/ETP (1), and recent projections from the GCAM (62). All three show increases in light-duty vehicle (LDV) travel of over 100%, but rather large differences. LDV efficiency improvements show an even bigger range, reflecting quite different expectations of how much improvement will occur in a future without substantial new (and strengthened existing) fuel economy policies around the world.

Somewhat similarly, truck-kilometer growth is projected to increase by more than 100% in each case, but fuel efficiency improvement varies greatly. This reflects differences in assumed changes in both truck technologies and truck loading. Nonpetroleum fuel shares remain low, although they are much higher than the current 3% and in one study reach 28% owing mainly to natural gas penetration as a transport fuel. Finally, the studies show a 75% to 95% increase in transport $CO_{2\text{-eq}}$ emissions on a well-to-wheels basis, suggesting that achieving an alternative future with reductions in $CO_{2\text{-eq}}$ emissions will be challenging.

Overall, these studies agree that car and truck travel will increase dramatically over the next 35 years to 2050 as a function of population and GDP growth, driving increases in energy use and CO_2 emissions. This is not surprising because the current rates of car ownership and truck travel per capita (activity and structure, in terms of the ASIF framework) are low in most developing

Table 1 Comparison of projections from three studies

	GEA	GCAM	ETP	Underlying units
LDV travel growth, 2010–2050	97%	117%	150%	Passenger-kilometers
	114%	132%	161%	Vehicle-kilometers
LDV stock average efficiency improvement, 2010–2050	14%	69%	37%	Kilometers per unit energy
Truck travel growth, 2010–2050	150%	142%	134%	Tonne-kilometers
Truck stock average efficiency improvement, 2010–2050	41%	(24%)	30%	Kilometers per unit energy
Transport nonpetroleum fuel share, 2050	2%	28%	16%	Fuel share
Transport $CO_{2\text{-eq}}$ emissions increase, 2050, WTW	86%	96%	76%	$CO_{2\text{-eq}}$ WTW emissions

All numbers are percentage changes, 2010–2050; negative changes are shown in parentheses. Underlying units used as the basis for percentages are also shown. Data from References 1, 13, and 62.
Abbreviations: ETP, Energy Technology Perspectives; GCAM, Global Change Assessment Model; GEA, Global Energy Assessment; LDV, light-duty vehicle; WTW, well-to-wheels.

countries compared with those rates in the richer countries. Clearly, the reference-case projections for CO_2 in transport are unsustainable.

4. STRATEGIES ALTERING ENERGY FOR TRANSPORT

Integrated strategies to reduce energy consumption in the transport sector typically combine national and local measures and the need to address drivers and factors related to the components of the ASIF framework (activity, structure, intensity, and fuels). The following subsections explore some of the key options that can be used to address these aspects.

4.1. Interventions to Limit the Growth of Travel Activity

4.1.1. Framework policies. Limiting travel activity growth (particularly via cars) is a goal often advanced by city governments in connection with traffic externalities such as air pollution, congestion, noise, and traffic fatalities. The interventions may include planning measures, pricing, regulatory restrictions on travel, economic incentives, soft information measures, and several other types. Strategic planning has a long tradition at the sectoral level for roads, air, rail, and waterborne transport, and it has lately gained prominence with the successes achieved in developing and emerging countries such as China (68, 69). Research and practice indicate that the most effective strategies typically integrate packages of policy instruments and periodically evaluate progress in order to guide further decision-making (70, 71). Effective policy instruments of relevance to an integrated package include those described below.

4.1.2. Pricing. Charging for using roads (particularly in congested areas), parking charges, fuel taxation, and differentiated vehicle taxation are some of the pricing policies that can encourage reductions in overall travel or travel during specific times or in specific locations. They may be particularly effective at encouraging changes in travel patterns when applied in combination with a sufficient provision of modal alternatives, such as public transport or nonmotorized transport

(72). Currently, few cities apply road charges apart from highway tolls. In contrast, a wide range of parking, fuel, and vehicle taxation systems exist around the world, some with much higher rates than others (73, 74). A general system on optimal pricing and levels has not been established globally.

Prices should incorporate external costs, such as the effects of pollution and GHG emissions. For example, differentiated vehicle taxation can be based on the levels of CO_2 emissions, as it is in many European countries (75, 76). Fuel taxes can create a strong tool to encourage in-use efficiency. Sustained fuel price increases can also result in considerable energy demand reductions; for example, a 10% fuel price increase is suggested to result in a 2.5% to 3% energy use decrease in the first year and up to 6% after five years (77). If these national policies are supported by measures at the local level, such as parking pricing and congestion charging, even greater efficiency gains and modal shifts can be facilitated.

4.1.3. Addressing city and transport planning systemically. Urban and transport planning are vital for shaping the efficiency with which transport systems operate in urban areas; conversely, poorly planned transport systems affect the functioning of cities as a whole (18). Sustainable urban mobility principles emphasize provision of high-quality public transport services and multimodal transport integration, affordable pricing and regulation, use of technology and urban management elements that promote safety for pedestrians and travelers using nonmotorized transport modes, and investment criteria that support social policies (78). Sustainability planning principles also promote economic activity and social connectivity that can positively contribute to the quality of life in cities.

Compact and integrated city planning generates higher population densities and can enable the integration of public transport and nonmotorized transport infrastructure (79). Combined with mixed land use, these factors can help reduce travel distances, enhance the role of nonmotorized modes, and improve accessibility and efficiency of public transport (18). Although the evolution of city form and transport infrastructure development are long-term processes, sustainable urban planning has the potential to exert influence over shorter time scales—particularly for currently small- to medium-size and rapidly growing cities that are not yet fully formed—and will add considerable infrastructure in the coming decades (16, 80).

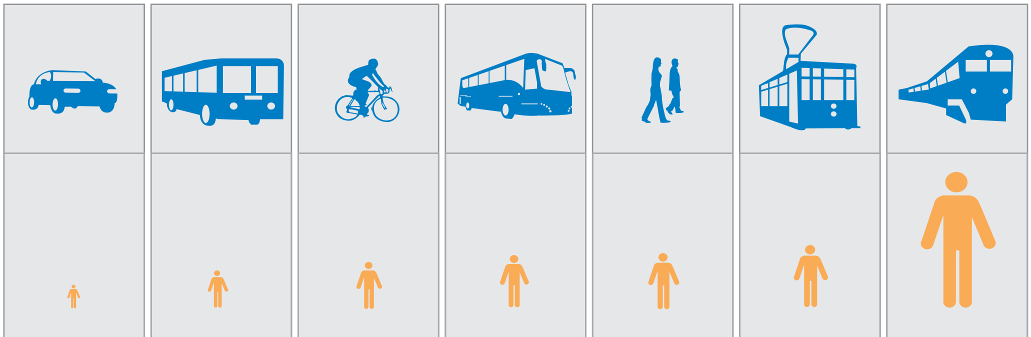
Irrespective of the urban scale, cities that invest considerably in public transport and in walking and cycling infrastructure tend to achieve higher shares of these modes, which increase the economic efficiency of transport and reduce public health and environmental impacts as well as congestion (81). At the metropolitan level, where traffic demand is high, a mix of measures and infrastructure to increase the uptake of the most efficient transport modes includes high-capacity mass-transit solutions such as metro, tram, and bus rapid transit (BRT). BRT provides many of the benefits of a metro system at a fraction of the cost by using large-capacity, high-speed buses on dedicated lanes, preboarding systems, easy transfers, and other features. BRT systems are spreading rapidly in cities across the world, with more than 4,400 km of BRT lines servicing more than 30 million passengers a day in more than 160 cities in Latin America, Asia, Europe, North America, Africa, and Oceania (**http://www.brtdata.org**). Favorable solutions have been achieved where BRT has been developed as a comprehensive and well-integrated system, developed in conjunction with land-use planning and housing policy (82). However, acceptance of BRT systems in many cities continues to be a challenge. The experiences to date with BRT implementation in cities in developing countries have made the following clear: For a system to be successful with high ridership, it needs to be developed to accommodate the urban middle class and poor, the users of nonmotorized transport, and the informal sector (83, 84).

The high densities achieved in several highly populated Chinese and other Asian cities and the associated societal cost in terms of traffic-congested and air-polluted environments (81) have focused attention on light rail transit (LRT) as attractive solution (85). In megacities, a metro can become a vital backbone of a high-capacity mass rapid transit (MRT) system. No single public transport system can cater to all transit needs in any city, but the most successful examples of cities with efficient public transport systems—such as London, Paris, Beijing, Singapore, and Hong Kong—have well-integrated, multimodal systems (18).

As a modal alternative, but also as a feeder for public transport, walking and cycling are also important. Dedicated infrastructure and coordinated planning (for example, of footpaths, sidewalks, and bike lanes) have been crucial for the improvement of traveler safety and for encouraging greater use of these modes (86, 87). Many cities do not have dedicated infrastructure for cycling or even many sidewalks or footpaths. Pedestrians and cyclists face high risks of becoming victims of road accidents in high- and low-income countries alike. The share of incidents involving pedestrian victims in some countries ranges from 35% to 50% of total traffic accidents (83). Studies related to mobility and poverty have provided evidence of differences in the mode choice, time spent, cost, and trip frequency of the poor relative to the nonpoor (88–90). This means that transportation planning has to take into account all income groups and should avoid one-size-fits-all solutions (84). These studies also suggest that there is clearly a gap in the academic literature on travel of the poor; in particular, use of nonmotorized transport is underresearched and underrepresented in the transport statistics of developing countries (26, 91).

At the metropolitan level, containing sprawl is challenging, and many developed countries have continued a trend toward declining density and urban sprawl (92). The expansion of the road infrastructure network associated with urban growth is likely to induce additional vehicular traffic (93). Better infrastructure and mobility services drive improvements in individual and social welfare benefits, but additional generated traffic is a source of congestion and of increase in energy/CO_2 emissions (94).

4.1.4. Behavior, transport technology, and social change. Aside from the major drivers of transport demand—namely, population and income growth—a large body of literature combining research from the fields of psychology, behavioral economics, and sociology has revealed a coherent view of the noneconomic, rational aspects of human behavior impacting travel choices. This literature has identified that people's social norms, attitudes, preferences, acceptance, lifestyle values (centered on, e.g., consumption or green values), and even their attachment to symbolic and affective motives justify their travel choices and transport-related behavioral patterns, and these influence the larger mobility system (50, 95, 96). Most of these studies provide strong arguments for pursuing both demand and supply solutions when the goal is to achieve voluntary car-use reduction, modal shifts, or the promotion of new low-carbon fuels or vehicle alternatives (97, 98). Policy intervention is also required to help fully exploit the opportunities from the adoption of new, more efficient technologies and to bridge the gap between societal and individual costs and benefits (99). In industrialized countries, measures to price or otherwise encourage reductions in travel typically benefit from educational campaigns and extensive information and motivational measures that address behavioral change. Most of these measures are investigated in the literature and implemented internationally as travel demand or mobility management (100). The use of information and communication technology (ICT) offers possibilities for substituting and enhancing the experience of travel, particularly the practices of telecommuting, electronic commerce, and other services (101). ICT has the potential to replace the need for car trips for some specific purposes but may not always manage to reduce overall travel demand (102).



a Passengers per hour	2,000	9,000	14,000	17,000	19,000	22,000	80,000
b MJ/p-km	1.65–2.45	0.32–0.91*	0.1	0.24	0.2	0.53–0.65	0.15–0.35
c €/p-km infrastructure	2,500–5,000	200–500	50–150	500–600	50–150	2,500–7,000	15,000–60,000
d Fuel	Fossil	Fossil	Food	Fossil	Food	Electricity	Electricity

Figure 5

(*a*) Comparative corridor capacity (passengers per hour). Values are for European and Asian cities and can vary significantly across cities, world regions, and particular situations. For example, BRT capacity can more than double with a second lane. Suburban rails in India can transport up to 100,000 passengers per hour. (*b*) Energy intensity in megajoules per passenger-kilometer. Sport utility vehicles can exceed depicted values for cars. Energy values for buses in the United States are generally higher owing to low ridership. Lower values in the range accompanied by an asterisk correspond to Austrian buses; upper values correspond to diesel buses in Mexico City before the introduction of a BRT system. Whereas BRT systems have energy efficiencies similar to those of normal buses, they provide significant systemic energy savings via modal shift, small bus substitution, and reduction in parallel traffic. BRT systems can also be converted from oil-based fuels to renewable-based electricity and hydrogen. (*c*) Estimated infrastructure costs in euros per passenger-kilometer are highest for subway systems and heavy rail. Costs for bus systems can be significantly lower than for modes of individual motorized transport. Infrastructure costs for nonmotorized transport are cost competitive and can realize significant social benefits. (*d*) Dominant fuels are given for each mode. Figure modified from Reference 103 and reproduced from Reference 13 with permission. Abbreviations: €, euro; BRT, bus rapid transit; MJ, megajoule; p-km, passenger-kilometer.

4.2. Changing the Modal Structure and Improving System Efficiency

4.2.1. Modal shift for passenger transport. Public transport can provide a level of urban mobility similar to that offered by a private car, but (at average occupancy) it requires significantly less energy and space per passenger-kilometer of travel (see **Figure 5**) (55). Public transport use can contribute not only to lower energy consumption and emissions but also to congestion reduction, which improves traffic flows and reduces travel times (103, 104).

The provision of high-capacity and reliability of public transport infrastructure and services and the physical integration with walking and cycling facilities are key to realizing the energy efficiency potential of public transport (102, 105). The trend toward car and bicycle sharing as a lifestyle choice can fit well with a more transit-oriented urban development pattern, reducing reliance on privately owned vehicles. Cars in vehicle-sharing systems are typically efficient and can be alternatively fuelled (e.g., Autolib in Paris; see **http://www.autolib.fr/autolib/**). Overall, a more energy-efficient urban transport system can be obtained, with a shift away from single-occupant private passenger vehicles to other forms of shared ownership as well as public motorized and nonmotorized modes (106, 107).

4.2.2. Innovations in urban freight logistical systems. In urban areas, the energy intensity of freight transport operations is likely to be significantly higher than on interurban corridors. The vehicles used for urban distribution are relatively small; their size is constrained by road infrastructure, the nature of the reception facilities, and the amounts of freight that can be delivered on a daily shift. The average utilization of these vehicles is relatively low, reflecting the small size of the typical order delivered and the limited opportunities for load consolidation. The relatively high traffic densities in cities result in delivery vehicles' running much of their annual mileage below fuel-efficient speeds with frequent stops and starts (108). There is also limited potential in urban areas for using rail and waterborne services, which use much less energy per tonne-kilometer than road transport.

Numerous studies have indicated that the movement of freight in urban areas is inefficient, although the focus usually is more on delivery costs, vehicle-kilometers, or transit times and less on energy consumption (109). Large quantities of freight are moved in people's cars and public transport systems, as consumers take responsibility for transporting goods on the so-called last mile. This last-mile delivery method is a latent form of freight movement that rarely appeared in official statistics until recently. The interface between freight and personal transport in urban areas and its effect on efficiency is also significant in other respects. For example, the decentralization of retail capacity from city centers to suburban and out-of-town locations has reduced the distance that shop delivery vehicles need to travel in urban areas, but at the expense of lengthening shopping trips for consumers, many of whom are car borne. Responsibility for the related energy consumption has shifted from logistics operators to shoppers, with total transport-related energy use probably increasing overall, although this has yet to be quantified (110).

The Internet is affecting the freight transport system is many ways, making it difficult to estimate its net effect on freight traffic volumes and related energy use. At both business-to-business and business-to-consumer levels, e-commerce is promoting wider sourcing of products, increasing the average distance that each unit of freight is moved. Online trading of freight services, in contrast, improves the utilization of vehicle, vessel, and aircraft capacity, cutting energy use per tonne-kilometer (111). Cloud computing also offers the potential for companies to share logistical data and thereby exploit opportunities to consolidate loads and backload empty vehicles (112). Online distribution of entertainment, education, and news media is replacing physical freight flows and drastically reducing the energy intensity of these information products on a life-cycle basis (see, e.g., 113). The switch from conventional to online retailing has also been shown, under certain circumstances, to cut energy use and emissions in the transport system (41, 114). Even though early studies sought to identify the likely effects of the Internet on freight transport (e.g., 115, 116), to date there have been no comprehensive or quantitative assessments of its overall impact. A review of innovations likely to improve energy efficiency and estimates of energy savings of improved logistics are provided in **Table 2**.

4.2.3. Firm behavior, role of industry, and freight truck operators. Energy costs represent a significant proportion of logistics companies' total expenditure, giving them a strong commercial incentive to maximize energy efficiency (110). It is estimated that fuel costs account for, respectively, 33%, 42%, and 56% of total expenditure by trucking, shipping, and airfreight operators. Fluctuations in world oil prices also expose carriers to a fuel cost risk, especially carriers that provide haulage service mainly on a spot (per-trip) hire basis and lack contracts containing fuel price compensation clauses.

Although their prime motive for cutting energy use is financial, logistics businesses are also under increasing pressure to reduce emissions, particularly of GHGs (117, 118). Efforts to cut carbon, cost, and energy are well aligned in the logistics sector. Many of the energy-related environmental

Table 2 Estimated energy savings of improved logistics innovations

Innovation	Purpose	Where implemented	Estimated energy savings	Reference(s)/ resource(s)
Channeling supplies through urban consolidation centers	Increase vehicle fill and rationalize the pattern of delivery	Several countries, e.g., the Netherlands and the United Kingdom; after many failed trials, viable consolidation center operations now exist there	To be determined	191, 192
Rescheduling of deliveries to off-peak periods	Reschedule to when the fuel efficiency of vehicles is less impaired by traffic congestion	US cities, most notably New York, and several towns in the United Kingdom; these locations feature pilot projects	Significant reductions in energy use and emissions	193, 194
Installing reception boxes at homes, shops, offices, and other premises	Permit unattended delivery at any time of day	Finland	Vehicle-kilometers cut by as much as 40%, with corresponding reductions in energy consumption	40
Adapting freight vehicles to the requirements of city logistics	Implement electrification of freight deliveries (one of the options reviewed by a collaborative project funded by Norden)	Denmark, Sweden	To be determined	**http://safe-project.eu/**
Switching urban deliveries from road modes to more energy-efficient and less polluting modes	Deliver supermarket supplies by rail Move automotive parts by tram Deliver parcels by canal Deliver parcels by bicycle	Paris Dresden Amsterdam Other cities in Europe (numerous cargo cycle operations) Cities in China (use of bicycle deliveries)	To be determined	195, 196

measures that logistics companies can apply are self-financing and offer a rapid payback. Environmental performance is also becoming a more important selection criterion for their clients, particularly large manufacturers and retailers that outsource their logistics and are committed to reducing their corporate carbon footprints (119, 120). Many of the large logistics companies have also been setting targets for reducing the carbon intensity of their logistics operations by 20–30% by 2020–2025 (121).

The amount of energy used in logistics operations is the result of a complex interaction among decisions made at the strategic, commercial, operational, and functional levels within the client companies (122, 123). Much managerial, public policy, and research focus has been on energy efficiency measures applicable at the functional level, such as improved driver training, the back-loading of delivery vehicles, and the use of computerized vehicle routing and scheduling (124). Energy savings achieved at this level, however, can be offset by effects of higher-level operational, commercial, and strategic decisions (125). For example, sourcing components on a just-in-time (JIT) basis cuts inventory levels, reduces space requirements, and enhances productivity, but often at the expense of vehicle utilization and higher energy use per tonne-kilometer.

These examples illustrate how sensitive energy use in logistics is to wider business trends driven by higher-level corporate objectives. It is possible, however, that some of these trends, such as the move to JIT methods and centralization, have yielded an overall reduction in energy consumption after allowance is made for an increase in the energy used in the freight transport/logistics sector. There is a need for more holistic assessments of the energy and carbon impacts of these business megatrends. These assessments would need to consider the possible rebound effect of fuel efficiency improvements. Reductions in freight-related energy costs at the functional level naturally improve the cost-effectiveness of changes at the operational, commercial, and strategic levels, which, in turn, generate more freight movement. Estimates of the magnitude of these second-order effects have so far been confined to particular countries and specific sectors of the freight market (see, e.g., 126).

Within the constraints currently imposed on logistics managers by higher-level corporate decisions, there remains considerable scope for improving the energy and carbon efficiency of freight transport at the functional level (127). Documentation regarding ways in which companies can cut freight-related energy use already exists (**http://www.freightbestpractice.org.uk**), as do industry-level initiatives to promote energy and emission reduction in freight in several parts of the world: the United States Environmental Protection Agency's SmartWay (**http://www.epa.gov/smartway**), the United Kingdom's Logistics Carbon Reduction Scheme (**http://www.fta.co.uk/policy_and_compliance/environment/logistics_carbon_reduction_scheme.html**; 128), Green Freight Europe (**http://www.greenfreighteurope.eu**), and the China Green Freight Initiative (**http://cleanairinitiative.org/portal/projects/GreenFreightChinaProgram**). Most of these initiatives are targeted at individual freight transport operators. When companies are prepared to engage in logistical collaboration with other businesses, however, the potential energy savings can be substantially increased (129).

4.3. Achieving the Full Potential of Vehicle Efficiency

A wide range of cost-effective technologies to improve the efficiency of both LDVs and medium/heavy-duty vehicles are commercially available. If accompanied by modal shifts and travel demand reductions, transport can significantly reduce its energy consumption. Introduction of new fuels will depend on both policy and direct investment, along with concepts that generate revenues that can be retargeted for the necessary investments.

4.3.1. Efficiency improvement potential across modes. End-use energy efficiency improvements have been identified as a potentially important and cost-effective contributor to the reduction of energy consumption in the transport sector (1, 13, 130–133). Efficiency technologies and strategies often are not taken up owing to a range of barriers, but regulatory and fiscal policies can help, and different approaches may work best in different types of markets (see Section 4.1).

According to *World Energy Outlook 2012* (66), most types of vehicles (cars, trucks, ships, aircraft) have the potential for a 30%–50% reduction in energy intensity between 2010 and 2050. Delivering continued fuel efficiency improvements for internal combustion engine vehicles remains vital for increasing transport efficiency (134). Improved engine and drivetrain efficiency, vehicle weight reduction, improved accessory efficiency, better aerodynamics, and better tires have the potential—heretofore unexploited—to contribute (133, 135). According to estimates from the IEA and the International Council on Clean Transportation (ICCT), deployment of existing and advanced technologies such as engine hybridization could achieve a 50% improvement (reduction in energy per tonne-kilometer) in the average fuel economy of new cars by 2030 compared with

2005 levels. With current stock turnover rates, this improvement would be fully reflected in all cars on the road by 2050.

Truck efficiencies also can be improved using many of the same approaches (engine improvements, weight reduction, and aerodynamics). Urban trucks can benefit from hybridization, whereas long-haul highway trucks benefit more from aerodynamic improvements (136). In either case, recent studies estimate potential improvements on the order of 30%–40% reductions in fuel use per kilometer. These are especially cost-effective for long-haul trucks, because they travel great distances and use far more fuel per year than do urban trucks.

Recent studies by the International Maritime Organization and others (137) indicate a large potential for efficiency improvements in ocean-going ships. Although some are applicable only to new builds, many can be deployed as retrofits to existing ships (e.g., propeller systems) and some are operational improvements (e.g., more frequent hull cleanings, slower steaming). The cost-effectiveness of many measures appears excellent with short payback times. Overall potential improvements on the order of 40%–50% reductions in energy intensity appear possible at least for new build ships, with only slightly lower estimates for existing ships (55).

For aircraft, recently introduced models have an approximately 20%–30% efficiency advantage over the models they replace, and an additional 20%–30% efficiency improvement potential is estimated for planes to be designed over the coming decade. Beyond that, it is more difficult to gauge efficiency improvement potential, but concepts such as "flying wing" and hybrid versions appear capable of additional major efficiency improvements, if deemed practical. Operational improvements such as those related to air traffic control systems can help as well; shorter flight plans, for example, are expected to yield 5%–10% efficiency advantages (38). The advantages and potential efficiency gains in different transport technology require contemplation of behavioral aspects such as rebound effect.

Whereas efficiency improvements directly save fuel, they also lower the cost of driving. Drivers and firms may respond by increasing their driving somewhat. Transport studies typically review this as a direct rebound effect. The available studies are mostly for OECD countries, covering a range of different data and methods and measuring the effect for personal automotive transportation (138, 139, 140). Sorrell & Dimitropoulos (139) find rebound effect values ranging from 5% to 87% in the short run and 5% to 66% in the long run. In North America, where the rebound effect has been extensively studied, it is estimated to be in the range of −0.05 to −0.30 (e.g., a 50% reduction in the fuel intensity of a car, resulting in a similar reduction in the fuel cost per kilometer, would result in a 2.5%–15% increase in driving). Several studies show that in North America, the effect has declined over time and with rising incomes (141–143). There is a lack of empirical literature on the rebound effect in developing countries (144), but the studies available show larger rebound effects. For example, China (145) is associated with an estimated national average rebound effect of 96%, with regional variations ranging from 2% direct rebound in Shanghai to 246% in Jilin province. The rebound effect may be higher in poorer countries, where price sensitivity is higher, although most drivers in any country are not necessarily poor. The rebound effect can be minimized by raising fuel taxes or applying road pricing in order to offset the lower travel costs created by efficiency improvements or reduced fuel prices (146–148). Implementation of pricing policies to minimize rebound effect may not be a viable option in developing countries where mobility levels are low, and net available income increases from efficiency gains can provide opportunities to fulfill unmet travel demand aspirations. Some researchers argue that this effect should be interpreted merely as an income effect and not as a rebound effect (138, 149).

4.3.2. Cost-effectiveness of energy-efficient technologies. The large and cost-effective potential of sustainable mobility across modes is not yet fully utilized. Estimates suggest that urban

Table 3 Overview of costs, benefits, cobenefits, and synergies of some key energy efficiency measures

Energy efficiency measures	Costs and benefits	Cobenefits and synergies
Activity (reduction and management: short distances, compact cities, and mixed use)	Potential to reduce energy consumption by 10% to 30% (181, 182)	Reduced travel times; improved air quality, public health, and safety; and more equitable access (77, 183–185)
Structure (shift to more energy-efficient modes)	Potential for energy efficiency gains; it varies greatly, but, for example, BRT systems can deliver up to 30% reductions at an investment cost of \$1–27 million per kilometer (1)	Reduced urban congestion and more equitable access (186, 187)
Intensity (vehicle fuel efficiency)	Efficiency improvement of 40%–60% by 2030, feasible at low or negative costs (1, 13)	Improved energy security, productivity, and affordability (188, 189)
Fuel (switch to electricity, hydrogen, CNG, biofuels, and other fuels)	Changing the structure of the energy consumption, but not necessarily overall demand	Diversification of the fuels used contributes to climate, air quality, and/or energy security objectives (2, 190)

Abbreviations: BRT, bus rapid transit; CNG, compressed natural gas.

transport energy consumption could be 40%–50% lower than the 2010 figure only through the use of currently available and cost-effective technological measures (55, 133, 150, 151). Studies exploring the cost-effectiveness and the potential for cobenefits of energy efficiency in transport are finding that most vehicle fuel efficiency technology improvements for LDVs are available at low or negative cost and with substantial cobenefits and synergies such as GHG emission reductions, improved air quality, and energy security (see **Table 3**) (152, 153).

Much of the technological and operational improvements will be cost effective, at least from a societal perspective (6). However, individual decision-making often only considers fuel savings over a two- to three-year period (in terms of required payback times for efficiency investments), which implies an individual discount rate that can be well above 20%, substantially higher than a societal discount rate of about 3–5%. To bridge this gap between individual and societal perspectives, policies are needed to encourage (via incentives), discourage (via pricing), and require (via regulation) a shift to more efficient transport technologies and mobility behavior (142, 154). Efficient technologies may also fail to penetrate the market or may penetrate it well below their potential owing to barriers such as up-front cost, lack of information and awareness, and risk aversion behavior on the part of consumers (6) (see Section 4.1.4).

4.4. Flexing the Fuels: A Portfolio of Options

Fast personal mobility was made possible by the unique characteristics and availability of liquid fossil fuels, with their excellent combustion properties and energy density. In addition, they have been associated with low cost during most of the twentieth century, and even today they are cost-effective relative to most competing options. This subsection reviews four potential replacement fuels or energy carriers: natural gas, biofuels, electricity, and hydrogen.

4.4.1. Role of natural gas. The use of natural gas in transport has been increasing in many countries in recent years. Compressed natural gas (primarily methane) and liquefied petroleum gas (primarily propane and butane) can replace gasoline vehicle engines after minor modifications to fuel and control systems, along with onboard compressed or liquefied storage of the fuel. There is significant use of natural gas for taxi fleets in India (e.g., Delhi and Mumbai) (155) and for buses in countries such as Iran and China (156). Natural gas has also emerged as an interesting fuel for delivery vehicles and even long-haul trucks in the United States.

During the past decade, new techniques involving the use of horizontal drilling with hydraulic fracturing have resulted in a substantial reduction in natural gas prices in the United States. In transport, long-haul trucking with predictable and periodic driving patterns is a particularly interesting application for natural gas because these long-haul trucks often travel more than 100,000 miles per year and gain a fairly rapid payback for lower-cost fuels (157). However, various issues are associated with this use, and specialized engines are just beginning to enter the market (158). Natural gas still has a very small market share for both trucks and cars in the United States, but if prices remain low, this could change in the coming years. As a substitute for diesel fuel, natural gas typically has a benefit in terms of particulate emissions (particularly in developing countries), but the benefits from a CO_2 perspective are less certain. One concern with natural gas is methane emissions (and system leakage), which could result in a higher overall GHG impact than that exerted by diesel fuels (159). As such, natural gas does not appear likely to play a major role in a decarbonized transport energy future.

4.4.2. Role of biofuels. Biofuels—typically liquid or gaseous transportation fuels derived from biomass—are perhaps the most successful nonpetroleum transport fuel, with close to a 3% global market share of gasoline fuel in 2013 (66). Nearly all biofuels currently are ethanol or biodiesel, although in the future, biomethane could become important in places with many natural gas vehicles.

Nearly all biofuels in 2013 were either ethanol from corn or sugarcane or biodiesel from soy or rapeseed. In other words, nearly all were derived from food crops. The case for sugarcane ethanol is distinct because it is already commercial, widely produced (with Brazil the globally dominant but not the sole producer), and cost competitive with gasoline in many contexts. However, biofuels that are food-crop derived have become controversial, with various studies finding that biofuels (particularly corn ethanol) negatively affect food supplies and prices (160) or that they provide relatively low GHG reductions, in particular when direct and indirect land-use changes are taken into account (**https://greet.es.anl.gov/results**; 161). According to the report *Climate Change 2014: Mitigation of Climate Change* (6), "Scientific debate about the marginal emissions of most bioenergy pathways, in particular around land-mediated equilibrium effects (such as indirect land-use change), remains unresolved" (p. 6 of Chapter 11).

Many challenges must be faced if biofuels are to be used, but there is also a growing demand for them in part because they are compatible with today's vehicles at least to some degree (although ethanol so far has not been able to break through the 10% "blend wall" in the United States). Furthermore, these liquid fuels (particularly "drop-in" gasoline and diesel-replacement biofuels) provide higher energy densities than some other low-carbon fuels or energy carriers (such as electricity or hydrogen). Fully drop-in fuels such as biomass-to-liquid fuel can be blended with petroleum fuels such as gasoline, diesel, and kerosene/jet fuel in any percentage and can fully replace these fuels with similar performance. For the aviation industry, biofuel use has become a central component of its low-carbon fuels strategy.

In fact, long-term low-carbon projections such as those by the IEA (66) include a very large quantity of drop-in biofuels by 2050, approximately 30 exajoules or 30 times more than today's total global biofuel production. A large share of this quantity goes to aircraft, ships, and long-haul trucks—all modes that are heavily dependent on dense liquid fuels. However, there remains the question whether enough truly low-carbon, sustainable drop-in biofuels can be produced to meet such a scenario—from a land availability point of view, a GHG point of view, and a cost point of view. Current policies have not succeeded in moving production away from food-crop-based practices and toward fuels from more sustainable feedstocks such as waste products, algae, and cellulosic crops. These policies include the US Renewable Fuel Standard, which, despite ambitious blending targets, has not succeeded in incentivizing significant production of advanced biofuels in the 2009–2013 time frame and whose future targets may now be dramatically scaled down. Meanwhile, production of conventional ethanol from feedstocks such as corn and sugarcane continues to rise but is reaching "blend-wall" limits, at least in the United States. This limit may eventually be reached in most countries if cars continue to be designed to operate on a maximum 10%–15% ethanol blend, which is the case everywhere in the world except Brazil. A transition to advanced, sustainable drop-in (particularly diesel-replacement) fuels is clearly needed, but progress to achieve this remains slow.

4.4.3. Transport electrification storage barriers and opportunities. It appears likely that the only potentially zero-carbon energy carriers will be electricity and hydrogen (162). Even these will be zero carbon only if their generation systems emit no CO_2, such as via wind or solar power. Such zero-carbon goals will take many decades to achieve around the world but seem integral to any serious global CO_2 reduction effort. However, in 2013, electricity systems ranged from fairly clean, dominated by renewables (Norway), to very dirty, dominated by coal (India, Poland). These differences in electricity systems can put electric-vehicle CO_2 emissions either well below or somewhat above conventional vehicle emissions.

In the past three years, plug-in electric vehicles (PEVs) have made some headway in penetrating car markets around the developed world. This includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), the latter of which combines an electric motor with an internal combustion engine, resulting in driving ranges similar to those of conventional vehicles. Given targets made by various countries (163), these sales numbers would need to increase by more than 50% each year until 2020 to achieve a combined target of approximately 5 million sales in that year. This goal appears unlikely, because, among other things, the average PEV is currently subsidized on the order of $5,000 or more, and the prospect of governments doing this for millions of vehicles per year may be unrealistic.

Even with strong subsidies, as of 2013, PEVs have achieved a maximum of only 1%–2% market share in all but a few countries (e.g., Norway and the Netherlands). A key question is what it will take for their market penetration rates to rise significantly. Probably the most important factor is vehicle price, which, even with subsidies, tends to run well above the price of similar conventional vehicles (164). This higher price is due mainly to the still fairly high cost of batteries [probably around $500 per kilowatt-hour (kWh) capacity in 2013, with 20–30 kWh storage on most PEVs] (165). Also important is driving range (for BEVs), which currently averages around 100 km per recharge. Thus, batteries, in terms of both cost and energy storage densities, appear to be the critical factor in EV success. PEVs, like hybrid vehicles before them, will get better—they are still in a first-generation phase (relative to the circa 2010 reintroduction of PEVs with lithium-ion batteries). However, new models are appearing almost monthly, with various improvements. The 2014 BMW i3, for example, has introduced many new features compared with those of older EVs (166).

Battery costs may continue to drop; a major US study in 2013 (167) projected that battery and EV costs will continue to drop until they reach parity with conventional vehicle cost, sometime around 2035. Such a price decrease relates to the optimization of lithium-ion batteries, although if there is a breakthrough with other technologies under research, it might happen sooner. Many new battery and energy storage concepts are in development (e.g., 168), although it may take decades for successful concepts to reach commercialization. PHEVs overcome the range problem now, and can be cheaper than BEVs now because they have fewer batteries, but they are expected to remain fairly expensive because they have both the battery/motor system and hybridized engine.

The biggest challenge for EVs may be finding applications beyond LDVs. Some trucks and buses are amenable if their daily driving range is short. Long-haul trucks, ships, and aircraft appear unlikely to be good applications for battery electric systems given their needs for long-range travel and energy-dense fuels.

Hydrogen may be able to solve some of these issues. Current demonstration hydrogen fuel cell vehicles typically have driving ranges two to three times those of BEVs. However, hydrogen poses a host of challenges such as costly onboard storage and production and distribution infrastructure, which mostly does not exist yet. Conversely, fuel cell systems and vehicles appear to be dropping in cost, and California and Europe are both making new efforts to promote them. Overall, electricity and hydrogen for vehicles are likely to play a role in transforming the energy use in transport, but they are unlikely to have a significant impact over the short or even the medium term and will require a fairly long-term commitment.

5. FUTURE RESEARCH NEEDS

5.1. Data Need to Support Evidence-Based Decision-Making

Robust and reliable data are vital for the development of baselines and an assessment of the costs and benefits of different transport policy options, which constitute important inputs for policy advice and decision-making processes (169). The availability of data varies greatly among countries: Developed countries usually have better transport data than do most developing countries, but data also vary across modes: Data on vehicle fleets are usually more comprehensive compared with data on freight or nonmotorized transport (170, 171). An important role for transport and energy research is to minimize uncertainty so that decision makers can close the gap between the potential of energy efficiency measures and their implementation (172).

Most OECD countries compile tonne-kilometer statistics and use this metric to show the relative importance of transport modes. At a macro level, the ratio of tonne-kilometers to energy use provides a useful index of the energy intensity of freight transport. Analysis of variations in this critical index by country and region requires additional data on the fuel efficiency of vehicles and their relative loading. Such data are sorely lacking outside Europe and North America. It is difficult and costly to collect data for road freight as the sector is highly fragmented, particularly in developing countries. In EU countries there are, nevertheless, much more data available on the loading of trucks than on the loading of other freight modes. Official statistics on vehicle payload, however, give only a partial view of vehicle fill as they are solely weight based and take no account of cube utilization (173). Also, in a growing number of developed countries, there is a lack of macro-level fuel efficiency data for freight modes and an overreliance on a few widely quoted average figures. Widening adoption of on-vehicle monitoring systems is providing operators with the fuel consumption data they need to manage energy use more effectively, although relatively few of these data are available to researchers and government statisticians.

5.2. Information Needs for Evaluation

To assess the potential impact of an innovative sustainable mobility solution, easily accessible and transparent information about the direct and indirect costs and benefits of various mobility options is required (174). Improved representation of urban form is needed in studies to help understand effects on final transport demand and energy use of the combined implementation of measures that alter structural factors such as land use, urban design, and modal choice. Variations in these relationships across regions and over time as cities grow and change also need more study, in particular in developing countries (175). Better evaluation of the effects of regulatory, locational, and pricing policies, along with the combined effects of changes in other sectoral areas (e.g., housing, financing, industrial, and commercial locational policies), is also needed (176). Existing research suggests that the potential to affect the level of demand and travel choices, and ultimately reduce energy use, is larger with integrated policy interventions, but further research on ways to optimize such policy packages is needed (177, 178).

Finally, there is a need for better measurement and analysis of transport costs, including both private and public market costs and nonmarket (external) costs. One of the assumptions that influences most modeling today is that transport cost reductions are viable and conforming key elements that shape spatial forms for regions and within cities. However, transport costs are being challenged by externalities, one of which is the need for climate protection (179). A future challenge for researchers is to determine whether the analytical tools adapted for low-cost transport conditions can also help analyze how future regional location and urban growth could proceed under scenarios of high transport cost (180).

6. CONCLUSION: TRANSPORT BEYOND FOSSIL ENERGY

It is likely that transport energy demand will continue to grow with the steady high per-capita travel level in developed countries and the impulse fostered by economic and population growth in developing and emerging countries, the activity and structure elements of the ASIF framework. These trends are immensely challenging and require interventions that integrate effects from activity, structure, intensity, and fuels factors managed toward achieving increasing sustainability. Current population and income trends have a major influence on the trends and evolution for three faster and high-energy-intensity modes of transport—passenger cars, freight trucks, and planes—that account for the energy use and fuels parts of ASIF. Managing transport energy demand growth will have to be advanced alongside efforts toward reducing the deep inequalities in access to transport services that currently affect the poor worldwide. This review emphasizes that (*a*) opportunities to manage and influence this evolution exist, (*b*) instruments and tools to help bring this about are being developed, and (*c*) we are seeing regulations and other policy interventions that are moving the drivers/components of transport energy demand in a sustainable direction. The research results and practical experience reviewed here suggest that the numerous options available to promote low-carbon services can help bring about many services and technologies equally important to addressing wider sustainability goals. Although a radical global replacement of petroleum as the principal energy source for transport will take time, our assessment of the costs and potential of existing policies, technologies, fuels, and urban planning options accounts for key areas of intervention today. These options are also promising from a wider societal perspective.

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