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High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California's future

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Abstract

Sustainable mobility policy for long-distance transportation services should consider emerging automobiles and aircraft as well as infrastructure and supply chain life-cycle effects in the assessment of new high-speed rail systems. Using the California corridor, future automobiles, high-speed rail and aircraft long-distance travel are evaluated, considering emerging fuel-efficient vehicles, new train designs and the possibility that the region will meet renewable electricity goals. An attributional per passenger-kilometer-traveled life-cycle inventory is first developed including vehicle, infrastructure and energy production components. A consequential life-cycle impact assessment is then established to evaluate existing infrastructure expansion against the construction of a new high-speed rail system. The results show that when using the life-cycle assessment framework, greenhouse gas footprints increase significantly and human health and environmental damage potentials may be dominated by indirect and supply chain components. The environmental payback is most sensitive to the number of automobile trips shifted to high-speed rail, and for greenhouse gases is likely to occur in 20–30 years. A high-speed rail system that is deployed with state-of-the-art trains, electricity that has met renewable goals, and in a configuration that endorses high ridership will provide significant environmental benefits over existing modes. Opportunities exist for reducing the long-distance transportation footprint by incentivizing large automobile trip shifts, meeting clean electricity goals and reducing material production effects.

Keywords: life-cycle assessment, high-speed rail, transportation, greenhouse gas

S Online supplementary data available from stacks.iop.org/ERL/7/034012/mmedia

1. Background

Deployment of new and more fuel-efficient transportation modes is expected in the coming decades. Next generation automobiles and aircraft are already entering the market. Despite major political and economic roadblocks in the United States, federal, state, and regional transportation and land-use planners are discussing high-speed rail (HSR) as a potentially better investment for future mobility. The discussion of new transportation options is often coupled with the identification of strategies to help reduce congestion and travel times. With increasing populations

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and long-distance transportation demand forecasts, HSR was made a centerpiece of the American Recovery and Reinvestment Act as a modal diversification strategy. While several corridors are under study, California in 2008 authorized \$9.95 billion in bonds for their 1200 km system and the state legislature recently approved funding to start construction. Engineering and planning work are already underway, with possible groundbreaking in 2013 (CAHSRA 2012). While many technical, legal, economic, community and political battles loom, the California HSR (CAHSR) Authority has made significant progress towards deploying the system, which will connect Sacramento, San Francisco, Los Angeles and San Diego. In addition to direct mobility benefits, CAHSR has the potential to reduce long-distance transportation energy consumption and air emissions, provided measures are taken to encourage high ridership, minimize construction effects, and establish clean electricity contracts (Chester and Horvath 2010).

To understand the comprehensive energy and air emissions effects of deployment and adoption of CAHSR, a life-cycle assessment (LCA) framework should be used to assess future modes in the California corridor. The energy and environmental tradeoffs of CAHSR have been examined with then-planned vehicles and fuels (Chester and Horvath 2010) by constructing a life-cycle inventory using information from CAHSRA (2005), the then-current design data and with groundbreaking expected around 2010. However, many new corridor plans and design considerations have been made warranting new outlooks for the system. Forecasts for a future long-distance transportation system should include emerging and expected automobile, aircraft and HSR improvements. In this study, an environmental assessment of future long-distance travel is developed using the California corridor as a case study. We start by developing a per passenger-kilometer-traveled (PKT) attributional assessment of future transportation systems that expands the results of Chester and Horvath (2010) by evaluating (i) emerging automobiles and aircraft, (ii) new train designs, and (iii) low-carbon electricity scenarios. We then develop a consequential assessment for the corridor to determine the net effects of the decision to build a new HSR system. Following our past work, we identify the critical system design parameters that lead to transportation systems having larger or smaller human and environmental footprints than their competitors. Our goal is to identify the potential design, construction and operation pitfalls early so that transportation planners and operators can reduce future impacts at potentially lower cost.

The goal of this research is to develop a framework for assessing the environmental effects of long-distance transportation in the California corridor to provide more comprehensive measures of the greenhouse gas, human health and other environmental damage potentials of future systems. We anticipate that this framework will (i) aid policy and decision makers in the assessment of long-distance transportation options, (ii) provide HSR designers, engineers and operators with information on how to best reduce environmental damage potentials, and (iii) provide a standard methodology by which other US and international transportation systems can be evaluated.

2. Methodology

An environmental assessment is developed for automobiles, aircraft and HSR operating in the California corridor between 2030 and 2050. When performing an LCA a year of analysis is generally defined. We choose to evaluate modes in a two-decade range to acknowledge the uncertainty in adoption of HSR and the challenges of estimating future life-cycle process improvements in a single year.

LCA is the preeminent framework for evaluating the energy and environmental effects of complex systems and can be used to understand the tradeoffs of transportation decisions. Life-cycle inventorying (LCI) is one stage of LCA, the quantification of environmental flows. Impact assessment must be performed to connect physical flows to the human health, ecosystem quality, climate change and resource effects of ultimate interest (ISO 2006, Jolliet *et al* 2003). End-use energy and air emissions are first inventoried. Air emissions include greenhouse gases (GHG) and conventional air pollutants (SO_x, CO, NO_x, VOCs, PM_{10} and $PM_{2.5}$). GHGs are reported as CO_2 equivalence (CO_2eq) using radiative forcing multipliers of 25 for CH_4 and 298 for N_2O for a 100 yr horizon. The US Clean Air Act established a regulatory framework for criteria air pollutants to reduce direct human and environmental impacts. SO_2, CO, NO_x, PM and ozone are regulated through National Ambient Air Quality Standards. We evaluate NO_x and VOCs because they are ozone precursors.

The LCI results are joined with human and environmental impact characterization factors from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, v2.03) in the development of a life-cycle impact assessment (LCIA) (Bare *et al* 2002). Impact characterization factors are used to show the maximum potential effects of pollutant releases. In addition to global warming (CO_2eq), human health respiratory, acidification, tropospheric ozone (smog) and eutrophication impact potentials are determined. We stress that impact potentials are the maximum effects that can occur and actual effects may be lower, or potentials may never turn into damages. However, given the challenge of combining air transport and chemistry modeling with concentration-response functions, endpoint damages have not been determined for this study. Bare *et al* (2002) provide background for TRACI and how air emissions are used to determine impact potentials.

2.1. Efficient and electric automobiles

Improved gasoline efficiency and plug-in hybrid electric vehicles (PHEV) are expected to have significant market penetration by 2030 (EPRI 2011). The 2007 US Energy Independence and Security Act established fleet-wide fuel economy standards at 35 mpg (15 km l^{-1}) by 2020. Furthermore, the US EPA and the National Highway Traffic Safety Administration have proposed a 102 g km^{-1} CO_2 standard for 2025, which is equivalent to a fuel economy of 54.5 mpg (23 km l^{-1}) (EPA 2011). Given these policies and trends, it is reasonable to expect future long-distance automobile travel to occur in a vehicle that has improved fuel economy from the 21 mpg (9.6 km l^{-1}) average today (ORNL 2011). While a fuel economy standard does not translate to actual onroad performance, the range of economies modeled is intended to illustrate future potential performance of improved vehicles. Congestion effects are not modeled and it is acknowledged that this would increase the automobile footprint. Second-generation biofuels are likely to be a widespread transportation fuel in the future (Scown *et al* 2012), but we focus on reformulated-gasoline and electric vehicles.

Vehicle manufacturing, battery manufacturing (including replacement) and operation are evaluated with the GREET 1 (fuel-cycle) and 2.7 (vehicle-cycle) models (ANL 2011). A 35 mpg, 1500 kg sedan and a 55 mpg, 900 kg (before batteries) PHEV (ANL 2011) are modeled to meet future fuel economy standards. Large battery pack plug-in and battery electric vehicles are expected to have market penetration gains in the next decades, and we evaluate a PHEV60 (60 mi, 97 km all electric range) assuming that the first 97 km of a 480 km California long-distance trip are in charge-depleting mode and the vehicle is configured as a parallel hybrid drivetrain. GREET models vehicle emissions with a drive cycle that is 43% city and 57% highway. Using drive cycle characterizations from Karabasoglu and Michalek (2012), vehicle emissions are adjusted assuming that the beginning and ending 24 km of the trip occur in cities with the remainder occurring on highways. We believe that our PHEV60 assessment is conservative as future vehicles may have improved battery energy densities and intelligent operational controls that more effectively utilize a blended mode. The PHEV60 is modeled with one lithium-ion battery replacement and specifications are consistent with those modeled by Michalek *et al* (2011). All automobiles are evaluated with a 260 000 km lifetime. Brake wear, tire wear and evaporative losses are included. General maintenance and tire replacement are evaluated using EIO-LCA (GDI 2011). Lead-acid and lithium-ion battery replacement are evaluated with GREET. The energy and environmental effects associated with insurance industry operation (e.g., electricity consumption, waste management) are captured using EIO-LCA (GDI 2011).

The energy inputs and air emission outputs generated by the construction and maintenance of the California highway (interstate and major arterial) system serve as the infrastructure basis for future long-distance statewide travel. There are currently 12 100 km of California highways facilitating 250 billion annual vehicle-kilometers-traveled (VKT) (FHWA 2009). Across all California roadways there are 380 billion annual VKT and this is forecast to increase to 480 billion VKT by 2040 absent a HSR system (CAHSRA 2012). The 74% of asphalt surfaces are specified with a 15 yr life and concrete surfaces at 25 yr (both surface sub-bases are assumed to last 100 yr). Material production, transport, equipment process, and direct emissions from construction and maintenance activities are modeled with PaLATE (2004). Roadway construction effects are allocated to vehicles based on VKT splits and maintenance to heavy duty vehicles since damage follows a fourth-power relationship to axle load (Huang 2004). Roadway design specifications, herbicide use and overhead lighting are included (Chester 2008).

Gasoline vehicle and PHEV60 energy production are evaluated with GREET and are specified with parameters commensurate with Michalek *et al* (2011). California reformulated gasoline is used, and GREET estimates that 18% of crude oil feedstock will be extracted from oil sands by 2020. For the PHEV60 and CAHSR, future regional electricity is used (this is detailed in later sections). Gasoline and electricity production include raw fuel feedstock inputs, transportation, processing (or generation) and distribution.

2.2. High-speed rail

HSR effects are determined following the approach of Chester and Horvath (2010) but updated to acknowledge that a future CAHSR system will likely see improved train performance and an opportunity for increased renewable electricity usage. The assessment by Chester and Horvath (2010) was designed to evaluate the high-speed rail system specified by CAHSRA (2005) under a life-cycle lens. CAHSRA (2005) performs an energy assessment based on large 1200 seat trains consuming an exaggerated 170 kWh of electricity per VKT. Despite acknowledging this over-estimate, Chester and Horvath (2010) chose not to redesign the CAHSRA (2005) system or challenge the publicized parameters. Given the uncertainty in the CAHSRA (2005) propulsion electricity estimate, primary data collection exercises were undertaken to develop improved electricity consumption estimates for a future CAHSR train. In this study, we evaluate three train sizes (400, 670 and 1200 seats) and use actual electricity consumption outcomes from Deutsche Bahn, instead of relying on literature. A range of HSR propulsion electricity exists in the literature and a survey and comparison are performed in the supplementary information (SI, available at stacks.iop.org/ERL/7/034012/mmedia). Actual electricity consumption factors for ICE trains (preliminarily chosen by CAHSRA 2005) were gathered from Deutsche Bahn (2011) and correspond to those reported by IFEU (2011) resulting in 13, 20 and 36 kWh/VKT for the respective train sizes. Regenerative braking effects are included. It is possible that the trains deployed in California will be several generations newer and will consume less electricity, but without data on future technologies we choose not to make projections, and instead assume current state-of-the-art technology for CAHSR.

A study has been performed for the CAHSR Authority to evaluate the feasibility of deploying wind and solar electricity to meet system-wide electricity demands (Navigant 2008) and strategies have been developed to power the stations and trains with 100% renewable energy (NREL 2011). While funding for a renewable electricity infrastructure remains uncertain, this future configuration is considered using existing PV and solar study LCIs (Pehnt 2006) with an 80% wind and 20% solar mix.

Vehicle (manufacturing, maintenance and insurance), infrastructure (construction, operation, maintenance and parking), and non-renewable electricity generation scenarios follow the methodology used in Chester and Horvath (2010, 2011) and are adjusted for future electricity inputs. The infrastructure assessment matches the results of Chang and Kendall (2011) when a commensurate system boundary is used. Whenever possible, we apply the Western Electricity Coordinating Council (WECC) electricity mix generation emission factors to scenario life-cycle components. Without a contract to purchase electricity from a particular supplier, electricity consumption by CAHSR should be evaluated in the WECC reliability network (Marriott and Matthews 2005), capturing flows across nearby states, including imports to California. Vehicle and infrastructure effects from WECC electricity use are based on a mix that has reached 2020 Renewable Portfolio Standards (WECC-RPS) (WECC 2011). Furthermore, a projected 2040 mix that has reduced coal inputs resulting in 60% carbon emissions intensity of today is also included (WECC-2040).

2.3. Next generation aircraft

Midsize aircraft (130–160 seats) were responsible for 79% of domestic US air travel PKT in 2009 (BTS 2011) and current and future planes are evaluated to capture significant improvements in engine fuel use and emissions. A Boeing 737–800 is used to evaluate currently operating state-of-the-art aircraft. The 737–800 seats 160 and uses CFM56-7B26/2 engines. The Bombardier CS300-ER is an emerging aircraft that offers 20% fuel savings (and commensurate GHG savings) and additional emissions reductions over in-service planes. The CS300-ER will use Pratt and Whitney (PW) 1524G PurePower engines offering propulsive efficiency gains while carrying up to 130 passengers. For both aircraft, maintenance and insurance costs are based on 737–800 airframe materials, engine materials, insurance and hourly costs of employee benefits, reported by BTS (2011). To provide perspective on energy and environmental gains in air travel, the 737–800 and CS300-ER are compared against the legacy Boeing 737 series ($<$800) which has been a workhorse of the mid-haul market (Chester and Horvath 2010).

Fuel and emission indices are used to determine landing–takeoff (LTO) and cruise phase effects for a San Francisco to Los Angeles flight. In previous studies, LTO effects were determined with FAA (2010) and cruise phase with EEA (2006) data. These software and data do not offer the flexibility or transparency to evaluate future engine improvements. FAA (2010) reports fuel and emission indices which are combined with time-in-mode and rated thrust estimates to determine total flight effects for the 737s. The CFM56-7526/2 engines on the 737–800 achieve 25% reductions in CO, 27% in HC, 31% in NO_x, and 97% in smoke emissions relative to CAEP6 engine emission standards (ICAO 2010). ICAO (2010) does not yet report PW1524G engine testing results, however, Hoke (2011) reports 64% reductions in CO, 96% in HC, 58% in NO_x, and 50% in smoke emissions relative to CAEP6 standards, which were used to determine the CS300-ER flight emissions. Flight LTO and cruise fuel consumption and emissions were validated by PW engineers (Pratt and Whitney 2011). Aircraft energy and environmental effects are determined with fuel and emission indices and rated thrust estimates by flight phase (see the SI for details, available at stacks.iop.org/ERL/7/034012/mmedia). The potential for respiratory, acidification and eutrophication impacts from non-LTO emissions are included (Barrett *et al* 2010, Tarrasón *et al* 2002).

3. Modal attributional footprinting

The assessment and allocation of direct and ancillary processes to each transportation mode reveal the life-cycle activities that should be targeted for the greatest environmental improvements. Consistent with existing transportation LCA studies, results are normalized to a per-PKT functional unit to evaluate the effectiveness of providing passenger mobility. For automobiles and CAHSR, a dearth of data exists to provide a rigorous assessment of expected occupancy rates. For aircraft, detailed reporting provides strong indicators for future utilization (BTS 2011). To avoid universally characterizing modal performance by normalizing to an average occupancy, reasonable and expected high and low occupancies are assessed to capture the *potential* of modes. For all modes, the high occupancy is the number of seats. Low occupancies are designed to consider off-peak ridership. While it is possible for CAHSR and aircraft to operate with a single passenger, this outlying case is not informative and therefore not shown. Low occupancy for CAHSR is approximately one-quarter of seats, and for aircraft is the lower occupancy quartile in 2009, determined from BTS (2011). Figure 1 shows global warming and human health respiratory life-cycle results for each mode for high and low occupancy.

GHG emissions are dominated by vehicle propulsion (energy production for CAHSR and vehicle operation for automobiles and aircraft) but show increases of 38–54% for automobiles, 77–116% for future CAHSR and 13–34% for aircraft when all life-cycle components are included. Results for future long-distance modes are consistent with those identified in past transportation LCA studies (Chester and Horvath 2010, 2009) even when new data and modeling are included (ANL 2011). Automobile vehicle manufacturing is dominated by steel and plastic use (ANL 2011), and maintenance effects are largely the result of supply chain electricity (GDI 2011). CAHSR infrastructure construction effects are dominated by concrete use. Approximately 67% of CAHSR infrastructure emissions are the result of cement production for concrete use and 9% are related to steel production. Automobile infrastructure effects are small compared to past studies because only highways are included to isolate long-distance infrastructure. The inclusion of trip-specific infrastructure provides a clearer comparison of corridor travel by focusing only on roads, tracks and airports needed for each trip. Non-propulsion fuel-cycle effects are primarily the result of refineries, oil and gas extraction activities, and supply chain electricity use (ANL 2011, GDI 2011). With distributed hard infrastructure and its long-distance nature, the life-cycle effects of air

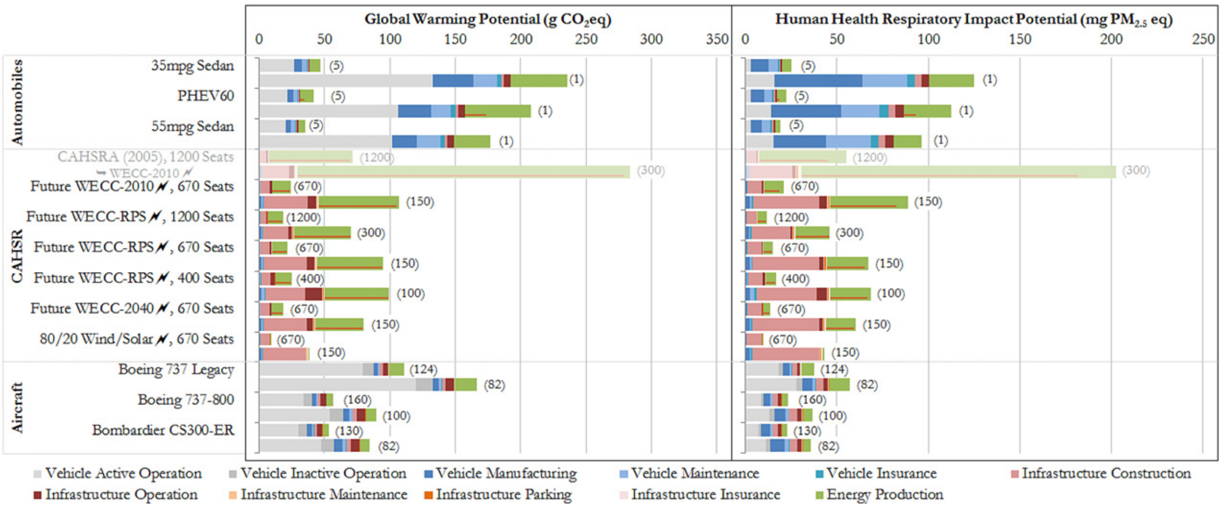

Figure 1. Global warming and human health respiratory impact potential results per PKT. For each mode, results at long-run average high and low occupancy (shown in parenthesis) are displayed as juxtaposing bars. Previous research by the authors reported electricity generation effects for electric vehicle propulsion in the *Vehicle Operation* life-cycle groupings. In an effort to improve the spatial characterization of effects, electricity generation for CAHSR propulsion is reported in *Energy Production* and differentiated from upstream effects (e.g., emissions from fuel extraction and transport) by a red line. The CAHSRA (2005) train is shaded gray to emphasize that it is an unlikely outcome, but reported for comparative purposes.

travel are diminished when results are normalized per PKT. WECC-2040 electricity reduces HSR GHG propulsion emissions by 26% but infrastructure construction effects continue to add heavy burdens to life-cycle results showing the need for low-CO_2 materials.

Across modes and life-cycle groupings, PM_{10} emissions are often generated by mining activities for raw materials, and $PM_{2.5}$ emissions by supply chain combustion processes including electricity generation, the latter contributing to human health respiratory impact potentials. While PHEV60s produce fewer $PM_{2.5}$ emissions during propulsion, battery manufacturing and associated electricity requirements have the potential to contribute significant $PM_{2.5}$ and SO_x emissions and increase respiratory impacts beyond the 35 mpg sedan. This implies that strategies should be developed that minimize human and environmental exposure as the battery industry expands, and that meeting or exceeding RPS standards will reduce impacts across automobiles and CAHSR. For CAHSR, concrete and steel production including upstream mining activities are larger than propulsion effects. The dominating share of environmental impact potentials are often in non-propulsion components and are shown in figure 2.

Several common processes dominate the environmental impact potentials. Vehicle manufacturing and maintenance are affected by assembly activities, but are dominated by the use of metals (i.e., steel, aluminum and copper) and its associated electricity demands for processing. Supply chain truck transport for these processes also contributes heavily to CO, NO_x and VOC emissions. Asphalt and concrete use dominate infrastructure construction and the use of these materials is affected primarily by direct emissions at hot-mix asphalt and cement kilns, and their associated electricity demands. Airport ground support equipment use contributes heavily to aircraft life-cycle results. For automobiles and aircraft, fuel production effects are largely the result of refinery electricity demands and extraction activities, and for HSR are dominated by primary fuel extraction, processing and transport. Air pollutant emission reductions may achieve the largest benefit-to-cost ratio by targeting infrastructure and supply chain effects.

Assuming that options exist, the decision by a traveler to take a mode produces marginal effects in the short-run, a subset of those reported in figures 1 and 2. For example, the decision to walk instead of driving immediately avoids fuel consumption and emissions from vehicle operation. Including mid-run life-cycle components avoids vehicle manufacturing, vehicle maintenance, vehicle insurance, infrastructure maintenance, and associated supply chain effects including fuel refining. Ultimately, a critical mass of travelers choosing to walk instead of drive would have long-run effects including reductions in roadway capacity needs avoiding future infrastructure construction. Marginal effects are critical for understanding the change in energy or environmental outcomes from a policy or decision. Long-run average effects are reported to provide a comprehensive set of indicators for analysts, however, future analyses with these results should consider marginal effects at specified timescales. Long-, mid- and short-run average and marginal comparisons are presented in the SI (available at stacks.iop.org/ERL/7/034012/mmedia).

Considering the potential of a mode to environmentally outperform another is critical to developing strategies that acknowledge different long-term operating characteristics. Modal potential considers the occupancy range in which transportation systems operate instead of averages which can mask peak and off-peak, position along lines and day-of-week characteristics, to name a few. Future CAHSR ridership forecasts have been developed and scrutinized (Brownstone *et al* 2010). Designs that do not access airports

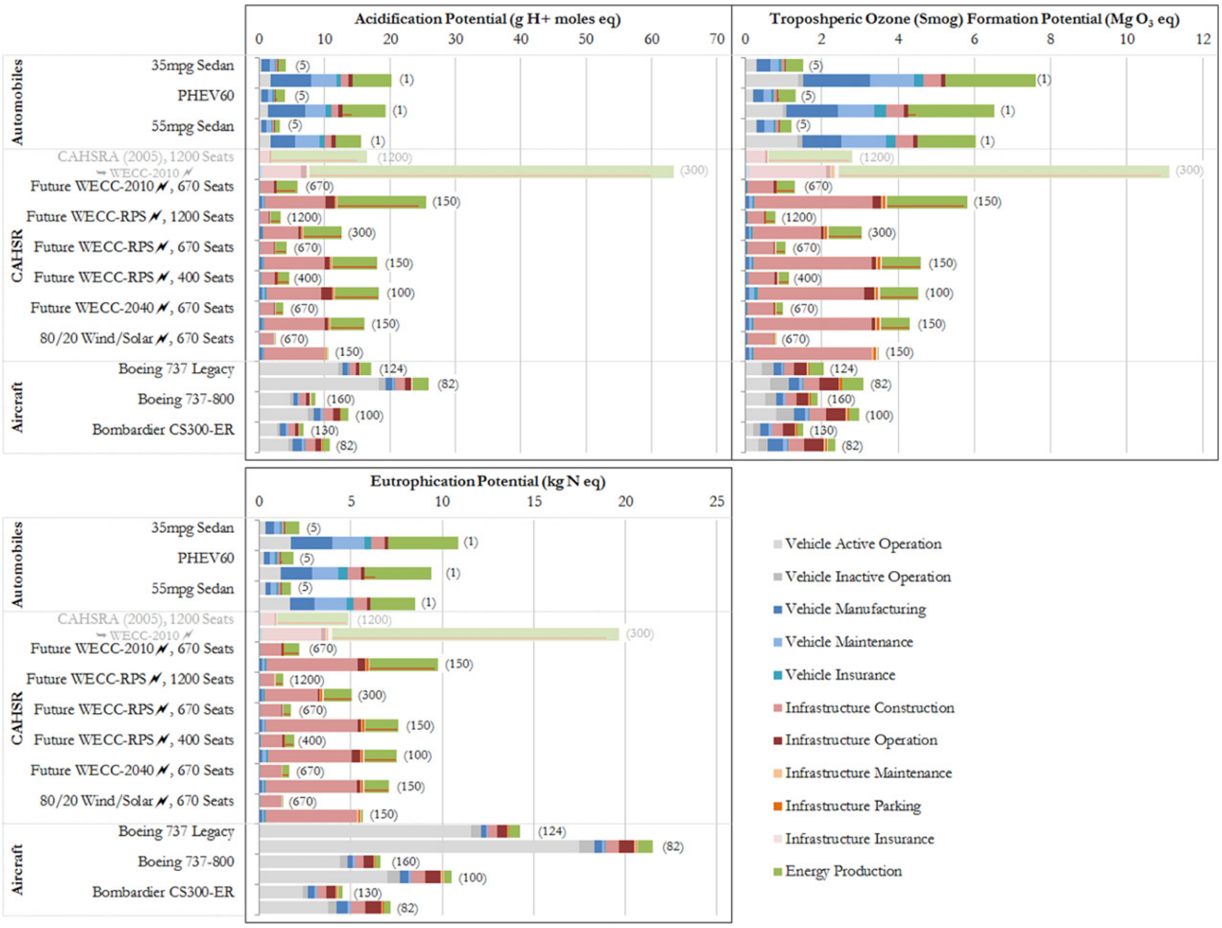

Figure 2. Environmental impact potentials per PKT.

and city centers, hub existing transit at HSR stations and encourage urban infill are inimical to high ridership, and risk disincentivizing trip takers switching from autos. Technical, political, community and economic roadblocks exist for many high ridership configuration options that could ultimately lead to lower than optimal adoption outcomes. Furthermore, even with high ridership configurations, the system will at times (whether during off-peak or end-of-lines) exhibit fluctuations and these instances should be considered in policies that target marginal operation. Given the large uncertainty in a future HSR system's ridership, figure 3 shows the CAHSR life-cycle and vehicle propulsion effects at varying occupancy levels against a current mean occupancy automobile and midsize aircraft (represented as a 2.2 passenger 35 mpg sedan and 116 passenger 737–800).

The sensitivity to vehicle occupancy is used to illustrate breakeven points, or the ridership levels where one mode is equivalent to another in the long-run. Occupancy levels of between 80 and 280 passengers produce HSR GHG-equivalency to future automobiles or aircraft (depending on train size). However, for acidification potential, this equivalency increases to between 160 and 420 passengers, or roughly 35–40% average occupancy for trains. This assumes that the WECC has met the RPS. The acidification breakeven points capture the dynamic of mode switching from low-sulfur liquid fuels to high-sulfur electricity and reaffirm the findings of Chester and Horvath (2010) that deployment of HSR should occur with mandates for cleaner propulsion electricity sources to avoid increased human and environmental impact potentials. The breakeven point assessment highlights the importance of future ridership scenario considerations in the determination of potential corridor effects.

4. Regional consequential effects

To evaluate the net effects of the decision to implement a new system in the corridor, a consequential assessment is developed. A consequential assessment should compare a *without HSR* future where additional automobile and aircraft capacities are needed to meet growing demands to a *with HSR* future where the new rail system reduces the need to fully build this capacity. Estimates of this capacity expansion have been produced by the Authority (PB 2011) and the LCA methods can be used to evaluate the change in effects in the corridor. The per-PKT results reported in figures 1 and 2 are valuable for understanding the footprint of each transportation system in the long-run but do not allow for direct assessment of the changes in corridor impacts when a new system is implemented. For example, an infrastructure will be constructed to facilitate an

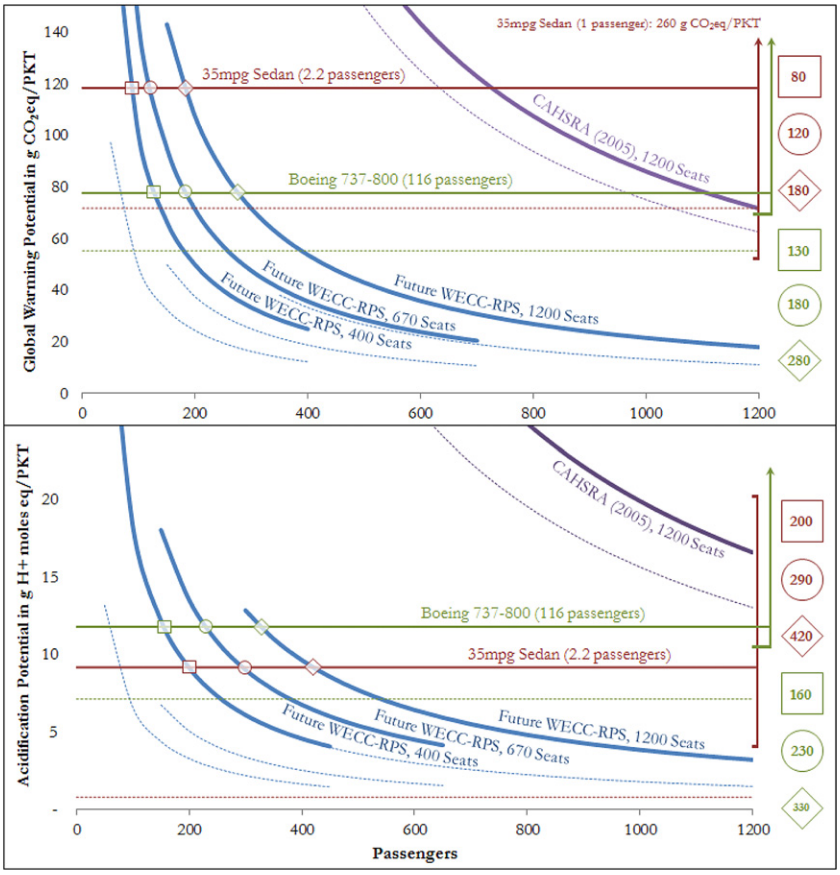

Figure 3. CAHSR global warming and acidification potential sensitivity to vehicle occupancy. Life-cycle results are shown as solid colored lines and vehicle propulsion as dotted. Breakeven points are shown as red and green shapes on the figure and corresponding ridership levels are shown on the right side. While average occupancies are shown for the 35 mpg sedan and 737–800, their potential ranges are shown as vertical lines on the right side.

expected level of service for CAHSR. This infrastructure may be flexible to accommodate more passengers if demand is greater than anticipated. Yet if the per-PKT GHG results in figure 1 are applied to the different PKT demand forecasts, different net infrastructure construction effects would be falsely determined (i.e., the infrastructure construction effects remain the same with different ridership outcomes). While the attributional assessment can inform questions like: *what are the major energy and environmental processes in the life-cycle of a transportation system, and how can they most effectively be reduced?* A consequential assessment is needed to answer questions such as: *how can California deploy a future multi-modal transportation system with the lowest human and environment impacts?*

The energy and environmental costs of a new HSR system should be compared against the avoided costs of automobile and air infrastructure expansion, assuming there is long-distance travel demand growth. PB (2011) estimated that 3600 freeway lane km and 13 000 m of runways, and 115 additional airport gates are needed to meet growing corridor demand in the coming decades. This is the only assessment of future infrastructure expansion needs to date and it is possible that this is an aggressive estimate. PB (2011) estimates are based on full corridor future capacity (117 million auto and air trips) and the most recent forecasts estimate 33 million HSR trips at high ridership. Therefore, 28% of infrastructure expansion effects are considered (i.e., 1000 lane km, 3600 m of runways and 32 additional airport gates) to account for only the avoided effects of HSR travelers and may be an aggressive allocation because of induced demand. Using roadway design guidelines (AASHTO 2001), construction and maintenance energy and emissions were calculated with PaLATE (2004) following Chester and Horvath (2009). The runway expansion would come with an estimated 670 000 m^2 of taxiways and tarmacs. Construction and maintenance of concrete runways and asphalt taxiways and tarmacs are also evaluated with PaLATE (2004) using dimensions reported by Chester (2008). For all surfaces, it is assumed that the wearing courses will last 20 yr and subbases 50 yr. It is also assumed that infrastructure expansion will start 10 yr after it has been decided not to build HSR, and will occur over 30 yr. Airport gate and corresponding concourse expansion construction follow the methodology of Chester (2008). Detailed construction and maintenance schedules for the infrastructure expansion are provided in the SI (available at stacks.iop.org/ERL/7/034012/mmedia).

Consequential effects are highly sensitive to modal shifts and forecasting of HSR energy and environmental effects should occur with uncertainty assessment. Forecasts for CAHSR adoption have only been reported by the Authority making rigorous uncertainty assessment challenging. Adoption discussions by the Authority have been presented through

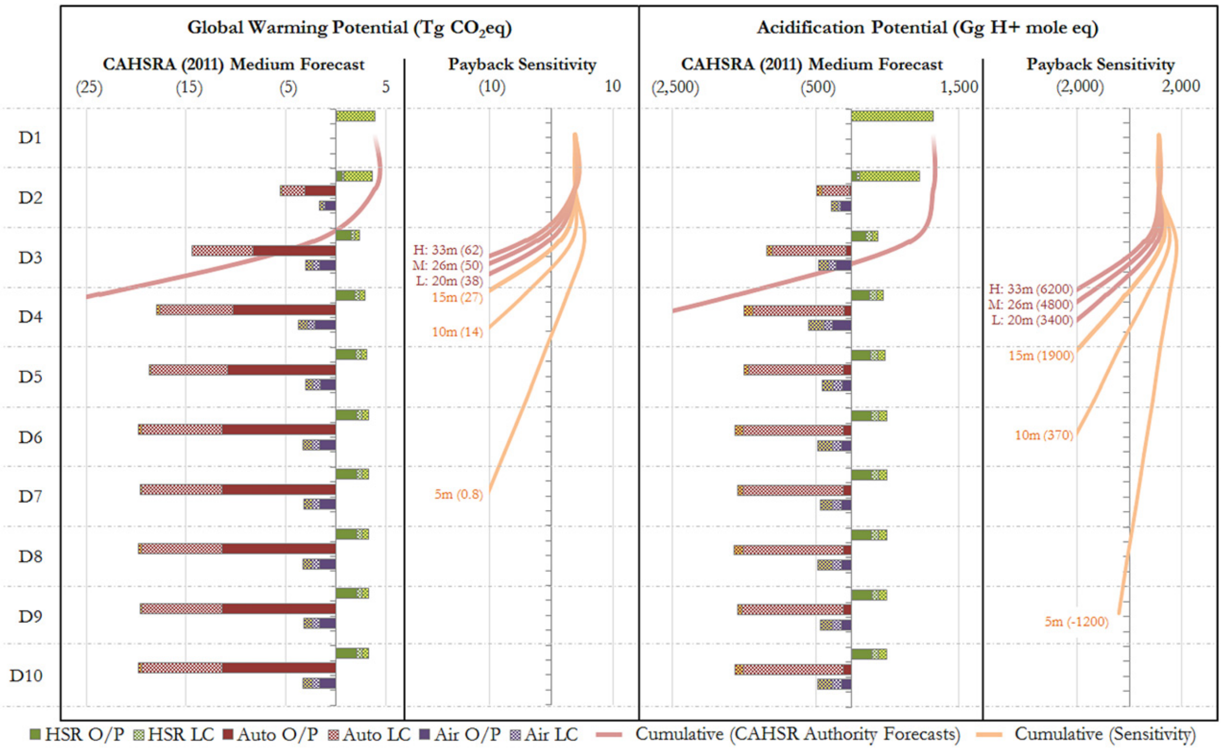

Figure 4. Decadal (D) consequential global warming and acidification potentials including payback for phase 1. O/P = operation and propulsion components (impacts from energy consumed to move vehicles). LC = life-cycle (excludes operation and propulsion components). Life-cycle effects are separated by infrastructure expansion (yellow background) and non-infrastructure (e.g., vehicle manufacturing and maintenance). After each ridership forecast (shown in millions (m) of annual trips in 2040), the 50 yr savings are shown in parentheses. These savings are the GHG or acidification benefit (negatives are costs) after 50 yr from groundbreaking.

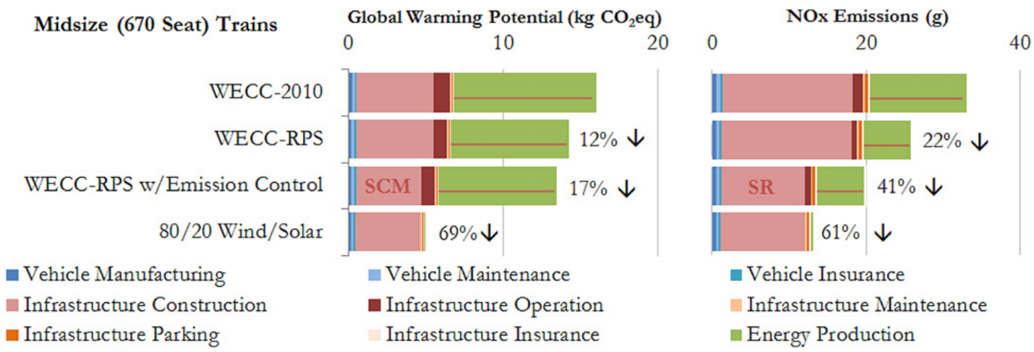

Figure 5. Energy and emission control strategies for reducing environmental impacts per VKT.

without HSR and *with HSR* forecasts. The consequential assessment considers the difference between these two, essentially, what environmental changes have occurred in California as a result of implementing HSR. The current forecasts report that by 2040 CAHSR Phase 1 (San Francisco to Los Angeles) will perform between 27 and 41 million annual VKT (PB 2012a). The Authority's medium *with HSR* forecast (34 million HSR VKT) displaces 5.8 billion auto VKT and 5.1 million air trips annually, generating between 20 and 33 million trips on the new mode (PB 2012a, 2012b). Using these forecasts, the Authority's medium (middle) projection is first evaluated to determine the consequential effects at full adoption in 2040. The WECC-RPS 670 seat HSR train is compared against displaced travel in a 35 mpg sedan and 737–800 aircraft (assumed to be reasonable representative vehicles for 2040). In the *without HSR* scenario, it is estimated that auto travel will increase from 380 billion VKT today to 480 billion VKT, and air travel will increase to 33 million trips (PB 2012b).

The deployment of CAHSR will create induced demand as a subset of trip takers who would not travel by auto or air now find the generalized cost for the journey lower than existing options (Outwater *et al* 2010). Additionally, access to and from HSR stations by autos and other modes may induce new system-wide demand. The CAHSRA (2012) *with HSR* forecast includes estimates of new trips and these are bundled in the aforementioned VKT. We model induced demand implicitly through the change in travel reported by CAHSRA (2012). A summary of the *with HSR* and *without*

HSR consequential analysis critical parameters is provided in the SI (available at stacks.iop.org/ERL/7/034012/mmedia).

The consequential assessment evaluates the difference between a future where CAHSR has or has not been constructed. Figure 4 shows the GHG and acidification potential for operation/propulsion and other life-cycle (including the avoided expansion of auto and air infrastructure) effects aggregated per decade for Phase 1 of the system (San Francisco to Los Angeles). The cumulative effect curve shows the time until payback. Given the uncertainty in the forecasts (Brownstone *et al* 2010), a payback sensitivity analysis is performed on the high adoption scenario as reported by the Authority (41 million VKT). The sensitivity analysis evaluates how long it takes CAHSR to achieve payback given certain adoption levels (for perspective, the Authority's low adoption scenario is 66% of ridership in the high adoption scenario) and considers the high (H), medium (M) and low (L) scenarios followed by decreases of 5 million (m) annual riders.

The payback sensitivity reveals several important considerations for transportation planners and air quality policy makers. The cumulative plum-colored lines for the high, medium and low forecast figures show that the GHG payback will likely occur between 20 and 30 yr (D3) after groundbreaking and acidification potential after 20–40 yr. However, payback is highly sensitive to reduced automobile travel. The 5.8 billion auto VKT displaced dominate emissions changes in the corridor and the effects from reduced air travel and CAHSR are small. The reduced auto impacts are significantly affected or dominated by life-cycle components, in particular, avoided vehicle manufacturing, vehicle maintenance and gasoline production. For GHGs the sooner the system is implemented the more opportunity it will have to help meet GHG reduction policies aiming for 80% of 1990 statewide emissions by 2050. Larger trains or more carbon-intensive electricity generation will delay the payback further. Acidification, the release of SO_x and NO_x emissions which are of concern for respiratory and cardiovascular (through secondary particle formation) effects, agricultural impacts and increased built environment maintenance costs, are dominated by life-cycle processes. For infrastructure life-cycle processes acidification is dominated by the combustion of sulfur-bearing compounds in clinker manufacturing for cement used in concrete freeways, and for non-infrastructure life-cycle processes supply chain electricity use. Ultimately, impacts should account for the time-based radiative forcing of GHGs, high-altitude CO_2 emissions effects, and the shifting of human and environmental effects from vehicle tailpipes to powerplants, to name a few additional factors. We reserve these analyses for future studies. The results of the consequential assessment are highly sensitive to automobile trips avoided and efforts should be made to validate the travel demand model used by the Authority.

5. Strategies for reducing environmental impacts

Given the dominating HSR life-cycle effects from electricity generation and infrastructure construction, strategies can be identified to reduce the system's footprint, prior to its construction and use. First, by meeting the RPS, GHG and NO_x emissions will be reduced by 12% and 22%. Next, emission control strategies are identified for reducing the infrastructure footprint. For GHGs, the use of supplementary cementitious materials (SCMs) such as fly ash or ground granulated blast furnace slag can reduce concrete's footprint by 14–22% depending on the mixture (Flower and Sanjayan 2007). It is expected that the portion of the infrastructure that impacts roadways will be required to use fly ash to meet California Department of Transportation requirements. Furthermore, if the Authority requires concrete producers to utilize cement kilns with selective catalytic and non-catalytic reduction (SR) advanced NO_x controls, material production emissions can be decreased between 35 and 95%, reducing the potential for acidification, respiratory, smog and eutrophication potential impacts (EPA 2007). Lastly, the use of 100% renewables lowers electricity generation impacts (to only power generation facility construction effects) and combined with the infrastructure control strategies produces the greatest reductions. The effects of these strategies are shown in figure 5.

The impact reduction strategies can decrease GHGs between 12 and 69% and NO_x emissions between 22 and 61%. The costs of implementing these strategies should be compared against other opportunities, particularly those identified by GHG and air quality policies. The 80/20 Wind/Solar train, outside of the infrastructure material footprint, has a payback within the first few years of operation and is equivalent to the GHG assessment developed by the Authority, based on NREL (2011), following California Environmental Quality Act requirements.

The transportation emissions reduction from CAHSR, if operating within a cap-and-trade system, should be evaluated. Cap-and-trade programs have been successfully implemented in the US for NO_x and SO_x, and California continues to discuss a GHG initiative. Cap-and-trade programs remove the potential of any single initiative to reduce aggregate emissions as offsets will be met by increases elsewhere in the economy (Millard-Ball 2009). This is because the cap is designed to equalize the marginal abatement cost and does not encourage each economic sector to undertake reductions. Furthermore, if road and rail emissions are part of the cap but aircraft emissions are not, then the only major GHG change resulting from HSR implementation will be the displaced airplane operational emissions. To meet GHG reduction goals, policy makers should consider where CAHSR potential reductions will be counted, whether that is in a cap-and-trade program or direct transportation mandates.

6. Planning for a sustainable mobility future

HSR has the *potential* to reduce passenger transportation impacts to people and the environment, but must be deployed with process and material environmental reduction measures and in a configuration that will ensure high adoption. We have highlighted the life-cycle hotspots that dominate modal success: (i) train size (affecting electricity consumption, frequency of service and ridership); (ii) infrastructure construction; and (iii) the fossil fuel intensity of the electricity mix. By identifying low and high adoption outcomes, the potential benefits can be discussed, instead of speculating on a normative long-distance transportation future, especially in light of large uncertainty that surrounds many critical factors of the system. Ultimately, this research aims to inform planners and decision makers about providing sustainable mobility options. Planners and policy makers should be asking how a future sustainable transportation infrastructure can be deployed to meet increasing travel demands with the lowest total cost, including externalities. The environmental benefits of HSR should be joined with other considerations when making decisions about the system. Ultimately, decision assessment should include changes in travel time, productivity, congestion, safety, transportation infrastructure resilience, freight synergies, urban development opportunities and employment, in addition to GHG, human health and environmental damages.

Acknowledgments

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CA: Reforms Key to Controlling Costs on Public Works Megaprojects, Say Experts

LISA VORDERBRUEGGEN
SOURCE: CONTRA COSTA TIMES
CREATED: NOVEMBER 14, 2013

Forget the $1 billion megaproject. It's all about the $10-billion-and-counting gigaproject now.

Forget the $1 billion megaproject. It's all about the $10-billion-and-counting gigaproject now.

Experts coined the expanded term to keep pace with the vastly more expensive bridges and other huge infrastructure projects on the drawing boards around the world, such as California's $68 billion high-speed rail plan.

But as megaprojects of yesterday proved, controlling costs and keeping schedules on track will remain unattainable without reforms in how agencies manage increasingly complex and expensive public works projects, experts from England to Berkeley testified Wednesday at a state Senate Transportation Committee hearing.

"Good luck," U.C. Berkeley civil and environmental engineering professor William Ibbs offered wryly at the close of the nearly 2 1/2 hour session in Sacramento.

Ibbs was one of four experts committee Chairman Mark DeSaulnier, D-Concord, invited to testify at the first of three hearings on why the new $6.4 billion Bay Bridge was a decade late and cost nearly five times more than engineers estimated.

The state senator said he will use the information next year to help craft legislation aimed at averting a costly repeat of the Bay Bridge, the most expensive public works project in the state's history.

"The Bay Bridge is a beautiful and spectacular bridge, fitting in its setting, but I do wonder if it was worth the cost and the delays," said DeSaulnier in his opening comments. "Now, we have high-speed rail in California and if you believe ... in the research around what happens with rail projects, Californians might be paying $300 billion or $350 billion instead of $68 billion."

Whether it is high-speed rail or California's proposed $22 billion water diversion tunnels through the Delta, overruns and delays are more likely than not, Oxford University megaprojects researcher Alexander Budzier told the senator.

In an Oxford study of 157 bridges and tunnel projects built in 1919-2001, costs rose on average 34 percent and estimates were low in nine out of 10 cases. High-speed rail and dams fared worse, he said.

Researchers blamed the phenomenon on project bias, described as excessive optimism and "strategic misrepresentation or, put simply, lying," Budzier said.

"People think they can do a project faster and so the cost estimates are that much less," Budzier said. " ... And project proponents are the most likely to intentionally misrepresent the risks just to get a project going because once it gets started, it is almost always finished no matter how big the overruns."

One of the keys to reversing this trend is sharing the risks — extra costs, delays and blame — more equitably between the public agencies, designers and contractors, said former Boston "Big Dig" manager Virginia Greiman, currently a professor of law at Kennedy School of Government and Law School at Harvard.

The "Big Dig," a series of tunnels beneath Boston that replaced a deteriorating elevated freeway system, started at $2.5 billion and ultimately cost $15 billion.

"Many states require balanced budgets but we never seem to require projects to do the same," Greiman said. And when those massive projects are completed, the state should follow France's example and mandate publications of an easy-to-understand report on how the endeavor scored on cost, schedule and other factors, suggested Louis Thompson, chairman of the California High Speed Rail peer review group.

"There is no way to get rid of (cost and timeline bias) unless the people making the estimates have something at stake," Thompson said. "Unless they know that at the end, 'Here is where you failed and here are the consequences,' nothing will change."

Among the experts' other recommendations:

- Commission outside people with no financial stake in the project to conduct mandatory cost-benefit analyses on every big project.
- Hire top-notch project managers with the skills to bring together the public agency, designers and contractors.
- "Mega-communicate" with the public and media.
- Use specialized computer systems that scour designs and project plans for conflicts or errors that could cost time and money.
- Convene citizen and technical oversight committees.

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Why is it so expensive to build a bridge in America?

The answer: Our greedy and undemocratic political culture

By Ryan Cooper | March 10, 2014

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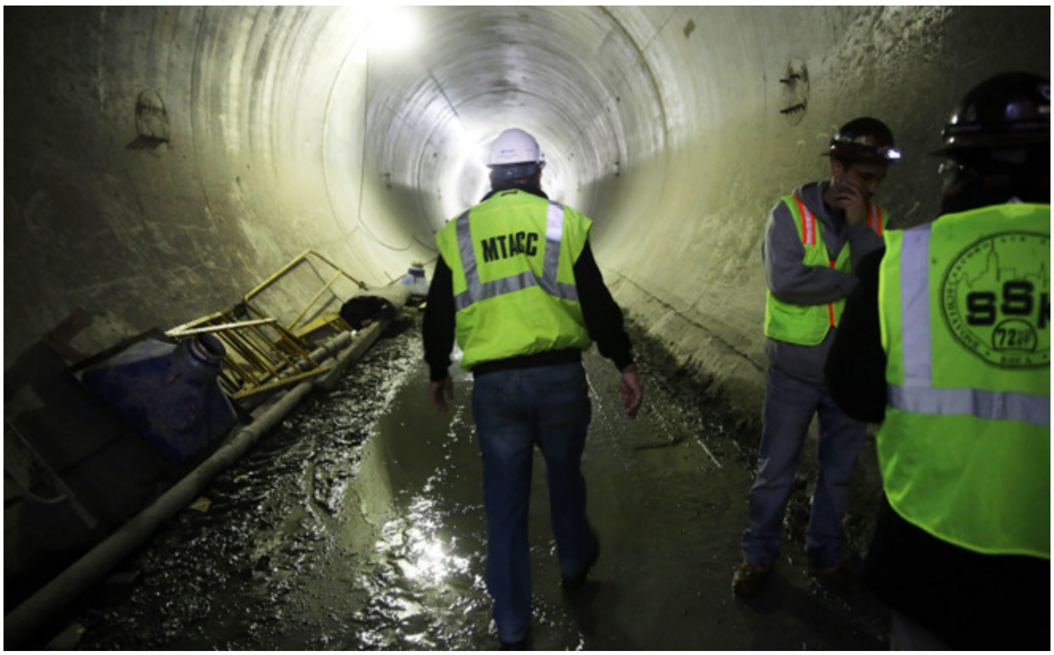

Good luck keeping costs down. (Spencer Platt/Getty Images)

It's become commonplace to note that U.S. infrastructure costs are very high. What is less appreciated is the staggering *scale* of the difference between American infrastructure costs and those of other nations. Like our health care, U.S. infrastructure isn't just a tad higher than the next most expensive country — we pay something like twice as much as our closest peer (usually the U.K., which is itself a very expensive place). And when you compare America to, say, Spain, we're talking order-of-magnitude differences.

In other words, Spain, a developed market democracy, gets *10 to 20 times* as much infrastructure for its money as America does, and it is of much higher quality to boot. Why is this?

People who have looked into the question have collected a range of fairly convincing explanations — though they come up short in a fundamental way. Let's quickly go through the major factors researchers have identified, in no particular order:

1. Expensive labor. From the top brass at New York's Metropolitan Transportation Authority: "The MTA is required to overstaff projects so that the same [tunnel boring machine] work, for instance, that can be done in Spain with nine workers must be done in [New York City] with 25 workers."

2. Out-of-control private contractors. From Stephen Smith at *Bloomberg*: "Agencies can't keep their private contractors in check. Starved of funds and expertise for in-house planning, officials contract out the

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project management and early design concepts to private companies that have little incentive to keep costs down and quality up."

3. A crap procurement process. The classic American way to pay for a big project is to round up about half of the funding (or even less), start construction, and then use a sunk-cost-fallacy to get the rest. This, obviously, is not conducive to efficient or speedy projects. (Looking at you, California high-speed rail.)

There are probably a lot more, but as Alon Levy points out, it would be a mistake to focus too much on particular techniques or failures. The reality is that when it comes to cost and quality, America is doing basically everything wrong. Again, we're not just a bit behind the curve — we're ridiculously, embarrassingly behind the curve.

The fact that both left- and right-aligned institutions (public employee unions and private contractors, respectively) are implicated here is evidence that this isn't a typical left-right situation. And if we look internationally, both Singapore (very free-markety) and Sweden (unembarrassedly socialist) manage *much* cheaper building costs than America.

This is basically about our greedy and opaque political culture.

Every American infrastructure project features a scramble on the part of all parties to skim as much for themselves as possible. This leads to a self-defeating cycle in which voters are reluctant to pay for new stuff, so elites try to fund new projects in a duplicitous way, which only leads to more cost overruns.

The U.S. is a low-trust society, by developed-world standards, and our infrastructure institutions are usually a complex, stunningly corrupt hodgepodge. It's nearly impossible to get transparently funded projects through our janky political institutions, so instead of doing the slow and patient work of building democratic support for a new project and explicitly voting for the needed spending, which can then be completed without fear of backlash, we try to hide it through "independent" authorities, or the tax code, or duplicitous ballot initiatives.

The classic example of the American style of infrastructure is Robert Moses' New York empire. Never elected to any office, he used political maneuvering and legal chicanery to install himself as the de facto emperor of New York City. He was by far the most important power broker in the city for 44 years, and controlled all infrastructure spending during that time. (Naturally, he nearly wrecked the place with highways.)

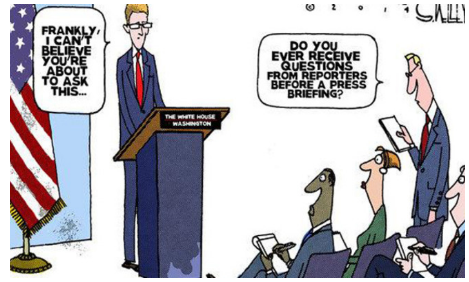
For a more recent example, look at the Port Authority, the supposedly independent transit agency that, as the Bridgegate scandal has revealed, is in fact a mess of patronage and corruption and always has been.

So when there's a new pot of money available for some infrastructure spending, nobody much considers value for the taxpayer or trying to do a good job for its own sake. They just try to grab what they can, because they can't trust anyone else not to do the same. Why should transit unions, for example, worry about economizing on labor when any worker givebacks would probably be devoured by agency executives or private contractors? And because these things are typically carried out through bizarre and complex legal machinery, the public can't figure out whom to hold responsible. Hence, they figure that infrastructure spending is just a bad deal.

The toxic nature of the process deep-sixes obvious win-win bargains, like cutting back on overstaffing to win more projects.

One might look at all this and despair, concluding that America is fundamentally incompetent and will never have nice things. But there are some reasons for optimism — and they start with getting our politics sorted out. An emergency, for example, can magically snap layers of corruption, and even lumbering monstrosities like the MTA are capable of awesome feats of efficiency. Just look at what happened after Hurricane Sandy:

> It has been less than two weeks since the most devastating storm in the New



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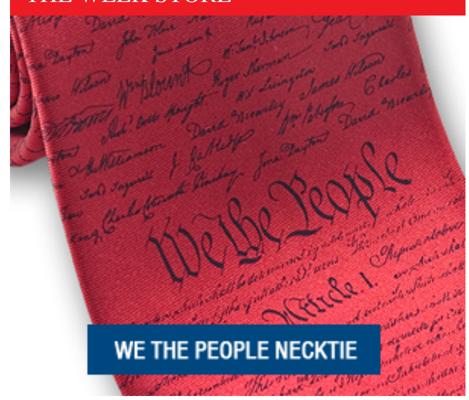

York City subway system's 108-year history. Seven tunnels beneath the East River flooded. Entire platforms were submerged. Underground equipment, some of it decades old, was destroyed....

Less than three days after the storm hit, partial subway service was restored. Most major lines were back within a week. Repairs came so quickly in some cases that the authority was ready before Consolidated Edison had restored power.

"Some of what they're doing borders on the edge of magic," said Gene Russianoff, the staff lawyer for the Straphangers Campaign, a rider advocacy group that is frequently critical of the authority. [*New York Times*]

Public agencies managed even more stupendous feats back in World War II.

Now, it's a tall and rather vague order to demand that all political institutions be fixed. But when we have the option, we ought to think about abandoning the authority model and folding our infrastructure institutions into more democratically responsible structures. And we should definitely vote for political candidates who advocate such changes.

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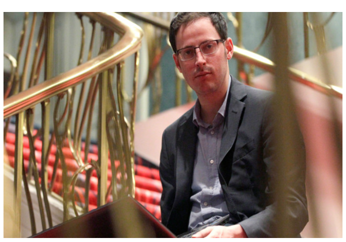

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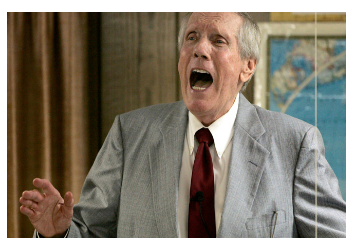

Christians should forgive Fred Phelps

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American transit activists need to speak up about exorbitant construction costs

Updated by Matthew Yglesias on December 17, 2014, 3:04 p.m. ET

@mattyglesias matt@vox.com

The City of Alexandria in the Washington suburbs would like to build a new Metro station alongside existing Blue/Yellow Line tracks somewhere near the Potomac Yard (http://www.mypotomacyard.com/) development and between the existing Reagan National Airport and Braddock Road Metro stations.

The Metro runs above ground in this area. Above-ground construction is cheaper than underground construction, and adding infill stations is cheaper than building whole new Metro lines. The project is already two years behind schedule, no definitive location has been selected, the costs at the four sites under consideration range from $209 million to $493 million, and "the project, after two decades of planning, is halfway through a required federal review." (http://m.washingtonpost.com/local/trafficandcommuting/alexandria-sights-a-2018-opening-of-metro-station-at-growing-potomac-yard/2014/05/24/c573c5dc-dba4-11e3-b745-87d39690c5c0_story.html)

About five years ago, Berlin built a new 1.8 kilometer underground Metro line (http://www.railwaygazette.com/news/single-view/view/berlin-u55-metro-line-opens.html) with three new stations for about $436 million in total — less than the high-cost estimate of a single station in Alexandria.

It's not just mass transit. Somehow Indiana and Kentucky are spending $2.6 billion to make a bridge wider (http://usa.streetsblog.org/2012/06/25/indianas-big-dig-raises-bar-on-absurdly-wasteful-highway-boondoggles/), there's a $1.7 billion highway interchange in Wisconsin (http://usa.streetsblog.org/2012/08/17/wisdot-faces-civil-rights-suit-over-1-7-billion-zoo-interchange/), and in New York the Tappan Zee Bridge upgrade project is getting so expensive that people worry the tolls needed to pay for it will deter drivers from actually using the bridge (http://www.nytimes.com/2014/03/26/nyregion/new-tappan-zee-bridge-rises-amid-unanswered-questions-over-funding.html).

But the problem hits transit the hardest because the basic fact of the matter is that political and economic elites don't rely on mass transit.

The clearest case is the growing popularity of mixed-traffic [streetcar (http://www.vox.com/cards/us-streetcar-trend-public-transportation)](http://www.vox.com/cards/us-streetcar-trend-public-transportation) projects. These are much cheaper than grade-separated light- or heavy-rail, but still far more expensive than a conventional bus without actually moving people any faster. In terms of offering a transportation service, spending money on a streetcar is much worse than spending the same amount of money on multiple new bus routes or upgrades to existing ones.

Soon this bus will have a streetcar in its way | Elvert Barnes/Flickr

Streetcars appeal, however, because those high costs create construction jobs and because the aura of classiness around them [appeals to real estate developers (http://www.nytimes.com/2014/04/16/business/washington-retail-districts-future-rides-on-streetcars.html)](http://www.nytimes.com/2014/04/16/business/washington-retail-districts-future-rides-on-streetcars.html) and other would-be drivers of gentrification. So cities across America are opening stub streetcar lines rather than investing in improving the transit experience of bus riders.

Shanghai [has opened six new Metro lines in the past five years (http://en.wikipedia.org/wiki/Shanghai_Metro#Lines)](http://en.wikipedia.org/wiki/Shanghai_Metro#Lines). In 2004,

Shenzhen had no Metro system. Today (
http://www.szmc.net/page/index.html) it has more stations and track than Washington's Metro or Boston's T. Of course DC is building the Silver Line, but Shenzhen has three new lines under construction.

The Second Avenue Subway in New York has been under construction since 2007 (
http://en.wikipedia.org/wiki/Second_Avenue_Subway#Current_developn
(or 1939 if you want to be ungenerous) and "Phase 1" — a two-mile tunnel — is still a year and a half from completion. It will cost $4.5 billion.

The Malmö City Tunnel (
http://en.wikipedia.org/wiki/City_Tunnel_(Malm%C3%B6)) in Sweden — not exactly a land of weak unions or cheap labor — is 3.7 miles and cost about $1.4 billion.

Train station in Malmö, Sweden | News Oresund/Flickr

Because transportation networks are *networks*, each over-priced project we build is less valuable than it would be if we actually built more projects. Developing more cost-effective means of undertaking transit construction projects, would mean not just more infrastructure but *more useful* infrastructure.

Identifying the causes of this cost crisis and feasible ways of addressing it ought to be a top priority for mass transit advocates. Yet the American Public Transit Association appears to have zero publicly available research (http://www.apta.com/resources/statistics/Pages/Surveys.aspx) on the matter — they prefer a posture of boosterism that emphasizes the benefits of transit spending and the case for doing more. The case for doing more is in fact strong. But it would be much stronger if the United States knew how to undertake cost-effective projects. In some transit circles it's considered bad manners or worse to talk about this. Or it's said to be a smear to focus on transit construction costs without talking about the fact that many US highway projects are also exorbitantly expensive.

But this is backwards. If you want the United States to move away from suburbanism and automobile dependency, then highway cost overruns aren't necessarily a huge problem. On the one hand, yes, it's a waste of money. On the other hand, were the money spent more efficiently we'd just have even more highways. If you care about transit, you ought to care about reducing project bloat in the transit space because more efficient transit spending would mean more and better transit projects. It's time to break the silence and start caring.

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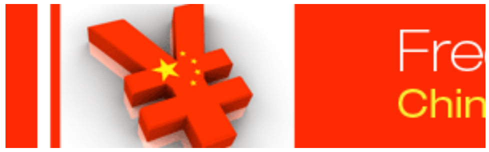

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Survival of the unfittest: why the worst infrastructure gets built—and what we can do about it

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Abstract

The article first describes characteristics of major infrastructure projects. Second, it documents a much neglected topic in economics: that *ex ante* estimates of costs and benefits are often very different from actual *ex post* costs and benefits. For large infrastructure projects the consequences are cost overruns, benefit shortfalls, and the systematic underestimation of risks. Third, implications for cost-benefit analysis are described, including that such analysis is not to be trusted for major infrastructure projects. Fourth, the article uncovers the causes of this state of affairs in terms of perverse incentives that encourage promoters to underestimate costs and overestimate benefits in the business cases for their projects. But the projects that are made to look best on paper are the projects that amass the highest cost overruns and benefit shortfalls in reality. The article depicts this situation as 'survival of the unfittest'. Fifth, the article sets out to explain how the problem may be solved, with a view to arriving at more efficient and more democratic projects, and avoiding the scandals that often accompany major infrastructure investments. Finally, the article identifies current trends in major infrastructure development. It is argued that a rapid increase in stimulus spending, combined with more investments in emerging economies, combined with more spending on information technology is catapulting infrastructure investment from the frying pan into the fire.

Key words infrastructure • cost overruns • benefit shortfalls • cost-benefit analysis • optimism bias • agency issues • reference class forecasting

JEL codes H43 • H54 • R42

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PAPERS

What You Should Know About Megaprojects and Why: An Overview

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ABSTRACT

This paper takes stock of megaproject management, an emerging and hugely costly field of study, by first answering the question of how large megaprojects are by measuring them in the units of mega, giga, and tera, and concluding with how we are presently entering a new "tera era" of trillion-dollar projects. Second, total global megaproject spending is assessed, at US$6 to US$9 trillion annually, or 8% of the total global gross domestic product (GDP), which denotes the biggest investment boom in human history. Third, four "sublimes"—political, technological, economic, and aesthetic—are identified and used to explain the increased size and frequency of megaprojects. Fourth, the "iron law of megaprojects" is laid out and documented: Over budget, over time, over and over again. Moreover, the "break–fix model" of megaproject management is introduced as an explanation of the iron law. Fifth, Albert O. Hirschman's theory of the "Hiding Hand" is revisited and critiqued as unfounded and corrupting for megaproject thinking in both the academy and policy. Sixth, it is shown how megaprojects are systematically subject to "survival of the unfittest," which explains why the worst projects get built rather than the best. Finally, it is argued that the conventional way of managing megaprojects has reached a "tension point," in which tradition is being challenged and reform is emerging.

KEYWORDS: megaproject management; scale; four sublimes; iron law of megaprojects; break–fix model of megaprojects; Hirschman's Principle of the Hiding Hand; survival of the unfittest; tension points

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Mega, Giga, Tera: How Big Are Megaprojects?

Megaprojects are large-scale, complex ventures that typically cost US$1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people.[1] Hirschman (1995, vii, xi) calls such projects "privileged particles of the development process" and points out that often they are "trait making"; in other words, they are designed to ambitiously change the structure of society, as opposed to smaller and more conventional projects that are "trait taking," that is, they fit into pre-existing structures and do not attempt to modify these. Megaprojects, therefore, are not just magnified versions of smaller projects. Megaprojects are a completely different breed of project in terms of their level of aspiration, lead times, complexity, and stakeholder involvement. Consequently, they are also a very different type of project to manage. A colleague of mine likes to say that if managers of conventional projects need the equivalent of a driver's license to do what they do, then managers of megaprojects need the equivalent of a pilot's jumbo jet license.[2] And, just like you wouldn't want someone with just a driver's license to fly a jumbo jet, you wouldn't want conventional project managers to manage megaprojects.

Megaprojects are increasingly used as the preferred delivery model for goods and services across a range of businesses and sectors, including infrastructure, water and energy, information technology, industrial processing plants, mining, supply chains, enterprise systems, strategic corporate initiatives and change programs, mergers and acquisitions, government administrative systems, banking, defense, intelligence, air and space exploration, big science, urban regeneration, and major events. Examples of megaprojects are high-speed rail lines, airports, seaports, motorways, hospitals, national health or pension information and communication technology (ICT) systems, national broadband, the Olympics, large-scale signature architecture, dams, wind farms, offshore oil and gas extraction, aluminum smelters, the development of new aircraft, the largest container and cruise ships, high-energy particle accelerators, and the logistics systems used to run large supply chain–based companies like Amazon and Maersk. Below, we will see just how big megaprojects and the megaprojects business are. We will also try to understand what drives scale.

To illustrate just how big megaprojects are, consider one of the largest dollar figures in public economic debate in recent years—the size of the U.S. debt to China. This debt is approximately US$1 trillion and is considered so large it may destabilize the world economy if the debt is not managed prudently. With this supersize measuring rod, now consider the fact that the combined cost of just two of the world's largest megaprojects—the Joint Strike Fighter aircraft program and China's high-speed rail project—is more than one half of this figure, US$700 billion (Figure 1). The cost of a mere handful of the largest

[1] As a general rule of thumb, "megaprojects" are measured in billions of dollars, "major projects" in hundreds of millions, and "projects" in millions and tens of millions. Megaprojects are sometimes also called "major programs."

[2] The colleague is Dr. Patrick O'Connell, Practitioner Director of Major Programme Management at Oxford University's Saïd Business School.

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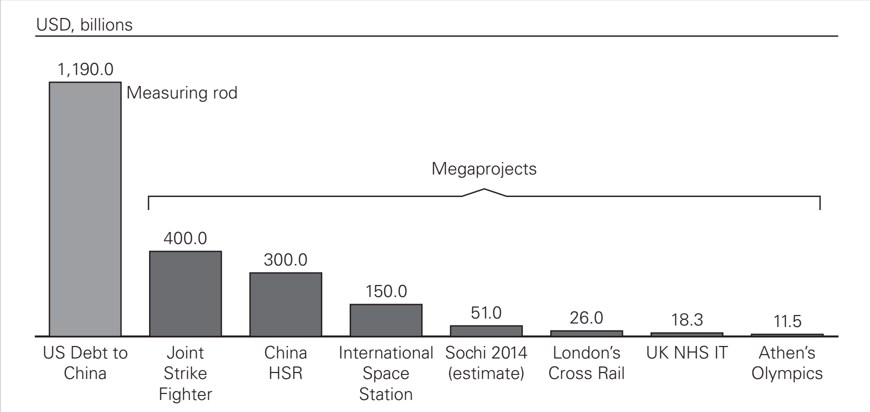

Figure 1: Size of selected megaprojects, measured against one of the largest dollar-figures in the world, the accumulated U.S. debt to China.

megaprojects in the world will dwarf almost any other economic figure and certainly any investment figure.

Not only are megaprojects large, however, they are constantly growing ever larger in a long historical trend with no end in sight. When New York's Chrysler Building opened in 1930 at 319 meters, it was the tallest building in the world. The record has since been surpassed seven times and from 1998, the world record for height has significantly been held by emerging economies, with Dubai's Burj Khalifa presently holding the record at 828 meters. This is a 160% increase in building height over 80 years. Similarly, the longest bridge span has grown even faster, by 260% over approximately the same period. Measured by value, the size of infrastructure projects has grown by 1.5% to 2.5% annually in real terms over the past century, which is equivalent to a doubling in project size two to three times per century (author's megaprojects database). The size of ICT projects, the new kid on the block, has grown much faster, as illustrated by a 16-fold increase between 1993 and 2009 in lines of code in Microsoft Windows, from 5 to 80 million lines. Other types of megaprojects, ranging from the Olympics to industrial projects, have seen similar developments. Coping with increased scale is therefore a constant and pressing issue in megaproject management.

"Mega" comes from the Greek word "megas" and means great, large, vast, big, high, tall, mighty, and important. As a scientific and technical unit of measurement, "mega" specifically means one million. If we were to use this unit of measurement in economic terms, then strictly speaking, megaprojects would be million-dollar (or euro, pound, etc.) projects; indeed, for more than one hundred years, the largest projects in the world were measured mostly in the millions. This changed with World War II, the Cold War, and the Space Race. Project costs had now escalated to the billions, led by the Manhattan Project (1939–1946), a research and development program that produced the first atomic bomb, and later the Apollo program (1961–1972), which landed the first humans on the moon (Morris, 1994; Flyvbjerg, 2014). According to *Merriam-Webster Dictionary*, the first known use of the term "megaproject" was in 1976; but before that, from 1968, "mega" was used in "megacity"; and later, from 1982, as a standalone adjective, indicating "very large."

Thus, the term "megaproject" caught on just as the largest projects were technically no longer megaprojects but, to be more accurate, were evolving into "gigaprojects"—"giga" being the unit of measurement meaning one billion. However, the term "gigaproject" never really caught on. A Google search reveals that the word "megaproject" is used 27 times more frequently on the Web than the term "gigaproject." For the largest of this type of project, a price tag of US$50 to US$100 billion is now common (e.g., the California and UK high-speed rail projects), and a price above US$100 billion is not uncommon (e.g., the International Space Station and the Joint Strike Fighter). If these were nations, projects of such size would rank among the world's top 100 countries measured by gross domestic product, larger than the economies of, for example, Kenya or Guatemala. When projects of such size go wrong, entire companies and national economies suffer.

"Tera" is the next unit up, and is the measurement for one trillion (one thousand billion). Recent developments in the sizes of the very largest projects and programs indicate we may presently be entering the "tera era" of large-scale project management. If we consider as projects the stimulus packages launched by the United States, Europe, and China to mitigate the effects of the 2008 financial and economic crises, then we can speak in terms of trillion-dollar projects and thus of "teraprojects." Similarly, if the major acquisition program portfolio of the United States Department of Defense (valued at US$1.6 trillion in 2013) is considered a large-scale project, then this, again, would be a teraproject (United States Government Accountability Office [GAO], 2013). Projects of this size compare with the GDPs of the world's top 20 nations, similar in size to the national economies of, for example, Australia or Canada. There is no indication that the relentless drive to scale is abating in megaproject development. Quite the opposite—scale seems to be accelerating.

How Big Is the Megaprojects Business?

Megaprojects are not only large and growing constantly larger, however, they

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Type of Sublime	Characteristic
Technological	The excitement engineers and technologists get in pushing the envelope for what is possible in "longest-tallest-fastest" types of projects
Political	The rapture politicians get from building monuments to themselves and for their causes, and from the visibility this generates with the public and media
Economic	The delight business people and trade unions get from making lots of money and jobs off megaprojects, including money made for contractors, workers in construction and transportation, consultants, bankers, investors, landowners, lawyers, and developers
Aesthetic	The pleasure designers and people who love good design get from building and using something very large that is also iconic and beautiful, such as the Golden Gate Bridge

Table 1: The "four sublimes" that drive megaproject development.

are also being built in ever greater numbers, at ever greater value. The McKinsey Global Institute (2013) estimates global infrastructure spending will be US$3.4 trillion per year between 2013 and 2030, or approximately 4% of the total global gross domestic product, mainly delivered as large-scale projects. *The Economist* (2008) similarly estimated infrastructure spending in emerging economies at US$2.2 trillion annually for the period between 2009 and 2018.

To illustrate the accelerated pace at which spending is taking place, consider that in the five years between 2004 and 2008, China spent more on infrastructure in real terms than during the entire 20th century, which is an increase in spending rate of a factor of 20. Similarly, between 2005 and 2008, China built as many kilometers of high-speed rail as Europe did in two decades; Europe was extraordinarily busy building this type of infrastructure during this period as well. Not at any time in the history of mankind has infrastructure spending been this high, measured as a share of world GDP, according to *The Economist,* (2008), who calls it "the biggest investment boom in history." And that's just for infrastructure.

If we include the many other fields in which megaprojects are a main delivery model—oil and gas, mining, aerospace, defense, ICT, supply chains, mega events, and so forth—then a conservative estimate for the global megaproject market is between US$6 and US$9 trillion per year, or approximately 8% of the total global gross domestic product. To put this into perspective, consider this is the equivalent of spending five to eight times the accumulated U.S. debt to China, *every year.* That's big business by any definition of the term.

Moreover, megaprojects have proved remarkably recession proof. In fact, the downturn from 2008 has helped the megaprojects business grow further by showering stimulus spending on everything from transportation infrastructure to ICT. From being a fringe activity—albeit a spectacular one—mainly reserved for rich, developed nations, megaprojects have recently transformed into a global multi-trillion-dollar business that affects all aspects of our lives, from our electricity bill to how we shop, what we do on the Internet to how we commute.

With so many resources tied up in ever-larger and ever-more megaprojects, at no time has the management of such projects therefore been more important. The potential benefits of building the right projects in the right manner are enormous and are only matched by the potential waste from building the wrong projects, or building projects erroneously. Never has it been more important to choose the most fitting projects and get their economic, social, and environmental impacts right (Flyvbjerg, Bruzelius, & Rothengatter, 2003). Never has systematic and valid knowledge about megaprojects therefore been more important to inform policy, practice, and public debate in this highly costly area of business and government.

The Four Sublimes

What drives the megaproject boom described above? Why are megaprojects so attractive to decision makers? The answer may be found in the so-called "four sublimes" of megaproject management (see Table 1). The first of these, the "technological sublime," is a term variously attributed to Miller (1965) and Marx (1967) to describe the positive historical reception of technology in American culture during the nineteenth and early twentieth centuries. Frick (2008) introduced the term to the study of megaprojects and here described the technological sublime as the rapture engineers and technologists get from building large and innovative projects, with their rich opportunities for pushing the boundaries for what technology can do, such as building the tallest building, the longest bridge, the fastest aircraft, the largest wind turbine, or the first of *anything.* Frick applied the concept in a case study of the multi-billion-dollar New San Francisco–Oakland Bay Bridge, concluding "the technological sublime dramatically influenced bridge design, project outcomes, public debate, and the lack of accountability for its [the bridge's] excessive cost overruns" (p. 239).

Flyvbjerg (2012; 2014) proposed three additional sublimes, beginning with the "political sublime," which here is understood to be the rapture politicians get from building monuments to themselves and for their causes. Megaprojects are manifest, garner attention, and lend an air of pro-activeness to their promoters; moreover, they are media magnets, which appeals to politicians who seem to enjoy few things better than the visibility they get from starting megaprojects, except, perhaps, the ceremonious ribbon-cutting during the opening of one in the company of royals or presidents, who are likely to be present, lured by the unique monumentality and historical import of many megaprojects. This is the type of public exposure that helps get politicians reelected; so, therefore, they actively seek it out.

Next, there is the "economic sublime," which is the delight business people and trade unions get from making lots of money and jobs from megaprojects. Given the enormous budgets for megaprojects, there are ample funds to go around for all, including contractors, engineers, architects, consultants, construction and transportation workers, bankers, investors, landowners, lawyers, and developers. Finally, the "aesthetic sublime" is the pleasure designers and people who appreciate good design get from building, using, and looking at something very large that is also iconically beautiful (e.g., San Francisco's Golden Gate Bridge or Sydney's Opera House).

All four sublimes are important drivers of the scale and frequency of megaprojects described above. Taken together they ensure that strong coalitions exist of stakeholders who benefit from megaprojects and who will therefore work for more such projects.

For policymakers, investing in infrastructure megaprojects seems particularly coveted because, if done right, such investing:

- Creates and sustains employment;
- Contains a large element of domestic inputs relative to imports;
- Improves productivity and competitiveness by lowering production costs;
- Benefits consumers through higher-quality services; and
- Improves the environment when infrastructures that are environmentally sound replace infrastructures that aren't (Helm, 2008, p. 1).

There is a big "if" here, however, as in "*if* done right." Only if this is disregarded—as it often is by promoters and decision makers for megaprojects—can megaprojects be seen as an effective way to deliver infrastructure. In fact, conventional megaproject delivery, infrastructure and other, is highly problematic, with a dismal performance record in terms of actual costs and benefits, as we will see below. The following characteristics of megaprojects are typically overlooked or glossed over when the four sublimes are at play and the megaproject format is chosen for the delivery of large-scale ventures:

1. Megaprojects are inherently risky due to long planning horizons and complex interfaces (Flyvbjerg, 2006).
2. Often, projects are led by planners and managers without deep domain experience who keep changing throughout the long project cycles that apply to megaprojects, leaving leadership weak.
3. Decision making, planning, and management are typically multi-actor processes involving multiple stakeholders, both public and private, with conflicting interests (Aaltonen & Kujala, 2010).
4. Technology and designs are often non-standard, leading to "uniqueness bias" among planners and managers, who tend to see their projects as singular, which impedes learning from other projects.[3]
5. Frequently there is overcommitment to a certain project concept at an early stage, resulting in "lock-in" or "capture," leaving analyses of alternatives weak or absent, and leading to escalated commitment in later stages. "Fail fast" does not apply; "fail slow" does (Cantarelli, Flyvbjerg, & Rothengatter, 2010; Ross & Staw, 1993; Drummond, 1998).
6. Due to the large sums of money involved, principal-agent problems and rent-seeking behavior are common, as is optimism bias (Eisenhardt, 1989; Stiglitz, 1989; Flyvbjerg, Garbuio, & Lovallo, 2009).
7. The project scope or ambition level will typically change significantly over time.
8. Delivery is a high-risk, stochastic activity, with overexposure to so-called "black swans"; i.e., extreme events with massively negative outcomes (Taleb, 2010). Managers tend to ignore this, treating projects as if they exist largely in a deterministic Newtonian world of cause, effect, and control.
9. Statistical evidence shows that such complexity and unplanned events are often unaccounted for, leaving budget and time contingencies inadequate.
10. As a consequence, misinformation about costs, schedules, benefits, and risks is the norm throughout project development and the decision-making process. The result is cost overruns, delays, and benefit shortfalls that undermine project viability during project implementation and operations.

In the next section, we will see just how big and frequent such cost overruns, delays, and benefit shortfalls are.

The Iron Law of Megaprojects

Performance data for megaprojects speak their own language. Nine out of ten such projects have cost overruns; overruns of up to 50% in real terms are common, over 50% are not

[3]"Uniqueness bias" is here defined as the tendency of planners and managers to see their projects as singular. This particular bias stems from the fact that new projects often use non-standard technologies and designs, leading managers to think their project is more different from other projects than it actually is. Uniqueness bias impedes managers' learning, because they think they have nothing to learn from other projects because their own project is unique. This lack of learning may explain why managers who see their projects as unique perform significantly worse than other managers (Budzier & Flyvbjerg, 2013). Project managers who think their project is unique are therefore a liability for their project and organization. For megaprojects this would be a mega-liability.

Project	Cost Overrun (%)
Suez Canal, Egypt	1,900
Scottish Parliament Building, Scotland	1,600
Sydney Opera House, Australia	1,400
Montreal Summer Olympics, Canada	1,300
Concorde Supersonic Aeroplane, UK, France	1,100
Troy and Greenfield Railroad, USA	900
Excalibur Smart Projectile, USA, Sweden	650
Canadian Firearms Registry, Canada	590
Lake Placid Winter Olympics, USA	560
Medicare transaction system, USA	560
Bank of Norway headquarters, Norway	440
Furka Base Tunnel, Switzerland	300
Verrazano Narrow Bridge, USA	280
Boston's Big Dig Artery/Tunnel project, USA	220
Denver International Airport, USA	200
Panama Canal, Panama	200
Minneapolis Hiawatha light rail line, USA	190
Humber Bridge, UK	180
Dublin Port Tunnel, Ireland	160
Montreal Metro Laval extension, Canada	160
Copenhagen Metro, Denmark	150
Boston–New York–Washington Railway, USA	130
Great Belt Rail Tunnel, Denmark	120
London Limehouse Road Tunnel, UK	110
Brooklyn Bridge, USA	100
Shinkansen Joetsu high-speed rail line, Japan	100
Channel Tunnel, UK, France	80
Karlsruhe–Bretten light rail, Germany	80
London Jubilee Line extension, UK	80
Bangkok Metro, Thailand	70
Mexico City Metroline, Mexico	60
High-speed Rail Line South, The Netherlands	60
Great Belt East Bridge, Denmark	50

Table 2: Large-scale projects have a calamitous history of cost overrun.

uncommon. The cost overrun for the Channel Tunnel, the longest underwater rail tunnel in Europe, connecting the United Kingdom and France, was 80% in real terms. The cost overruns for the Denver International Airport were 200%; for Boston's Big Dig, 220%; and for the Sydney Opera House, 1,400% (see more examples in Table 2). Overrun is a problem in private as well as public sector projects, and things are not improving; overruns have stayed high and constant for the 70-year period for which comparable data exist. Geography doesn't seem to matter either; all countries and continents for which data are available suffer from overruns. Similarly, benefit shortfalls of up to 50% are also common and above 50% not uncommon, again with no signs of improvements over time and geography (Flyvbjerg, Holm, & Buhl, 2002, 2005).

Combine the large cost overruns and benefit shortfalls with the fact that business cases, cost–benefit analyses, and social and environmental impact assessments are typically at the core of planning and decision making for megaprojects and we see that such analyses can generally not be trusted. For example, for rail projects, an average cost overrun of 44.7% combines with an average demand shortfall of 51.4%, and for roads, an average cost overrun of 20.4% combines with a 50-50 risk that demand is also incorrect by more than 20%. With errors and biases of such magnitude in the forecasts that form the basis for business cases, cost–benefit analyses, and social and environmental impact assessments, such analyses will also, with a high degree of certainty, be strongly misleading. (Flyvbjerg, 2009) "Garbage in, garbage out," as the saying goes.

As a case in point, let's consider the Channel Tunnel in more detail. This project was originally promoted as highly beneficial both economically and financially. At the initial public offering, Eurotunnel, the private owner of the tunnel, tempted investors by telling them that 10% "would be a reasonable allowance for the possible impact of unforeseen circumstances on construction costs" (The Economist, 7 October, 1989, 37–38). In fact, costs went 80% over budget for construction, as mentioned above, and 140% over budget for financing. Revenues have been one half of those forecasted. As a consequence, the project has proved non-viable, with an internal rate of return on the investment that is negative, at minus 14.5% with a total loss to the British economy of US$17.8 billion; thus, the Channel Tunnel detracts from the economy instead of adding to it. This is difficult to believe when you use the service, which is fast, convenient, and competitive with alternative modes of travel. But, in fact, each passenger is heavily subsidized—not by the taxpayer this time, but by the many private investors who lost their money when Eurotunnel went insolvent and was financially restructured. This drives home an important point: A megaproject may well be a technological success, but a financial failure, and many are. An economic and financial ex post evaluation of the Channel Tunnel, which systematically compared actual with forecasted costs and benefits, concluded that "the British Economy would have been better off had the Tunnel never been constructed" (Anguera, 2006, p. 291). Other examples of non-viable megaprojects are Sydney's Lane Cove Tunnel, the high-speed rail connections at the Stockholm and Oslo Airports, the Copenhagen Metro, and Denmark's Great Belt Tunnel, the second-longest underwater rail tunnel in Europe, after the Channel Tunnel.

Large-scale ICT projects are even more risky. One in six such projects becomes a statistical outlier in terms of cost overrun, with an average overrun for outliers of 200% in real terms. This is a 2,000% over incidence of outliers compared with normal and a 200% over incidence compared with large construction projects, which are also plagued by cost outliers (Flyvbjerg & Budzier, 2011). Total annual project waste from failed and underperforming ICT projects for the United States alone has been estimated at US$55 billion by the Standish Group (2009).

Delays are a separate problem for megaprojects and they cause both cost overruns and benefit shortfalls. For example, preliminary results from a study undertaken at Oxford University, based on the largest database of its kind, suggest that delays on dams are 45% on average. Thus, if a dam was planned to take 10 years to execute, from the decision to build until the dam became operational, then it actually took 14.5 years on average. Flyvbjerg, Holm, and Buhl (2004) modeled the relationship between cost overrun and length of implementation phase based on a large data set for major construction projects; they found that, on average, a one-year delay or other extension of the implementation phase correlates with an increase in percentage cost overrun of 4.64 percentage points.

To illustrate, for a project the size of London's US$26 billion Crossrail project, a one-year delay would cost an extra US$1.2 billion, or US$3.3 million per day. The key lesson here is that in order to keep costs down, implementation phases should be kept short and delays small. This should not be seen as an excuse for fast-tracking projects, in other words, rushing them through decision making for early construction start. Front-end planning needs to be thorough before deciding whether to give the green light to a project or stopping it before it starts (Williams & Samset, 2010). But often the situation is the exact opposite. Front-end planning is scant, bad projects are not stopped; implementation phases and delays are long; costs soar, and benefits and revenue realization recedes into the future. For debt-financed projects this is a recipe for disaster, because project debt grows, whereas there is no revenue stream to service interest payments, which are then added to the debt, which increases interest payments, and so on in a vicious cycle. As a result, many projects end up in the so-called "debt trap," where a combination of escalating construction costs, delays, and increasing interest payments makes it impossible for income from a project to cover costs, rendering the project non-viable. That is what happened to the Channel Tunnel and Sydney's Lane Cove Tunnel, among other projects.

This is not to say that there are no projects that were built on budget and on time and delivered the promised benefits. The Guggenheim Museum Bilbao is an example of that rare breed of project. Similarly, recent metro extensions in Madrid were built on time and to budget (Flyvbjerg, 2005), as were a number of industrial projects (Merrow, 2011). It is particularly important to study such projects to understand the causes of success and test whether success may be replicated elsewhere. It is far easier, however, to produce long lists of projects that have failed in terms of cost overruns and benefit shortfalls than it is to produce lists of projects that have succeeded. To illustrate this, as part of ongoing research on success in megaproject management, this author and his associates are trying to establish a sample of successful projects large enough to allow statistically valid answers; but, thus far have failed. Why? Because success is so rare in megaproject management that, at present, it can only be studied as small-sample research; whereas, failure may be studied with large samples of projects.

Success in megaproject management is typically defined as projects being delivered on budget, on time, and with the promised benefits. If, as the evidence indicates, approximately one out of ten megaprojects is on budget, one out of ten is on schedule, and one out of ten delivers the promised benefits, then approximately one in one thousand projects is a success, defined as "on target" for all three. Even if the numbers were wrong by a factor of two—so that two, instead of one out of ten projects were on target for cost, schedule, and benefits, respectively—the success rate would still be dismal, now eight in one thousand. This serves to illustrate what may be called the "iron law of megaprojects": *Over budget, over time, over and over again* (Flyvbjerg, 2011).[4] Best practice is an outlier, average practice a disaster in this interesting and very costly area of management.

The "Break–Fix Model" of Megaproject Management

The above analysis leaves us with a genuine paradox, the so-called "megaprojects paradox," first identified by

[4] The Economist (March 10, 2012, p. 55) describes the near-certainty of large cost overruns and delays in transportation infrastructure projects as "the iron law of infrastructure projects." Our data show the iron law is not limited to infrastructure; it applies to megaprojects in general and covers benefit shortfalls in addition to cost overruns and delays.

Flyvbjerg et al. (2003, pp 1–10). On one side of the paradox, megaprojects as a delivery model for public and private ventures have never been more in demand, and the size and frequency of megaprojects have never been larger. On the other side, performance in megaproject management is strikingly poor and has not improved for the 70-year period for which comparable data are available, at least not when measured in terms of cost overruns, schedule delays, and benefit shortfalls.

Today, megaproject planners and managers are stuck in this paradox because their main delivery method is what has been called the "break–fix model" for megaproject management.[5] Generally, megaproject planners and managers—and their organizations—do not know how to deliver successful megaprojects, or do not have the incentives to do so, and therefore such projects tend to "break" sooner or later, for example, when reality catches up with optimistic, or manipulated, estimates of schedule, costs, or benefits; delays, cost overruns, and benefit shortfalls follow. Projects are then often paused and reorganized—sometimes also refinanced—in an attempt to "fix" problems and deliver some version of the initially planned project with a semblance of success. Typically, lock-in and escalation make it impossible to drop projects altogether, which is why megaprojects have been called the "Vietnams" of policy and management: "easy to begin and difficult and expensive to stop" (White, 2012; Cantarelli et al., 2010; Ross & Staw, 1993; Drummond, 1998). The "fix" often takes place at great and unexpected cost to those stakeholders who were not aware of what was going on and were unable or lacked the foresight to pull out before the break.

The break–fix model is wasteful and leads to misallocation of resources, in both organizations and society, for the simple reason that under this model decisions to go ahead with projects are based on misinformation more than on information. The degree of misinformation varies significantly from project to project, as documented by the large standard deviations that apply to cost overruns and benefit shortfalls (Flyvbjerg et al., 2002; 2005). We may therefore *not* assume, as is often done, that on average all projects are misrepresented by approximately the same degree and, therefore, we are still building the best projects, even if they are not as good as they appear on paper. The truth is, we don't know, and often projects turn out to bring a net loss to the economy, rather than a gain. The cure to the break–fix model is to get projects right from the outset so they don't break, through proper front-end management.

Hirschman's Hiding Hand, Revisited

One may argue, of course, as famously done by Hirschman (1967a, pp 12–13) that if people knew in advance the real costs and challenges involved in delivering a large project, "they probably would never have touched it" and nothing would ever get built; so, it is better not to know, because ignorance helps get projects started, according to this argument. The following excerpt is a recent and particularly candid articulation of the nothing-would-ever-get-built argument, by former California State Assembly Speaker and Mayor of San Francisco, Willie Brown, discussing a large cost overrun on the San Francisco Transbay Terminal megaproject in his *San Francisco Chronicle* column (27 July 2013, with emphasis added):

> "News that the Transbay Terminal is something like $300 million over budget should not come as a shock to anyone. We always knew the initial estimate was way under the real cost. Just like we never had a real cost for the [San Francisco] Central Subway or the [San Francisco–Oakland] Bay Bridge or any other massive construction project. So get off it. In the world of civic projects, the first budget is really just a down payment. *If people knew the real cost from the start, nothing would ever be approved.* The idea is to get going. Start digging a hole and make it so big, there's no alternative to coming up with the money to fill it in."

Rarely has the tactical use by project advocates of cost underestimation, sunk costs, and lock-in to get projects started been expressed by an insider more plainly, if somewhat cynically. It is easy to obtain such statements off the record, but few are willing to officially lend their name to them, for legal and ethical reasons, to which we will return later. Nevertheless, the nothing-would-ever-get-built argument has been influential with both practitioners and academics in megaproject management. The argument is deeply flawed, however, and thus deserves a degree of attention and critique. Hirschman's text contains the classic formulation of the argument and has served widely as its theoretical justification, as has Sawyer (1952), who directly inspired and influenced Hirschman.[6] A recent celebration of Hirschman's thinking on this point may be found in Gladwell (2013).

Hirschman (1967a, pp. 13–14) observed that humans are "tricked" into doing big projects by their own ignorance. He saw this as positive because, just as humans underestimate the difficulties in doing large-scale projects they also underestimate their own creativity in dealing with the difficulties, he believed, and "the only way in which we can bring our creative sources fully into play is by misjudging the nature of the task, by presenting it to ourselves as more routine, simple, undemanding of genuine creativity than it will turn out to be." Hirschman called this the "prin-

[5] The author owes the term "break-fix model" to Dr. Patrick O'Connell, Practitioner Director of Major Programme Management at Oxford University's Saïd Business School.

[6] Two versions of Hirschman's text exist (1967a, 1967b). The version of the text referenced here is the one published in *Development Projects Observed* (Hirschman, 1967a), which is the original text. The differences between the two texts are minor and are mainly due to the editing of Irving Kristol, editor of *The Public Interest* at the time of publication (Adelman, 2013, p. 405).

ciple of the Hiding Hand" and it consists of "some sort of invisible or hidden hand that beneficially hides difficulties for us"—where the error of underestimating difficulties is offset by a "roughly similar" error in underestimating our ability to overcome the difficulties, thus helping "accelerate the rate at which 'mankind' engages successfully in problem-solving."

Sawyer (1952, pp. 199, 203), in a study of early industrial infrastructure projects that he called a work "in praise of folly," similarly identified what he called "creative error" in project development as, first, "miscalculation or sheer ignorance" of the true costs and benefits of projects; second, such miscalculation being "crucial to getting an enterprise launched at all." Sawyer argued that such "creative error" was the key to building a number of large and historically important projects, including the Welland Canal between Lake Erie and Lake Ontario, the Panama Canal, the Middlesex Canal, the Troy and Greenfield Railroad, and early Ohio roads. For these and other projects, Sawyer found that "the error in estimating costs was at least offset by a corresponding error in the estimation of demand" (p. 200). Hirschman (1967a, p. 16) explicitly mentioned Sawyer as an inspiration and his "creative error" as a close "approximation" to the Hiding Hand principle.

It is easy to understand why Hirschman's and Sawyer's theories have become popular, especially with people who benefit from megaprojects. The theories encourage promoters and decision makers, such as Willie Brown quoted above, to just go ahead with projects and not worry too much about the costs or other problems, because the Hiding Hand will take care of them, eventually. And, in any case, who wants to be the killjoy stopping large projects from going ahead by an overdose of truth? Hirschman (1967b) was an immediate hit with practitioners—from Washington's policy establishment to the United Nations, to the World Bank. The head of the World Bank's Economics Department told Hirschman: "You've helped in part to remove the unease that I have had in reflecting on the fact that if our modern project techniques had been used, much of the existing development in the world would never have been undertaken" (Adelman, 2013). Hirschman's thinking also eventually penetrated academia. Teitz and Skaburskis (2003) follow the Hiding Hand logic when they ask of the huge cost overrun on the Sydney Opera House: "Did people really think that the Sydney Opera House would come in on budget? Or did we all agree to accept the deception and engage in wishful thinking in order to make something that we really wanted happen? … [D]o Australians really regret those dramatic sails in the harbour? Or would they have regretted more the decision [not to build] that would most reasonably have been based on a fair prediction of costs?"

The logic is seductive, yet precarious. In retrospect, of course Australians do not regret the Sydney Opera House, given what it has done for Australia though, at first, the building was not called "dramatic sails in the harbour," but "copulating white turtles" and "something that is crawling out of the ocean with nothing good in mind" designed by an architect with "lousy taste" (Reichold & Graf, 2004, p. 168). Non-Australians may feel regret, however; for example, the architect of the Opera House: What's his name? Does anybody know? Only few do, which seems surprising given we are talking about the architect of arguably the most iconic building of the 20th century. And, if anybody knows the architect is the Dane Jørn Utzon, how come they can hardly ever mention another building designed by him? Because the overrun on the Opera House, and the controversy that followed, destroyed Utzon's career and kept him from building more masterpieces. He became that most tragic figure in architecture: the one-building-architect. This is the real regret—and real cost—of the Sydney Opera House, not premier Joe Cahill's deliberate deception about the cost—to get approval in Parliament—and the consequential huge cost overrun (Flyvbjerg, 2005).

In a meeting held in support of Utzon at Sydney Town Hall in March 1966—six weeks before the controversy made Utzon leave Australia and the Opera House, in the middle of construction and never to return—the Vienna-born Australian architect Harry Seidler said, "If Mr. Utzon leaves, a crime will have been committed against future generations of Australians" (Murray, 2004, p. 105). Seidler was more right than he could have imagined, except the crime would not be limited to Australians—it became a crime against lovers of great architecture everywhere. After winning the Pritzker Prize, the Nobel for architecture, in 2003, Utzon again became widely acclaimed, even in Australia, where the Sydney Opera tour guides for years had been forbidden to even mention his name. But it was too late. Utzon was now 85 years old and had not built anything major for decades. So instead of having a whole oeuvre to enjoy, as we have for other architects of his caliber, we have just the one main building. Utzon was 38 when he won the competition for the Opera House. How would other works by the mature master have enriched our lives? We will never know.

As a thought experiment, consider the collected works of architect Frank Gehry, who is in the same league as Utzon; then consider which building you would choose, if you could choose only one, and the rest would have to go. So if you chose, say, the Guggenheim Museum Bilbao, then Los Angeles' Disney Concert Hall, Chicago's Jay Pritzker Pavilion, Prague's Dancing House, and Seattle's Experience Music Project Museum would be eliminated. This illustrates the high price the government of New South Wales has imposed on the world by mismanaging the planning of the Sydney Opera House and deliberately playing the game of creative error and Hiding Hand. Even if the Opera House is an extreme case, Sydney drives home an important point: managing by creative error is risky and disruptive, sometimes in drastic and unexpected ways, and the Hiding Hand isn't big enough to hide all, or even most, errors.

Hirschman's and Sawyer's theories are also flawed on a more basic level, that of validity. A close look reveals the theories to be based on small samples and biased data. Hirschman studied only 11 projects or a few more if we take into account the subprojects, and Sawyer studied 10 to 15. This important fact is typically ignored when the Hiding Hand principle is discussed. Hirschman (1967a, pp. 7, 14) seemed aware of the weak foundations and limited applicability of the principle when he called it "speculative" and useful only "[u]p to a point." To a colleague he admitted at the time of publication that his book was "an exploration, an experiment"; to another he said he had deliberately biased his analysis "to emphasize unexpected successes" (Adelman, 2013, pp. 404–405). Even so, Hirschman went on to call the Hiding Hand a "general principle of action" and brazenly used a name for it with clear connotations to Adam Smith's famous Invisible (Hidden) Hand. Evidently, the temptation to formulate an "economic law" was too strong, despite the weak and biased data. Sawyer (1952, p. 204) warned the reader up front that his study must be considered a "marginal and distinctly limited note." He admitted the study considers only a "quite special kind of case" and neglects projects that were "failures" in order to focus on projects that were "successful" in the sense that "an original gross miscalculation as to costs ... was happily offset by at least a corresponding underestimation of demand." Sawyer's results, thus, do not describe a general characteristic of large projects, but a characteristic of his biased sample that includes only projects lucky enough to have had large underestimates of costs compensated by similarly large or larger underestimates of demand. Some would call this dubious data fishing, and the only redeeming factor is that Sawyer was disarmingly honest and tongue-in-cheek humoristic about it. He appears to not have expected to be taken wholly seriously, which he unfortunately was by some, including Hirschman.

Today we have much better data and theories on megaproject performance than at the time of Hirschman and Sawyer. We now know that, although there may be elements of truth in these authors' theories for certain types of projects and contexts, their samples and conclusions are not representative of the project population. In particular, their odd asymmetrical assumption that optimism would apply to cost estimates, yet pessimism to estimates of benefits, has been solidly disproved by Kahneman and Tversky (1979a, 1979b) and by behavioral economists building on their work. They found that optimism bias applies to estimates of both costs and benefits. An optimistic cost estimate is low and leads to cost overrun, whereas an optimistic benefit estimate is high and results in benefit shortfalls. Thus, errors of estimation do not cancel each other out, as Hirschman would have it; the exact opposite happens—errors generally reinforce each other.

Megaproject planners and managers would therefore be ill advised to count on Hiding Hands, creative errors, or any other general principle according to which underestimates of costs would be balanced by similar underestimates of benefits. We also now know it would be equally foolhardy to assume that downstream human creativity may be generally counted on to solve problems that planners and managers overlook or underestimate when the decision is made to go ahead with a project. The data show that for too many projects with front-end problems, such creativity never materializes and projects end up seriously impaired or non-viable. Initial problems, if not dealt with up front, tend not to go away. The iron law of megaprojects, described above, trumps Hirschman's Hiding Hand at a high level of statistical significance, and we know why. The Hiding Hand is itself an example of optimism and does therefore not capture the reality of megaproject management. For such capture, and true explanatory power, we must turn to theories of optimism bias, the planning fallacy, strategic misrepresentation, and principal–agent behavior.

Survival of the Unfittest

In sum, one does megaprojects—and megaproject management—a disservice if one claims they can only be done through the Hiding Hand, creative error, or downright deception. It is, undoubtedly, quite common for project promoters and their planners and managers to believe their projects will benefit society and they, therefore, are justified in "cooking" costs and benefits to get projects built (Wachs, 1990; Pickrell, 1992). Such reasoning is faulty, however. Underestimating costs and overestimating benefits for a given project (which is the common pattern, as described above) leads to a falsely high benefit–cost ratio for that project, which in turn leads to two problems. First, the project may be started despite the fact it is not financially and economically viable. Or, second, it may be started instead of another project, which would have shown to yield higher returns than the project started had the real costs and benefits of both projects been known. Both cases result in Pareto inefficiency; that is, the misallocation of resources and, for public projects, waste of taxpayers' money. Thus, for reasons of economic efficiency alone, the argument must be rejected that cost underestimation and benefit overestimation are justified for getting projects started.

But the argument must also be rejected for legal and ethical reasons. In most democracies, for project promoters, planners, and managers to deliberately misinform legislators, administrators, bankers, the public, and the media about costs and benefits would not only be considered unethical but, in some cases also illegal, for example, where civil servants would intentionally misinform cabinet members, or cabinet members would intentionally misinform parliament. In private corporations, Sarbanes-Oxley-like legislation similarly makes deliberate misrepresentation a crime under many circumstances, which in the United States is punishable by imprisonment of up to 20 years.[7] There is a formal "obligation to truth" built into most democratic constitutions—and now also in legislation for corporate governance—as a means for enforcing accountability. This obligation would be violated by deliberate misrepresentation of costs and benefits, whatever the reasons for such misrepresentation may be. Not only would economic efficiency suffer but also democracy, good governance, and accountability.

A first answer to the skeptics' question of whether enough megaprojects would be undertaken if some form of misrepresentation of costs and benefits was not involved is, therefore, that even if misrepresentation was necessary in order to get projects started, such misrepresentation would typically not be defensible in liberal democracies—and especially not if it was deliberate—for economic, legal, and ethical reasons.

A second answer to the skeptics' question is that misrepresentation is not necessary to undertaking projects, because many projects exist with sufficiently high benefits and low enough costs to justify building them. Even in the field of innovative and complex architecture, which is often singled out as particularly difficult, there is the Basque Abandoibarra urban regeneration project, including the Guggenheim Museum Bilbao, which is as complex, innovative, and iconic as any signature architecture, and was built on time and budget. Complex rail projects, too, including the Paris–Lyon high-speed rail line and the London Docklands light railway extension have been built to budget. The problem is not that projects worth undertaking do not exist or cannot be built on time and on budget. The problem is that the dubious and widespread practices of underestimating costs and overestimating benefits used by many megaproject promoters, planners, and managers to promote *their* pet project create a distorted hall-of-mirrors in which it is extremely difficult to decide which projects deserve undertaking and which do not.

In fact, the situation is even worse than that. The common practice of depending on the Hiding Hand or creative error in estimating costs and benefits, thus "showing the project at its best" as an interviewee put it in a previous study, results in an inverted Darwinism, i.e., the "survival of the unfittest" (Flyvbjerg, 2009). It is not the best projects that get implemented in this manner, but the projects that look best on paper, and the projects that look best on paper are the projects with the largest cost underestimates and benefit overestimates, other things being equal. But the larger the cost underestimate on paper, the greater the cost overrun in practice; and the larger the overestimate of benefits, the greater the benefit shortfall. Therefore, the projects that have been made to look best on paper become the worst, or unfittest, projects in reality, in the sense that they are the very projects that will encounter the most problems during construction and operations in terms of the largest cost overruns, benefit shortfalls, and risks of non-viability. They have been designed like that—as disasters waiting to happen.

The result is, as even the industry's own organization, the Major Projects Association, has stated that "too many projects proceed that should not have done" (Morris & Hough, 1987, p. 214). One might add that projects also exist that do not proceed but should have, had they not lost out, not to better projects but to projects with "better" creative error; that is, "better" manipulated estimates of costs and benefits.

Light at the End of the Tunnel?

Fortunately, signs of improvement in megaproject management have recently appeared. The tacit consensus that misrepresentation is an acceptable business model for project development is under attack. Shortly after taking office, U.S. President Barack Obama openly identified "the costly overruns, the fraud and abuse, the endless excuses" in public procurement for major projects as key policy problems (White House, 2009). The *Washington Post* rightly called this "a dramatic new form of discourse" (Froomkin, 2009). Other countries are seeing similar developments. Before Obama came into office, it was not common in government or business to talk openly about overruns, fraud, and abuse in relation to megaprojects, although they were as widespread then as now. The few who did so were ostracized; however, as emphasized by Wittgenstein (2009), we cannot solve problems we cannot talk about. So talking is the first step.

A more material driver of improvement is the fact that the largest projects are now so big and consequential in relation to individual businesses and agencies that cost overruns, benefit shortfalls, and risks from even a single project may bring down executives and whole corporations. This happened with the Airbus A380 superjumbo jet, when delays, cost overruns, and revenue shortfalls cost the CEO and other top managers their jobs. The CEO of BP was similarly forced to step down and the company lost more than half its value when the Deepwater Horizon offshore oil drilling rig caught fire and caused the world's largest oil spill in

[7] The Sarbanes-Oxley Act of 2002 pioneered this area in the United States, but many other countries have since followed suit with similar legislation. Section 802[a] (18 U.S.C. § 1519) of the original act states that whoever knowingly alters, destroys, mutilates, conceals, covers up, falsifies, or makes a false entry in any record, document, or tangible object with the intent to impede, obstruct, or influence the investigation or proper administration of any matter within the jurisdiction of any department or agency of the United States or any case filed under title 11, or in relation to or contemplation of any such matter or case, shall be fined, imprisoned not more than 20 years, or both.

the Gulf of Mexico in 2010. At Kmart, a large U.S. retailer, the entire company went bankrupt when a new multi-billion-dollar ICT enterprise system, which was supposed to make Kmart competitive with Walmart and Target, went off the rails (Flyvbjerg & Budzier, 2011). In China, corruption and related safety issues on the country's US$300 billion high-speed rail program have caused massive reputational damage, and cost the railway minister his political career in 2011. Today, if you are a CEO, minister, permanent secretary, or other top manager and want to be sure to keep your job, you will want to manage your megaprojects properly. Episodes such as these have triggered leaders to begin looking for better megaproject delivery.

Even the wealth of whole cities and nations may be affected by a single megaproject failure. In Hong Kong, months of obstacles during the opening of a new international airport made traffic go elsewhere, resulting in a fall in GNP for the entire city state. For Greece, a contributing factor to the country's 2011 debt default was the 2004 Olympic Games in Athens, for which cost overruns and incurred debt were so large they negatively affected the credit rating of the whole nation, substantially weakening the economy in the years before the 2008 international financial crisis. This resulted in a double dip—and disaster—for Greece, when other nations had only a single dip. Likewise, in Japan in 2011, the nuclear tragedy at Fukushima significantly and negatively impacted the national economy as a whole. It is becoming increasingly clear that when megaprojects go wrong they are like the proverbial bull in the china shop: it takes just one bull to smash up the entire store. It is becoming similarly clear to many involved that something needs to be done about his.

In the United Kingdom, at the beginning of the century, cost underestimation and overrun were rampant in so many projects and in so many ministries that the reliability of national budgets suffered, leading the chancellor to order a Green Book on the problem and how to solve it (HM Treasury, 2003). This move inspired other countries to follow suit. Lawmakers and governments have begun to see that national fiscal distress and unreliable national budgets are too high a price to pay for the conventional way of managing megaprojects. In 2011, the UK Cabinet Office and HM Treasury joined forces to establish a Major Projects Authority, with an enforceable mandate directly from the Prime Minister to oversee and direct the effective management of all large-scale projects that are funded and delivered by central government. In 2012, the Authority established, in collaboration with Oxford University, a Major Projects Leadership Academy—the first of its kind in the world—to train and authorize all UK civil servants in charge of central government major projects.[8]

Outside of government, private finance in megaprojects has been on the rise over the past twenty years, which means that capital funds, pension funds, and banks are increasingly gaining a say in management. Private capital is no panacea for the ills in megaproject management, to be sure; in some cases, private capital may even make things worse (Hodge & Greve, 2009). But private investors place their own funds at risk; therefore, funds and banks can be observed to not automatically accept at face value the cost and revenue forecasts of project managers and promoters. Banks typically bring in their own advisers to do independent forecasts, due diligence, and risk assessments, which are important steps in the right direction (Flyvbjerg, 2013). The false assumption that one forecast or one business case may contain the whole truth about a project is problematized. Instead, project managers and promoters are getting used to the healthy fact that different stakeholders hold different forecasts and that forecasts are not only products of data and mathematical modeling but also of power and negotiation. And why is this healthier? Because it undermines trust in the misleading forecasts often produced by project promoters.

Moreover, democratic governance is generally getting stronger around the world. Corporate scandals, from Enron, WorldCom, and onward have triggered new legislation and a war on corporate deception that is spilling over into government with the same objectives: to curb waste and promote good governance. Although progress is slow, good governance is gaining a foothold even in megaproject management. The main drivers of reform come from outside the agencies and industries conventionally involved in megaprojects and this is good because it increases the likelihood of success. For example, the UK Treasury now requires that all ministries develop and implement procedures for megaprojects that will curb so-called "optimism bias" (Flyvbjerg, 2006). Funding will be unavailable for projects that do not take into account such bias, and methods have been developed for doing this (UK Department for Transport, 2006). Switzerland and Denmark have followed the lead of the United Kingdom (Swiss Association of Road and Transportation Experts, 2006; Danish Ministry for Transport and Energy, 2006, 2008). In Australia, the Parliament of Victoria has conducted an inquiry into how government may arrive at more successful delivery of significant infrastructure projects (Parliament of Victoria, 2012). Similarly, in the Netherlands, the Parliamentary Committee on Infrastructure Projects did extensive public hearings to identify measures that will limit the misinformation about large infrastructure projects presented to the Parliament, public, and media (Dutch Commission on Infrastructure Projects, 2004). In Boston, the government sued to recoup funds from contractor overcharges for the Big Dig

[8] For full disclosure: The author was involved in the planning, start up, and delivery of the UK Major Projects Leadership Academy.

related to cost overruns. More countries and cities are likely to follow the lead of the United Kingdom, Australia, Switzerland, Denmark, the Netherlands, and the United States in coming years.

Finally, research on how to reform megaproject management—examples of which have been referenced above—is beginning to positively impact practice. Such research has recently made great strides in better understanding what causes the many failures in megaproject delivery and how to avoid them. For example, we now understand that optimism bias and strategic misrepresentation are significantly better explanations of megaproject outcomes than previous explanations, including Hirschman's Hiding Hand and Sawyer's creative error discussed above. And with a better understanding of causes a better grasp of cures has followed, from front-end management (Williams & Samset, 2010) to reference class forecasting (Kahneman, 2011, pp 243–254; Flyvbjerg, 2006) to institutional design for better accountability (Scott, 2012; Bruzelius et al., 1998). Moreover, research is beginning to help us understand success and how to replicate it. Perhaps most importantly, researchers have begun to take seriously the task of feeding their research results into the public sphere so they may effectively form part of public deliberation, policy, and practice (Flyvbjerg, 2012; Flyvbjerg et al., 2012).

With these developments, things are moving in the right direction for megaproject management. It is too early to tell whether the reform measures being implemented will ultimately be successful. It seems unlikely, however, that the forces that have triggered the measures will be reversed, and it is those forces that reform-minded individuals and groups need to support and work with in order to improve megaproject management. This is the "tension point," where convention meets reform, power balances change, and new things are happening. In short, it is the place to be as a megaproject planner, manager, scholar, student, owner, or interested citizen.[9]

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[9]See Flyvbjerg et al. (2012) regarding the use of tension points for triggering change in policy and practice, including for megaprojects.

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Challenges and Opportunities for Integrating Climate Adaptation Efforts across State, Regional and Local Transportation Agencies

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A White Paper from the National Center for Sustainable Transportation

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EXECUTIVE SUMMARY

Disruptions caused by extreme weather events are imposing significant and rising costs on transportation agencies throughout the United States, and climate change is projected to increase both the frequency and severity of these events. In response, transportation agencies and organizations are exploring climate adaptation measures. This white paper presents a five-step transportation adaptation framework synthesized from common elements of an array of existing resources, and assesses the state of the practice within each of the five steps. The five steps are:

1) inventorying and monitoring transportation assets;
2) assessing climate threats;
3) evaluating asset vulnerability;
4) rating asset importance or criticality; and
5) identifying and executing adaptation actions.

The objective of establishing a common framework is to facilitate broader discussion among transportation agencies and their partners in order to identify current adaptation barriers and opportunities for interregional and interagency collaboration.

The roles for state and local agencies in implementing these steps have yet to be clearly delineated. Our review indicated implementation barriers exist in each step but can be reduced through collaboration. Because the surface transportation system functions as an integrated unit that crosses multiple jurisdictional boundaries, collaboration among state, local and regional transportation agencies is essential to maximize the efficiency and effectiveness of overall adaptation efforts, especially since many local agencies face significant resource limitations.

Key Findings

Uncertainty about emissions scenarios and the future climate conditions to design for is a major barrier to adaptation planning.

There is a need for **more robust tools** to evaluate asset criticality. Project prioritization is vulnerable to politicization.

Vulnerability assessment tools are maturing for sea level rise but are less well-developed for other threats.

Criticality is linked to vulnerability and must be assessed in full regional networks regardless of jurisdictional ownership or political boundaries.

Limited financial resources inhibit implementation of adaptation planning. It is the main limitation for the asset inventory step.

Readiness for adaptation planning varies significantly between agencies, with agencies at the local and regional level facing the most severe challenges.

Increasing interagency cooperation, especially vertical integration, will be required to maximize the efficiency of adaptation at all levels.

Workforce development needs are impacting adaptation planning.

The first step in climate adaptation planning, *inventorying transportation assets,* is conceptually straightforward and best undertaken by the agencies that own and manage transportation infrastructure. However, maintaining these databases can be costly and time consuming. Thus the biggest challenge at the state level is the resources required to develop and maintain these inventories. At the sub-state level, many smaller agencies lack the technical experience to develop asset databases. State leadership setting uniform asset database standards would facilitate the data integration required for other steps in the adaptation planning process.

The second step in climate adaptation planning is to *assess climate threats*. While many transportation agencies understand the types of climate threats they face in general terms, advances in climate modeling and model downscaling will be needed to support policy decisions and the development of new design standards. Broader consensus on the appropriate emissions/climate change scenarios to use for planning purposes, including cost benefit analysis, is also essential. Conducting climate threat assessments at the state level, likely in collaboration with partners outside the transportation sector, will provide efficiency benefits.

The third step in climate adaptation planning is to evaluate each asset's *vulnerability* to the threats identified in step two. Vulnerability is a function of the type, magnitude and probability of the climate threats. Given the uncertainties in step two, this step is technically feasible but challenging. A number of state department of transportation (DOT) officials indicated that more precise vulnerability modeling tools would be valuable and that uncertainty about the magnitude of future weather-related threats complicated vulnerability assessment.

The fourth step in the framework is to rate the relative importance or *criticality* of all infrastructure in the system. Given the resource constraints facing transportation agencies, criticality ratings are necessary in order to prioritize adaptation projects, but methods for assessing criticality are not fully developed, leaving project prioritization vulnerable to politicization. Agencies often rely on metrics such as traffic volumes that do not account for network connectivity and redundancy effects. It is clear, moreover, that criticality assessment is fundamentally cross-jurisdictional and cross-modal. National leadership is needed to develop criticality rating methods suitable for complete, multimodal, regional transportation networks.

The fifth step in the framework is to identify, select and *execute adaptation actions*. Adaptation actions can involve *infrastructure* or *processes*. Infrastructure adaptations include physical changes to infrastructure to reduce its vulnerability ("hardening"), adding infrastructure to increase redundancy, and potentially relocating or abandoning assets. Analysis of the costs and benefits of infrastructure adaptations can be challenging due to multiple temporal scales for infrastructure life and weather event return periods. Currently *process* adaptations, such as improved pre- and post-disaster response planning, are more common because they can be undertaken even with considerable uncertainty about the magnitude of future climate threats.

All steps in the adaptation planning process are iterative and interconnected. Once implemented, adaptation actions frequently impact the whole system and require ongoing monitoring and changes to asset inventories, vulnerabilities and criticality assessments.

Introduction

Disruptive events caused by weather and climate extremes are imposing significant and rising costs on transportation agencies in the United States (Meyer, Rowan et al. 2013). These events – ranging from dust storms to landslides to floods – adversely impact transportation system infrastructure integrity, reliability, level of service, and user safety. Increasingly, state DOTs, and in some cases regional and local agencies, are altering their priorities and staffing patterns to prioritize planning for severe weather events and adapting to long-term climate changes (Meyer, Rowan et al. 2013). The burden of preparing for and recovering from extreme weather events can strain the financial and human resources of transportation agencies at all levels, and the indirect costs associated with longer travel times and reduced level of service impose wider societal costs. The importance of planning for disruptive events and long-term changes has spurred numerous agencies and groups to develop resources to assist state DOTs and other transportation agencies in developing adaptation strategies to reduce the surface transportation system's vulnerability to weather extremes.

The objective of this report is to present a straightforward, five-step framework for climate adaptation planning and to use this framework to consider the challenges facing transportation agencies engaged in the adaptation process. The report is intended to summarize the state of the practice for transportation agency professionals, especially those affiliated with state DOTs, at different stages of the adaptation planning process. It is also intended to provide a simplified language and framework in order to widen the adaptation discussion and facilitate a clear delineation of the policy and research needs that must be addressed in order to advance adaptation planning. This report is based on existing published resources and interviews with transportation practitioners. Barriers to implementing the five steps include: resource constraints, workforce development needs, political constraints, uncertainty about future climate conditions, and a lack of well-developed tools for assessing the relative criticality of specific infrastructure. Broader consensus on assessment methods and probable emissions scenarios will be required moving forward. Since the transportation system functions as a unified whole across jurisdictional boundaries, ensuring that adaptation efforts are effectively implemented will require extensive collaboration among transportation agencies at all levels, and state DOTs will have a leadership role in the process. Therefore, after presenting the five-step adaption framework, this report summarizes the implementation barriers facing state DOTs for each of the five steps and then discusses the need to and opportunities for integrating regional and local agencies into the adaptation process.

Background

Recent reports by the U.S. Global Change Research Program (USGCRP) (U.S. Global Change Research Program 2014) and the International Panel on Climate Change (IPCC) (IPCC 2013) have documented ongoing changes in sea level, heat extremes and heavy precipitation events. The reports project that the frequency and severity of many extreme weather events will increase in both the medium and long term. Changing temperature, precipitation and extreme weather trends are present throughout the country, although the magnitude and direction of these trends can vary considerably from region to region. The USGCRP's National Climate Assessment (NCA) reports that average temperatures in the United States have increased between 0.7 and 1.1º Celsius since 1895 with warming accelerating since 1970 (U.S. Global Change Research Program 2014). All regions have experienced warming, especially during winter and spring seasons, but warming has been more moderate in the Southeast. Heat waves have increased in frequency throughout the country while droughts have increased in some regions. Precipitation patterns have also changed with the country as a whole experiencing both higher total precipitation and more frequent heavy precipitation events (U.S. Global Change Research Program 2014). The intensification of precipitation has been most pronounced in the upper Great Plains, Midwest and Northeast, and lowest in the Southwest. Correspondingly, the magnitude of river flooding has increased in parts of the Great Plains, Midwest and Northeast while decreasing in the Southwest (U.S. Global Change Research Program 2014). Hurricane intensity, frequency and duration have all increased since the 1980s as has the frequency and intensity of winter storms since 1950 but there has not been a clear trend in other storms such as hail, thunderstorms and tornados (U.S. Global Change Research Program 2014).

Extreme weather events linked to the trends documented in the NCA can shut down or compromise components of the surface transportation system for short or prolonged periods of time. While some projected climate trends also offer benefits to the transportation sector, such as a longer construction season in some parts of the country, the potential harms and benefits of climate changes are asymmetrically distributed, with significantly more, and more severe, negative effects than positive ones. Consequently, transportation practitioners are exploring how to adapt the transportation system and associated management processes to lessen the impact of these extremes. Some agencies are actively pursuing adaptation planning efforts. These agencies tend to be in places that have experienced a recent significant event, such as the Vermont Agency of Transportation, or that have participated in Federal Highway Administration (FHWA) pilot programs such as the Washington Department of Transportation. Other agencies are just beginning, or have not yet begun, their climate planning efforts because of other priorities (in some cases climate mitigation), limited resources, minimal projected impacts in their region, or political skepticism toward climate change.

Since climate adaptation and climate mitigation efforts are frequently discussed together, it is worth clarifying their definitions. In its Fifth Assessment Report, the IPCC (IPCC 2014) defined climate adaptation as the "process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploits beneficial opportunities." In this paper, climate adaptation is discussed in terms of the process of adjusting the transportation systems (both the physical infrastructure as well as processes for planning, management and operations) in response to current and projected climate and extreme weather conditions to moderate the adverse impacts on short-term and long-term system performance. This paper focuses specifically on the highway system but many of the impacts and adaptation processes highlighted here have implications for air, rail and water infrastructure. On the other hand, mitigation is defined in the same IPCC report (IPCC 2014) as "human intervention to reduce the sources or enhance the sinks of greenhouse gases."

Mitigation and adaptation efforts may be synergistic or antagonistic to one another. Many "green infrastructure" measures, for example, advance both mitigation goals (by acting as carbon sinks) and adaptation goals (by absorbing precipitation and reducing flooding impacts). In contrast, efforts to improve system redundancy by adding alternative routes as an adaptation strategy may also result in increases in travel and greenhouse gas emissions.

Impacts of Climate and Extreme Weather Events on the Transportation System

The precise challenges that extreme weather events pose to the transportation system vary considerably from region to region, in their severity and in the duration of the disruptions that they cause. Impacts vary among modes and depend on infrastructure conditions and design characteristics. The stages of an extreme weather disruption in the transportation system are illustrated in Figure 1. Some events can be forecast in advance and this warning period provides a window to prepare for these events while other events occur with minimal or no warning (Stage A). The warning period can vary from days to months or even years depending on the event type. The warning time for sea level rise is on the scale of years and decades. Flooding or drought linked to seasonal precipitation levels may be predicted weeks or months in advance. The Missouri River floods in 2011, for example, were in large measure the result of near-record snowfall and the risk of flooding was recognized months in advance of the flood itself (NOAA 2012). Coastal and river valley flooding, in contrast, may happen with comparatively little warning. Forecasts for Tropical Storm Irene in Vermont in 2011 and Hurricane Sandy in the New York/New Jersey region in 2012 preceded the storm by only days. Dust storms and landslides can occur without any warning. In some cases, agencies may preemptively close parts of the transportation system to facilitate preparation for or faster recovery from an event (Stage B).

Similarly, the durations of the events themselves (Stage C) and of the recovery periods (Stage D) associated with them are highly variable. Some events, such as dust storms, which are linked to heat waves and drought conditions, last only minutes or hours. Dust storms can cause road and airport closures due to low visibility conditions during the storm, but they typically do not significantly damage infrastructure, and the recovery time after these events pass is minimal. In contrast, some types of flooding events can last for weeks and can destroy roads, bridges and other infrastructure. In these cases, the recovery period can last for months or even years.

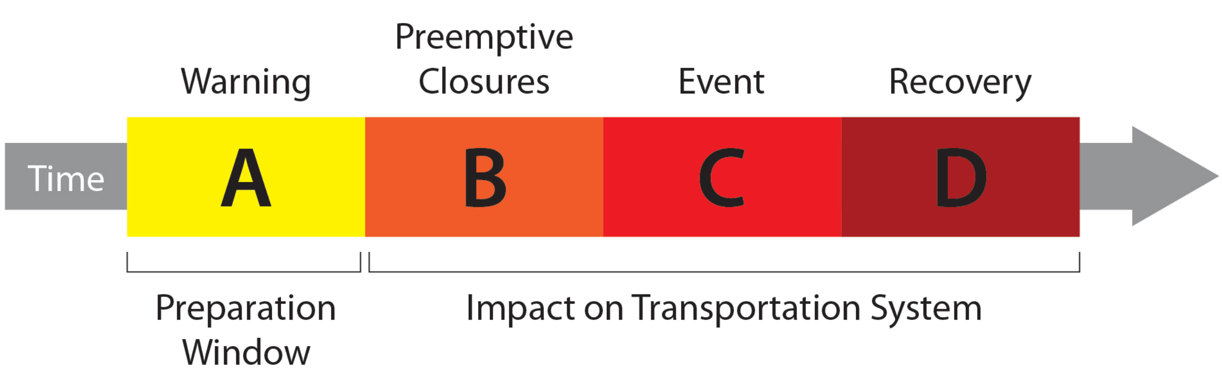

Figure 1: Stages of Extreme Weather Disruption

The examples in the sidebar at right (letter and color codes are taken from Figure 1) illustrate how much variability there is in the duration of each stage of a disruption. As these examples make clear, the recovery period is the longest stage in the disruption for many event types.

The direct impact of a given event reflects a combination of the advanced warning of the event, the event duration and the recovery period for the event. Adaptation planning needs to consider measures that increase agencies' capacity to take advantage of the preparation window, minimize the damages sustained during the event itself and facilitate a rapid recovery period.

In addition to the direct impact that these events have on the transportation system, some events cause changes to the natural or built environment that elevate the risk for future disruptions. For example, though forest fires do not tend to cause major damage to transportation infrastructure, fires reduce vegetation cover and char the ground, significantly raising the risk of subsequent flash flooding and mudflows.

Considering the variety of events that impact the transportation system, transportation professionals must consider a host of different adaptation actions, ranging from changes in maintenance and communication procedures to changes in infrastructure design and even the relocation or replacement of infrastructure. The importance and complexity of this work is spurring a rapid expansion of new

Selected Extreme Weather Disruptions

Missouri River Flooding – Iowa (2011)

Six Months Total:

A – Heavy winter snow cover provides an early *warning* of elevated flooding risk. (Winter/spring 2011).

C – Flooding washes out four miles of I-680 and inundates sections of I-29. The interstates remain flooded for over a month. (June – July/2011)

D – Interstate 680 reopens, ending a *recovery period of more than three months.* (11/2/2011)

Tropical Storm Irene – Vermont (2011)

Four Months Total:

A – Irene reaches hurricane strength in the Caribbean a week before making landfall in New Jersey. (8/21-28/11)

C – Seven inches of rain results in extensive flooding, closing 321 roads, 124 bridges and isolating 11 communities in Vermont. (8/28-29/2011)

D – All state facilities are re-opened after a four-month recovery period. Over 40 town bridges remain closed.

Dust Storm – Oklahoma (2012)

Less Than One Day Total:

C – A large dust storm causes near blackout conditions and a multi-vehicle accident on Interstate 35.

D – The Interstate remains closed for several hours after the storm abates as accident debris is cleared from the roadway. (10/18/12)

Hurricane Sandy – New York/New Jersey (2012)

Seven Months Total:

A – Hurricane Sandy forms in the Caribbean. Several states declare states of emergency. (10/22-27/14)

B – Amtrak, MTA subway, commuter rail and bus services close preemptively ahead of landfall. (10/27-28/12)

C – Hurricane Sandy makes landfall in New Jersey. The storm duration in the New York/New Jersey area lasts for 24 to 48 hours. (10/29-30/12)

D – Service is restored for the A Train from Long Island to Manhattan, one of the last stages in a recovery period lasting for seven months. (5/30/13)

Oso Landslide – Washington (March 2014)

Six Months Total:

C – A massive landslide in Snohomish County inundates State Route 530. The event duration is only one minute. (3/22/14)

D – State Route 530 reopens to two-way traffic concluding a six-month recovery period. (9/27/14) adaptation tools and numerous pilot projects.

Efforts To Support Adaptation Planning For Transportation Agencies

Developing adaptation guidance and strategies has become a key initiative for many transportation organizations. In recent years, the American Association of State Highway and Transportation Officials (AASHTO) (Meyer, Rowan et al. 2013) and the Association of Metropolitan Planning Organizations (AMPO) (Resource Systems Group 2008) have both convened climate adaptation meetings to facilitate information exchange, share best practices and determine what data and tools are needed to respond to weather extremes. The FHWA and the Federal Transit Administration (FTA) have also been very active in this arena. The FHWA developed a conceptual Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012) and funded five state and local transportation agencies to pilot the application of this tool in 2010. A second round of 20 pilot projects, launched in 2013, are now nearing completion. The FTA has also funded several adaptation pilots. The Transportation Research Board (TRB), through the National Cooperative Highway Research Program (NCHRP), has issued synthesis reports on both climate (Meyer, Flood et al. 2014) and extreme weather (Baglin 2014). Other agencies such as National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA) are developing resources to help inform adaptation efforts. The Presidential Task Force on Climate Preparedness and Resilience has been charged to provide recommendations to remove barriers to investment in resilience, including in the transportation sector (Office of the Press Secretary 2013).

Many of these resources are available through Georgetown Climate Center[1] (GCC) Adaptation Clearinghouse. The Clearinghouse also includes 100 community case studies, developed by the Center as part of a cooperative agreement with FHWA. All resources are categorized by type (assessments, funding, law and governance, planning and solutions), location and climate threat. The number or resources and categorizations themselves speak to the complexity of the issue as faced by state and local planning agencies. The complexity has resulted in much of the work to date taking the form of case studies and synthesis reports.

In addition to these valuable case studies and synthesis reports, several specific tools have recently been released by FHWA. These include a tool to capture downscaled climate data from the Coupled Model Intercomparison Project (CMIP), the Vulnerability Assessment Scoring Tool (VAST), and an interactive version of the Climate Change and Extreme Weather Vulnerability Assessment Framework.

As indicated in Table 1, a large number of organizations are active in the adaptation arena. Their exact role and mission in promoting transportation sector adaptation is still evolving and several of the transportation officials interviewed for this report indicated that the sheer volume of information they produce can be overwhelming. There are extensive efforts underway to promote information exchange and to develop planning frameworks and tools.

[1] www.georgetownclimate.org

Significantly fewer organizations are developing climate and weather forecasts suitable for establishing design standards.

Table 1. Organizations and Agencies Active in Transportation Sector Climate Adaptation

Organization	Activities			
	Developing Frameworks & Tools	**Infrastructure Data Collection**	**Climate/Weather Forecasts**	**Facilitating Exchange**
AASHTO				X
FEMA			X	
FHWA	X			X
FTA	X			X
NCHRP				X
NOAA			X	X
State DOTs	X	X		X
MPOs		X		X
Counties, cities, towns		X		
Universities, NGOs and research institutes	X	X	X	X

Methods

In order to assess the obstacles to the successful implementation of adaptation strategies, this paper combines a review of adaptation publications by FHWA, FTA, AASHTO and others with findings from standardized, open-ended interviews of transportation practitioners in state DOTs, Metropolitan Planning Organizations (MPOs), city government, non-governmental organizations, and research institutions. Based on this review, we identified common steps used in most adaptation processes. To assess current obstacles to adaptation efforts, particular attention was paid to lessons learned from the first round of pilot adaptation projects supported by the FHWA – Washington DOT (WSDOT 2011), Virginia DOT (VDOT 2011), New Jersey TPA (NJTPA 2011), Metropolitan Transportation Commission – San Francisco Bay Area (Nguyen, Dix et al. 2011), and the Oahu Metropolitan Planning Commission (SSFM International 2011). In addition, we conducted interviews with nine state agencies, six MPOs and local agencies, and four transportation NGOs or research institutions. All interviews were conducted by telephone by the same individual using a structured question format. The agencies were distributed across five of the six continental climate regions identified in the National Climate Assessment. In evaluating the implementation potential of the adaptation framework for state DOTs, we highlight common themes that arose across multiple interviews; given the occasionally sensitive nature of these comments, however, we do not attribute these findings to individual agencies. We subsequently touch on the role of regional and local agencies in climate adaptation and the unique challenges and opportunities these agencies face.

It is important to note that in our interviews, we encountered practitioners who stated that climate change was not a concern or that the political climate in their jurisdiction made it difficult to discuss issues related to climate change. Consequently, several of the interviews focused less explicitly on "climate change" and more on resiliency, emergency preparedness and extreme weather hazards. Our interview sample was not large enough to indicate whether this political constraint was correlated with adaptation activity. Instead, we observed that agencies in regions that had experienced extreme weather disruptions to the transportation system, including longstanding hurricane risks, were more advanced in their planning than regions that had not experienced disruptive events in the recent past.

A Five-Step Common Framework

Several groups have developed adaptation guidance and frameworks for identifying adaptation needs (FTA 2011, FHWA 2012, Meyer, Flood et al. 2014). Broadly speaking, these documents, as well as several international adaptation protocols (Wall and Meyer 2013), outline similar processes for assessing adaptation needs though with some differences in terminology and different groupings of actions. The FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework (FHWA 2012) is fairly typical of these documents and actually includes steps that precede as well as follow the vulnerability assessment, although it goes into relatively less detail about these components of the adaptation process. It has gained considerable traction with DOTs and MPOs through the FHWA's pilot program to test the framework with state and local agencies. This framework (Figure 2) presents an iterative process of collecting infrastructure and climate data, assessing asset sensitivity, an optional assessment of risk, a vulnerability rating, and optional criticality rating that feeds into monitoring and integrated decision making. The framework was also adopted by

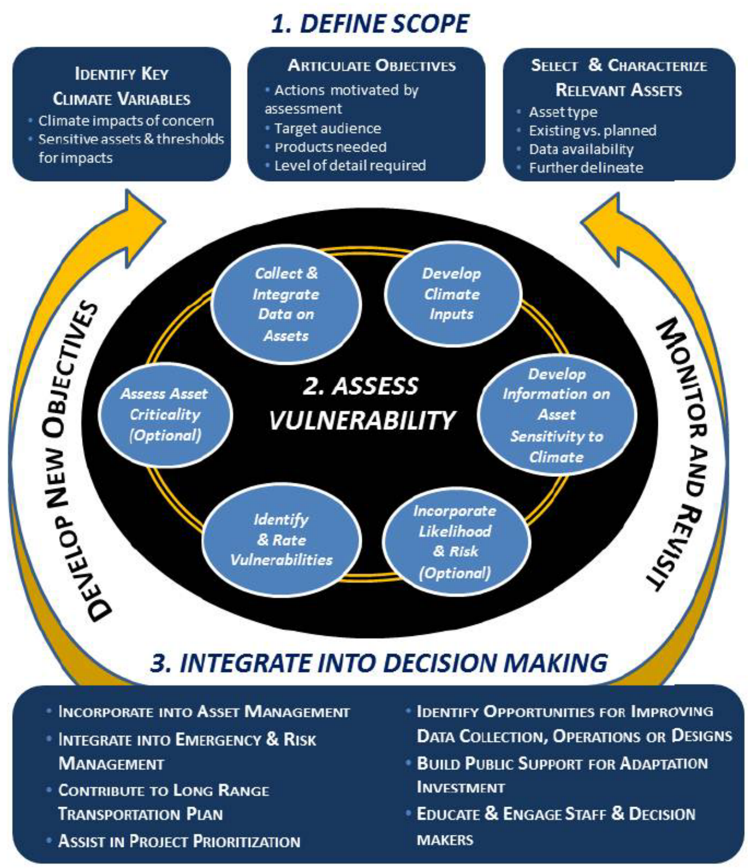

Figure 2. The FHWA's "Climate Change and Extreme Weather Vulnerability Assessment Framework" from (FHWA 2012).

the FTA (FTA 2011). The adaptation framework that appears in NCHRP's *Practitioners Guide* (Meyer, Flood et al. 2014) includes many of these same steps plus several steps devoted to identifying, assessing and implementing adaptation strategies.

For the purpose of evaluating barriers to climate adaptation, we have drawn five key steps in the adaptation planning process from other frameworks (Figure 3):

1) inventorying and monitoring the system assets;
2) assessing climate threats;
3) evaluating asset vulnerability (given the asset conditions and climate threats identified in steps 1 and 2);
4) rating the importance or criticality of each asset to overall system performance; and
5) identifying and executing adaptation actions to reduce adverse impacts based on the vulnerability and criticality evaluations.

The adaptation process is continuous and non-linear with important feedback mechanisms, as represented by the arrows in Figure 3. For example, adaptation actions themselves are designed to reduce vulnerability but may also change the asset inventory in ways that affect not only the vulnerability of the altered asset but also the criticality of multiple assets in the system. Additionally, many of the steps do not need to be completed sequentially or are conducted in an ongoing and iterative manner. Assessing climate threats, for example, is independent of criticality rating steps. Inventorying and monitoring assets must happen on an ongoing basis to support the evaluation of adaptation actions. Finally, the adaptation process is embedded in a larger social context with a wide variety of actors and stakeholders. Changing understanding of the issues may lead to a redefinition of the problems facing the transportation sector and consequently the solutions that are available to transportation agencies (Moser and Ekstrom 2010).

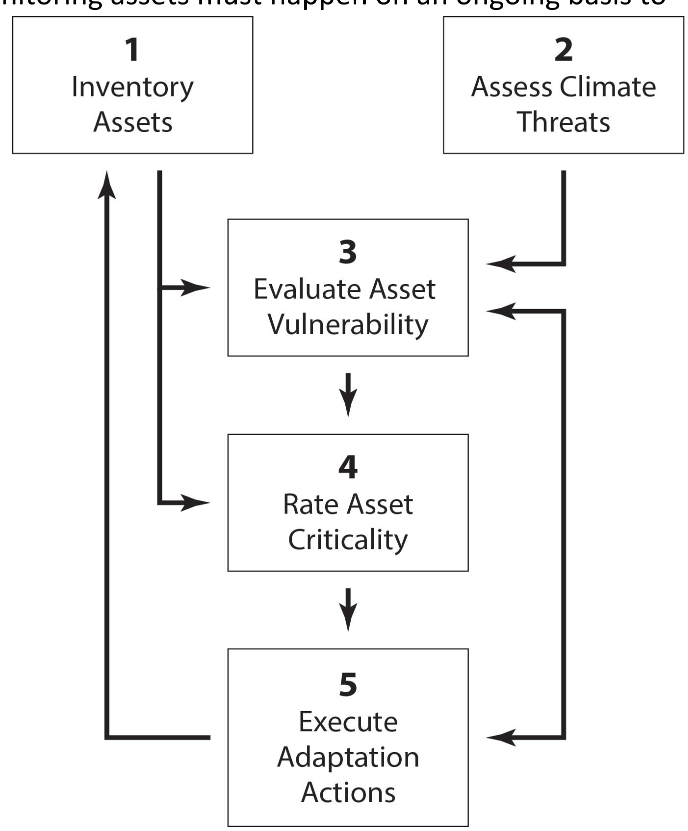

Figure 3. Five-step Common Framework for Climate Adaptation Planning for Transportation Systems.

Implementing each of these steps represents different challenges to transportation agencies. In some cases, these challenges are related to resource constraints. In other cases, data limitations or conceptual uncertainty can pose significant challenges. Objective methods for rating criticality are still not well-developed, so the criticality rating component requires improvements in methods that are best developed at a national level. Assessing climate threats is subject to considerable uncertainty in long-term emissions trends and therefore in climate forecasts. The selection and execution of adaptation actions is hindered by the limitations inherent in each of the proceeding components. For some steps, the expertise, data and methods needed to complete the step are found completely within DOT agencies. Other steps require cooperation and exchange with other agencies that may have different priorities and missions. Table 2 outlines the current capacity of leading state DOTs to implement each of the steps in the adaptation process as expressed in our interviews and the reviewed literature. The actual capacity of DOTs varies from state to state and the challenges within each of these steps are discussed in more detail below.

Table 2. Capacity of State DOTs to Implement Adaptation Framework Components

Step	Conceptual Understanding	Adequacy of Tools and Data	Challenges
Inventory and Monitor Assets	High	Moderate to High: Asset management tools offer a solid base for comprehensive asset inventories. Data quality is highly variable across agencies and jurisdictions.	Funding and time constraints to populate and maintain databases
Assess Climate Threats	High	Poor to Moderate: Tools for modeling climate are increasingly sophisticated but appropriate inputs for these tools are uncertain. The spatial and temporal resolution of these tools remains limited.	Uncertainty with regards to emissions scenarios; further development of down scaling methods
Evaluate Vulnerability	High	Poor to High: Vulnerability modeling is dependent on climate inputs. Modeling tools are better for sea level rise than other climate threats.	Quality and resolution of future climate data
Rate Asset Criticality	Moderate	Poor: Quantitative/comprehensive tools have not yet been developed.	Lack of consensus on methodology; politicization
Select and Execute Adaptation Actions	Moderate	Tools are *poor to moderate* for *infrastructure* actions (vulnerability output lacks the resolution needed by engineers for design purposes) but *high* for *process* adaptations.	Limitations in prior steps; lack of data for design standards; challenges in cost-benefit analysis; funding

Inventorying and Monitoring Assets

The first component of the common framework is to inventory and monitor system assets. Without an understanding of the assets that compose the system, including the condition and functional and physical context of each asset, it is impossible to determine these assets' vulnerability or criticality (steps 3 and 4). Condition data is important in assessing an asset's vulnerability to extreme events. Physical context such as surrounding slopes, land use, proximity to water, and soil type all influence how weather events impact the infrastructure. Traffic or operational capacity is one component that significantly affects asset criticality. In order to maximize the usefulness of the inventory, all data must be routinely maintained and updated so that vulnerability and criticality assessments can be kept current as well as to evaluate adaptation actions once they have been implemented. All records need to be digitized and spatially explicit so that they can be easily accessed and integrated with other data sources.

The requirements for asset inventory are well-understood within the transportation community. State DOTs have experience maintaining inventory and condition databases for asset and maintenance management systems. For example, data collected for the National Bridge Inventory Program (Meyer, Rowan et al. 2012) includes bridge latitude and longitude and information about its condition that could be integrated with additional variables (such as elevation above the water) into adaptation planning (NJTPA 2011). Many states also have culvert inventories and pavement condition monitoring systems that require similar systems and skills to maintain (Meyer, Rowan et al. 2012, Meyer, Flood et al. 2014). Asset inventory requirements for state DOTs are also increasing as part of Moving Ahead for Progress in the 21st Century Act (MAP-21), but states are just beginning to implement these requirements. States are mandated to include a summary listing of all bridge and pavement assets that are part of the National Highway System (NHS) in the asset management plan, and encouraged to include all infrastructure assets within the highway rights-of-way (FHWA 2014).

In spite of the clear understanding of the asset inventory process, few states have undertaken systematic asset inventories adequate for adaptation planning (Meyer, Flood et al. 2014). During the interviews conducted with transportation professionals, several state DOT officials expressed concern about the implementation of comprehensive asset inventory programs. These concerns largely revolved around the financial and personnel costs associated with establishing and maintaining an accurate inventory – a challenge that grows as asset inventories become more comprehensive and include the additional variables needed for adaptation. For example, many states currently maintain culvert inventories but only for culverts above a certain size threshold (Meyer, Flood et al. 2014). As extreme weather events become more frequent, however, smaller culverts are at increased risk of failure and the value of including these culverts in the asset inventory increases. Even for data that states already collect, integrating disparate data sources is often a significant difficulty. As part of the FHWA's Climate Change Resilience Pilot program, Washington State DOT (WSDOT) sought to bring together data from a variety of state sources, but this proved to be considerably more difficult than the WSDOT team anticipated (WSDOT 2011). This step of the adaptation framework is conceptually straightforward but it can be difficult and costly to implement.

To lessen the burden associated with the inventory portion of the framework, several agencies engaged in adaptation efforts looked for ways to reduce the assets that need to be included in the asset inventory. The FHWA suggested limiting assets by type (FHWA 2012) while the Oahu MPO and the San Francisco MPO preselected assets based on expert knowledge of system criticality (Nguyen, Dix et al. 2011, SSFM International 2011).

In short, state DOTs have the technical capacity to undertake comprehensive asset inventories. The major barriers to accomplishing this are the financial and personnel resources required.

Assessing Climate Threats

Both the IPCC and the U.S. Global Change Research Program have released updated reports that layout current and projected regional climate trends (IPCC 2013, U.S. Global Change Research Program 2014). The National Climate Assessment provided information about general regional trends in climate and extreme weather for the United States. These documents are useful for understanding the types of events that states are dealing with currently and provide general indications of future threats. The documents also provide a sense of the general impacts that these threats might have on the transportation system. It is clear, for example, that current climate trends have already resulted in increased precipitation frequency and intensity across much of the United States as well as more prolonged heat waves and drought in other parts of the country. The state DOT officials interviewed were aware of the general weather extremes of greatest significance to their states but also stated that they needed more geographically specific, higher resolution climate/weather data, explicit design standards and guidance on what emissions scenarios to consider.

General trends lack the specificity required to evaluate individual asset vulnerabilities and to establish the specific adaptation actions necessary to adjust to current climate extremes, let alone to establish design standards for infrastructure with a multi-decade life expectancy. In order to improve the management of current extremes, NOAA is updating the Precipitation Frequency Atlas (NOAA) while FEMA is updating its Flood Insurance Rate Maps see e.g. (FEMA 2013). While these resources are valuable, the updating process is slow and the updates reflect only current climate conditions that could be outdated within the lifetime of some transportation assets. Managing the transportation system for future climate threats is more difficult because of uncertainty about future emissions, the accuracy of global climate modeling and the adequacy of the spatial and temporal resolution of downscaled data. Respondents expressed that longer term global climate projections need to be downscaled to produce forecasts that are usable for design of specific infrastructure and adaptation actions at the regional scale. Downscaled climate data is not yet widely available and some important variables, especially precipitation at the watershed level, are very difficult to model (NJTPA 2011). The FHWA's recently released CMIP Climate Data Processing Tool provides practitioners with a simplified interface for interacting with data from the U.S. Bureau of Reclamation's Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections, which will facilitate access to regional data. This tool outputs downscaled precipitation and temperature statistics and represents a valuable advancement for the transportation community. However, additional outputs are still required, such as precipitation intensities in time increments smaller than 24 hours and resulting peak hydrological flows. In addition, policy decisions related to the appropriate emissions scenario to use for adaptation planning will be needed in order to establish design standards and conduct cost benefit assessments for adaption actions.

Given the uncertain magnitude of future climate threats, several of the DOT officials interviewed emphasized the possibility of focusing on adapting the highway transportation system to be more resilient to current weather impacts. Many cited recent experience with extreme weather events and trends in the disruptive events as the basis for their adaptation efforts. Several of these agencies are focused on collecting and updating data about current climate conditions. Given this experience, it is unsurprising that the states contacted that were least actively engaging with adaptation issues had experienced relatively little change in weather and few extreme events. Asked about other states that might serve as sources of useful information, most DOT officials responded by pointing to immediately neighboring states and to states in the FHWA or FTA pilot assessments. Focusing on current climate conditions and drawing lessons from neighboring states are both sensible approaches given the time and resource limitations facing state DOTs. In the longer term, however, it may be important to expand these efforts to include a more comprehensive analysis of future conditions and to draw lessons from a wider set of states.

Several of the agencies participating in the FHWA pilots also noted the urgent need for better downscaled climate data (SSFM International 2011) or opted to use scenario-based approaches to characterize climate threats due to the challenges and uncertainties involved in projecting future climate conditions (NJTPA 2011, VDOT 2011). The WSDOT (WSDOT 2011) pilot project is notable for its use of downscaled climate data provided by the University of Washington's Climate Impact Group.

Ultimately, state DOTs should not and will not be solely responsible for developing the climate and extreme weather scenarios and standards that drive adaptation actions. Developing climate models that output the information needed by transportation engineers and planners will require collaboration among state agencies, among federal agencies and between state and federal agencies. In addition, the selection of the climate scenarios to prepare for reflects a social tolerance for risk and therefore will require public input to inform policy decisions. As noted in Table 2, the conceptual understanding of the climate threat step is high, but the adequacy of tools and data, while improving, is still poor to moderate.

Evaluating Infrastructure / Asset Vulnerability

The FHWA adopted a definition of vulnerability as the degree of susceptibility to adverse effects of climate change and defined susceptibility as "a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (FHWA 2012). As discussed above, the probable magnitude of future climate threats remains a source of uncertainty that inhibits vulnerability evaluations. Vulnerability assessments for some climate threats, such as determining how susceptible infrastructure is to inundation, is a comparatively straightforward engineering analysis, but assessing infrastructure sensitivity to other climate threats is less straightforward. During the interview process, a number of DOT officials indicated that more concrete vulnerability modeling tools would be valuable and that uncertainty about the magnitude of future hazardous climate conditions and extreme events hindered the vulnerability assessment phase of adaptation planning. Since an asset's vulnerability depends upon the severity of the extreme events that it is exposed to, uncertainty about the magnitude of these events necessarily adds uncertainty to the vulnerability assessment. Better probabilistic forecasts of the magnitude of future events, especially of events that can cause sudden infrastructure failure (such as precipitation and storm intensity), would improve agencies' capacity to undertake the vulnerability step of the adaptation planning.

Given these constraints, some DOTs are relying on experienced practitioners to identify historically vulnerable infrastructure. Outputs from these efforts include mapping the location of past infrastructure failures due to flooding, landslides and other weather related disruptions. This represents a good start and, in the short run, this approach may be advantageous because it leverages existing expertise and focuses attention on infrastructure with demonstrated vulnerability to past conditions. In the long run, however, this approach may fail to identify infrastructure that could be highly vulnerable under uncertain, variable and seemingly unpredictable future conditions. Failure to anticipate new and evolving vulnerabilities could have dramatic, adverse effects on system performance.

One area where assessing vulnerability is more advanced is for sea level rise and inundation scenarios, a major focus of the first round of FHWA vulnerability assessment pilots. Modeling for the San Francisco Bay MTC pilot, for example, looked at combined effects of sea level rise and extreme tides but did not consider inland flooding impacts from increased precipitation intensity and riverine overbank flooding (Nguyen, Dix et al. 2011). In other pilot studies and at several of the agencies that were included in our interview process, vulnerability was primarily assessed qualitatively using expert knowledge from within the state and local agencies (SSFM International 2011, WSDOT 2011). Many of the second round of FHWA pilots are focused on threats other than sea level rise and may help to produce vulnerability modeling tools for a wider range of threats. The FHWA's Excel-based tool, VAST, provides an indicator based framework for considering infrastructure vulnerability (ICF International 2014). While this tool provides an organized framework for considering indicators of vulnerability, it does not include an objective rationale for the weighting of these indicators. Currently, as indicated in Table 2 although conceptual understandings are high, the data and tools supporting efforts to evaluate vulnerability are variable and may or may not be identifying the vulnerabilities that are most important for overall adaptation planning.

Rating Infrastructure / Asset Criticality

Because resources available for adaptation actions are limited, adaptation actions, especially those related to physical infrastructure, must be prioritized. The FHWA Framework and others suggest prioritization of adaptation actions based on a combination of asset vulnerability and asset criticality. Methods for measuring criticality that incorporate full network analysis and all regional infrastructure, however, are not well-established. Failure to fully consider all components of the system could result in erroneous prioritizations, even with perfect analytical tools.

Many DOTs reported difficulty with the criticality assessment phase and several also reported that the prioritization process could become politicized. DOTs working to assess criticality relied on expert judgment or metrics such as Average Daily Traffic (ADT), roadway functional class, importance to freight traffic, and status as an evacuation or lifeline route. The San Francisco Bay Area MTC considered the role of roadway embankments in limiting the spread of inland inundation (Nguyen, Dix et al. 2011), an example of the protective capacity that infrastructure can provide. Since assets that provide this type of protection prevent the serial failure of other assets, protective capacity is important to consider when rating asset criticality. Table 3 summarizes factors that contribute to asset criticality during routine and emergency system operation. None of the agencies that participated in the interview process or completed the first round of FHWA pilots used all these factors and there is not yet a consensus on which factors to consider. Methods to incorporate multiple factors and modes are not fully developed.

Table 3. Factors Contributing to Asset Criticality

Traffic Volumes and Proxies: • Average Daily Traffic (ADT) • Functional class • Surrounding population	**Connectivity Measures:** • Availability of alternate routes • Evacuation routing • Access to important destinations (e.g. hospitals)
Protective Capacity: • Asset functions as a barrier to protect other critical infrastructure • Asset functions as a conduit or diverter of damaging flows of water/other elements	**Non-systematic Factors:** • Replacement cost • Historic/cultural significance • Political considerations

Conceptually, many DOT officials understand that, despite wide-spread use, traffic volumes (or proxies), are not a sufficient metric by which to assess criticality and that, at a minimum, route redundancy needs be considered in conjunction with volume measures. Several approaches to quantifying criticality that account for traffic volumes and the redundancy inherent in the network layout are based on modeling the total travel delay caused when the capacity of a road segment or link is disrupted or removed. This approach is the basis for a number of studies that look at single link disruptions as a means for assessing criticality and robustness (Jenelius, Petersen et al. 2006, Scott, Novak et al. 2006, Erath, Birdsall et al. 2009, Sullivan, Novak et al. 2010). Phase II of the FHWA's Gulf Coast study (ICF International 2011), also used this approach but only assessed the criticality of a small set of "representative" links which are unlikely to accurately capture the full typology of the network. Two primary shortcomings of this method, as applied in these examples, are that they assess criticality based only on single link disruption and that the models typically include only main road links, not the whole road network, even though smaller local roads may provide important functional redundancy. Since extreme weather events have the capacity to disrupt multiple links simultaneously, this approach may overstate the security of the system's redundancy and identify incorrect links as most critical. Recent work has begun to consider area, rather than single link, disruptions (Jenelius and Mattsson 2012) but it is unclear how realistically these areas represent actual infrastructure vulnerability. Thus, to most accurately measure the criticality of a link, it is important to consider not just the availability of alternate routes but the vulnerability of those alternate routes. Note that the FHWA uses criticality as a component of the vulnerability measure but the approach that we are suggesting requires that vulnerability be assessed prior to assessing criticality.

The appropriate methods for assessing criticality may also vary over different temporal and spatial scales. Temporally, the criticality of some infrastructure may vary with the length of the disruption depending on the destinations to which the infrastructure provides access. For example, a link that provides access to employment centers might be considered highly critical in the context of vulnerability to sea level rise that could permanently impact that link's capacity. The same link might be considered less critical for short-term disruptions such as those caused by extreme winter weather or hurricanes. In contrast, links to hospitals would be considered highly critical even for short-term disruptions. Moreover, the infrastructure that is most important for emergency service during and immediately after an extreme weather event may not be the same as the infrastructure that is most important to normal traffic operations. In terms of geographic scale, freight corridors can cross several states and thus their overall economic importance may not be evident at some scales of analysis. When measuring criticality it is extremely important to define the space, time and type of event that are being considered.

In summary, methods to establish criticality are currently limited and a lack of consensus on what factors to include or how to weight these factors relative to one another can lead to highly subjective criticality rankings. Development of better methods for criticality assessment is necessary and an area for national organizations and academic institutions to provide leadership. As suggested by Table 2, the rating of criticality may be the weakest link in the common five-step framework.

Identifying and Executing Adaptation Actions

As is shown in Figure 2, identifying and executing adaptation actions depends on the steps that precede it in the adaptation process. Moreover, given the wide variety of climate impacts that are expected to affect the transportation system, a state DOT can see adaptation benefits from a wide range of actions, including strengthening infrastructure so that it is less vulnerable to particular events (often referred to as infrastructure hardening), relocating built infrastructure so that its exposure to particular events is reduced, altering land use patterns, improving pre- and post-disaster response planning, and budgeting for increased maintenance costs. Green infrastructure adaptation efforts, which manage vegetation and natural areas to moderate weather impacts, have been shown to provide other co-benefits (Foster, Lowe et al. 2011). Actions with co-benefits that justify the cost of a project before considering the adaptation benefits are often termed "no regrets" strategies since society benefits regardless of the climate and extreme weather outcomes. These projects may be limited in number and in most cases calculating realistic cost benefit ratios is complicated by variable infrastructure life expectancies, uncertainty about projected planning timeframes and unknown weather event return periods. The transportation chapter of the NCA characterized potential adaptation actions as either strategies that reduced the impact of extreme events (e.g. infrastructure hardening) or strategies that reduce that consequence of extreme events (e.g. updating evacuation/contingency plans) (U.S. Global Change Research Program 2014).

It is useful to further divide adaptation actions into either process or infrastructure adaptation actions. Looking at adaptation actions through this lens reveals that many process adaptation actions can be undertaken even with considerable uncertainty about the magnitude of climate threats and the specific vulnerabilities that they will cause. In contrast, infrastructure adaptation actions are considerably more costly and require greater certainty in terms of vulnerability or criticality to implement with confidence.

Process adaptations, which generally reduce the consequences of extreme events, include the following actions:

- improving communications procedures;
- including climate risk in planning processes;
- developing hazard mitigation and emergency response plans;
- changing maintenance schedules and practices; and
- improving monitoring and data collection.

Adjustment of maintenance schedules or practices is one of the few process adaptations that can reduce the impact of extreme events, rather than just their consequences. Increasing the frequency of culvert clearing activities, for example, can reducing flooding when extreme weather events do occur. Many of the state DOT officials interviewed are currently implementing at least one of these process adaptations. Because process adaptations are generally lower in cost and can offer benefits that translate regardless of the magnitude of extreme events, these actions are also cited as best practices in recent AASHTO (Meyer, Rowan et al. 2013), FHWA (ICF International 2013), and NCHRP (Baglin 2014) synthesis reports.

Infrastructure adaptations include strengthening and protecting infrastructure, enhancing redundancy and abandoning vulnerable infrastructure (FTA 2011). Given uncertainty about future conditions, DOTs could also opt to build lower cost infrastructure that is designed to be replaced more frequently rather than undertaking the hardening effort required to withstand all potential extreme weather scenarios. Many of the DOT officials interviewed stated that identifying and implementing infrastructure adaptation actions was a “next step.” Those few infrastructure adaptations that are underway tend be low cost or to serve multiple purposes and to be considered “no regrets” projects. Relatively, low cost measures include options like raising subway vents to prevent flooding of subway tunnels. Multipurpose actions include building larger bridges to facilitate fish and wildlife passage that simultaneously improves resilience to flooding events. In contrast to process adaptation, infrastructure adaptation tends to be costly and to require significant planning processes and a degree of certainty with regards to climate threats and cost benefits that is currently very challenging.

At this time, the conceptual understanding of adaptation actions is moderate (Table 2) and actively increasing. However, the adequacy of tools and data varies significantly. Progress on process changes is advancing rapidly in some places, but the tools and data to guide large-scale infrastructure adaptations are inadequate, mainly due to reliance on output from prior steps in the framework.

Integrating Local and Regional Agencies

While the states and federal government provide approximately 70% of all surface transportation funding (Rall, Wheet et al. 2011), towns, municipalities and counties own more than 75% of all road miles and nearly 50% of all bridges in the United States (FHWA 2012b). Consequently, many of the effects of extreme weather events impact locally owned and managed transportation infrastructure, and adaptation planning must incorporate local and regional agencies and infrastructure. To date, there is considerable variability in the level of engagement in adaptation by local and regional transportation agencies with existing efforts concentrated in large, coastal MPOs and municipalities as well as those that have received FHWA or other external funding. Similar to state agencies, the emphasis that these local agencies place on climate and extreme weather adaptation is influenced by their recent experience with weather-related disruptions, the projected trends in the frequency and intensity of extreme events in their area, and broader public and political perceptions about climate change. While some regions are at the forefront of the adaptation process (Nguyen, Dix et al. 2011), generally speaking adaptation at the regional and local level is considerably more limited than at the state level (Parson Brinckerhoff 2011). The adaptation barriers at the state level are frequently exacerbated at the local and regional level by the smaller size of the agencies, greater workforce development needs, and the large amount of infrastructure that they own. Moreover, the overlapping jurisdictions and the division of different responsibilities between local and regional transportation entities (the structure of which varies across the nation) create the potential for inefficient duplication of effort and confusion over the appropriate roles of each agency in the adaptation process.

A large number of different entities are involved with transportation planning and infrastructure management at the sub-state level. These entities frequently have overlapping jurisdictions and responsibilities and are very different in size and resource level. These entities include counties, cities, towns and townships, port and transit authorities as well as transportation planning organizations. Among these entities, local governments and transportation authorities own considerable infrastructure (see Table 4) but are limited in geographic extent or focused on single transportation modes, a structure that imposes limits on the ability of these agencies to undertaken broader adaptation planning.

Table 4. Selected State and Sub-state Transportation Agencies in the United States

Entities	Number of Organizations	Road Ownership[1] (% of total road length)	Bridge Ownership[1] (% of all bridges)
State DOTs	50	19%	48%
MPOs	393[2]	0%	0%
RPOs	Unknown	0%	0%
Counties	3,033[3]	44%	37%
Cities and Towns	36,011[3]	32%	12%

[1] Ownership of roads and bridges from (FHWA 2012b)
[2] Number of MPOs from (FHWA and FTA 2014)
[3] Number of counties, cities and towns from (National League of Cities 2013)

Planning organizations, including MPOs, rural planning organizations and other regional planning and economic development bodies, frequently have a relatively broad geographic reach based on system functionality and travel patterns. These jurisdictions can cross state boundaries and occupy a unique position as liaison between city, town, state and federal agencies. Additionally, many MPOs are integrated within councils of government, regional planning commissions, or other regional entities with land-use planning, economic development, and disaster recovery responsibilities, and this integration can be beneficial for adaptation planning. Consequently, MPOs offer some advantages as a sub-state locus of adaptation planning even though they do not own transportation infrastructure. The FHWA has sought to engage MPOs in the adaptation process through its climate adaptation pilot projects (Nguyen, Dix et al. 2011, SSFM International 2011) and by sponsoring a series of webinars on climate change and energy planning presented by AMPO (Parsons Brinckerhoff 2011). In 2008, AMPO convened a conference on climate change that included some discussion of adaptation measures (Resource Systems Group 2008). Several multi-county partnerships, such as the Southeast Florida Regional Climate Change Compact (now participating in the second round of the FHWA adaptation pilot projects), and individual MPOs are undertaking climate assessments that include adaptation components (McGahan and Wolfe 2012). In addition, the California DOT has issued a guide on how to incorporate adaptation in regional transportation plans (Cambridge Systematics 2013).

The size and resources of transportation planning organizations vary widely, however. Urbanized areas with a population larger than 50,000 people are required to designate an MPO to conduct transportation planning and as of 2010, there were more than 390 MPOs in the United States (FHWA and FTA 2014). These agencies covered urbanized areas ranging in size from 34 to more than 38,000 square miles and populations from 21,000 to 18 million people. MPO jurisdictions often include smaller cities, towns and surrounding rural areas as well as the urbanized area (Peckett, Daddio et al. 2014). Nonetheless, close to 80 million Americans live outside of the jurisdiction of an MPO (FHWA and FTA 2014). In many of these rural areas and smaller communities, planning functions are conducted by other regional agencies, but the degree to which these organizations conduct transportation planning is highly variable. MAP-21 provided for the designation of Regional Transportation Planning Organizations (RTPOs) but unlike MPOs, RTPOs are not required by the federal government. Currently, 32 states have adopted the RTPO model (NADO n.d.). Note, as well, that the level of resources for planning vary widely between large and small MPOs as well as these different rural agencies. Planning agencies in some cases are leaders in adaptation but in other cases lack the resources to tackle this complex topic.

Given the different capacities of agencies involved in local and regional transportation issues and the overlap of responsibilities with adaptation implications, no single local or regional agency is well-positioned to conduct all of the steps in the adaptation planning process individually (Figure 2). Instead engaging different agencies in different steps of the adaptation process is likely to maximize the overall effectiveness of adaptation planning and avoid inefficient replication of effort. It is possible that the exact role of these agencies will vary from area to area depending on the resources and capacity of local agencies, and that the state agency will have to play a larger role in poorer and more rural areas outside the jurisdiction of transportation planning organizations. In addition, a recent GCC report of community case studies makes a strong case for a significant role for citizens and non-governmental organizations in the process of planning for adaptation in the transportation system (Goldstein and Howard 2015), and additional work is need to understand the appropriate role of these organizations. The respective roles of state, regional and local agencies in each of the five steps of the adaptation framework are shown in Table 5 and discussed in greater detail in the text that follows.

The asset inventory step is logically the responsibility of the agency that owns the infrastructure. Agency personnel are frequently in contact with their own assets and some degree of condition monitoring is inherent in agencies' maintenance responsibilities. As at the state level, resource constraints were identified as the largest challenge to asset inventory and smaller agencies may have more staffing challenges and less sophisticated database management capabilities. Since asset inventory ultimately feeds the vulnerability and criticality assessments, asset inventories across levels and agencies need to be maintained in a way that allows for easy integration of these databases. This means that the state will have to take a leadership role in developing standard methods for recording asset inventory data. These standardizations may need to be done across state lines given that metropolitan areas, travel patterns and supply chains cross state boundaries suggesting a potential national role in standard development.

Detailed climate threat assessment requires considerable technical expertise as well as decisions about what climate change scenarios ought to be considered. Developing the technical expertise to conduct climate assessment at multiple levels would be duplicative and is beyond the typical scope of a local transportation agency. Moreover, the determination of what emissions scenarios ought to be considered is a social decision, reflecting the degree of risk tolerance of the society at large. Both of these factors suggest that climate threat assessment should be conducted at the state level. In many cases, the most relevant climate threats may vary from one part of the state to another (e.g. differing threats for coastal versus inland regions or mountainous versus non-mountainous regions), in which case threat assessment will need to be regionally specific. For example, determining the threat of riverine flooding due to increased precipitation intensity might include hydrological modeling, which is best undertaken at the level of watersheds. The appropriate scale for regional assessment should be determined in consultation with climate and other natural scientists. Once the climate threats have been assessed, this information needs to be passed on to local and regional agencies for planning and infrastructure design purposes.

Table 5. Adaptation Planning Role for Local Infrastructure

Component	Primary Responsibility	Notes
Inventory and Monitor Assets	Local/infrastructure owning agency	State agencies will need to provide technical support and guidance to ensure inventory asset databases maintained by local agencies can be integrated with one another.
Assess Climate Threats	State	For large states or topographically diverse states, climate threats can vary at the sub-state level and threat assessment will need to be regionally specific. Unified assessment of climate threats will reduce replicated efforts and ensure that consistent climate scenarios are used by all agencies.
Evaluate Vulnerability	Local/infrastructure owning agency	Varies based on type of threat and condition of infrastructure
Rate Asset Criticality	State or MPO/RPO	The criticality of specific infrastructure depends on network characteristics and is fundamentally cross jurisdictional and cross modal. The exact scale of analysis and appropriate boundaries, especially for non-metropolitan areas, are not yet clear.
Select and Execute Adaptation Actions	Infrastructure adaptations – owning agency Procedural adaptations – all agencies.	Owning agencies will undertake infrastructure adaptation using guidance developed at the state or national level.

The vulnerability assessment for specific infrastructure can be conducted by the agency that owns that infrastructure. The vulnerability of a specific asset to a given threat is a function of the likelihood of the threat being realized as well as the likelihood and degree that the threat will disrupt or damage the asset. For some combinations of infrastructure and climate threats, disruption is certain and, in these cases, the infrastructure vulnerability can be determined directly from the output of the climate threats assessment phase. For example, in the case of sea level rise, modeling outputs will directly reveal which roadways will be inundated for a given sea level rise scenario and all inundated roadways will be disrupted. In this case, completing the climate threat assessment directly reveals vulnerability. However, in many cases, the likelihood of disruption is related to the condition and design of the infrastructure and other local factors. For example, the likelihood that a culvert will fail during an intense precipitation event may depend on the condition of the culvert as well as the amount of upstream debris. In these cases, determining the likelihood of disruption will require additional analysis by local agencies and, once again, the staffing and resource levels required to conduct extensive vulnerability analysis is likely to be challenging. Although the vulnerability of infrastructure can be conducted town by town at the local level, it is essential to recognize that the vulnerability of all infrastructure in a given region needs to have been accurately assessed for any one agency to accurately evaluate criticality, because criticality is dependent on the vulnerability of alternative routes (across modes) regardless of asset ownership.

The criticality assessment phase may be especially prone to duplication of effort and error since asset criticality should ideally be evaluated with a complete, multi-modal representation of the full regional transportation network. This means that criticality assessment is dependent on inventory and vulnerability inputs from agencies at all levels and crosses ownership and jurisdictional boundaries. For example, adjacent bridges provide redundancy for each other and reduce the criticality of either bridge individually even if one is owned by the state and one owned by a town. As discussed previously, however, the appropriate temporal and spatial scales for conducting criticality assessment are not yet clear. The appropriate spatial scale almost certainly exceeds the size of individual cities and towns since important destinations are often outside of these boundaries. The temporal scale of criticality assessment may be threat specific, as access to some destinations are critical on the scale of hours (e.g. hospitals) and others on the scale of days or longer (e.g. grocery stores). Moreover, the appropriate scales may vary between large and small communities due to different expectations about the frequency of access to important destinations. Depending on the size of the state and planning organization, this analysis might be conducted by the state or by the MPO/RPO but it should not be limited based on infrastructure ownership. Criticality of surrounding rural areas might best be incorporated into metropolitan analysis since access to services and goods in proximate metropolitan areas is frequently important to the rural areas. Criticality assessment is a large challenge for adaptation planning for agencies of all types. Because criticality assessment requires further the methodological development, the most effective means of implementation are yet to be established.

The execution of adaptation action includes both changes to infrastructure and adaptations to agency processes. The agency that owns the infrastructure will execute the infrastructure adaptation. Guidance for infrastructure adaptation, such as appropriate culvert sizing to manage increased precipitation or pavement specifications to withstand higher temperatures, must be appropriate to the regional climate threats and is most appropriately developed at the state or national level. When infrastructure adaptations involve significant costs, the state will likely bear some portion of these costs, but prioritization will include overall importance to the regional network regardless of asset ownership. Procedural adaptations include improving inter-agency collaboration and disaster preparedness, incorporating risk in planning procedures and adjusting monitoring/maintenance schedules. Adaptations that include local land use change may be the most controversial to implement. Since many procedural adaptations have a relatively low cost, can be implemented even when the magnitude of threats is uncertain, and provide general operational benefits, all agencies may be expected to implement procedural adaptations.

Conclusions

Climate adaptation methods are advancing rapidly and both state DOTs and local transportation agencies are devoting increasing resources to adaption efforts. Nonetheless, these agencies face many barriers in implementing comprehensive climate adaptation programs. Overcoming these barriers will require a combination of additional resources, workforce development, improved cooperation, external policy decisions, and additional methodological advancements. A common, straightforward language and framework are needed to advance debate and cooperation amongst diverse partners for adaptation planning for the highway transportation system. The five-step common framework presented here uses language present in prior frameworks and reduces them to their most essential components. This approach is useful for identifying barriers to implementation and for facilitating opportunities for interregional and interagency cooperation.

Climate threats are well-understood in general terms but the magnitude of these threats is uncertain, particularly at the local scale. Without good climate forecasts, and corresponding design standards that reflect publicly accepted risk and cost benefit ratios, the extent of the infrastructure adaptation that is required to counter these threats cannot be accurately determined. Vulnerability assessment is hindered by uncertainty about climate threats and a need for better modeling tools. Methods for criticality assessment largely remain non-comprehensive or subjective, inhibiting project prioritization. Methodological research to advance criticality models, including refinements to the spatial and temporal frame of analysis as well as technical algorithms, are needed to support practitioners. Finally, all agencies face financial constraints and workforce development needs that severely limit the resources available for adaptation.

Of the five steps in our framework, our research indicates most state agencies and some local agencies have the clear expertise needed to accomplish one component (asset inventory), although they may require additional resources to complete this in a comprehensive manner. Transportation agencies also need better data on climate threats in order to adequately assess vulnerability. National and regional leadership is needed to establish greater local consensus about the appropriate emissions scenarios to use in adaptation planning. DOTs have the expertise to take both process and infrastructure adaptation actions but, again, the data, tools and resources to implement these actions are limited. Moreover, it is unclear if the infrastructure adaptation actions will be appropriately prioritized because methods to assess criticality are not well-developed. This lack of a national consensus on measurement of criticality opens the door to political and non-systematic prioritization that may be undesirable.

Given the significant infrastructure owned by local agencies, both local and regional agencies have an important role to play in the adaptation process. Unfortunately, the degree to which local agencies are currently able to engage in adaptation efforts varies widely. It is crucial to find ways to promote collaboration between these agencies and state DOTs, because collaboration reduces wasteful duplication of efforts and the technical burdens faced by smaller agencies. Moreover, we suggest that the criticality of any asset cannot be accurately assessed without knowledge of the entire regional system, regardless of ownership, and the vulnerability of the all constituent assets. A reasonable delineation of responsibilities between agencies in a partnership that minimizes duplication of effort has been outlined for the adaptation steps in this paper. Another way to improve local and regional agency efforts in adaptation planning is to increase peer-to-peer knowledge transfer. This can be further supported by helping regions and municipalities understand who is facing similar climate threats. While cities and regions often look to their immediate neighbors as examples, this many not always be the most beneficial method. The threats that an area faces are influenced by a number of geographic and topological factors that vary at the sub-state level. Developing a typology of climate threats would enable agencies to delineate the set of regions/localities that they considered peers. Climate adaptation planning is a complex, challenging endeavor and must address threats that vary considerably by region. Together, agencies and organizations have clearly established the core components of adaptation planning. The highway transportation community is increasingly active and engaged in the adaptation arena. Further advancement of a clear uniform language and appropriate tools for adaptation planning is important and will promote the transfer of knowledge from the agencies that are leading in this endeavor to other state DOTs and local agencies that are just starting their adaptation processes.

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THE NEW CLIMATE ECONOMY

The Global Commission on the Economy and Climate

NCE Cities – Sprawl Subsidy Report

ANALYSIS OF PUBLIC POLICIES THAT UNINTENTIONALLY ENCOURAGE AND SUBSIDIZE URBAN SPRAWL

Lead Author: Todd Litman, Victoria Transport Policy Institute

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The New Climate Economy

The New Climate Economy (NCE) is the flagship project of the Global Commission on the Economy and Climate. It was established by seven countries, Colombia, Ethiopia, Indonesia, Norway, South Korea, Sweden and the United Kingdom, as an independent initiative to examine how countries can achieve economic growth while dealing with the risks posed by climate change. The NCE Cities Research Programme is led by LSE Cities at the London School of Economics. The programme includes a consortium of researchers from the Stockholm Environment Institute, the ESRC Centre for Climate Change Economics and Policy, the World Resources Institute, Victoria Transport Policy Institute, and Oxford Economics. The NCE Cities Research Programme is directed by Graham Floater and Philipp Rode.

SUMMARY

This report investigates evidence that current development policies result in economically excessive sprawl. It defines sprawl and its alternative, "smart growth," describes various costs and benefits of sprawl, and estimates their magnitude. It identifies policy distortions that encourage sprawl. It discusses factors to consider when determining the optimal amount and type of urban expansion for various types of cities. It discusses the implications of this analysis for rapidly urbanizing countries. It identifies potential policy reforms that could result in more efficient and equitable development patterns, and describes examples of their implementation. It also discusses criticisms of sprawl cost studies and smart growth policies.

An abundance of credible research indicates that sprawl significantly increases per capita land development, and by dispersing activities, increases vehicle travel. These physical changes impose various economic costs including reduced agricultural and ecological productivity, increased public infrastructure and service costs, plus increased transport

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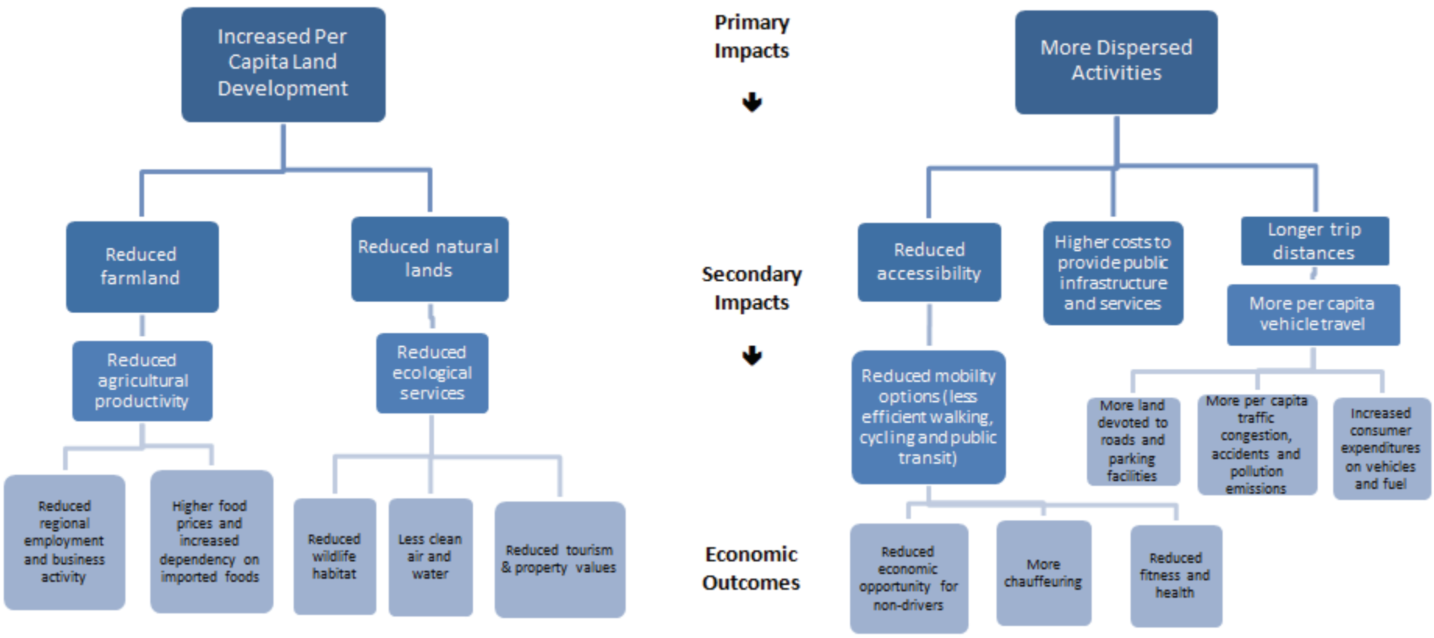
costs including consumer costs, traffic congestion, accidents, pollution emissions, reduced accessibility for non-drivers, and reduced public fitness and health. Sprawl provides various benefits, but these are mostly direct benefits to sprawled community residents, while many costs are external, imposed on non-residents. This analysis indicates that sprawl imposes more than $400 billion dollars in external costs and $625 billion in internal costs annually in the U.S., indicating that smart growth policies which encourage more efficient development can provide large economic, social and environmental benefits. Although these costs reflect North American conditions, the results are transferable to developing countries.

EXECUTIVE SUMMARY

The world is experiencing rapid urbanization. How this occurs will have immense economic, social and environmental impacts. To help identify optimal urban development policies, this report investigates the costs of sprawl (dispersed, segregated, automobile-oriented, urban-fringe development) and potential benefits of smart growth (compact, mixed, multi-modal development).

This analysis starts by identifying basic physical impacts of sprawl, which include increases in the amount of land developed per capita, and by dispersing destinations, increases in total motor vehicle travel. Compared with smart growth development, sprawl typically increases per capita land consumption 60-80% and motor vehicle travel by 20-60%.

Figure ES-1
Sprawl Resource Impacts

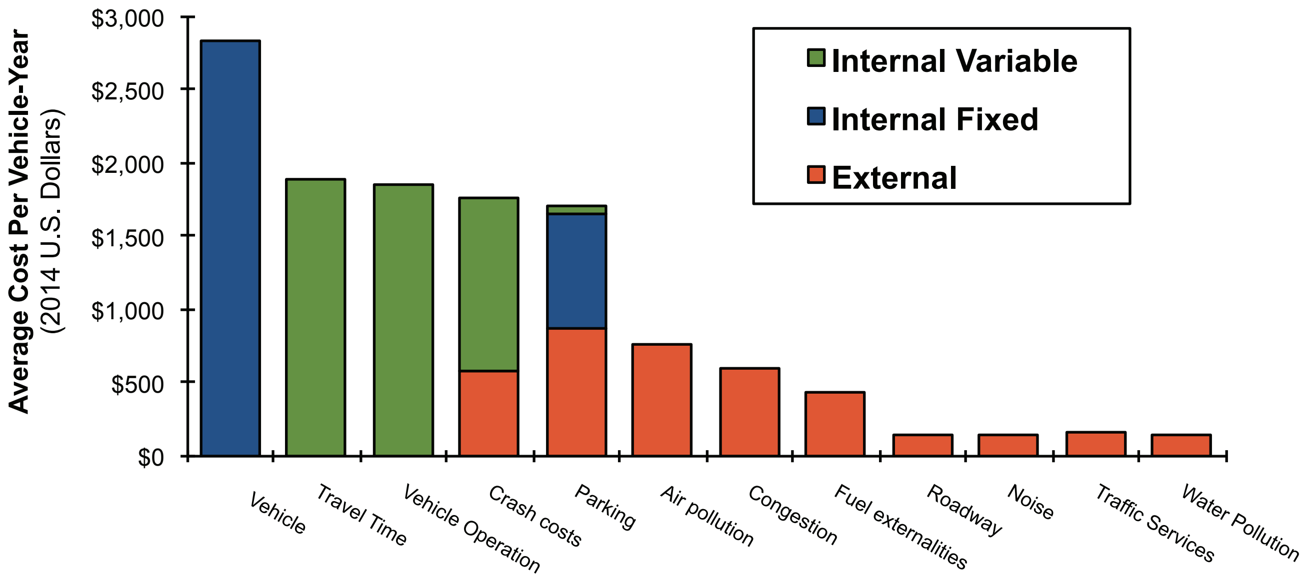


Sprawl has two primary resource impacts: it increases per capita land development, and by dispersing destinations, it increases total vehicle travel. These have various economic costs. This figure illustrates these impacts.

This provides a framework for understanding various economic costs of sprawl, including displacement of agriculturally and ecologically productive lands, increased infrastructure costs, and increased transportation costs including increases in per capita facility costs, consumer expenditures, travel time, congestion delays, traffic accidents and pollution emissions, plus reduced accessibility for non-drivers, and reduced public fitness and health. To the degree that sprawl degrades access by affordable modes (walking, cycling and public transit), these impacts tend to be regressive (they impose particularly large burdens on physically, economically and socially disadvantaged people). To the degree that sprawl concentrates poverty in urban neighborhoods, it tends to exacerbate social problems such as crime and dysfunctional families. To the degree that it reduces agglomeration efficiencies, increases infrastructure costs, and increases expenditures on imported goods (particularly vehicles and fuel), it tends to reduce economic productivity. Sprawl also provides benefits, but these are mostly direct internal benefits to sprawled community residents; there is little reason to expect sprawl to provide significant external benefits to non-residents.

Figure ES-2 indicates the typical costs of automobile travel under urban conditions, including internal-fixed (ownership), internal-variable (operating), and external (imposed on other people) costs. These total thousands of dollars per vehicle-year.

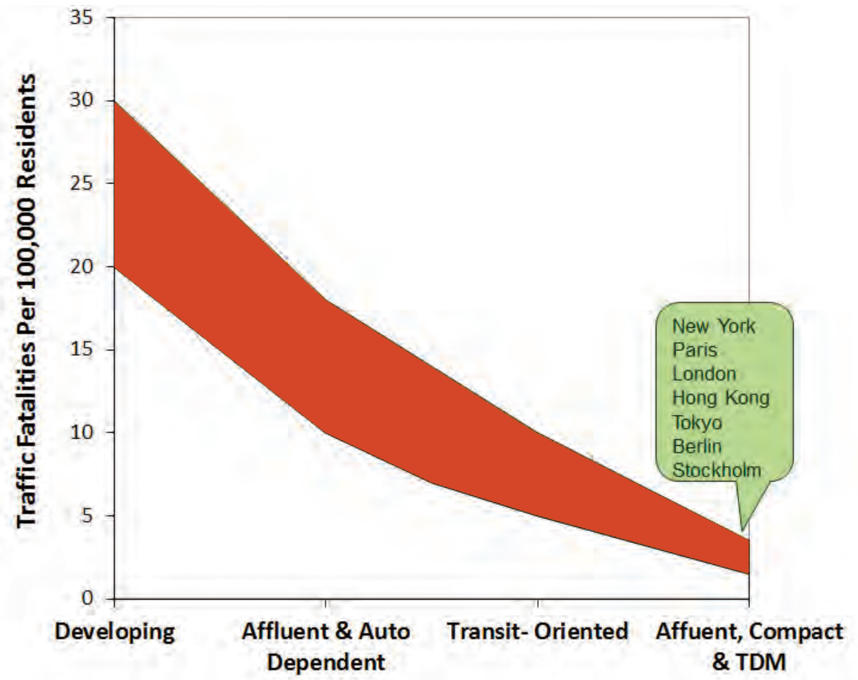
Figure ES-2
Estimated Urban Automobile Costs



Source: based on Litman 2009
This figure illustrates the estimated costs of motor vehicle ownership and use.

Sprawled urban areas typically have two to five times the traffic fatality rates as in smart growth communities. Very low crash casualty rates (under 5 annual traffic fatalities per 100,000 residents) generally require a combination of smart growth development and transportation demand management strategies, as indicated in Figure ES-3.

Figure ES-3
Traffic Death Rates



Traffic fatalities per 100,000 residents typically average 20-30 in developing country cities, 10-20 in affluent, automobile-dependent cities, 5-10 in affluent, compact cities, and just 1.5-3 in affluent, compact cities with strong transportation demand management (TDM) programs.

To quantify sprawl costs, this study divided U.S. cities into quintiles (fifths) and estimated the additional land consumption, infrastructure and public service, transport and health costs of more sprawled development. For example, this analysis indicates that sprawl increases annualized infrastructure costs from $502 per capita in the smartest growth quintile cities up to $750 in the most sprawled quintile cities. This analysis indicates that sprawl's incremental costs average approximately $4,556 annual per capita, of which $2,568 is internal (borne directly by sprawl location residents) and $1,988 is external (borne by other people). These external costs probably total more than $400 billion per year in the U.S. Sprawl also provides benefits, including cheaper land, which allows households to afford more private open space (yards and gardens), and it lets affluent households move away from urban social problems such as concentrated poverty and associated crime. However, these are internal benefits and economic transfers (some people benefit but others are worse off), there are seldom significant external benefits since consumers and businesses rationally internalize benefits and externalize costs.

Although many of these costs are lower in absolute value in developing countries, due to lower wages and property values, they are probably similar relative to incomes and regional economies. As a result, smart growth policies that create more compact communities can provide substantial economic, social and environmental benefits in both developed and developing countries.

A key question for this analysis is the degree that sprawl results from policy distortions. It identified various sprawl-inducing planning and market distortions including development practices that favor dispersed development over compact urban infill, underpricing of public infrastructure and services in sprawled locations, underpricing of motor vehicle travel, and transport planning practices that favor mobility over accessibility and automobile travel over more resource-efficient modes. Consumer preference research suggests that more optimal planning and pricing would cause many households to choose more compact communities, drive less, and rely more on alternative modes. Table ES-1 identifies policy reforms that reflect economic principles including consumer sovereignty, efficient pricing and neutral planning. These reforms tend to increase economic efficiency and equity.

Table ES-1
Examples of Efficient Smart Growth Policies

Improved Consumer Options	More Efficient Pricing	More Neutral Planning
• Improved walking, cycling and public transit in response to consumer demands – such as better sidewalks, bike and bus lanes on most urban arterials. • Reduced and more flexible parking requirements and density limits in urban areas. • More diverse and affordable housing options such as secondary suites. • Improved public services (schools, policing, utilities) in smart growth locations.	• Efficient pricing of roads and parking, so motorists pay directly for using these facilities, with higher fees during congested periods. • Distance-based vehicle registration, insurance and emission fees. • Location-based development fees and utility rates so residents pay more for sprawled locations and save with smart growth. • Vehicle registration auctions in large cities where vehicle ownership should be limited.	• More comprehensive evaluation of all impacts and options in the planning process. • Accessibility- rather than mobility-based planning, so accessibility is given equal consideration as mobility when evaluating transport impacts. • *Least-cost transport planning*, which allocates resources to alternative modes and transportation demand management programs when they are effective investments, considering all impacts.

These smart growth policies reflect economic principles. They tend to increase economic efficiency and equity.

This study identified various factors to consider when determining how cities should expand, as summarized in Table ES-2.

ES-2
Optimal Urban Expansion, Density and Development Policies

Factor	Optimal Expansion
Open space (farm and natural lands)	Policies should encourage compact development to minimize farm and ecologically productive land displacement.
Consumer demands	Cities should develop diverse housing options, including affordable housing in accessible, multi-modal areas. In unconstrained cities, the majority of housing may be small-lot single-family. In constrained cities, more housing should be multi-family.
Infrastructure and public services	Policies should encourage moderate- to high-density development along major utility corridors, and discourage leapfrog development distant from existing services.
Transport system efficiency	Policies should encourage densities exceeding 30 residents per hectare along transit lines with frequent service and good walking and cycling conditions.
Economic development	Policies should encourage compact, multi-modal development, favor resource-efficient transport modes, and preserve valuable farmland.
Safety and health	Favor compact development, lower traffic speeds, and transportation demand management to reduce automobile travel and encourage walking and cycling.
Social equity	Provide sufficient space for low-income residents, and encourage development of affordable housing and transport options.
Social problems	Encourage affordable compact development with features that improve at-risk residents' economic opportunities and quality of life.
Optimal roadway supply	Devote 20-25% of land to roads in denser areas, and 10-15% in less dense areas. Design and manage roads to balance various planning objectives. Minimize the amount of land devoted to off-street parking lots through efficient parking management.

Various factors should be considered when determining optimal urban expansion and development policies.

To help determine the optimal densities in specific situations, cities are divided into three categories:

1. Unconstrained cities are surrounded by an abundant supply of lower-value lands. They can expand significantly. This should occur on major corridors and maintain 30 residents per hectare densities. A significant portion of new housing may consist of small-lot single-family housing, plus some larger-lot parcels to accommodate residents who have space-intensive hobbies such as large-scale gardening or owning large pets. Such cities should maintain strong downtowns surrounded by higher-density neighborhoods with diverse, affordable housing options. In such cities, private automobile ownership may be common but their use should be discouraged under urban-peak conditions by applying complete streets policies (all streets should include adequate sidewalks, crosswalks, bike lanes and bus stops), transit priority features on major arterials, efficient parking management, and transport pricing reforms which discourage urban-peak automobile travel.

2. Semi-constrained cities have a limited ability to expand. Their development policies should include a combination of infill development and modest expansion on major corridors. A significant portion of new housing may consist of attached housing (townhouses) and mid-rise multi-family. Such cities should maintain strong downtowns surrounded by higher-density neighborhoods. In such cities, private automobile ownership should be discouraged with policies such as requiring vehicle owners to demonstrate that they have an off-street parking space to store their car, pricing of on-street parking with strong enforcement, roadway design that favors walking, cycling and public transit, and road pricing that limits vehicle travel to what their road system can accommodate.

3. Constrained cities cannot significantly expand, so population and economic growth requires increased densities. In such cities, most new housing will be high-rise and few households will own private cars. Such cities require strong policies that maximize livability in dense neighborhoods, including well-designed streets that accommodate diverse activities; adequate public greenspace (parks and trails), building designs that maximize fresh air, privacy and private outdoor space; transport policies that favor space-efficient modes (walking, cycling and public transit); and restrictions on motor vehicle ownership and use, particularly internal combustion vehicles.

Because motor vehicles are very space-intensive – each automobile requires more space for roads and parking than used for a typical urban resident's house – vehicle densities are as important as population densities. As a result, to maximize economic efficiency and livability, cities must efficiently manage roads and parking facilities and limit automobile ownership to what these facilities can accommodate. This requires an integrated program of improvements to space-efficient modes (walking, cycling, ridesharing and public transit), incentives for travelers to use the most efficient mode for each trip, and compact, multi-modal development that maximizes overall accessibility. Since buses are very space-efficient, cities should provide bus lanes on most major urban arterials.

To maximize social welfare it is important that smart growth development respond to consumer demands, for example, by creating communities with diverse housing options, high quality public services (such as policing, schools and local parks), attractive and multi-functional urban streets (including sidewalks, shops, cafes, landscaping and awnings), and programs that encourage positive interactions among residents (local festivals, outdoor markets, recreation and cultural centers, etc.).

Table ES-3 summarizes various factors that should be considered in determining optimal urban expansion, densities and development policies.

Table ES-3
Optimal Urban Expansion, Densities and Development Policies

Factor	Un-Constrained	Semi-Constrained	Constrained
Growth pattern	Expand as needed	Expand less than population growth	Minimal expansion
Optimal regional density (residents / hectare)	20-60	40-100	80 +
Housing types	A majority can be small-lot single-family and adjacent	Approximately equal portions of small-lot single-family, adjacent, and multi-family.	Mostly multi-family
Optimal vehicle ownership (vehicles per 1,000 residents)	300-400	200-300	< 200
Private auto mode share	20-50%	10-20%	Less than 10%
Portion of land devoted to roads and parking	10-15%	15-20%	20-25%
Examples	Most African and American cities.	Most European and Asian cities.	Singapore, Hong Kong, Male, Vatican City.

Different types of cities may have different growth patterns, densities and transport patterns.

Some previous sprawl cost studies have been criticized for various reasons. Critics argue that sprawl cost estimates are exaggerated, that such costs are offset by benefits of equal magnitude, or that more compact, smart growth development patterns impose equal external costs. However, much of this criticism reflects inaccurate assumptions (for example, that smart growth eliminates single-family housing and private automobile ownership) and outdated or inaccurate research (for example, outdated studies which suggested that smart growth provides no energy or infrastructure savings). Although sprawl does provide benefits, these are largely internal benefits to sprawl community residents; there is little evidence of significant external benefits which offset external costs. Probably the most legitimate criticism of smart growth is that it can reduce single-family housing affordability, but many smart growth policies increase overall affordability by allowing more compact housing types and reducing infrastructure and transport costs. This criticism therefore depends on whether single-family housing affordability is more important than more compact housing affordability, and whether house purchase affordability is more important than infrastructure and transport affordability.

Much of the research in this report is based on North American conditions because that is where the best data are available. However, the basic relationships are transferable: more dispersed and automobile-oriented development imposes various costs, including external costs, which can be reduced with smart growth policies which improve transport options, particularly walking, cycling and public transit, and increase housing supply in central cities (Guerra 2015). Smart growth policies can ultimately benefit consumers by improving their housing and transport options and providing new opportunities to save money to households that choose smart growth locations. Smart growth benefits tend to be particularly large:

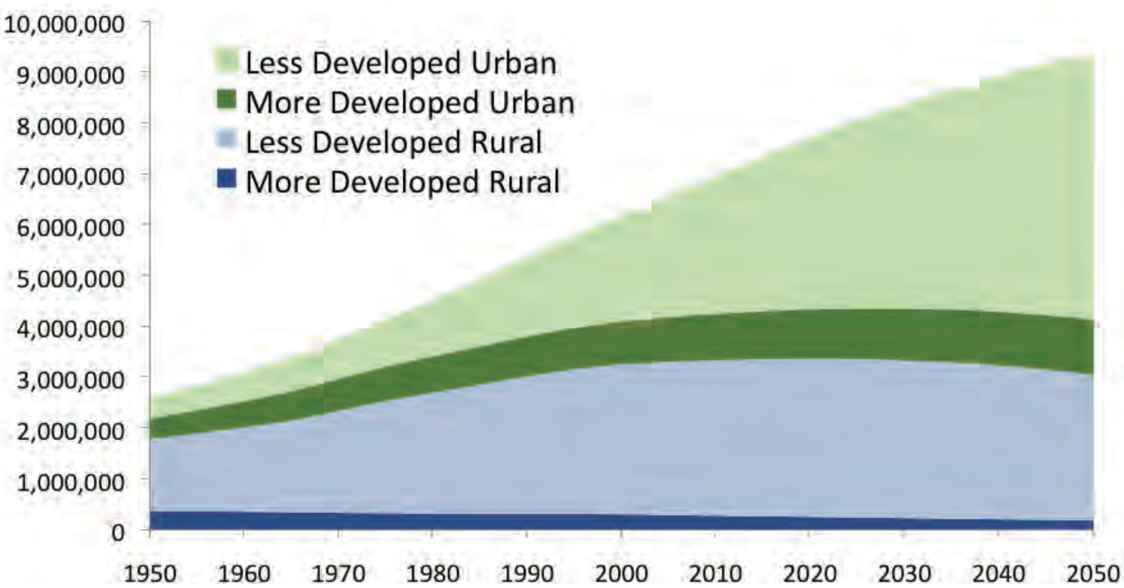
- In rapidly growing urban areas.
- In urban areas making significant infrastructure investments.
- In cities where urban fringe land has high social or environmental values.
- Where infrastructure and vehicle fuel are costly to produce or import, for example, if a low-income country must import equipment and energy.
- If communities have goals to improve mobility options for disadvantaged populations, improve public fitness and health, or support environmental objectives.

These are complex issues. Urban planning decisions involve numerous trade-offs between various planning objectives, so many different factors must be considered when evaluating policies and projects. There is no single set of development policies that should be imposed everywhere. Every city is unique and must develop in ways that respond to local geographic, demographic and economic factors. The analysis in this report provides ideas and guidance that public officials, practitioners and the general public can use to help identify the truly best way to develop their city, considering all impact and options. More research is needed to better understand the full benefits and costs of specific policy and planning decisions and determine the best policies to implement in a particular situation.

INTRODUCTION

Our world is currently engaged in massive urbanization. Between 1950 and 2050 the human population will approximately quadruple and shift from 80% rural to nearly 80% urban (Figure 1). Most of this growth is occurring in developing countries, resulting in approximately 2.2 billion new urban residents in developing countries between 2015 and 2050. How these cities grow has huge economic, social and environmental impacts. It is important that public policies guide this development to maximize benefits and minimize costs, in order to leave a sustainable legacy for future generations.

Figure 1
World Urbanization



Source: UN 2011
The world is currently experiencing rapid urbanization, particularly in developing countries.

This study investigates an important and timely issue: the degree that current public policies and planning practices unintentionally encourage resource-intensive sprawled development, and therefore the potential economic savings and benefits of "smart growth" policies which create more compact, multi-modal communities. This is not to suggest that there is a single optimal development pattern that should be imposed on all households, rather, it highlights the importance of objective and comprehensive analysis of policies that affect development patterns.

This report examines the following questions:
1. What are sprawl and smart growth?
2. What are the incremental costs and benefits of sprawl?
3. What is the estimated magnitude of sprawl costs?
4. How much urban expansion is optimal?
5. What policy distortions lead to economically excessive sprawl?
6. What are the policy implications of these findings, particularly for rapidly urbanizing countries?

This research is based largely on developed country experience because that is where the urbanization process is most mature and data available, but most results are transferable to rapidly-urbanizing countries. This information can help developing countries balance various economic, social and environmental goals (Adaku 2014; CCICED 2011; Economist 2014; Floater and Rode 2014a).

WHAT ARE SPRAWL AND SMART GROWTH?

This section describes sprawl and smart growth, and how they are commonly measured.

Sprawl refers to dispersed, segregated (single-use), automobile-oriented, urban-fringe development. The alternative, called smart growth in this report, involves more compact, mixed, multi-modal development. Table 1 compares these two development patterns.

Table 1
Sprawl and Smart Growth

	Sprawl	Smart Growth
Density	Lower-density, dispersed activities.	Higher-density, clustered activities.
Land use mix	Single use, segregated.	Mixed.
Growth pattern	Urban periphery (greenfield) development.	Infill (brownfield) development.
Scale	Large scale. Larger blocks and wide roads. Less detail, since people experience the landscape at a distance, as motorists.	Human scale. Smaller blocks and roads. Attention to detail, since people experience the landscape up close.
Services (shops, schools, parks, etc.)	Regional, consolidated, larger. Requires automobile access.	Local, distributed, smaller. Accommodates walking access.
Transport	Automobile-oriented. Poorly suited for walking, cycling and transit.	Multi-modal. Supports walking, cycling and public transit.
Connectivity	Hierarchical road network with many unconnected roads and walkways.	Highly connected roads, sidewalks and paths, allowing direct travel.
Street design	Streets designed to maximize motor vehicle traffic volume and speed.	Reflects *complete streets* principles that accommodate diverse modes and activities.
Planning process	Unplanned, with little coordination between jurisdictions and stakeholders.	Planned and coordinated between jurisdictions and stakeholders.
Public space	Emphasis on private realms (yards, shopping malls, gated communities, private clubs).	Emphasis on public realms (shopping streets, parks, and other public facilities).

Source: SGN 2009

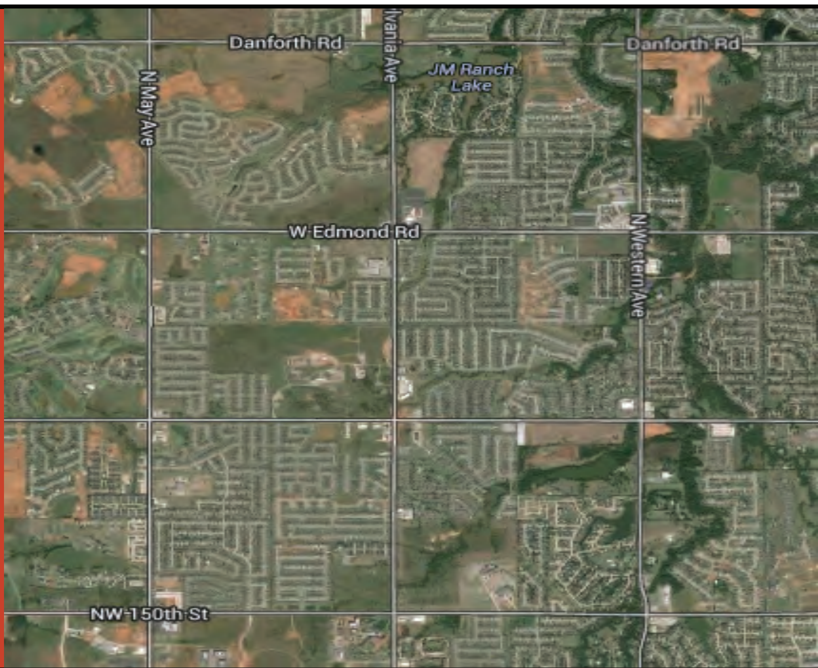
This table compares various features of smart growth and sprawl.

Smart growth is a general set of principles that can be applied in many different ways. In rural areas, it creates compact, walkable villages with a mix of single- and multi-family housing organized around a commercial center. In large cities, smart growth creates dense, mixed-use neighborhoods organized around major transit stations. Between these is a wide range of neighborhood types, their common theme is compact and multi-modal development. In mature cities, smart growth consists primarily of incremental infill in existing neighborhoods, but in growing cities it often consists of urban expansion. Smart growth does not necessarily require all residents to live in high-rise apartments and forego automobile travel; excepting cities with severe constraints on expansion, a major portion of households can live in single-family or adjacent housing, and many can own or share cars.

Figure 2 illustrates typical examples of sprawl and smart growth development (Campoli and MacLean 2002; Hartzell 2013).

Figure 2
Sprawl and Smart Growth Illustrated

Sprawl



This U.S. suburb has residential development scattered among farms. Many streets lack sidewalks and there is virtually no transit service. This results in high rates of automobile travel.

Smart Growth

This German town has concentrated and mixed development, with houses close to services and well-defined boundaries. A major portion of travel is by walking, cycling and public transit.

Although sprawl and smart growth differ in many ways, they are often measured based only on density (residents or employees per acre or hectare) or its inverse land consumption (e.g., square meters per resident or employee). Density is a useful indicator because it is widely available and easy to understand, and because it tends to be positively correlated with other smart growth factors including development mix (the proximity of residential, commercial and institutional buildings), transport network connectivity (density of sidewalks, paths and roads), centricity (the degree that employment is concentrated into commercial centers), and transport diversity (quality of walking, cycling and public transport). However, by itself, density is an imperfect indicator since it is possible to have dense sprawl (high-rise buildings in isolated, automobile-dependent areas), and rural smart growth (such as compact, walkable villages linked by high quality public transit). If possible, smart growth should be analyzed using an index which reflects various land use factors including density, mix and connectivity (Ewing and Hamidi 2014). People sometimes confuse density (people per land area) with crowding (people per housing unit, room or square meter of building space) although they are very different. For example, many residents of low-density rural areas live in crowded homes, while many residents of high-density neighborhoods live in spacious apartments.

Density analysis can be confusing because it is measured in many different ways:

- What is measured: residents, residents plus employees, dwelling units (du) and motor vehicles.
- Land area units: acre, hectare, square mile or kilometer.
- Geographic scale: parcel (just the land that is developed), neighborhood (including local streets, schools, parks, etc.), or region (including industrial areas and regional open space). Residential parcels typically represent 70-80% of neighborhood and 40-60% of regional land area (Angel 2011).
- Weighting: Population-weighted density, which measures the density that residents actually experience, is a better indicator than simple average densities for evaluating land use economic and livability impacts, but is more difficult to compute (Florida 2012; US Census 2012).

Table 2 compares how 10 dwelling units per parcel acre would be measured using various units.

Table 2

Comparing Density Units (10 Dwelling Units Per Acre)

	Parcel	Neighborhood	Region
	Residential land only	All land in a neighborhood, including streets, schools, local parks, etc.	All land in a region including industrial areas and open space
Residential land/total Land	*1.0*	*0.75*	*0.5*
Dwelling units per acre	10.0	7.5	5.0
Residents per acre	25.0	18.8	12.50
Dwelling units per hectare	24.7	18.5	12.4
Residents per hectare	61.8	46.3	30.9
Residents per square-mile	16,000	12,000	8,000
Residents per square-kilometer	6,178	4,633	3,089

This table shows various equivalencies for 10 dwelling units per parcel acre. It is important to use consistent units and measurement methods when comparing densities.

Table 3 compares typical densities of various housing types. Developing country cities often have high densities due to larger families which result in more people per housing unit. The amount that densities decline with affluence depends on public policies. Many affluent European and Asian cities are relatively dense due to geographic constraints and policies that encourage compact development, while some low-income cities, particularly in Africa and South America, have relatively low development densities.

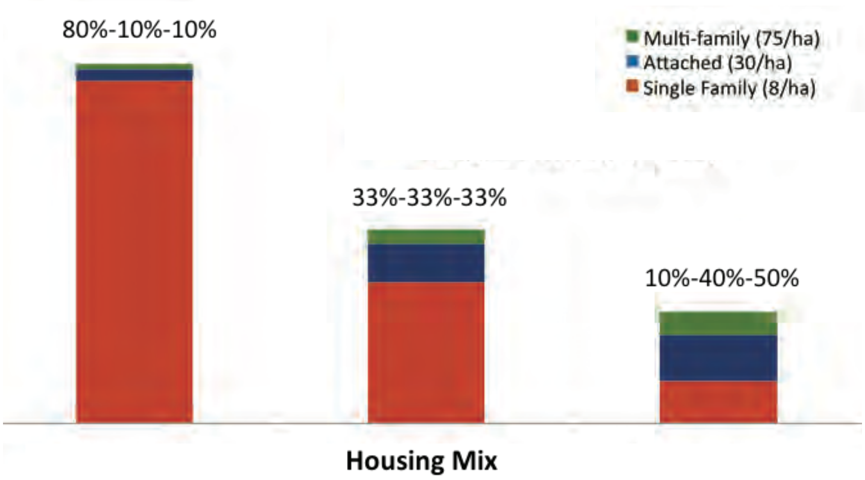
Table 3
Typical Densities of Various Housing Types

	Large-lot Single-family	Medium-Lot Single-Family	Small-Lot Single-Family	Attached (Townhouses)	Mid-Rise Multi-Family	High-Rise Multi-Family
Stories	1-3	1-3	2-3	2-3	3-8	Over 8
Units/Hectare	Less than 5	5-10	10-30	20-40	30-60	Over 100
People/Hectare	Less than 10	10-20	20-80	40-100	60-150	Over 200

Densities vary significantly by housing type. Denser cities have a greater portion of compact housing types.

Figure 3 illustrates the land required by 1,000 units for various housing type combinations. Sprawled cities with 80% single-family, 10% attached and 10% multi-family housing (80%-10%-10%), require about twice times as much land as an equal mix of housing types (33%-33%-33%), and more than three times as much land as 10% single-family, 40% adjacent and 50% multi-family.

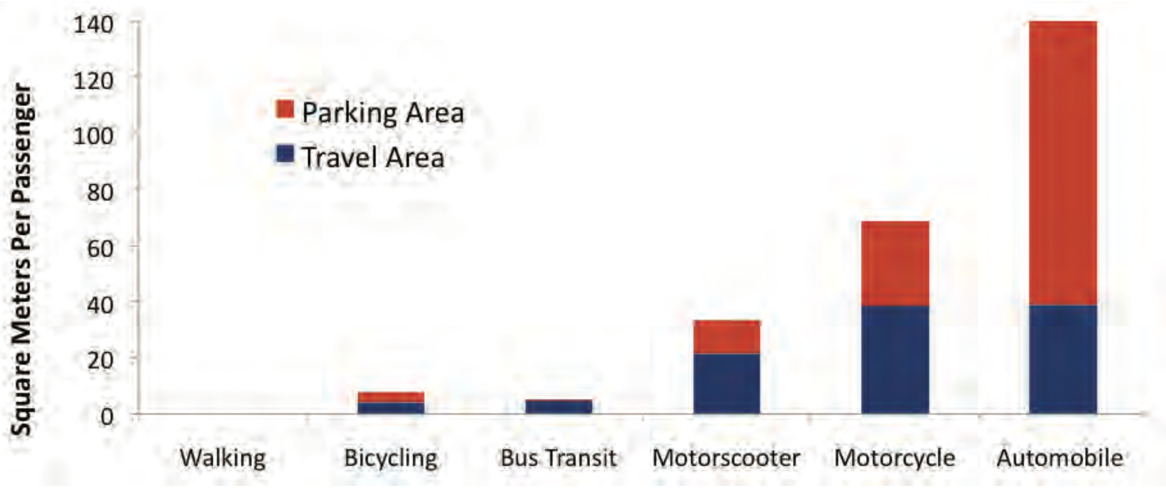
Figure 3
Land Use Consumption by Housing Type Mix



Shifting to more compact housing types significantly reduces residential land consumption. A mix of 80% single-family, 10% attached and 10% multi-family housing requires about twice times as much land as an equal mix of housing types, and more than three times as much land as 10% single-family, 40% adjacent and 50% multi-family.

Transport policies also affect development densities. Because of their size and speed, automobiles require much more space for roads and parking than other modes. In U.S. cities there is approximately 45 square meters (m2) of road space (FHWA 2013, Table HM72), plus two to six off-street parking spaces averaging about 30 square meters, per automobile (Davis, et al. 2010; Litman 2009). This indicates that in order to keep road and parking congestion to the moderate levels that occur in the U.S., each automobile requires 100 to 200 m2 of land for roads and parking facilities, far more than required for other modes, as indicated in Figure 4.

Figure 4
Space Required By Travel Mode[1]



Automobiles require far more road and parking space than other modes due to their size and speed.

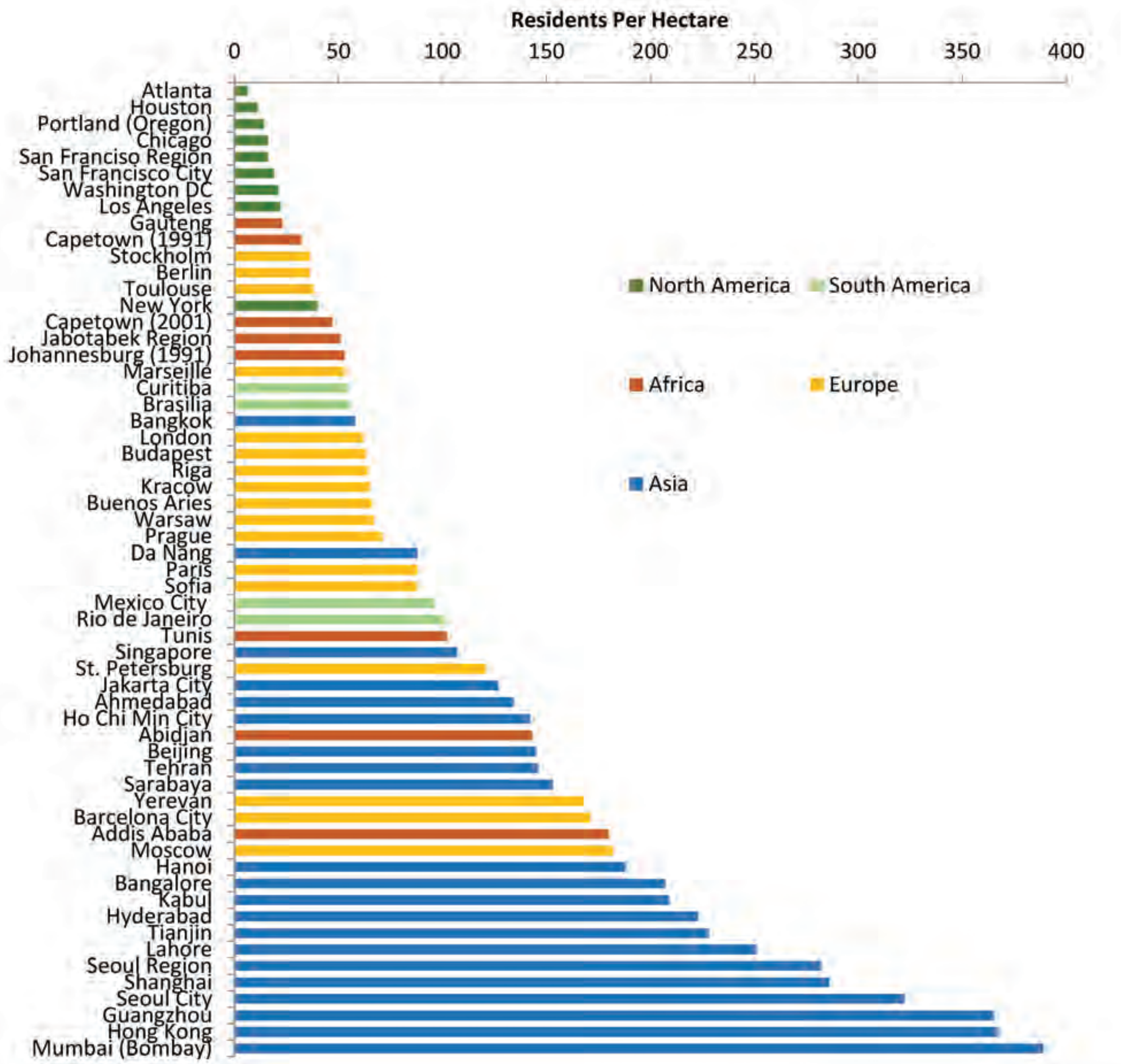
As a result, high vehicle ownership rates can limit urban population densities. For example, a one-hectare parcel might accommodate 50 townhouses if there are only 10 on-site parking spaces, but if each unit has two surface parking spaces, as many zoning codes require, the number of potential units declines to 30. Similarly, wider roads reduce the amount of land available for housing and greenspace.

Figure 5 shows the densities of urban regions around the world. Typical urban densities range from 5-20 residents per hectare in North America, 20-100 residents per hectare in Europe, and more than 100 residents per hectare in many Asian cities. Similar variations exist within urban regions, for example, between central city and urban fringe neighborhoods.

Smart growth generally requires at least 30 residents per neighborhood hectare in order to provide sufficient demand for local services such as stores, schools and public transit within walking distance of homes (Pushkarev and Zupan 1977). Not every house needs to reflect that threshold, smart growth communities can include some lower density development provided they are offset by a similar amount of higher-density development. Smart growth densities can generally be achieved with 30-50% single-family, 25-35% adjacent (townhouse), and 25-35% multi-family housing, resulting in 40-80 residents per regional hectare, although higher densities are needed in cities where expansion is constrained.

1 Transport Land Requirements Spreadsheet (www.vtpi.org/Transport_Land.xls). Assumes 45 m2 of road space and four 30 m2 parking spaces per automobile, with the following passenger car equivalent (PCE) values for other modes: walk 0.01; bicycle 0.1; bus 3.0 divided by 25 average peak-period passengers; motorcycle 0.5.

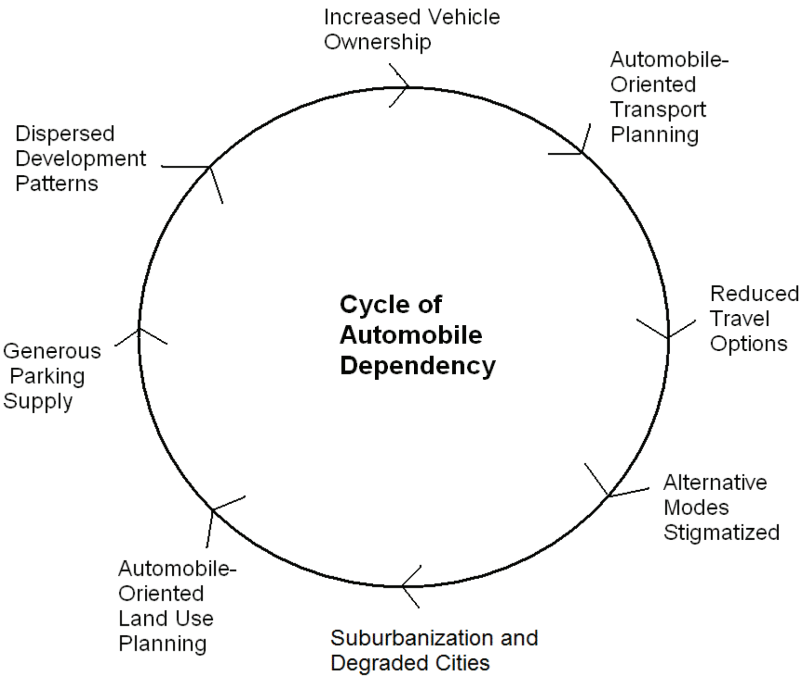
Figure 5
People Per Hectare In Various World Cities



Source: (Bertaud 2012)
Urban population densities vary significantly from under 10 to more than 300 residents per hectare.

Smart growth represents a major policy shift. During the last century, many development policies encouraged sprawl and automobile dependency. These included planning practices that favored urban expansion over infill development, restrictions on building density and height, minimum parking and setback requirements, transport planning that favored automobile travel over other modes, plus utility pricing and tax rates that fails to reflect the higher costs of providing public services in sprawled locations. Although individually these pro-sprawl policies may seem modest and justified, they contribute to a self-reinforcing cycle of sprawl and automobile dependency (Figure 6). These polices reduce housing and transport options, and increase economic and environmental costs (Garceau, et al. 2013; ITDP 2012). In response, many governments and professional organizations now support smart growth policies (ADB 2009; ICMA 2014; ITE 2010; UN 2014).

Figure 6
Cycle of Sprawl and Automobile Dependency



This figure illustrates the self-reinforcing cycle of increased automobile dependency and sprawl.

THE DEMAND FOR SPRAWL

This section examines the "demand for sprawl," which refers to the amount that people and businesses will choose sprawl over smart growth locations, and factors that influence these decisions.

The "demand for sprawl" refers to the degree that consumers prefer to live in dispersed, automobile-dependent locations, the amount they would be willing to pay to do so, and the factors that affect those decisions. Understanding these factors can help evaluate potential land use policies, such as the number and type of households that would choose compact neighborhoods, and how to successfully attract households to such neighborhoods.

As households become wealthier they tend to demand larger houses and gardens, but responding to this demand does not necessarily require sprawl (Cheshire 2009). As discussed previously, in most urban regions (depending on a city's ability to expand), smart growth can accommodate 35-70% single-family or adjacent (townhouse) housing. Advocates of low-density development policies claim that nearly all households prefer sprawl neighborhoods (Bruegmann 2005: Kotkin 2013), citing consumer surveys which indicate that most households aspire to own a single-family home in a quiet neighborhood. However, more detailed analysis indicates that households also want smart growth attributes and will often choose more compact neighborhoods if they have suitable features (Levine, et al. 2002).

For example, the U.S. National Association of Realtors Community Preference Survey (NAR 2013) found that although most Americans prefer single-family homes and place a high value on privacy, they also desire the convenience of walkable, mixed-use communities with shorter commutes and convenient access to public services. When faced with trade-offs between specific attributes, a majority of respondents choose smaller-lot homes that provide shorter commutes and short walks to schools, stores and restaurants over large-lot houses in more automobile-dependent neighborhoods. Another survey found that households would prefer an urban townhouse over a suburban single-family home if they saved on average CA$130 per month in housing costs (Hunt 2001). This price incentive is comparable in magnitude to the public services savings provided by more compact development, as described later in this report, indicating that many households would choose smart growth locations in response to more efficient development and utility pricing.

Much of the preference for sprawl reflects economic and social factors, such as the perceived safety, affordability, public school quality, prestige and financial security of suburban neighborhoods, rather than physical features of sprawl, as summarized in Table 4. As a result, many households will choose smart growth neighborhoods if they are considered safe, convenient, attractive, and prestigious (Pembina 2014). Policies that make compact neighborhoods more attractive responds to these consumer demands, which benefit residents directly, in addition to the external benefits from reduced economic, social and environmental costs described later in this report.

Table 4
Attractions of Sprawl

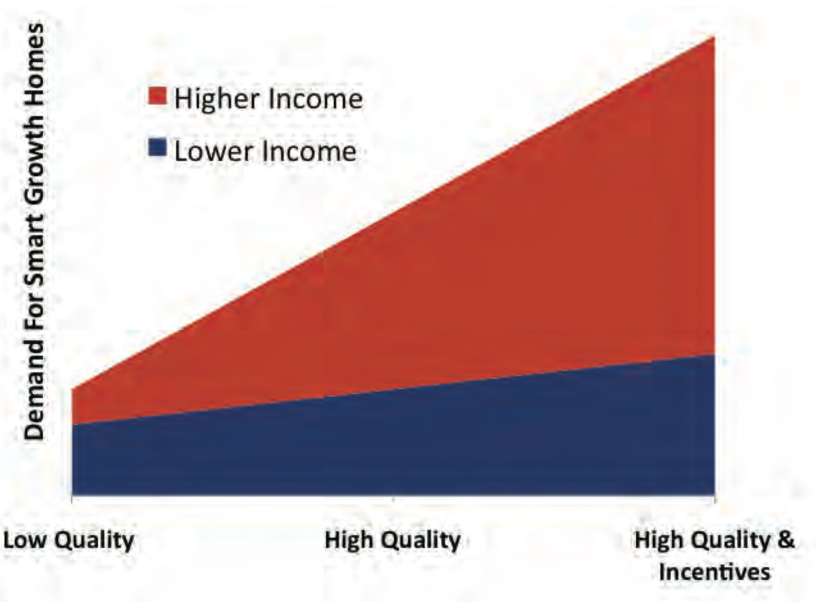
Physical Features	Economic and Social Features
• Lower land prices, allowing households to afford larger lawns and gardens • More privacy (more distance between homes) • More and cheaper parking	• Perceived safety • Less concentrated poverty and associated social problems • Better public services (e.g., schools) • More prestige

Many of the attractions of sprawl are economic and social factors that can be replicated in compact communities.

Single-family housing tends to be valued most by households with younger children that want outdoor play areas, or that have space-intensive hobbies such as gardening, large pets or vehicle repair. These demands can be served in smart growth communities with suitable features. For example, smart growth neighborhoods can include small-lot single-family and townhouses with yards, apartments with shared play areas and rooftop gardens, public parks and allotment gardens, plus studios, workshops and garages included in residential buildings or available for rent nearby.

Many policy and planning decisions can affect household location decisions. As residents become more affluent they demand higher quality housing. As a result, to be successful in economically developing cities smart growth must place more emphasis on housing quality and neighborhood livability, with high quality amenities such as parks and plazas, attractive sidewalks and streetscaping, high quality transit services, and incentives to encourage residents to choose resource efficient transport modes when possible. Pricing reforms, such as development charges and utility fees that reflect the costs of providing public infrastructure and services in specific locations, resulting in lower fees in compact neighborhoods, can attract more households to smart growth areas. Similarly, transport pricing reforms, such as efficient road and parking pricing, and employer-subsidized transit fares, can encourage residents to drive less and rely more on other transport modes.

Figure 7
Smart Growth Requires Suitable Quality and Incentives



Lower income households often choose compact housing out of necessity. Higher income households have the option of choosing sprawled location homes, so to be successful, smart growth must offer appropriate high quality compact housing and incentives that attract affluent households.

Table 5 lists various factors that affect the demand for sprawl, and ways that smart growth policies can respond to them. For example, many families choose sprawled housing so their children can attend better-ranking suburban schools. This creates a self-fulfilling prophecy by concentrating poverty and academically disadvantaged students in urban schools which further degrade their ranking. Smart growth policies can address this obstacle by improving urban school quality, for example, with targeted improvement programs and specialized “magnet” courses and curricula that attract highly-qualified students. Urban school improvement programs are justified for many reasons. Not only do they help achieve social equity objectives and reduce crime, by attracting more middle-class households to compact, multi-modal neighborhoods, they can also help reduce sprawl and its associated costs

Table 5
Factors That Affect The Demand For Sprawl

Factor	Smart Growth Policies
Demographics. Families with young children want larger houses with secure play areas.	Develop suitable housing options, including townhouses and apartments with numerous bedrooms and children's play areas.
Special space needs. Some households enjoy gardening or have hobbies or businesses that require extra space.	Design housing that incorporates or is located close to gardens (rooftop and allotment gardens), lofts, studios, workshops and garages.
Affordability. Housing tends to be cheaper in suburbs than urban neighborhoods.	Include affordable housing in smart growth neighborhoods. Reduce development fees, utility charges and taxes for smart growth locations, reflecting the lower costs of providing public services. Provide information on smart growth consumer savings.
Perception that public services (policing and schools) are better in suburban areas.	Improve public services, such as policing and schools, in urban neighborhoods.
Perceived safety of suburban locations.	Improve urban neighborhood safety and security. Reduce concentrated urban poverty. Provide information on smart growth safety and security benefits.
Relative accessibility.	Improve walking, cycling, public transit and carsharing. Reduce automobile travel subsidies, such as road, parking and vehicle fuel underpricing. Apply complete streets policies (design streets to accommodate all users) in urban neighborhoods.
Prestige of suburban locations and automobile travel.	Promote smart growth neighborhoods as safe, healthy, attractive places suitable for successful and happy households.

Many factors affect the demand for sprawl. Smart growth strategies can respond to those demands.

Box 1
Smart Growth Helps Generate Household Wealth

Real estate tends to appreciate in value. Vehicles tend to depreciate, and expenditures on vehicle operation (fuel, tire replacement, tolls, etc.) provide no durable assets. In addition, real estate in more accessible neighborhoods tends to retain its value better than in sprawled areas during real estate market declines, reflecting the value of urban accessibility (USEPA 2014). As a result, households tend to gain more long-term wealth by choosing smart growth over sprawl housing options. For example, in the short-term a smart growth house with a $20,000 annual mortgage and $5,000 annual transport expenses appears to have the same total costs as a sprawl location house with $15,000 annual mortgage and $10,000 transport expenses; both have $25,000 total annual expenses. However, after a decade the smart growth option, with higher housing and lower transport expenditures, typically generates $50,000 to $150,000 in additional household equity (wealth) compared with the sprawled location where $5,000 more is spent each year on vehicles and fuel rather than invested in real estate.

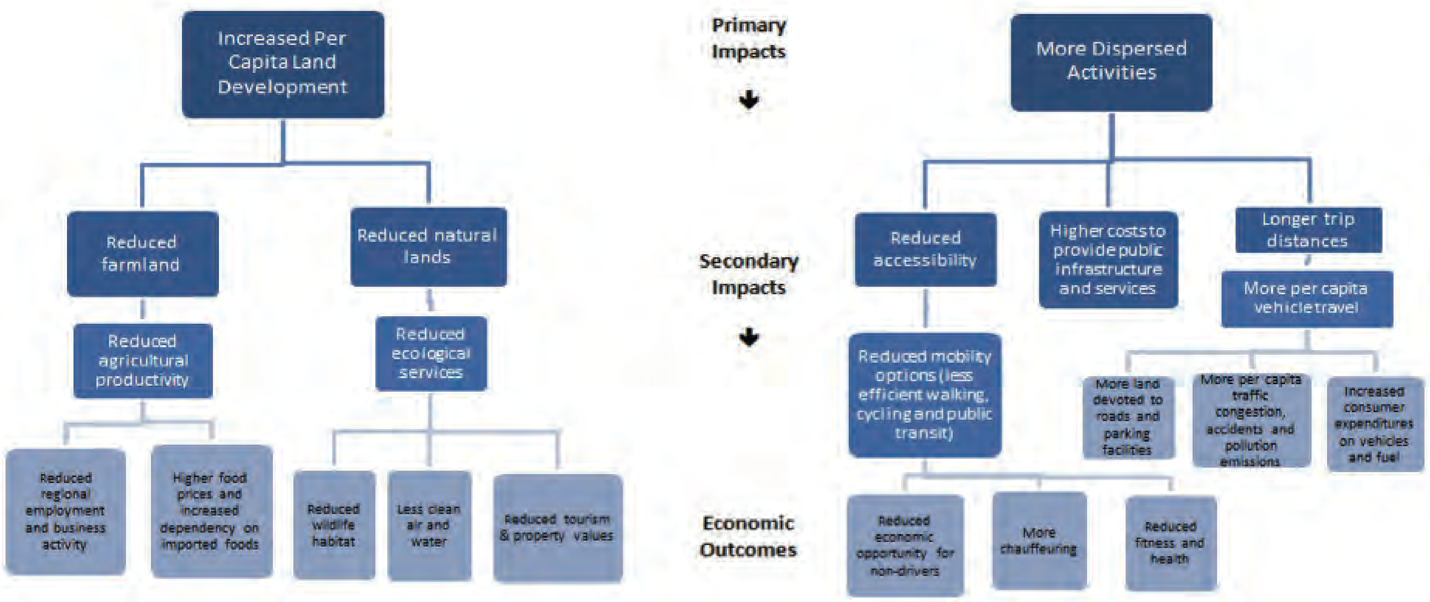
Source: USEPA (2014), Smart Growth And Economic Success: Investing In Infill Development, U.S. Environmental Protection Agency (www.epa.gov); at www.epa.gov/smartgrowth/pdf/economicsuccess/Developer-Infill-Paper-508b.pdf.

WHAT ARE THE INCREMENTAL COSTS AND BENEFITS OF SPRAWL?

This section describes various costs and benefits of sprawl, and factors that affect them.

Sprawl can have various economic, social and environmental impacts (benefits and costs). These result from two primary impacts: sprawl increases per capita land development, which reduces the amount of land available for openspace (farming and ecologically productive lands, and it disperses activities (homes, businesses, services, jobs, etc.), which increases infrastructure requirements (e.g., meters of roads and utility lines per capita) and the travel distances required to reach destinations, which, in turn, increases per capita motor vehicle travel. These have various economic outcomes such as reduced agricultural productivity, increased infrastructure and transport costs, and an increased need to import vehicles and fuel. Figure 8 illustrates these relationships.

Figure 8
Sprawl Resource Impacts



Sprawl has two primary resource impacts: it increases per capita land development, and it increased the distances between destinations, which increases per capita vehicle travel. These have various economic costs. This figure illustrates the relationships between these impacts.

Various studies have quantified and monetized (measured in monetary units) many of these impacts (Bartholomew, et al. 2009; Bhatta 2010; Burchell and Mukherji 2003; Ewing and Hamidi 2014; NHOEP 2012). Such studies vary in scope and methods. Some only consider infrastructure (road, utility, school, etc.) costs, while others also consider public service costs (emergency response, garbage collection, school busing, etc.). Some include transport costs (vehicle costs, accidents, fuel consumption and pollution emissions). Some include other economic, social and environmental impacts.

These studies also vary in geographic scale (neighborhood, city, region and country) and how sprawl is measured. Most studies have been performed in North America, since that is where debates about sprawl are most intense and suitable data most available. However, most of these economic impacts occur throughout the world so most of analysis results are transferable to developing countries, provided that they are scaled to reflect each city's demographic and geographic conditions.

The following section summarizes comprehensive sprawl cost studies and examines specific impacts in more detail.

Comprehensive Impact Studies

- A major study for the Transportation Research Board (a division of the U.S. National Academy of Sciences) titled, *The Costs of Sprawl – 2000* (Burchell, et al. 2002; Burchell and Mukherji 2003), identified various sprawl impacts, including:
  - Land conversion from farm and wild lands to housing and commercial development.
  - Water and sewage infrastructure.
  - Local roads.
  - Local public services.
  - Real estate development costs.
  - Increased vehicle travel and associated costs.
  - Residents' quality of life.
  - Urban decline (negative impacts on urban residents).

  The study monetized some of these impacts and estimated the net savings if growth management were applied in the U.S. between 2000 and 2025. Under a managed growth scenario a major portion of potential rural county development is shifted to urbanized counties, densities increase 20%, and the portion of households in attached (townhouse) and multi-family (apartment) housing increases by a quarter. The analysis indicates that managed growth reduces land consumption by 21% (2.4 million acres), reduces local road lane-miles 10%, reduces annual public service costs about 10% and housing costs about 8%, saving on average $13,000 per dwelling unit, or 7.8% of total development costs. This analysis only considers relatively modest smart growth policies (most new housing continues to be single-family) and so represents a lower-bound estimate of potential savings.

- The report, *The High Costs of Sprawl: Why Building More Sustainable Communities Will Save Us Time and Money*, (Environmental Defense 2013) identified various external costs of sprawl including higher infrastructure costs, loss of open space and farmland, increased driving and related health problems, increased air pollution emissions, and reduced community cohesion (positive interactions among neighbors). It calculates the costs of sprawled development and compares this with current development cost charges in various jurisdictions; it concludes that these fees fail to reflect the full incremental costs of sprawl, resulting in taxpayers in existing communities paying the additional costs of new sprawled development. It emphasizes the unfairness that results from these cross subsidies and external costs.

- The Utah's Governor's Office used an integrated transportation and land use impact model to predict regional, subregional and on-site infrastructure costs of various development scenarios in the Salt Lake City region. The results indicate that more compact and multi-modal development options, typically reduce total per capita land consumption 39%, water consumption 25%, infrastructure by 39%, and air pollution by 6%, as well as improving mobility options for non-drivers. *Utah's Governor's Office (2003), Municipal Infrastructure Planning and Cost Model User's Manual,* Utah Governor's Office of Planning and Budget (www.governor.state.ut.us); at www.governor.state.ut.us/planning/mipcom.htm. Also see www.fhwa.dot.gov/planning/toolbox/utah_methodology_infrastructure.htm.

- The report, *Suburban Sprawl: Exposing Hidden Costs, Identifying Innovations* (SP 2013), identified various government costs that tend to increase with sprawl (construction and maintenance of roads, sewers, water, community centres and libraries, plus fire protection, policing, and school busing) and compared the incremental costs with the incremental tax revenues. It concluded that incremental revenues from suburban developers and households rarely cover the full incremental costs of the new infrastructure. It also discussed various economic benefits of more compact development, including cost savings, agglomeration efficiencies, and support for social equity objectives.

- The report, *Measuring Sprawl*, calculated a Sprawl Index (although, since ratings increase with more compact development, it would be more accurate to call it a Smart Growth Index) score for 221 U.S. metropolitan areas and 994 counties based on four factors: density (people and jobs per square mile), mix (combination of homes, jobs and services), roadway connectivity (density of road network connections) and centricity (the portion of jobs in major centers). The index averages 100, so scores below 100 indicate sprawl and above 100 indicate smart growth. The table below summarizes the study's key results.

Table 6
Summary of Smart Growth Outcomes

Outcome	Relationship to Compactness	Impact of 10% Score Increase
Average household vehicle ownership	Negative and significant	0.6% decline
Vehicle miles traveled	Negative	7.8% to 9.5% decline
Walking commute mode share	Positive and significant	3.9% increase
Public transit commute mode share	Positive and significant	11.5% increase
Average journey-to-work drive time	Negative and significant	0.5% decline
Traffic crashes per 100,000 population	Positive and significant	0.4% increase
Injury crash rate per 100,000 population	Positive and significant	0.6% increase
Fatal crash rate per 100,000 population	Negative and significant	13.8% decline
Body mass index	Negative and significant	0.4% decline
Obesity	Negative and significant	3.6% decline
Any physical activity	Not significant	0.2% increase
Diagnosed high blood pressure	Negative and significant	1.7% decline
Diagnosed heart disease	Negative and significant	3.2% decline
Diagnosed diabetes	Negative and significant	1.7% decline
Average life expectancy	Positive and significant	0.4% increase
Upward mobility (probability a child born in the lowest income quintile reaches the top quintile by age 30)	Positive and significant	4.1% increase
Transportation affordability	Positive and significant	3.5% decrease in transport costs relative to income
Housing affordability	Negative and significant	1.1% increase in housing costs relative to income.

Source: Ewing and Hamidi 2014
This table summarizes various economic, health and environmental impacts from more compact development.

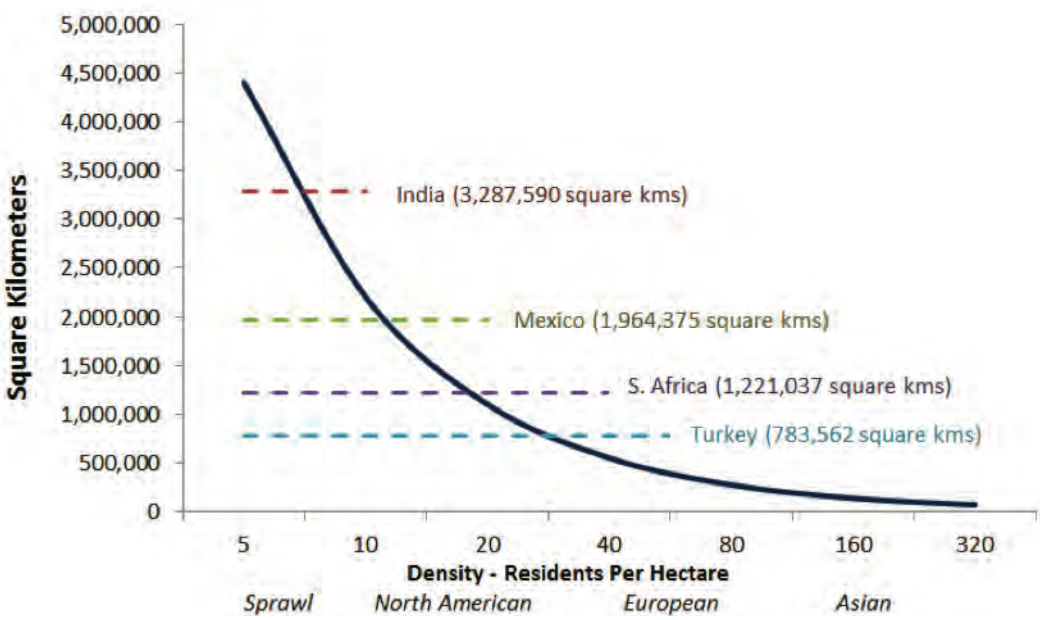
- A detailed study for Halifax, Nova Scotia (Stantec 2013) found that the most compact development scenario, which increased the portion of new housing located in existing urban centers from 25% to 50%, with reductions in suburban and rural development, reduced infrastructure and transportation costs by about 10%, and helped achieve other social and environmental objectives including improved public fitness and health, and reduced pollution emissions.

The following sections discuss specific categories of impacts.

Land Development

Land is a valuable and scarce resource. Sprawl increases the amount of land developed per capita. For example, at 5 residents per hectare, which is typical for North American suburbs, each resident uses about ten times as much land as in European cities with 50 residents per hectare, and 100 times as much land as residents of high-density Asian cities. These impacts can be significant. For example, at typical sprawl densities of 5 residents per hectare, the 2.2 billion new urban residents expected in developing countries would require 4,400,000 square kilometers, which is more than the area of India (3,287,590 square kilometers), but at smart growth densities of 50 residents per hectare they require a much smaller 440,000 sq. kms, as illustrated in Figure 9.

Figure 9
Land Needed to Accommodate 2.2 Billion People At Various Densities



At sprawled densities, housing 2.2 billion new urban residents requires more land than the total area of India. Smart growth policies can reduce development area, leaving more land for farms and other openspace.

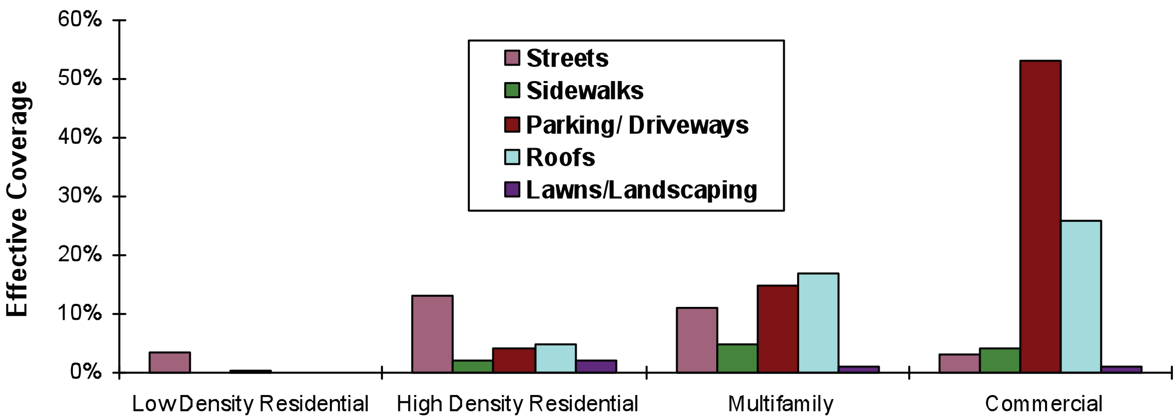
We sometimes say that sprawl consumes land but this is not really accurate since the land still exists after development occurs, but it is changed in ways that reduce some important benefits. Development displaces open space such as farmland, wetlands, parks and forests, and sometimes culturally significant sites. In addition to direct impacts, development can reduce the productivity of nearby lands, for example, by disrupting farming activities, disturbing wildlife, contaminating groundwater, and driving up land prices beyond what local residents can afford. This tends to reduce agricultural productivity and ecological services such as groundwater recharge, wildlife habitat, recreation and aesthetic values, which in turn, can require more expensive potable water sources or reduce economic activities such as tourism. Cities are often located in areas with highly productive farmlands, unique ecological lands, and important cultural sites, so these impacts can be large.

In addition to its direct benefits to owners, open space provides various external benefits to society (Harnik and Welle 2009; Litman 2009; McConnel and Walls 2005). Undeveloped natural lands such as shorelines, forests and deserts tend to provide the greatest ecological benefits, including wildlife habitat, groundwater recharge and aesthetic values. Farms provide agricultural productivity. Gardens and lawns provide modest ecological benefits since they support fewer wildlife species and usually have significant fertilizer and pesticide contamination. Impervious surfaces such as buildings, parking lots and roadways provide the least environmental benefits: they increase stormwater management costs and heat island effects (they absorb sunlight which increases ambient temperatures). These negative impacts can be reduced somewhat with design features such as rooftop gardens, street trees and pervious pavements, but this does not eliminate the importance of open space preservation. Below is a ranking of external benefits of various land use types.

Ranking of External Value of Land Use Types (McConnel and Walls 2005)
1. Shorelands and wetlands such as lake and marshes.
2. Unique natural lands such as forests and deserts, and cultural sites.
3. Farmlands
4. Parks and gardens
5. Lawns
6. Impervious surfaces (buildings, parking lots and roads)

Smart growth tends to reduce development area but increases its intensity, as indicated by the portion of land that is impervious surface. Described differently, smart growth tends to reduce land use impacts per capita but increases impacts per hectare of developed land. Figure 10 illustrates the impervious surface coverage of various land uses. Impervious surface typically represents 5-10% of land in suburban areas, 20-30% of land in compact urban neighborhoods, and 40-60% of land in dense commercial centers.

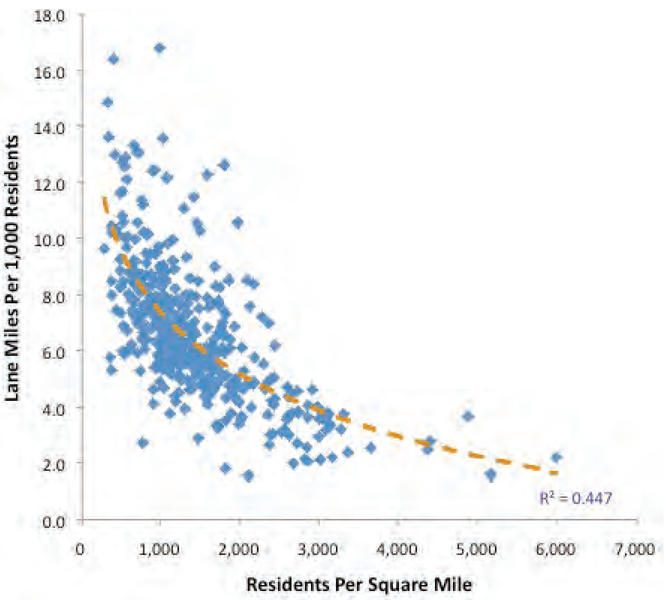
Figure 10
Surface Coverage



Arnold and Gibbons 1996
This figure illustrates land coverage in various urban conditions.

Sprawl tends to increase per capita road and parking area. Figure 11 shows how per capita lane-miles tend to decline with increased density. U.S. cities with less than 1,000 residents per square mile (approximately 8 residents per hectare) have nearly three times as much roadway area per capita as denser cities with more than 4,000 residents per square mile (approximately 30 residents per hectare). This suggests that sprawled communities require approximately 55 square meters of road area per motor vehicle, compared with 19 square meters in smart growth communities.

Figure 11
Urban Density Versus Roadway Supply

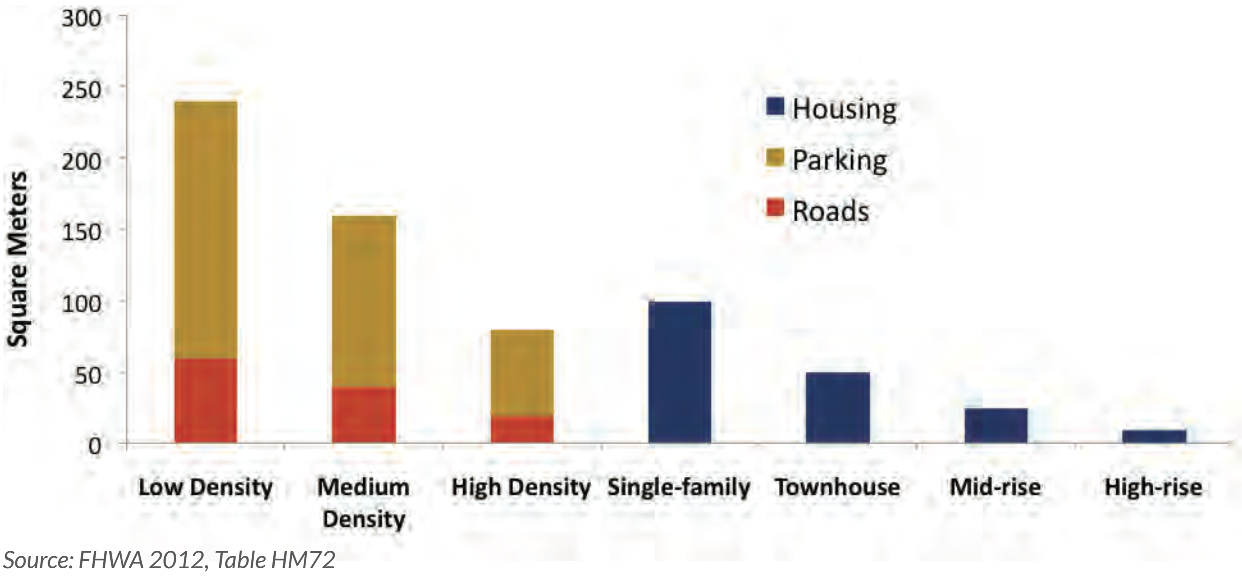


Source: FHWA 2012, Table HM72
As urban densities decline, per capita roadway increases. This increases infrastructure costs, hydrologic and stormwater management costs and environmental impacts. (Each dot represents a U.S. urban region.)

Motor vehicles also require parking facilities at each destination. A typical parking space is 2.4-3.0 meters wide and 5.5-6.0 meters deep, totaling 13 to 19 square meters ("Parking Costs," Litman 2009; ULI 2014). Off-street parking also requires driveways (connecting the parking lot to a road) and access lanes (for circulation within a parking lot), and so typically requires 28 to 37 total square meters per space. Various studies have estimated the number of parking spaces in a community (McCahill and Garrick 2012). Using detailed aerial photo analysis of Midwest urban areas, Davis, et al. (2010) estimated there are 2.5 to 3.0 off-street, non-residential parking spaces per motor vehicle. This represents a lower-bound estimate because it excluded residential, structured and covered parking. This and other studies suggest that in sprawled areas there are 2 to 6 off-street parking spaces per vehicle, using 60 to 200 square meters of land, with lower rates in smart growth areas where parking facilities are managed for efficiency. More compact, multi-modal development tends to reduce motor vehicle ownership, typically by 20-50% (Arrington and Sloop 2008), and allows more efficient parking management, such as more use of shared facilities that serve multiple destinations rather than single use parking lots (USEPA 2006). As a result smart growth development can significantly reduce per capita parking requirements.

This suggests that for convenient driving and parking, compact urban areas must devote 20 square meters of land to roads and 60 square meters to parking (two off-street parking spaces), totaling 80 square meters per vehicle. Sprawled areas must devote about 60 square meters to roads and 180 square meters to parking (six off-street parking spaces), totaling 240 square meters per vehicle, which is more than the amount of land typically devoted to an urban house, as illustrated in Figure 12.

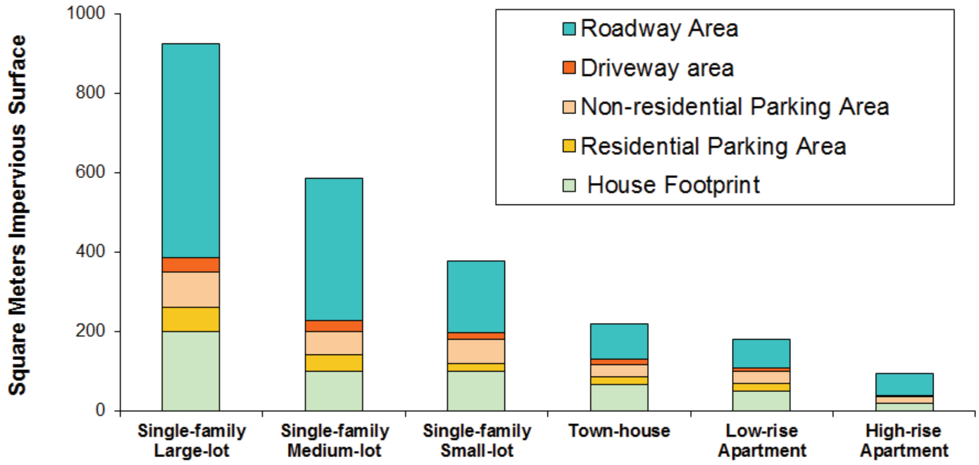
Figure 12
Urban Density Versus Roadway Supply



Source: FHWA 2012, Table HM72
In high density urban areas each automobile requires about 80 square meters of land for roads and off-street parking facilities. In lower-density, sprawled areas each automobile requires about 240 square meters of land for roads and parking, which significantly exceeds the amount of land devoted to most urban houses.

Figure 13 indicates total land area typically required for various housing types that provide the same 200 square meters of interior floor area. This illustrates how factors such as development density, building type, vehicle ownership, parking and road supply affect per capita impervious surface coverage.

Figure 13
Impervious Surface Area Of Various Housing Types

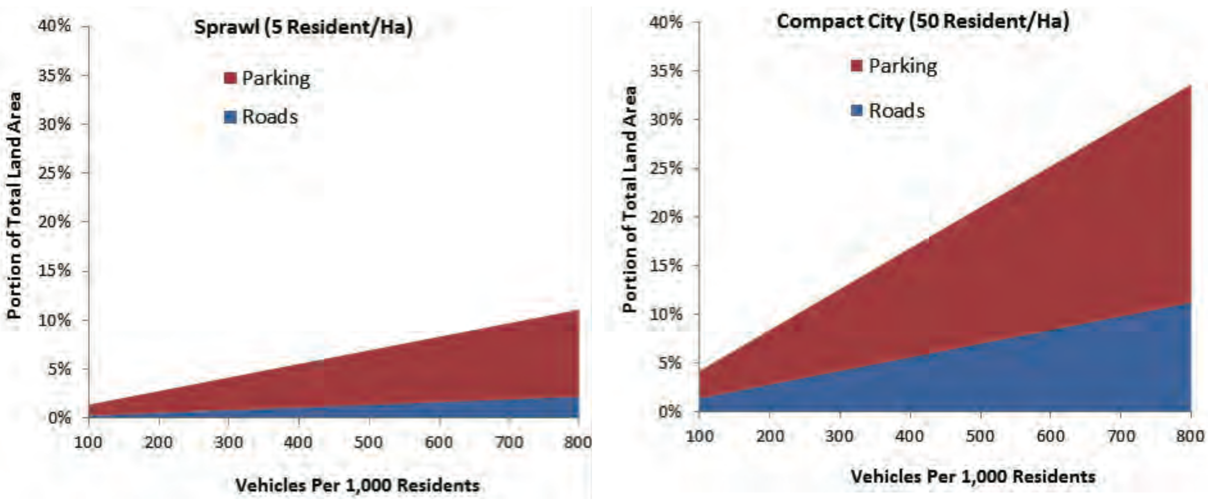


Source: Litman 2011b

Sprawl tends to increase per capita impervious surface (buildings and pavement) by encouraging lower larger building footprints and requiring more parking and roadway supply.

Because automobiles require so much land for roads and parking facilities, reducing vehicle ownership rates is a key strategy for reducing per capita land consumption. Figure 14 illustrates how the portion of urban land devoted to roads and parking increases with per capita vehicle ownership. This impact is particularly significant in compact cities where high vehicle ownership rates requires a major portion of land to be paved for roads and parking facilities. This reduces the amount of land available for building and greenspace, imposing economic and environmental costs.

Figure 14
Portion of Land Used for Roads and Parking[2]



The portion of land devoted to roads and parking increases with vehicle ownership, which reduces the amount of land available for housing and urban greenspace. This impact is particularly significant in compact cities.

2 Assumes each vehicle requires 55 m2 of roads and 222 m2 of parking in sprawled areas, and 28 m2 of roads and 56 m2 of parking in compact cities.

A common justification for sprawl is that it increases residents' access to "nature" (open space). Sprawl advocates sometimes argue that urban living results in "nature deficit disorder." However, smart growth does include open space, including local and regional public parks, street trees and preserved farmlands. Although sprawl residents may have more private open space, they displace more total open space per capita, so sprawl residents can be considered to consume nature while smart growth residents preserve nature, resulting in more open space overall.

Open space external benefits are well recognized, including agricultural productivity, wildlife habitat, stormwater percolation, and support for tourism. The loss of these benefits can sometimes be quantified and monetized based on direct economic costs, such as reduced agricultural production or tourism activity, or increased stormwater management costs, or based on the value nearby residents place on greenspace (Banzhaf and Jawahar 2005; EDRB 2007; Litman 2009; McConnel and Walls 2005). However, there is no standard method for measuring total open space displacement costs. These costs tend to be particularly high for development that degrades high value farmlands, productive natural lands, or unique cultural sites."

Public Infrastructure and Service Costs

Dispersed development tends to increase the per capita length of roads and utility lines (water, sewage, power, etc.), and the travel distances needed to provide public services (garbage collection, policing, emergency response, etc.). Rural residents tend to accept lower service quality (unpaved roads, slower emergency response times, etc.) and provide many of their own services (well water, septic systems, garbage disposal, etc.), but suburban development tends to attract residents who demand urban quality services in dispersed locations, which increases government cost burdens (Stantec 2013). Various studies have quantified these costs.

- Burchell and Mukherji (2003) found that sprawl increases local road lane-miles 10%, annual public service costs about 10%, and housing costs about 8%, increasing total costs an average of $13,000 per dwelling unit, or about $550 in annualized costs.
- A Charlotte, North Carolina study found that a fire station in a low-density neighborhood with disconnected streets serves one-quarter the number of households at four times the cost of an otherwise identical fire station in a more compact and connected neighborhood (CDOT 2012).
- In a detailed analysis of 2,500 Spanish municipalities' expenditures, Rico and Solé-Ollé (2013) found that lower-density development patterns tend to increase per capita local public service costs.
- The Delaware Valley Regional Planning Commission (DVRPC 2003) estimated the infrastructure costs of five alternative development scenarios for the Philadelphia region. They found that roads, schools and utilities would cost $25,000 per household for the most compact scenario, 44% less than the $45,000 required by the most sprawled scenario. The compact option provides approximately $850 in annual savings per household.
- Analysis of options for accommodating 1.25 million additional residents and 800,000 additional jobs in Central Texas found $3.2 billion ($2,560 per capita) lower infrastructure costs if development is concentrated in existing urban areas, 70% less than the $10.7 billion ($8,560 per capita) required if lower-density development trends continue (Envision Central Texas 2003).
- Using data from three U.S. case studies, the study, Smart Growth & Conventional Suburban Development: Which Costs More? (Ford 2010) found that more compact residential development can reduce infrastructure costs by 30-50% compared with conventional suburban development.
- More compact development could save Calgary, Canada about a third in capital costs and 14% in operating costs for roads, transit services, water and wastewater, emergency response, recreation services and schools (IBI 2008).
- Building Better Budgets: A National Examination of the Fiscal Benefits of Smart Growth Development (SGA 2013) found that smart growth development costs one-third less for upfront infrastructure costs and saves an average of 10% on ongoing public services costs.
- The Utah Governor's Office (2003) sponsored the Municipal Infrastructure Planning and Cost Model (MIPCOM), an easy-to-use spreadsheet model that estimates how factors such as development location and density affect various costs including regional (regional roads, transit and water supply facilities), subregional (water, sewage and stormwater networks, and minor arterials) and on-site infrastructure (local roads, water and sewer lines, stormwater systems, telephone, electricity, etc.).

These relationships are complex (Ewing 1997). Denser, infill development can increase some costs due to higher design standards and infrastructure development costs in dense areas, and sometimes brownfield remediation (cleaning up hazardous conditions such as polluted soils), but such costs are not significantly related to development density. A tall building has similar utility connection and brownfield remediation costs as a smaller building, so unit costs often decline with smart growth policies that allow higher densities. Critics argue that sprawl infrastructure costs are exaggerated (Cox and Utt 2004; Richardson and Gordon 1997), citing studies which indicate that per capita government expenditures are often higher in higher-density counties, although such aggregate analyses do not account for important factors such as the tendency of rural residents to supply their own utilities and services (such as water, sewage and garbage collection), and incomes (including those for municipal employees which tend to be higher in larger cities, so urban-rural differences are smaller when measured as a portion of income), and the additional public service costs borne by cities because they contain a disproportionate share of businesses and low income residents (Litman 2015). In addition, such aggregate analysis, which only considers population density at a jurisdictional scale, does not accurately reflect smart growth policies which include other factors related to the location and type of development that occurs within a jurisdiction. Two cities or counties can have the same overall density but differ significantly to the degree that they reflect smart growth principles. If evaluated at an aggregate scale, any smart growth public service cost savings would be invisible.

This review indicates that numerous credible studies demonstrate that sprawl typically increases the costs of providing a given level of infrastructure and public services by 10-40%, and sometimes more. These studies reflect lower-bound impacts since most only consider a subset of total public service costs and relatively modest smart growth policies, such as more compact single-family development, as opposed to substantial shifts from single-family to multi-family housing. Comprehensive smart growth policies that result in greater density increases can provide even larger savings and efficiency benefits.

Transportation Costs

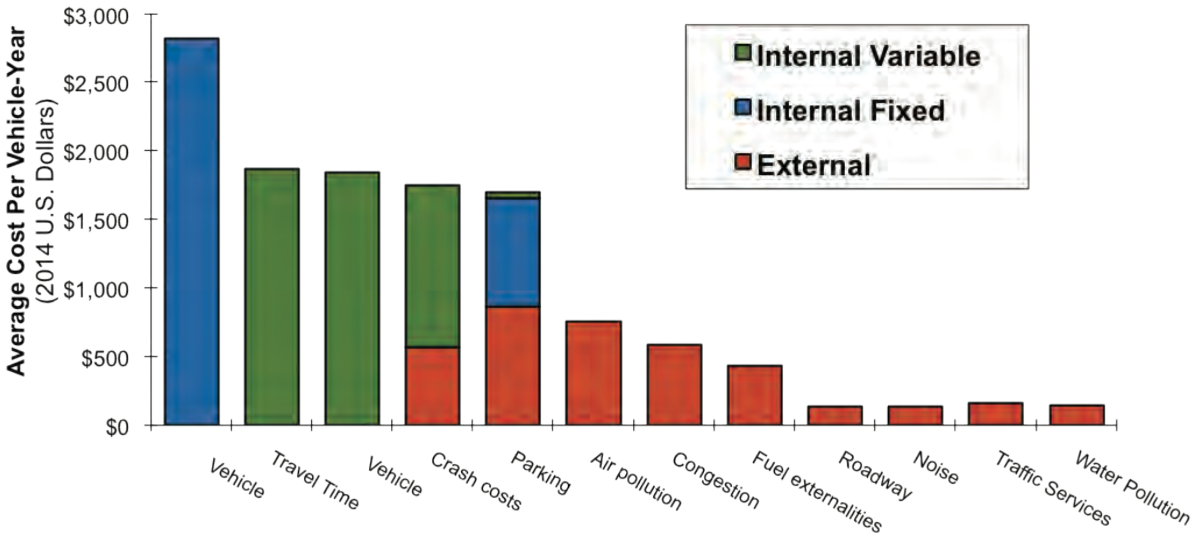
Sprawl increases the distances that must be traveled to reach activities and reduces the efficiency of walking and public transit, and so tends to increase per capita vehicle travel (CTS 2010; Rode and Floater 2014). It typically increases motor vehicle travel 20-50%, and reduces walking, cycling and public transit use by 40-80%, compared with compact, multi-modal development (Ewing and Cervero 2010; JICA 2011; Mackett and Brown 2011; Marshall and Garrick 2012; USEPA 2013; Zhang, et al. 2012).

To understand how these development patterns affect travel activity, consider how residents make common trips. In sprawled communities, most trips are made by automobile due to inadequate alternatives and dispersed destinations. Smart growth communities have more diverse transport systems and shorter distances between destinations so most local errands are made by walking and cycling, many trips along major travel corridors are made by public transit, and trips are shorter. As a result, smart growth community residents typically drive 20-60% fewer annual kilometers than in sprawled, automobile-dependent areas.

The increased vehicle travel in sprawled communities increases various costs (Ewing, et al. 2007). For example, Ewing and Hamidi (2014) find that a 10% change in their sprawl index increases household transport expenditures 3.5% and auto commute travel time 0.5. Kuzmyak (2012) found that households in more compact, mixed neighborhoods experience less traffic congestion delay than residents of sprawled neighborhoods. Conventional transport economic evaluation tends to overlook many of these impacts and so underestimates the full costs of policies that increase vehicle travel. For example, when evaluating transport or land use policies, conventional evaluation usually ignores the incremental road and parking facility costs caused by planning decisions that stimulate vehicle ownership and use, and so underestimates the benefits of improving alternative modes and more compact development.

Several studies have monetized these costs (Becker, Becker and Gerlach 2012; Litman, 2009; Maibach, et al. 2009; Park 2009; Timilsina and Dulal 2011; Zhang, et al., 2005), including some in developing countries (Adaku 2014; JICA 2011; Zegras 1997). Figure 15 illustrates one comprehensive estimate. These costs are classified as internal-fixed (vehicle ownership and residential parking), internal-variable (travel time, vehicle operation and vehicle occupants' uncompensated crash injuries), and external costs (accident risk, congestion, parking costs and environmental damages imposed on other people).

Figure 15
Estimated Urban Automobile Costs



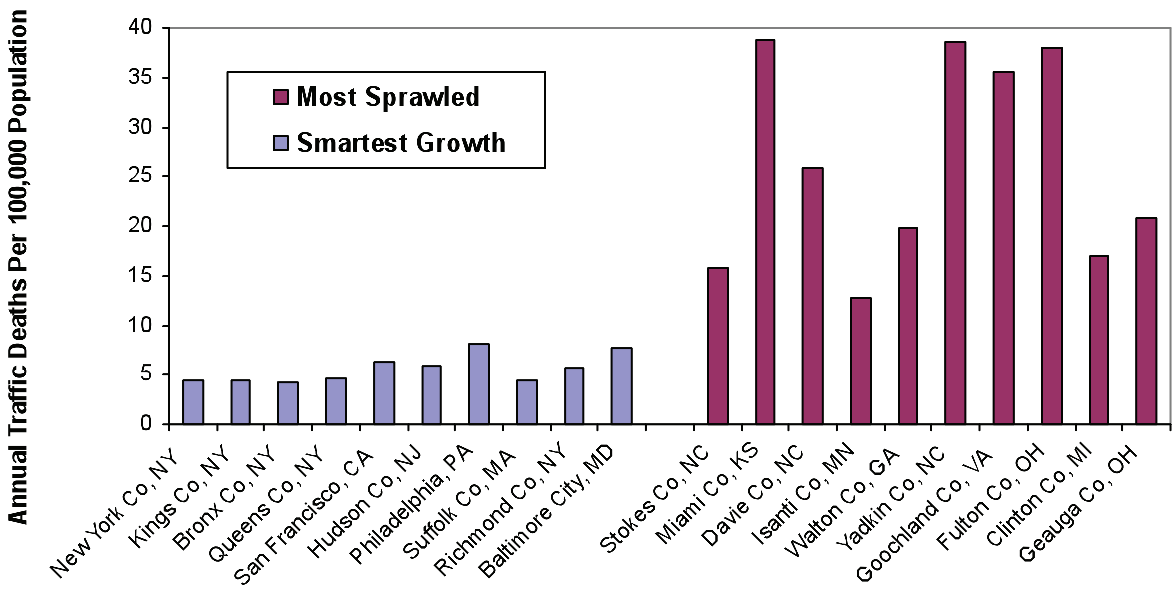
Source: based on Litman 2009
This figure illustrates the estimated costs of motor vehicle ownership and use.

These studies indicate that motor vehicle ownership has fixed costs that average $2,000-4,000 per vehicle-year, internal-variable costs (vehicle operation, travel time and users' accident risk) that average 20-50¢ per vehicle-kilometer, plus external costs (parking subsidies, crash risks imposed on other road users, congestion, air and noise pollution, and roadway costs not borne by user fees) that average 20-60¢ per vehicle-kilometer, with higher external costs under urban-peak conditions. Some of these costs may be somewhat lower in developing countries. Sprawl impacts on traffic safety and health are discussed in more detail below.

Traffic Risk

One particularly important transport cost is traffic accident risk. Various studies using a variety of analysis methods and data sets indicate that sprawl increases traffic casualty (injury and death) rates. For example, comparing 280 U.S. counties, per capita traffic fatality rates are about five times higher in the ten most sprawled counties compared with the ten smartest growth counties, as indicated in Figure 16.

Figure 16
Annual Traffic Death Rate



Source: Ewing, Schieber and Zegeer 2003
The ten counties with the lowest sprawl rating have about a quarter of the per capita annual traffic fatality rates of the most sprawled counties.

Ewing and Hamidi (2014) found that a 10% increase in their smart growth index reduces per capita crash fatality rates by 13.8%. Dumbaugh and Rae (2009) analyzed crash rates in San Antonio, Texas neighborhoods. Accounting for various demographic and geographic factors they found that:

- Increased vehicle travel tends to increase crash rates, with approximately 0.75% more crashes for every additional million miles of vehicle travel in a neighborhood.
- Population density is significantly associated with fewer crashes, with each additional person per net residential acre decreasing crash incidence 0.05%.
- Each additional mile of arterial roadway is associated with a 15% increase in total crashes.
- Each additional arterial-oriented retail or commercial parcel increased total crashes 1.3%, and each additional big box store increased total crashes 6.6%, while pedestrian-scaled commercial or retail uses were associated with a 2.2% reduction in crashes.
- The numbers of both young and older drivers were associated with increased total crashes.
- Each additional freeway mile within a neighborhood is associated with a 5% increase in fatal crashes, and each additional arterial mile is associated with a 20% increase in fatal crashes.

Scheiner and Holz-Rau (2011) find considerably higher per capita crash injury rates in suburban and rural locations than in urban areas in Germany. Evaluating factors that affect crash rates in California cities, Garrick and Marshall (2011) found that more compact, connected and multi-modal urban areas have about a third of the traffic fatality rates as those that are more sprawled, automobile dependent.

Safer Cities

- 106/sq mile average intersection density.
- 16% walking/biking/transit mode share.
- 3.2 average annual traffic deaths per 100,000 population.

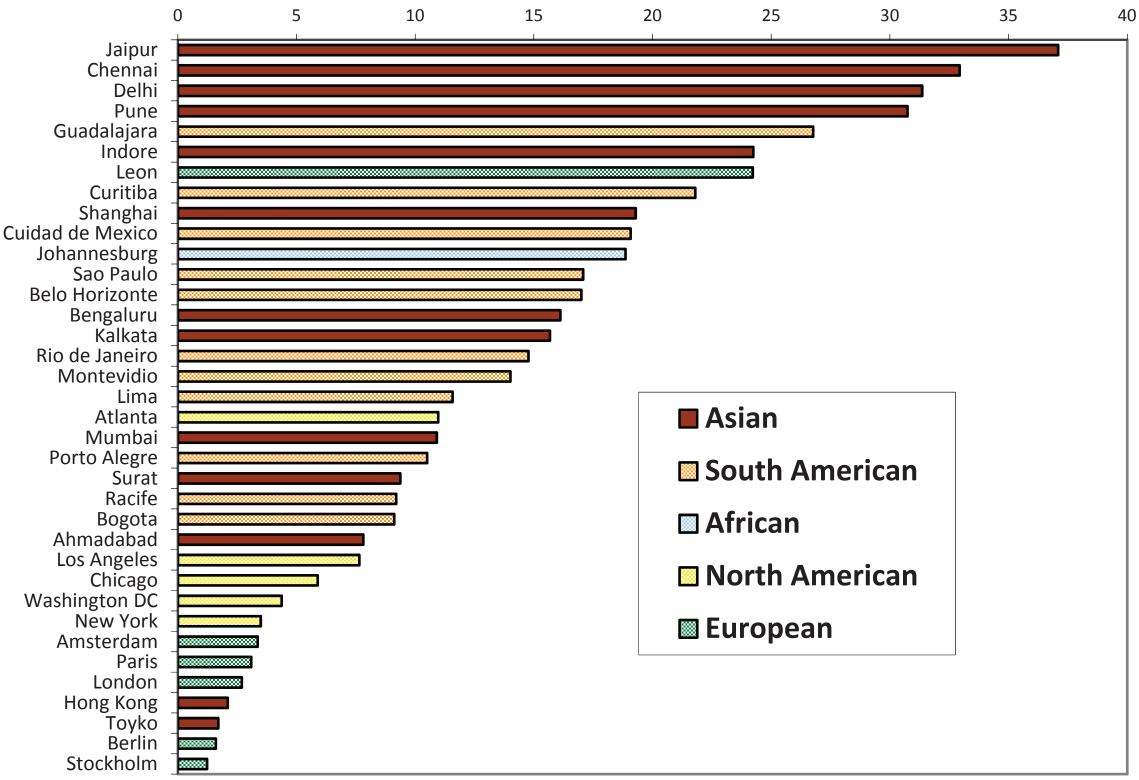
Less Safe Cities

- 63/sq mile average intersection density.
- 4% walking/biking/transit mode share.
- 10.5 average annual traffic deaths per 100,000 population.

Several factors help explain why sprawl causes such large increases in crash casualty rates. Sprawl increases total vehicle travel, including higher-risk driving (youths, seniors, alcohol drinkers, etc.) because they lack alternative mobility options. Sprawl also increases traffic speeds, which increases the severity of crashes which occur, and increases emergency response times.

Traffic casualty rates tend to be particularly high in lower-income countries and decline with economic development. Figure 17 compares traffic fatality rates of various world cities. Most lower-income cities have more than 20 deaths per 100,000 residents, compared with 10-20 deaths in North American cities, and fewer than 5 deaths in high-income European and Asian cities.

Figure 17
Traffic Death Rates For Selected Cities

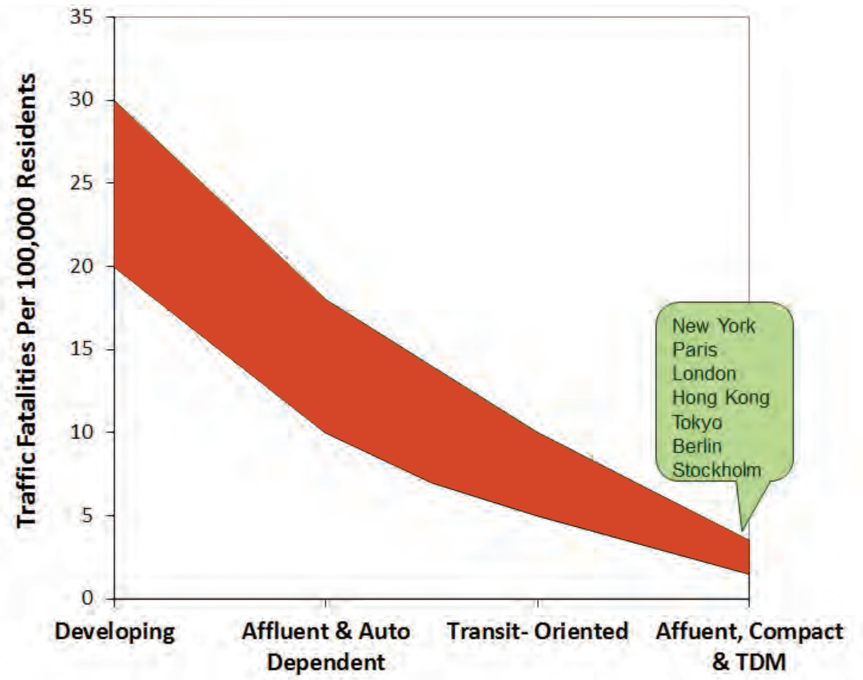


Source: Welle 2014

Traffic fatality rates tend to be highest in lower-income cities and decline as they develop economically, but the amount they decline depends on transport and land use policies. The lowest fatality rates occur in affluent cities with aggressive policies that limit automobile traffic, such as Berlin, Hong Kong, London, Stockholm and Tokyo.

This indicates that, all else being equal, sprawl increases traffic risk. Sprawled areas typically have two to five times the traffic fatality rates as in smart growth communities Very low crash casualty rates (under 5 annual traffic fatalities per 100,000 residents) generally require a combination of smart growth development and transportation demand management strategies, as indicated in Figure 18.

Figure 18
Traffic Deaths Trends



Traffic fatalities per 100,000 residents typically average 20-30 in developing country cities, 10-20 in affluent, automobile-dependent cities, 5-10 in affluent, compact cities, and just 1.5-3 in affluent, compact cities with strong transportation demand management (TDM) programs.

There is extensive literature on traffic crash costs (Blincoe, et al. 2014; EDRG 2007; Litman 2009; Zhang, et al. 2005). Some studies only consider direct economic costs, such as vehicle damages, emergency response, medical and disability expenses, and lost productivity due to crashes; others also include pain and suffering, which results in substantially higher cost estimates. Described differently, the value of preventing accidents tends to be much higher than economic damages or compensation costs of accidents that occur. In 2009, the U.S. Department of Transportation valued a statistical life at $6.0 million, with lower values for various types of non-fatal crashes (Trottenberg 2011). A major portion of these costs are external (i.e., borne by somebody other than the individual making a travel decision), although there is some debate concerning how these externalities should be calculated (Edlin and Mandic 2001). Total crash costs are estimated to range from about 10¢ to 30¢ per vehicle-kilometer in developed countries, and can be scaled to other countries based on incomes (IRAP 2009).

Public Fitness and Health

Sprawl tends to increase sedentary living, and therefore obesity rates and associated health problems (Frumkin, Frank and Jackson 2004; WHO 2013). Although there are many possible ways to exercise, one of the most effective ways to increase physical fitness by at-risk people (people who are sedentary and overweight) is to improve active transport (walking and cycling) conditions (Ball, et al. 2009; CDC 2009).

Frank, et al. (2010) measured how neighborhood walkability factors affect residents' travel activity, physical activity and fitness. They found that after normalizing for other factors:

- Adults living in the top 25% most walkable neighborhoods walk, bike and take transit 2-3 times more, and drive approximately 58% less than those in more auto-oriented areas.
- Residents living in the most walkable areas were half as likely to be overweight than those in the least walkable neighborhoods.
- Living in a neighbourhood with at least one grocery store was associated with a nearly 1.5 times likelihood of getting sufficient physical activity, as compared to living in an area with no grocery store, and each additional grocery store within a 1-kilometer distance from an individual's residence was associated with an 11% reduction in the likelihood of being overweight.

A ten-year study found that the overall health of residents improved when they moved to more compact, walkable urban neighborhoods (Giles-Corti, et al. 2013). The study examined the impact of urban planning on active living in metropolitan Perth, Western Australia. The study found that for every local shop, residents' physical activity increased an extra 5-6 minutes of walking per week, and for every recreational facility available such as a park or beach, residents' physical activity increased by another 21 minutes per week. Ewing and Hamidi (2014) found a significant, positive correlation between smart growth and longevity: each 10% increase in their compactness index is associated with a 0.4% increase in lifespans. For the average American with a life expectancy of 78 years, doubling the index translates into a three year difference. However, increased urban densities can increase some health risks such as exposure to noise and local air pollutants. Public safety and health therefore justifies smart growth strategies that create communities where residents drive less and rely more on active modes, plus targeted strategies to reduce urban noise and air pollution emissions.

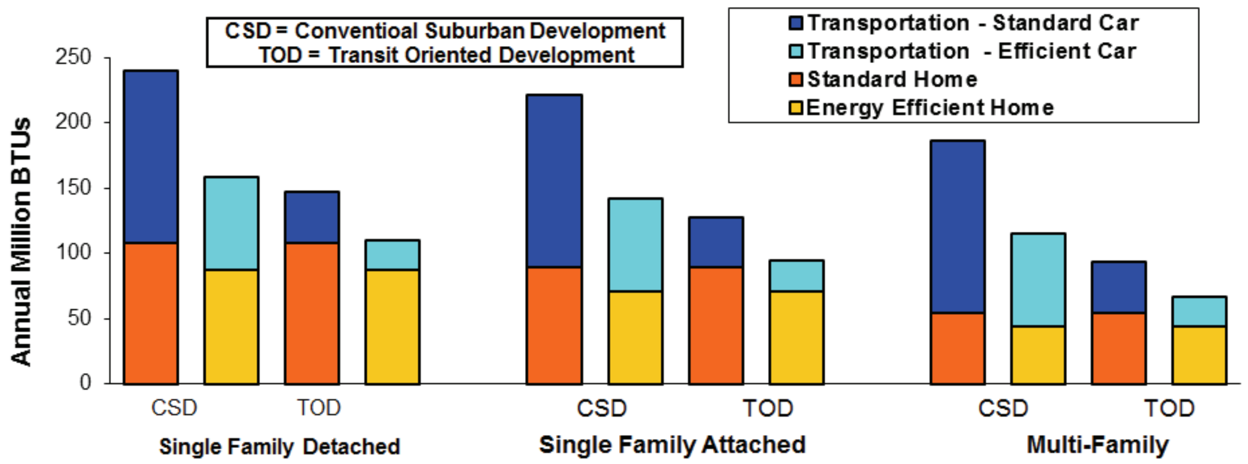
Overall, sprawled community residents are less safe and healthy than in smart growth communities (Lucy 2003; Myers, et al. 2013).

Various studies have monetized active travel health benefits (Ball, et al. 2009; Fishman, et al. 2012). Applying values of statistical life commonly used to calculate crash casualty costs indicates that each additional kilometer of walking and cycling provides $1.00 to $3.00 in health benefits (WHO 2014).

Energy Consumption and Pollution Emissions

By increasing motor vehicle travel, building heating requirements (due to more single-story buildings) and infrastructure energy requirements (e.g., longer utility lines which increases embodied energy, water and sewage pumping loads, street lighting, etc.) sprawl tends to increase per capita energy consumption and associated pollution emissions (Ewing and Rong 2008; Lefèvre 2009; Litman 2011). Figure 19 illustrates one estimate of how housing type affects energy consumption in U.S. conditions.

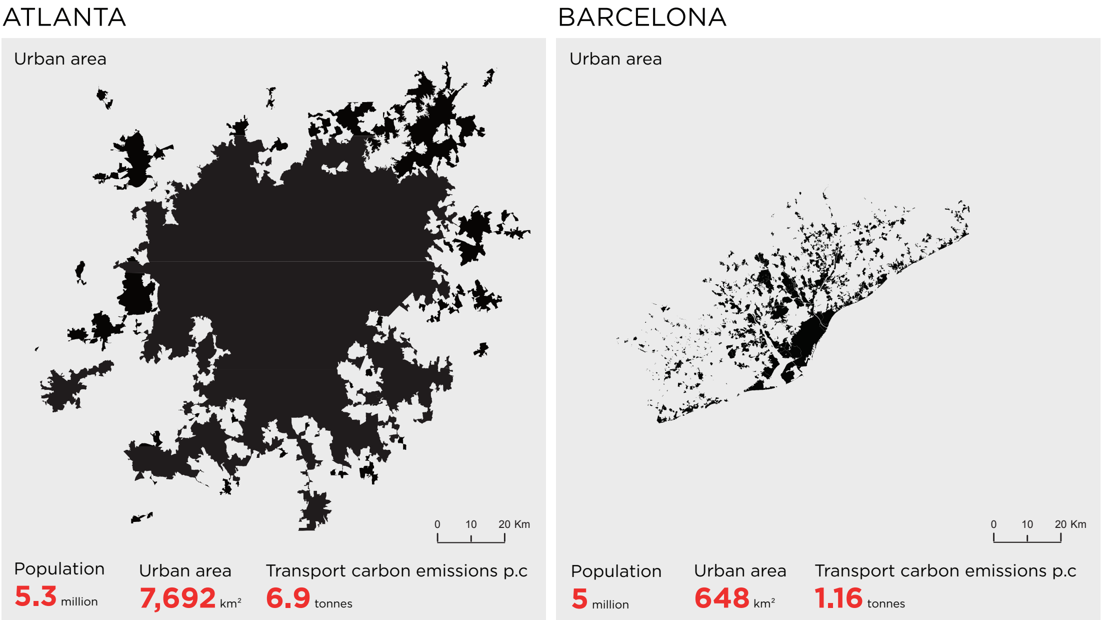
Figure 19
Household Transportation Energy Use By Location



Source: JRC 2011
Housing location and type have more impact on household energy use than vehicle or home efficiency.

Other studies indicate that more compact development can provide substantial energy savings (Ewing, et al., 2009; UNEP 2011). For example, at similar wealth levels, sprawling Atlanta produced six times more transport-related carbon emissions than relatively compact Barcelona, as illustrated in Figure 20 (ATM 2013; D'Onofrio 2014; LSE Cities 2014). Even modest policy changes can have large impacts. For example, increasing from less than 20 to more than 40 residents per hectare typically reduces per capita transport energy consumption by 40-60%, as illustrated in Figure 21.

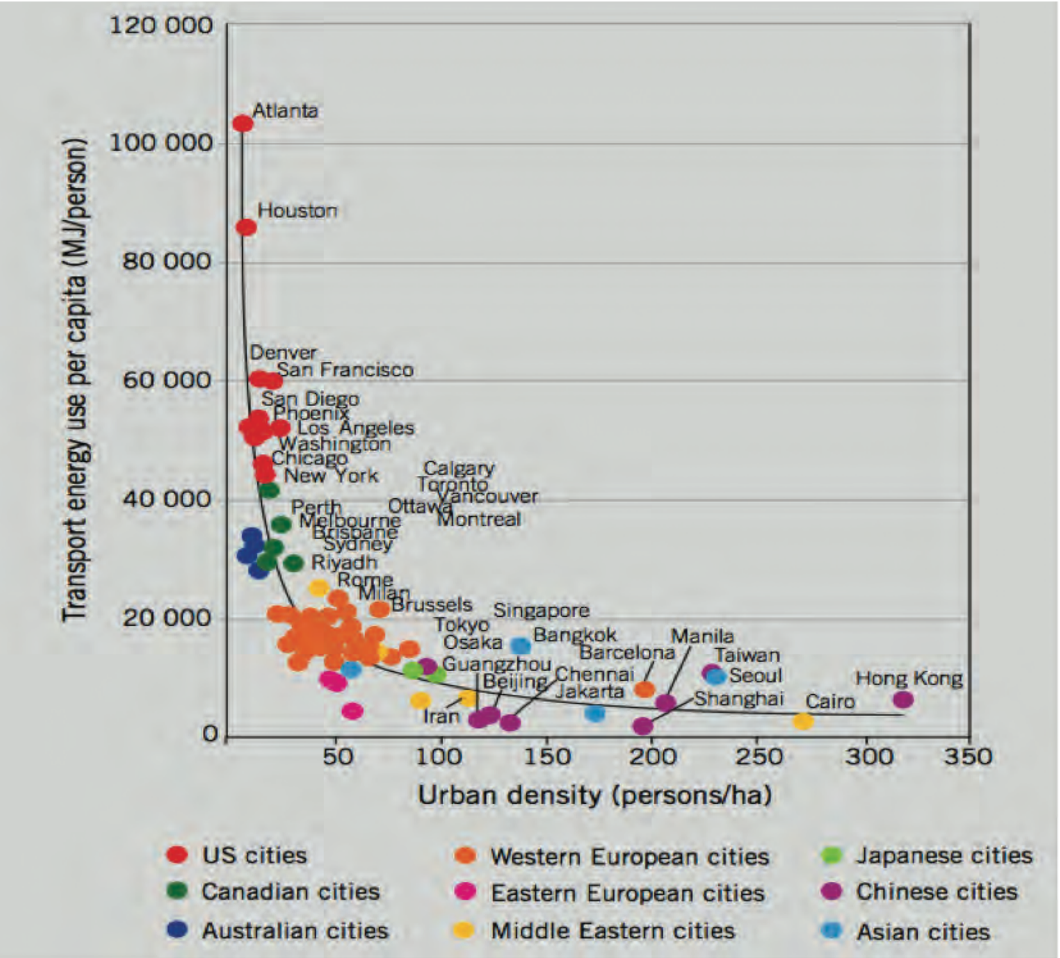
Figure 20
Land Use Impacts on Transport Emissions



Source: LSE Cities 2014
More compact development can reduce transport emissions by an order of magnitude.

Critics argue that there is no evidence that compact development reduces pollution emissions (Fruits 2011), but that research has been discredited (Litman 2011).

Figure 21
Urban Density and Transport-Related Energy Consumption



Source: WHO 2011

Energy efficiency tends to increase with densities, particularly from 5 to 50 residents per hectare.

Energy consumption and pollution emissions impose various external costs. These include fuel subsidy costs, environmental costs of petroleum production, economic costs of importing fuel, political and military costs of maintaining access to petroleum markets (for example, U.S. military interventions in Iraq), and various pollution health and environmental damage costs (CE, INFRAS, ISI 2011; del Granado and Coady 2010; Litman 2009; Maibach, et al. 2009; NRC 2009; Park 2009; Timilsina and Dulal 2011; Zhang, et al., 2005). Some of these studies include monetized estimates of these external costs. Aggregating these together indicates that total energy external costs are 10-50% of the internal costs (i.e., if fuel prices are $1.00 per liter, external costs are 10-50¢ per liter), depending on which costs are included, how they are calculated and when and where the energy is consumed. Fuel subsidy and import economic costs tend to be particularly large for lower-income countries that are heavily dependent on imported petroleum. Pollution costs tend to be particularly large in dense cities.

Social Equity

Social equity refers to the distribution of impacts (benefits and costs), and the degree that this is considered fair and appropriate (DfT 2014; Litman 2002). Sprawl can have various social equity impacts:

- To the degree that sprawl increases external costs, it is horizontally inequitable. As previously discussed, sprawl tends to increase the costs of providing public services, which causes urban residents to cross-subsidize these costs (Blais 2010). Sprawl also increases vehicle travel, and therefore road and parking facility costs, congestion, accident risk and pollution costs imposed on other people. Unless these are efficiently priced with significantly higher development fees, utility rates and taxes in sprawled areas, plus road tolls, parking fees and fuel taxes to internalize all vehicle costs, sprawl tends to be horizontally inequitable.
- Sprawl tends to degrade walking and cycling conditions, and public transit service quality, and increases the distances between destinations, which reduces non-drivers accessibility and increases transport financial costs (CNT 2013). This tends to harm physically, economically and socially disadvantaged groups, leading to social exclusion (physical, social and economic isolation). This is vertically inequitable.
- Sprawl tends to reduce single-family housing costs, but tends to reduce compact housing options and increases household transport costs. This benefits some households (those that prefer larger-lot housing and automobile travel) but harms others (those that prefer adjacent and multi-family housing, and cannot drive).

This indicates that sprawl can reduce social equity by imposing unjustified external costs, and reducing affordable housing and transport options used by disadvantaged populations. Social equity is an important planning objective. There are various ways to evaluate it, for example, by quantifying specific impacts, and using stakeholder surveys to assess a community's social equity objectives and priorities (Arora and Tiwari 2007; CTE 2008; DFID 2013; DfT 2014; EDRG 2007; Litman 2002). There are no standard methods for monetizing social equity impacts.

Social Problems

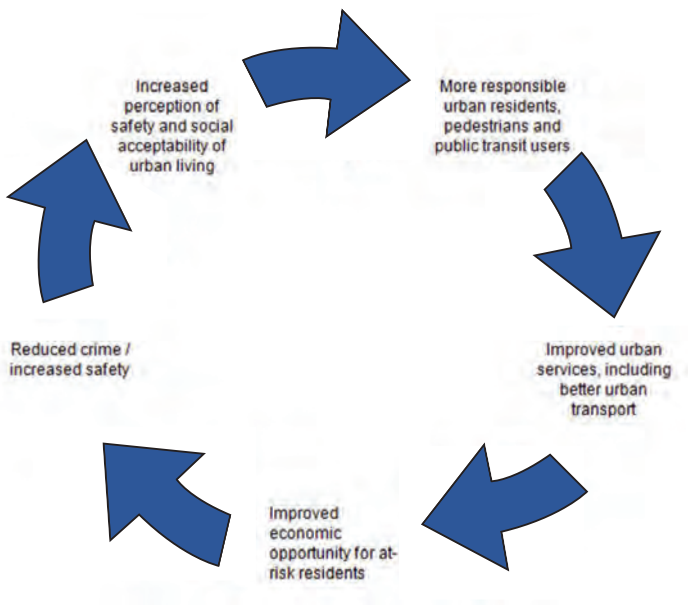
Social problems such as poverty, crime, and mental illness tend to be more concentrated and visible in cities. This occurs because poor people tend to locate in cities in order to access services and economic opportunities (Glaeser, Kahn and Rappaport 2008), while suburbs tend to exclude disadvantaged people by discouraging affordable housing and affordable transport modes (walking, cycling and public transit). As a result, suburban residents tend to be more economically successful and satisfied than urban residents (Mathis 2014; NAR 2013). People sometimes assume that denser development increases social problems and lower density development can reduce them. However, this confuses cause and effect. There is actually no evidence that compact development increases total poverty, crime or mental illness (1000 Friends 1999), on the contrary, research suggests that smart growth policies can reduce total social problems.

For example, studies show that more compact, multi-modal development tends to increase poor resident's economic opportunity by reducing concentrated poverty and improving access to education and employment (Cortright and Mahmoudi 2014). Using data from the Equality of Opportunity Project (Chetty, et. al. 2014), Ewing and Hamidi (2014) found that in the U.S., each 10% increase in their smart growth index is associated with a 4.1% increase in residents' upward mobility (probability a child born in the lowest income quintile reaches the top quintile by age 30).

All else being equal, per capita crime rates tend to decline with urban density and mix (Litman 2014c). For example, after adjusting for socioeconomic factors such as age, employment status and income, Browning, et al. (2010) found that per capita violent crime rates decline with density in Columbus, Ohio urban neighborhoods, particularly in the most economically disadvantaged area. Similarly, after adjusting for socioeconomic factors, Christens and Speer (2005) found a significant negative relationship between census block population density and per capita violent crime rates in Nashville, Tennessee and nearby suburban communities. Hillier and Sahbaz (2006) analyzed residential burglary and robbery rates in an economically and socially diverse London neighborhood. They found that, all else being equal, these crime rates were inversely related to the number and density of dwellings on a street, on both through streets and cul-de-sacs. For example, the mean cul-de-sacs burglary rate is 0.105, but those with fewer than 11 dwellings have a higher 0.209 rate. Similarly, grid street segments with more than 50 dwellings have a burglary rate of 0.142, but those with 100 dwellings have a much lower rate of 0.086. The researchers conclude that crime risk tends to decline on streets that have more through traffic, and crime are lower if commercial and residential buildings are located close together.

Similar impacts occur in developing country cities: crime rates declined after the TranMilenio Bus Rapid Transit system started operating in Bogota's lower-income neighborhoods. Overall, cities tend to be safer and healthier than sprawled communities (Lucy 2003). Several factors can help explain how smart growth tends to reduce crime rates. More compact, mixed development reduces poverty concentration and increases disadvantaged people's economic opportunity, it increases passive surveillance (by-passers who might report threats and intervene in conflicts), it can improve policing efficiency and response times, and it reduces the large number of motor vehicle crimes such as vehicle thefts and assaults. Figure 22 illustrates how smart growth can contribute to a positive security cycle.

Figure 22
The Positive Security Cycle



Communities tend to become safer as more compact and mixed development increases the number of responsible (non-criminal) people who live and walk in an urban neighborhood, creating a positive feedback cycle.

Poverty, crime and mental illness impose large costs on individuals and society, so reducing these problems is an important planning objective. However, they are difficult to measure so there is no standard way to quantify or monetize the amount that sprawl increases these cost (CTE 2008; DFID 2013; DfT 2014; EDRG 2007).

Affordability

Affordability refers to households' ability to afford basic goods such as housing and transport. Affordability is often defined as households spending less than 30% of income on housing, or less than 45% of income on housing and transport combined (CNT 2013).

Sprawl tends to reduce some household costs but increase others, as indicated in Table 7. It allows development of inexpensive urban-fringe land, which reduces land costs per hectare but increases lot size and therefore land per housing unit. Pro-sprawl policies such as minimum lot sizes, building density and height limits, restrictions on multi-family housing and minimum setback requirements tend to reduce development of less expensive housing types, such as adjacent and multi-family housing. Sprawl increases residential parking costs and total transport expenses (Glaeser and Ward 2008; Ewing and Hamidi 2014). As previously described, sprawl increases the costs of providing infrastructure and public services which can increase housing costs and general tax burdens.

Table 7
Sprawl Household Affordability Impacts

Increases Affordability	Reduces Affordability
• Reduces land unit costs (per square meter). • Reduces some infrastructure requirements (curbs, sidewalks, sound barriers, etc.).	• Increases land use per housing unit • Reduces affordable (adjacent and multi-family) housing options. • Increases parking requirements and associated costs. • Increases transport costs. • Increases infrastructure and utility costs.

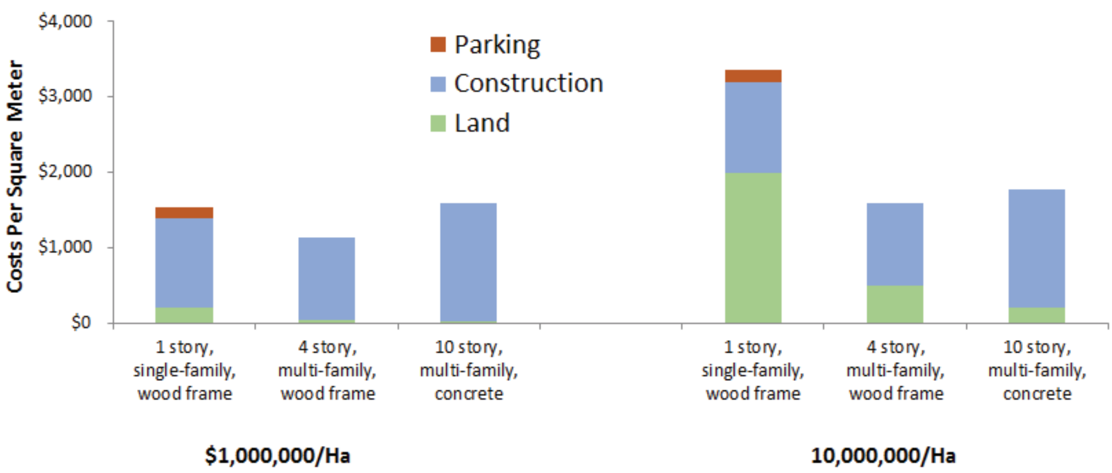
Sprawl reduces some household costs but increases others.

Critics claim that by restricting urban expansion, smart growth reduces housing affordability (Cheshire 2009; Demographia 2009; Mildner 2014) but their analysis is incomplete. Restrictions on urban expansion may increase land unit costs (per square meter), but smart growth reduces other costs including land required per housing unit, residential parking requirements, infrastructure and utility costs, and household transport expenses. As a result, smart growth policies can increase affordability overall, particularly for lower-income urban residents who live in multi-family housing and rely on walking, cycling and public transit.

Academic studies indicate that regulations that restrict development density and require large amounts of parking are a major cause of housing inaffordability (Ganong and Shoag 2012; Manville 2010; Nelson, et al. 2002). Lewyn and Jackson (2014) analyzed land use regulations in 25 typical jurisdictions. They found that sprawl-inducing regulations, such as density limits and minimum parking requirements, are far more common than sprawl-reducing regulations such as urban growth boundaries, parking maxima and density minima.

Overall, low-rise, wood frame, multi-family housing in accessible, multi-modal neighborhoods tends to be most affordable type of housing to develop because it minimizes land, construction and parking costs. High-rise, concrete buildings cost more to construct but require less land per unit, and so become cost-effective when land prices are very high (over about $10 million per hectare), as illustrated in Figure 23. This indicates that smart growth policies that encourage development of low-rise, multi-family housing in accessible, multi-modal neighborhoods tends to maximize overall affordability.

Figure 23
Typical Building Construction Costs (ICC 2014) [3]



Wood frame tends to have the lowest construction costs. Concrete construction costs about 50% more, but can be taller, which reduces land costs and so becomes cost-effective with high land prices.

Critics cite correlations between density and housing costs as evidence that smart growth policies reduce housing affordability (Cox and Pavletich 2015), but their analysis is incomplete. Cox and Pavletich (2015) appear to oversample single-family housing, ignore utility and transport costs, and exclude the often substantial portion of lower-priced housing that is supplied by government agencies and non-profit organizations, or obtained informally (Arnott 2009; Litman 2015). Denser cities tend to have higher average incomes and lower transport costs, so residents can afford to spend more on housing. Geographic features such as shorelines and mountains tend to limit urban expansion and make a city attractive, which increases real estate prices. It is the combination of restrictions on expansion and on higher density infill development which tend to reduce housing affordability (Cutler 2014). These factors tend to exaggerate actual housing costs and housing inaffordability problems in more compact cities.

A few recent studies have investigated how sprawl affects household affordability in developing countries (Adaku 2014; Aribigbola 2011; JICA 2011). Isalou, Litman and Shahmoradi (2014) found that in Qom City, Iran, suburban-area households spend more than 57% of their monthly income on housing and transport, significantly more than the 45% spent by households in the central district, and more than is considered affordable.

3 Construction cost data from the International Code Council's Building Validation Data – August 2014 (www.iccsafe.org/cs/Documents/BVD/BVD-0814.pdf) for R-3 Residential, VB ($111.36/sf), R-2 Residential, VB ($101.14/sf), and R-2 Residential, IB ($145.39/sf), assuming 50% lot coverage, and 10% additional costs for parking for single-family housing. For more analysis of urban building costs see Chung (2014).

Economic Development

Economic development refers to progress toward a community's economic objectives including increased productivity, employment, incomes, property development and tax revenues. Both theoretical and empirical evidence indicates that sprawl tends to reduce economic development because it (Ecola and Wachs 2012; Kooshian and Winkelman 2011):

- Increases per capita land consumption, which leaves less land for agriculture.
- Reduces accessibility and agglomeration efficiencies (Melo, Graham, and Noland 2009).
- Increases transport costs including road and parking facilities, accidents and pollution damages.
- Increase public infrastructure and service costs, which tends to increase tax and utility costs.
- Increase expenditures on vehicles and fuel, which most regions must import. This tends to reduce local employment and business activity.

When cities at similar levels of economic development are compared, more compact and multi-modal cities tend to be more economically productive than sprawled, automobile-dependent cities (Litman 2014a). Compact development is particularly important for knowledge-based industries such as education, technology and the arts (Abel, Dey, and Gabe 2011).

Of course, motor vehicle transport contributes to economic productivity in many ways: it delivers raw materials, distributes final products, and transport employees to worksites, but like most economic inputs, there is an optimal level beyond which marginal costs exceed marginal benefits (McMullen and Eckstein 2011; Litman 2014a). Policies that increase land use accessibility and transport system efficiency are likely to support economic productivity, while policies which underprice motor vehicle travel and encourage sprawl tend to reduce economic productivity overall. For example, Hsieh and Moretti (2014) analyzed the economic impacts of density-limiting policies in large, highly-productive U.S. cities. They estimate that such policies reduce aggregate national economic output by 13%, or more than $1 trillion annually.

External Benefits of Sprawl?

Sprawl can provide various benefits, including larger residential lot sizes which allow residents to have larger gardens and more privacy, reduced exposure to noise and some air pollutants, lower crime rates and better schools (Burchell, et al, Table ES-17). However, these are mostly internal benefits or economic transfers (one group benefits at another's expense). For example, the lower crime rates and better schools in sprawled neighborhoods largely results from their ability to exclude poor households that cannot afford cars. This can benefit those community's residents but concentrates poverty and associated costs (crime, inferior schools and increased burdens on social service agencies) in urban areas. Similarly, sprawl residents' lower exposure to noise and air pollution is often offset by their increased vehicle travel which increases noise and air pollution imposed on urban neighborhoods.

There is little evidence that increased sprawl can provide significant external benefits (benefits to people who live outside the sprawled community). This absence of external benefits is expected since rational people and businesses externalize costs and internalize benefits (Rothengatter 1991; Swiss ARE). If sprawl really did provide external benefits, developers or occupants would find ways to capture those benefits, for example, by demanding subsidies.

Sprawl Impacts Summary

Table 8 summarizes various benefits and costs of sprawl. Some are internal (they directly affect the people who choose sprawled locations) and others are external (they affect other people). These have a mirror image relationship with smart growth: a sprawl cost is a smart growth benefit and vice versa.

Table 8
Sprawl Costs and Benefits

	Internal (Users)	External (Other People)
Costs	Reduced accessibility, increased distances between destinations. Increased transport costs (vehicle expenses and time). Reduced mobility options for non-drivers. Increased drivers' chauffeuring responsibilities. Reduced economic mobility (less economic opportunity for lower-income residents). More traffic accident risk. Reduced fitness and health.	Reduced open space (farm and environmental lands). Increased infrastructure and public service costs (utilities, policing, emergency services, etc.). Increased roadway and parking facility costs. Increased traffic congestion imposed on others. Increased crash risk imposed on others. Healthcare and disability costs due to reduced physical activity. Reduced community cohesion (fewer positive interactions among neighbors due to use of local services). Less efficient public transit services (higher costs per passenger-mile). Increased fuel consumption and pollution emissions.
Benefits	Lower land prices (cost per hectare). More private greenspace (lawns and gardens). More privacy. Cheaper vehicle parking. Reduced local traffic congestion. Less exposure to some local pollutants. Reductions in some infrastructure costs such as curbs and sidewalk.	More greenspace per hectare of developed land. Savings on some public infrastructure costs, such as reduced curbs and sidewalks.

Source: (Burchell, et al 2002; Litman 2013)
This summarizes various sprawl costs and benefits. These impacts can vary depending on specific conditions.

Some of these impacts are both internal and external. For example, sedentary living causes health problems which directly burden sprawl-community residents, and can increase healthcare and reduce productivity costs which burden people and businesses regardless of where they are located.

These impacts can vary depending on conditions and perspectives. For example, more dispersed development tends to reduce the intensity of impacts such as traffic congestion and pollution emissions, measured per hectare of developed land, but increases the number of hectares that are developed. As a result, sprawl may reduce local congestion and pollution costs, but increase total regional costs.

What is the Estimated Magnitude of Sprawl Costs?

This section describes modeling analysis for this study which estimates the magnitude of sprawl costs.

For this analysis, the Sprawl Cost Analysis Spreadsheet Model was built to calculate sprawl costs (VTPI 2015). It categorizes U.S. urban regions into quintiles (fifths) from 1 (Smartest Growth) to 5 (Most Sprawled). This model incorporates Sprawl Factors which reflect the average percentage change in an impact's magnitude resulting from a one-Quintile shift. Quintile 1 (Q1) is used as a baseline. For example, a 10% Sprawl Factor for infrastructure costs indicates that, compared with Q1, infrastructure costs average 10% higher in Q2, 20% higher in Q3, 30% higher in Q4, and 40% higher in Q5 cities. This baseline is modest by international standards. For example, the Smartest Growth quintile (Q1) has an average density of 23.5 residents per hectare, which is dense by North American standards but about half the typical densities found in European cities, and about a tenth of the densities found in some Asian cities (Figure 4). Similarly, per capita vehicle ownership exceeds 600 vehicles per 1,000 residents in most North American cities, about twice the rate in affluent European cities such as Berlin, London and Stockholm, and three times the rate in affluent Asian cities such as Seoul, Taipei and Tokyo (Di 2013).

The Sprawl Factors and cost estimates are based on the various sources indicated in footnotes. Quintile 3 reflects overall average values. For example, the U.S. Bureau of Labor Statistic's Consumer Expenditure Survey indicates that local property taxes and utility fees affected by land use development patterns average $1,482 annually per capita, so that is the Q3 value. A 10% Sprawl Factor means that this cost declines 10%, to $1,344 in Quintile 2, and to $1,201 in Q1. Incremental infrastructure and public service costs are estimated based on studies such as Burchell, et al (2002), DVRPC (2003) and the Utah Governor's Office (2003). Previously described studies indicate that shifts from sprawl to more compact, infill development can reduce public infrastructure and services costs by 10-50%. Those studies only consider relatively modest smart growth policies (for example, none include major shifts from single- to multi-family housing, or comprehensive road pricing), which suggests that a more comprehensive set of reforms would provide greater impacts and savings.

Targeted research was required to determine how sprawl affects some of these costs. For example, not all government and utility costs are directly affected by land use development patterns. This value was estimated based on a typical municipal government's budget, as summarized in Table 9. This indicates that sprawl affects about two-thirds of municipal expenditure categories, by requiring longer road and utility lines, and increasing travel distances needed for policing, emergency response and garbage collection. This analysis assumes 66%.

Table 9
Municipal Expenditures Affected By Sprawl

Budget Category	How Affected by Sprawl	Percent
Policing	Longer travel distances to serve a given population.	24%
Engineering	More road-kilometers, street lighting, etc. to build and maintain	11%
Water utility	Longer water lines to build, maintain and pump	8.6%
Parks and recreation	More dispersed facilities, increased travel distances	7.7%
Emergency services	Longer distances to travel to serve a given population	6.8%
Sewers	Longer sewer lines to build, maintain and pump	3.7%
Planning and development	Longer distances to travel to serve a given population	2.5%
Public library	More dispersed buildings and services	2.1%
Total		**66.40%**

Source: Victoria 2012

About two-thirds of this municipal budget is affected by development density and per capita vehicle travel.

Another issue of uncertainty is the portion of sprawl costs that are currently internalized through location-based fees, such as development impact fees. Since few jurisdictions currently apply location-based development and utility fees, this value is probably small, so the model assumes 10%.

Some of the largest impacts result from the way that sprawl increases per capita vehicle travel, which increases transport costs including road and parking facility costs, consumer expenditures, traffic accidents and pollution emissions. The vehicle travel Sprawl Factors are based on data from the Federal Highway Administration's Highway Statistics Report (FHWA 2013, Table HM72). The results are close to Ewing and Hamidi's (2014) analysis which indicates that each 10% increase in their Sprawl Index reduces per capita vehicle mileage by 7.8% to 9.5%. Motor vehicle cost values are from the report, Transportation Cost and Benefit Analysis and the associated Transportation Cost Analysis Spreadsheet (Litman 2009). That spreadsheet was adjusted in the following ways:

- Units converted from miles to kilometers, and cost values increased 15% to account for 2007 to 2014 inflation.
- Assumes 33% urban-peak and 66% urban off-peak vehicle travel; since this analysis applies to urban conditions it excludes rural travel.
- Excludes "Operating Subsidy" (which only applies to public transit), "Transport Diversity" and "Land Use Impacts," assuming that they are inappropriate for this analysis.

Table 10 summarizes the results, showing estimated costs for an average automobile traveling under urban conditions.

Table 10
Estimated Urban Automobile Costs, 2014 U.S. Dollars

	Internal Fixed	Internal Variable	External	Totals	
	Per Vehicle-Kilometer				Annual Per Capita
Vehicle ownership	$0.187			$0.187	$2,861
Vehicle operation		$0.122		$0.122	$1,865
Internal crash		$0.078		$0.078	$1,193
External crash			$0.038	$0.038	$578
Internal parking	$0.050	0.0051		$0.055	$841
External parking			$0.057	$0.057	$876
Congestion costs imposed on others			$0.039	$0.039	$596
Road facilities financed by general taxes			$0.018	$0.018	$273
Roadway land value			$0.023	$0.023	$358
Traffic services financed by general taxes			$0.011	$0.011	$161
Air pollution			$0.038	$0.038	$582
GHG			$0.012	$0.012	$186
Noise			$0.009	$0.009	$137
Resource externalities			$0.029	$0.029	$442
Barrier effect			$0.012	$0.012	$186
Water pollution			$0.010	$0.010	$147
Waste			$0.000	$0.000	$4
Totals – Per vehicle-kilometer	**$0.237**	**$0.206**	**$0.297**	**$0.740**	
Totals - Annual per capita	**$3,623**	**$3,136**	**$4,526**		**$11,286**

Source: Litman 2009

This table summarizes vehicle costs, which are categorized as Internal-Fixed, Internal-Variable and External.

Tables 11 summarizes the analysis results. For example, this indicates that sprawl increased infrastructure costs from $502 annual per capita for cities in the Smartest Growth category up to $750 annual per capita in the Most Sprawled quintile cities. The bottom of the table indicates total annual costs per capita; for example, residents of the Most Sprawled quintile cities bear an estimated $5,825 in internal costs and impose about $4,467 in external costs.

Table 11
Sprawl Costs Measured Annual Per Capita

			Sprawl Index Quintile				
Impact	**Units**	**Sprawl Factor[1]**	**1**	**2**	**3**	**4**	**5**
			Smartest Growth		Average		Most Sprawled
Urban density[2]	People/hectare	40%	23.5	16.8	12.0	7.2	4.3
Infrastructure capital costs[3]	Annualized $/capita	10%	$502	$558	$620	$682	$750
Public service costs[4]	Annual $/capita	10%	$1,201	$1,334	$1,482	$1,631	$1,794
Motor vehicle travel[5]	Annual km/capita	17%[6]	10,389	13,182	15,174	17,684	22,896
Fuel consumption[7]	Annual litres/capita	17%	1,039	1,318	1,517	1,768	2,290
Vehicle internal costs[8]	Annual $/capita	17%	$4,603	$5,840	$6,723	$7,835	$10,144
Vehicle external costs[7]	Annual $/capita	17%	$3,082	$3,911	$4,502	$5,246	$6,793
Active transport[9]	Annual walk-bike km/ca.	20%	360	300	250	200	160
Active transport benefit[10]	$/km walked/biked	$1.00	-$360	-$300	-$250	-$200	-$160
Traffic fatalities	Deaths/100,000 pop.	28%	4.3	5.9	8.2	10.5	13.4
			Total Per Capita Costs				
Internal costs			*$4,414*	*$5,730*	*$6,683*	*$7,866*	*$10,239*
Incremental internal costs			*$0*	*$1,316*	*$2,270*	*$3,453*	*$5,825*
External costs			*$4,615*	*$5,614*	*$6,394*	*$7,328*	*$9,082*
Incremental external costs			*$0*	*$999*	*$1,779*	*$2,713*	*$4,467*
Total costs			**$9,028**	**$11,343**	**$13,077**	**$15,194**	**$19,321**
Total incremental costs			**$0**	**$2,315**	**$4,049**	**$6,165**	**$10,293**

Source: (www.vtpi.org/Sprawl_Cost.xls)

This table summarizes sprawl costs analysis. It indicates how various costs change between smart growth and sprawl. For example, governments spend, on average, about $1,482 on public services that are affected by development patterns, ranging from a low of $1,201 in Smart Growth locations and up to $1,794 in the most sprawled locations. Smart growth also increases active transport which provides health benefits, since the spreadsheet measures costs these are indicated by negative values.

4 Sprawl Factors reflect the change in an impact (e.g., density, vehicle travel) for each one-quintile Sprawl Index shift. The values are based various studies described in this report. These represent lower-bound impacts since most studies only consider a limited set of changes, so more comprehensive Smart Growth programs could provide greater benefits.

5 Based on the range of densities in large U.S. urban areas reported in FHWA 2012, Table HM-72.

6 DVRPC (2003) estimate of $35,000 average infrastructure costs, or $14,000 per capita at 2.5 residents per household. Increased 26% for inflation to $17,650, and annualized over 30 years at 4%.

7 BLS (2012). Average urban household property taxes ($1,892) and utilities, heating fuel and public services ($3,723), divided by 2.5 persons per household.

8 FHWA (2013), Table VM202, 2,968 billion VMT divided by 313 million U.S. residents = 9,482 VMT or 15,257 vehicle-kilometers per capita.

9 Based on the range of average per capita VMT in large U.S. urban areas reported in FHWA 2012, Table HM-72.

10 Assumes 10 liters/100 km fleet average.

11 Litman (2009) and associated Transportation Cost Analysis Spreadsheet (www.vtpi.org/tca/tca.xls). See notes below.

12 Based on Pucher, et al. 2011.

13 Ball, et al. (2009) and WHO (2014). Also see the "Health and Safety" chapter of Litman (2009).

Table 12 estimates the total magnitude of these costs in the U.S. This indicates that sprawl imposes incremental external costs totaling nearly $500 billion annually, plus nearly $650 billion in internal costs.

Table 12
Best Sprawl Cost Estimate

	Sprawl Index Quintiles					Totals
	1	2	3	4	5	
Urban residents (millions)	**50**	**50**	**50**	**50**	**50**	**250**
Total incremental internal costs	$0	$66	$112	$173	$291	**$642**
Total incremental external costs	$0	$50	$88	$136	$223	**$497**
Total incremental costs	$0	$116	$200	$308	$515	**$1,139**

Source: 2014 U.S. Billions

According to this estimate, the incremental external costs of sprawl total nearly $500 billion annually, plus nearly $650 in internal costs. External costs tend to reduce economic productivity and equity.

This "best estimate" of sprawl costs includes a comprehensive set of economic impacts. Such analyses are sometimes criticized for including cost categories not traditionally included in economic evaluations. Conventional economics generally recognizes a more limited set of external costs which typically consists of roadway and parking subsidies, traffic congestion, accident and air pollution external costs (FHWA 1997 and 2000; Maibach, et al. 2009; Zhang, et al. 2005). Table 13 illustrates a lower-bound estimate that excludes the value of land used for road rights-of-way, greenhouse gases, resource externalities (external costs of producing and importing petroleum and other natural resources), the barrier effect (the delay that motor vehicle traffic causes to walking and cycling), water pollution, and the health benefits of increased walking and cycling, and assumes that 20% of infrastructure costs are internalized through user fees. Even using these lower-bound assumptions, sprawl imposes at least $400 billion in external cots and $626 billion in internal costs in the U.S..

Table 13
Lower-Bound Sprawl Cost Estimate

	Sprawl Index Quintiles					Totals
	1	2	3	4	5	
Urban residents (millions)	**50**	**50**	**50**	**50**	**50**	**250**
Total incremental internal costs	$0	$64	$109	$168	$286	**$626**
Total incremental external costs	$0	$40	$71	$109	$179	**$400**
Total incremental costs	$0	$104	$180	$277	$465	**$1,026**

Source: 2014 U.S. Billions

Lower-bound values indicate that sprawl imposes at least $400 billion in external costs and $626 billion in internal costs annually in the U.S.

There are two additional reasons to consider these estimates lower-bound values. First, the sprawl impact studies used for much of this analysis (Burchell, et al. 2005; SP 2013, etc.) only consider relatively modest changes; most compare current development patterns with somewhat more compact development options that require minimal shifts from single-family to multi-family and modest reductions in automobile ownership or mode share. Much larger impacts and benefits could be expected from full implementation of all the economically-justified smart growth policies, discussed later in this report, including efficient pricing of roads, parking, development and utility fees.

Second, this analysis only considers a limited set of sprawl costs. Table 14 lists the various sprawl costs identified in this report and indicates which were included in this model. It does not quantify or monetize reduced open space, social impacts such as reduced accessibility for non-drivers, or reduced economic productivity, although these are generally considered important.

Table 14
Scope of Sprawl Cost Analysis

Sprawl Cost Categories	Consideration In Analysis
Land development (open space displacement and disruption)	Quantified but not monetized
Increased infrastructure and public service costs	Quantified and monetized
Increased traffic risk	Quantified
Reduced public fitness and health	Quantified and monetized
Increased motor vehicle internal and external costs	Quantified and monetized
Increased energy consumption and pollution emissions	Quantified but not monetized
Social equity (external costs, and opportunity for disadvantaged people)	Not quantified
Social problems (poverty, crime and mental illness)	Not quantified
Affordability (housing and transport cost burdens to lower-income people)	Not quantified
Economic development (increased employment and productivity)	Not quantified

This analysis only quantified and monetized a subset of sprawl costs, so results represent a lower-bound estimate.

This analysis provides order-of-magnitude estimates of sprawl costs, and potential smart growth benefits. The model reflects U.S. conditions, since that is where suitable data are most available, but most of the sprawl cost functions are transferable to other regions. In some urban areas, smart growth policies might increase densities from 5 to 10 residents per hectare and reduce average automobile travel from 10,000 to 8,000 annual kilometers, and in other areas they might increase densities from 30 to 60 residents per hectare and reduce vehicle travel from 2,500 to 2,000 annual kilometers, but the savings and benefits should be approximately proportionate since a 50% reduction in per capita land consumption and a 20% reduction in per capita vehicle travel should provide similar percentage savings and benefits in both types of cities. Table 15 indicates sprawl costs relative to average household incomes; this approach allows sprawl cost estimates to be scaled to different economies.

Table 15
Estimated External Costs of Sprawl Relative To Incomes

	Sprawl Index Quintiles				
	1	2	3	4	5
External costs relative to average income	18%	22%	25%	29%	36%
Incremental external costs relative to average income	0.0%	4.0%	7.1%	10.8%	17.8%

Assuming that the basic relationships are universal (more compact development and reduced automobile travel tends to reduce external costs), these impacts can be scaled to developing country conditions.

HOW MUCH URBAN EXPANSION IS OPTIMAL?

This section describes various factors that should be considered when evaluating optimal urban expansion, density and therefore development policies.

The optimal amount of urban expansion, and optimal densities and development policies can vary significantly depending on specific geographic conditions. For this analysis, cities are divided into three categories:

1. Unconstrained (they can easily expand into adjacent lands that have low agricultural, environmental and cultural values).
2. Semi-constrained (they can expand, but the economic, environmental and social costs of land displacement are moderate to high).
3. Constrained (they cannot expand due to significant physical or political boundaries).

Various planning objectives should be considered when evaluating optimal densities and development policies, as discussed below.

Open Space Preservation

Open space (farmlands and environmentally productive lands) provides various external benefits. Even apparently unproductive lands, such as deserts, often provide unique wildlife habitat and aesthetic value. Open space preservation justifies minimizing urban expansion, particularly into productive farmlands, and ecologically or culturally valuable lands. Policies should strive to protect these values with strategies such as natural landscaping and on-site stormwater percolation.

Cities surrounded by relatively low value open space are considered "unconstrained," and so can expand sufficiently to allow most households to live in small-lot single-family housing. Semi-constrained cities can accommodate moderate expansion, resulting in approximately equal shares of small-lot single-family, attached, and multi-family housing. In highly constrained cities, most population growth must be accommodated by infill development, resulting in primarily attached and multi-family housing, including high-rise.

Housing And Neighborhood Demands

Housing demands are diverse: households vary in their housing needs and preferences, and their ability to pay. In response, cities should develop diverse housing options, including various types, sizes and prices (Bertaud 2014). For example, households with young children or space-intensive hobbies such as gardening or vehicle repair, demand larger homes. In unconstrained cities these demands can be met with single-family houses that include private yards and garages. In constrained cities these demand can be accommodated with more compact housing types, such as townhouses and apartment with yards and rooftop gardens, located near parks and schools, and with flexible workspaces such as lofts, studios and garages incorporated into the building or available for rent nearby. Higher density buildings can be designed with features such operable windows, rooftop gardens and balconies in order to provide natural lighting, fresh air, greenspace and privacy (Urban Strategies 2012). Neighborhoods can be designed with attractive, walkable streets, local parks and trails, and allotment gardens. The most affordable housing overall generally consists of low-rise, wood frame, multi-family homes located in accessible, multi-modal neighborhoods, with densities up to 100 residents per hectare. In highly constrained cities, affordable housing may require special policies and subsidies to provide high-quality, highrise housing at prices affordable to lower-income households.

Demand can also be evaluated at the neighborhood level, which affects optimal neighborhood densities, and therefore, the optimal amount of urban infill, urban expansion, development policies, and mix of housing types that should occur in a region. This can be defined from three perspectives:

- Current residents select a neighborhood that reflects their preferences.They often bear costs from urban infill development, including the disruption (noise, traffic, etc.) caused by construction, plus increased local traffic and parking congestion, and lost privacy, once the new residences are occupied. Existing residents are often particularly threatened by any significant increase in lower-income residents since this may increase local social problems. They often perceive little direct benefit, although they may benefit from more local economic activity, such as more neighborhood services and jobs, and those that own land in the neighborhood may benefit economically over the long run. As a result, from current residents' perspective the optimal neighborhood density is what currently exists, lower-priced housing is undesirable, and any regional population growth should be accommodated by urban expansion.

- Potential future residents are households that would live in a neighborhood if suitable housing were available there. They benefit from the additional housing in accessible urban neighborhoods, and self-select for those who accept the resulting level of density. For example, if a high-rise replaces single-family housing, the new residents will consist of households that are willing to live in high-rise housing and those that insist on single-family will choose a different location. They therefore generally favor affordable urban infill development. However, they often have little influence on local planning decisions: they are generally unaware of which house they will eventually live in, and they often do not live or vote in the neighborhood being considered for development. As a result, their demands are represented by developers motivated by potential future rents, and sometimes by public officials or advocates who support more development of affordable-accessible housing (affordable housing located in an accessible location).

- Regional economic, social and environmental interests are people who live outside the neighborhood but are impacted by the development that occurs there, including businesses that want a pool of suitable employees, residents who want regional economic development, and anybody concerned with environmental protection. These interests generally benefit from more compact development which supports agglomeration efficiencies and urban fringe open space preservation.

As a result, the development density considered optimal by existing urban neighborhood residents will usually be much lower than what is considered optimal by households that want more affordable urban housing, or for achieving regional economic, social and environmental objectives. Conversely, the density considered optimal by regional interests will be higher than what nearby residents want. This helps explain many land use conflicts, such as local opposition to infill development, conflicts between residents and developers, and conflicts between local and regional officials concerning the location and type of development. Described differently, to achieve urban densities that are overall optimal from a regional perspective it will be necessary to overcome local opposition to infill development (Glaeser and Ward 2008; Hsieh and Moretti 2014). Smart growth therefore requires policy instruments that compensate local neighbors for the negative impacts of infill development and can overcome local opposition, so urban communities will shift from "not in my backyard" to "yes in my backyard."

Public Infrastructure and Services Cost Efficiency

Previously described studies indicate that compact development can significantly reduce infrastructure and public service, although some of these costs may increase at very high densities. The greatest savings are achieved by shifting from dispersed development at low densities (under 5 residents per hectare), to infill or urban fringe development at moderate densities (40-60 residents per hectare); very high densities (more than 80 residents per hectare) are generally not needed to maximize infrastructure efficiency. To achieve this objective, it is desirable to encourage urban infill, maintain moderate to high development densities, and where urban expansion occurs, to be systematic and efficient by concentrating development along major utility corridors.

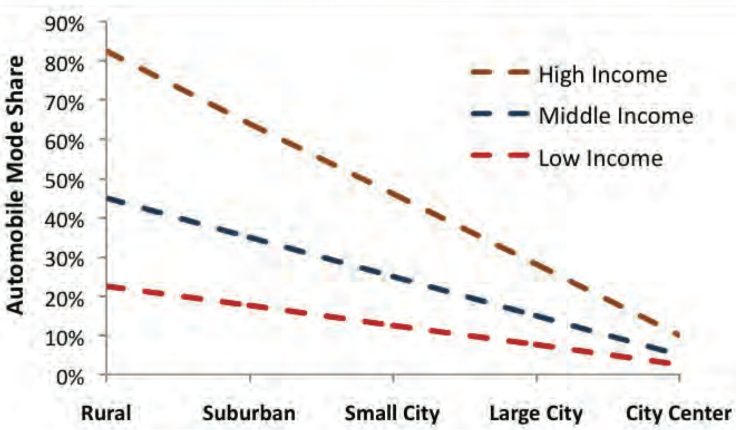
Transport System Efficiency

An efficient transport system maximizes overall accessibility (Rode and Floater 2014). The following factors can affect overall accessibility:

- Development density and mix. This reduces the distance between destinations.
- Roadway and path network connectivity. This allows more direct travel between destinations.
- Improved walking and cycling conditions, and improved public transit service quality and affordability. This improves mobility options.
- Increase automobile travel speed and affordability. This improves motorists' mobility.
- Transportation demand management that encourages travelers to use the most efficient mode for each trip. This maximizes system efficiency and reduces problems such as congestion.

Smart growth tends to support these objectives and so tends to increase overall transport system efficiency, affordability and equity. As cities become larger and denser, and where incomes are lower, the optimal automobile mode share declines, as illustrated in Figure 25. Critics sometimes argue that, by increasing development density, smart growth increases traffic congestion, but this is not necessarily true. Although density tends to increase congestion intensity (the amount traffic speeds decline during peak periods), this is often offset by shorter trip distances and improved travel options, so more compact, multi-modal neighborhoods tend to have lower per capita congestion delays (Kuzmyak 2012; Levine, et al. 2012).

Figure 25
Optimal Automobile Mode Share



As cities become larger and denser, the portion of trips made by automobiles should decline. With an efficient transport system, event wealthy people walk, bicycle and use public transit for a major portion of urban trips.

Public transit services experience scale economies (unit costs decline with increased use), so increasing development near transit lines, and providing incentives for travelers to use transit, tend to increase transit system efficiency (Cervero and Guerra 2011). Table 16 indicates threshold densities typically considered necessary for various types of transit services, although higher densities provide additional efficiencies and benefits. For example, if 30 residents per hectare justifies hourly service, 40 residents per hectare can justify half-hourly service, 50 residents per hectare can justify fifteen-minute service, and 60 residents per hectare can justify five-minute service.

Table 16
Transit Density Requirements

Mode	Service Type	Minimum Density (DU Per Hectare)	Area and Location
Dial-a-Bus	Demand response.	10 to 15	Community-wide
Minimum Local Bus	1/2-mile route spacing, 20 buses per day	10	Neighborhood
Intermediate Local Bus	1/2-mile route spacing, 40 buses per day	20	Neighborhood
Frequent Local Bus	1/2-mile route spacing, 120 buses per day	35	Neighborhood
Express Bus – Foot access	Five buses during two-hour peak period	35	Average density over 50-square-km area around a large city.
Express Bus – Auto access	Five to ten buses during two-hour peak period	35	Average density over 50-square-km area around a large city.
Light Rail	Five minute headways or better during peak hour.	25	Within walking distance of transit line, serving large downtown.
Rapid Transit	Five minute headways or better during peak hour.	30	Within walking distance of transit stations serving large downtown.
Commuter Rail	Twenty trains a day.	2 to 5	Serving very large downtown.

based on Pushkarev and Zupan 1977
This table indicates minimal residential densities typically needed for various types of transit service. These values may vary due to additional demographic, geographic and economic factors.

As discussed earlier, because automobiles are more space-intensive than other modes, efficient transportation requires limiting vehicle ownership and use levels that can be accommodated by available road and parking supply. As cities become denser, vehicle ownership rates should decline.

Economic Development

More compact, multi-modal development tends to increase productivity due to agglomeration efficiencies and cost savings (Hsieh and Moretti 2014; Melo, Graham and Noland 2009). Increased livability can also support economic development by making a city more attractive to residents, workers and visitors, and therefore businesses. Economic development therefore justifies policies that encourage compact development and efficient transport, plus consideration of livability factors such as the quality of the public realm and housing affordability.

Safety and Health

More compact development tends to increase safety and health by reducing vehicle traffic speeds and per capita vehicle travel, and increasing active transport which increases public fitness and health (CDC 2010; WHO 2013). However, compact development can also increase residents' exposure to noise and air pollutants. As a result, public safety and health objectives justify smart growth policies that create compact, multi-modal communities where residents drive slower, drive less, and rely more on walking and cycling, plus targeted strategies to reduce urban noise and air pollution.

Social Equity

For this analysis, social equity refers to the degree that policies benefit physically, economically and socially disadvantaged people, including their health and wealth. Cities can play important roles in achieving social equity objectives. They can provide affordable basic services to disadvantaged residents, including healthcare, utilities, housing, education and transport, and they can increase economic opportunities, such as their ability to obtain jobs. Whereas, in traditional peasant societies farmland ownership provided economic security and opportunity to poor households, the modern equivalent in industrial societies is to provide affordable-accessible housing that lets lower-income households conveniently access urban jobs. Affordable urban housing and transport options are therefore key to achieving social equity objectives, as well as supporting urban economic development by increasing the pool of workers available to businesses.

Table 17 compares four possible poverty reduction strategies: policies that increase some households' incomes benefits those households, but if affordable-accessible housing supply is fixed, other groups will be displaced. Increasing affordable urban-fringe housing supply reduces housing costs but increases transport costs. Increasing affordable-accessible housing supply provides the greatest total benefits.

Table 17
Poverty Reduction Policy Equity Impacts

Policy	Equity Impacts
Rent subsidies for a particular group (e.g., people with disabilities, pensioners, poor households).	The group that receives the subsidy is better off, but unless the total supply of affordable-accessible housing increases, other low-income groups have fewer housing options.
Raise minimum wages.	Working poor are better off, but unless the total supply of affordable-accessible housing increases, other low-income groups (people living on public assistance or pensions) have fewer housing options.
Increase the supply of low-priced urban-fringe housing.	Helps low-income households that prefer urban-fringe locations, but increases transport costs, particularly for non-drivers.
Increase the supply of affordable-accessible housing (low-priced housing in accessible neighborhoods.	Helps low income households.

This table summarizes equity impacts of various poverty-reduction policies. If affordable-accessible housing supply is fixed, rent subsidies or wage increases benefit recipients but displace other households. Increasing affordable urban fringe housing reduces housing costs but increases transport costs. Increasing affordable-accessible housing supply tends to provide the greatest total benefits.

This analysis suggests that to achieve social equity objectives cities should develop affordable housing in accessible, walkable neighborhoods with good public services such as parks and schools (Rodier, et al. 2010). Exactly how this is done will vary depending on specific conditions. In some cities, some affordable housing can develop from informal and unserviced settlements that evolve into officially-recognized neighborhoods (Arnott 2009; FIG 2008). In other cities, particularly those that are geographically constrained and relatively affluent, affordable-accessible housing will consist of large, government-subsidized, multi-family housing projects. In many cities, affordable-accessible housing will be provided by allowing small private property owners to add housing units, for example, by allowing secondary suites, subdividing existing parcels to allow two houses where there was previously only one, and by adding additional floors to existing residential and commercial building. Public policies can allow, support and guide such development so it is consistent with strategic development goals.

Social Problems

Smart growth policies can help reduce multi-generational poverty, crime and mental illness by reducing poverty concentration, improving economic opportunities for at-risk residents, increasing daily physical activity, and increasing community cohesion. More research is needed to better understand these impacts and design policies to best achieve these goals.

Roadway Supply and Design

Urban areas need to dedicate the optimal amount of land to roads – not too little and not too much – and to design and manage urban streets to balance diverse and sometimes conflicting objectives. In dense city centers, 20-25% of land should be devoted to road rights-of-way, as development density declines this can decline to 10-15% of land (UN-Habitat 2013).

Table 18 summarizes various strategies that can help optimize roadway design and management.

Table 18
Roadway Design and Management Strategies

Objective	Design and Management Strategies
Active transport (walking and cycling) mobility, comfort and safety	Urban roads should be designed and managed to ensure safe walking and cycling. This requires well designed and maintained sidewalks and crosswalks, and where there is sufficient demand, bikelanes. All pedestrian facilities should reflect universal design features so they accommodate the widest range of possible users including people with disabilities, handcars and wheeled luggage, and other special needs.
High value vehicle trips.	Use dedicated lanes or pricing to favor higher-value vehicle travel (emergency, public service, high-occupant, and freight vehicles). On major urban arterials this should generally be center median lanes, since that tends to minimize traffic conflicts. Urban arterials should be designed with convenient, comfortable and attractive bus stops and stations.
General motor vehicle traffic	Provide capacity for motor vehicles, including large vehicles such as trucks and buses. Urban roadways should be designed for relatively low speeds with narrower lane widths and more traffic speed controls than what is optimal in rural areas.
Multi-modal traffic safety	For urban streets to be safe for all users they should be designed and managed to keep motor vehicle traffic speeds to 20-40 km/hr. With few exceptions, urban arterials should be no more than six lanes wide and all six-lane roads should have dedicated HOV lanes. Streets with four or more lanes should have center medians that provide pedestrian refuges, so pedestrians need only cross two lanes at a time.
Efficient parking	Efficient management uses pricing and regulations that make the most convenient spaces available to higher value uses. On-street parking can be very efficient, it can serve multiple users, for example, delivery vehicles in the morning, shoppers during the day, restaurant patrons during the evening, and local residents at night.
Local residents	To protect the livability of urban neighborhoods, urban streets should be designed and managed to control excessive traffic speeds, and managed to address specific problems, for example, some cities may choose to limit heavy diesel vehicle traffic to minimize neighborhood noise and air pollution. As much as possible, on-street parking should be managed to accommodate local residents' parking demands, for example, by allowing residents to park overnight.
Local businesses	Local businesses want attractive streets that provide good walking, cycling and automobile travel conditions, moderate traffic speeds, and efficient parking management which ensure that delivery vehicles, customers and employees can easily access businesses.
Aesthetics	Streets should be designed with attractive features including trees and awnings that provide shade and shelters, trash cans, seating and other amenities. These should be designed to be attractive and integrated.

Source: ADUPC 2009; NACTO 2012

Roadway design and management should balance various planning objectives.

In addition to devoting land for roads, cities may also need to devote land to off-street parking. Parking land requirements increase with per capita vehicle ownership. Cities should design and manage parking to minimize the amount of land that must be devoted to off-street parking lots through efficient sharing and pricing, and using structured (underground and multi-story) parking facilities where this is cost effective.

Summary

Table 19 summarizes various factors that should be considered when evaluating the overall optimal amount and type of urban expansion.

Table 19
Optimal Urban Expansion, Density and Development Policies

Factor	Optimal Expansion
Open space (farm and natural lands)	Policies should encourage compact development to minimize farm and ecologically productive land displacement.
Consumer demands	Cities should develop diverse housing options, including affordable housing in accessible, multi-modal areas. In unconstrained cities a majority of housing may be small-lot single-family. In constrained cities, more housing should be multi-family.
Infrastructure and public services	Policies should encourage moderate- to high-density development along major utility corridors, and discourage leapfrog development distant from existing services.
Transport system efficiency	Policies should encourage densities exceeding 30 residents per hectare along transit lines with frequent service and good walking and cycling conditions. Automobile ownership and use should be limited to what urban road and parking supply can efficiently accommodate without congestion. Vehicle ownership rates should decline with population density and should generally be less than 300 vehicles per 1,000 residents in compact, multi-modal urban areas.
Economic development	Policies should encourage compact, multi-modal development, favor resource-efficient transport modes, and preserve valuable farmland.
Safety and health	Favor compact development, lower traffic speeds, and transportation demand management to reduce automobile travel and encourage walking and cycling.
Social equity	Encourage development of affordable housing and transport options, and provide suitable neighborhood amenities that serve disadvantaged residents, such as local parks and healthcare services
Social problems	Encourage affordable compact development with features that improve at-risk residents' economic opportunities and quality of life.
Optimal roadway supply	Devote 20-25% of land to roads in denser areas, and 10-15% in less dense areas. Design and manage roads to balance various planning objectives. Minimize the amount of land devoted to off-street parking lots through efficient parking management.

Various factors should be considered when determining optimal urban expansion and development policies.

Table 20 summarizes optimal expansion, density and development policies for the three types of cities.

Table 20

Optimal Urban Expansion, Densities and Development Policies

Factor	Un-Constrained	Semi-Constrained	Constrained
Growth pattern	Expand as needed	Expand less than population growth	Minimal expansion
Optimal regional density (residents / hectare)	20-40	40-100	80 +
Optimal vehicle ownership (motor vehicles per 1,000 residents)	300-400	200-300	< 200
Housing types	A majority can be small-lot single-family and adjacent	Approximately equal portions of small-lot single-family, adjacent, and multi-family.	Mostly multi-family
Private auto mode share	20-50%	10-20%	Less than 10%
Portion of land devoted to roads and parking	10-15%	15-20%	20-25%

Different types of cities may have different growth patterns, densities and transport patterns.

WHAT POLICY DISTORTIONS LEAD TO ECONOMICALLY EXCESSIVE SPRAWL?

This section examines various land development policy distortions that result in economically excessive urban expansion (sprawl), and estimates the magnitude of these impacts.

Efficient markets ensure that resources are allocated efficiently, which maximizes benefits to consumers and society. To be efficient, markets must reflect certain principles:

- Consumer Sovereignty. An efficient market ensures that households have diverse housing and transport options, so they can choose the combination that best meets their demands.
- Cost-based Pricing. Efficient pricing (what users pay for a good) reflects marginal costs (the full incremental costs of producing that good), which ensures that society does not devote $2 to producing a good that consumers only value at $1.
- Policy Neutrality. Economic neutrality means that policies and planning practices do not arbitrarily favor one housing or transport option over others.

Current land use and transport markets often violate these principles. The following section examines these market distortions, their impacts on development patterns, and how they can be corrected.

Consumer Sovereignty

An efficient and responsive real estate market ensures that households have diverse housing types available in various types of neighborhoods, plus diverse transport options including walking, cycling, public transit, taxis and automobiles available for rent and purchase. In most cities, it is easy to find expensive housing in accessible locations, and low-priced housing in undesirable locations, but it is often difficult to find lower-priced housing in accessible neighborhoods with high quality services such as good schools. Similarly, in most cities, driving is relatively convenient and comfortable (although slow during peak periods), but walking, cycling and public transit travel are often difficult, uncomfortable and dangerous. The limited availability of affordable-accessible housing, and the inferiority of affordable transport modes results in part from development policies which unintentionally reduce consumer housing and transport options.

For example, most jurisdictions have policies and planning practices that limit development densities and mix, building heights, floor area ratios (FARs), multi-family housing, and heritage building redevelopment (Blais 2010; Levine 2006). Most zoning codes mandate high levels of parking supply, which are automatically bundled with building space, regardless of whether or not occupants demand parking (Manville 2010). These policies tend to reduce the supply of affordable housing in accessible urban neighborhoods (Cheshire and Vermeulen 2009; Glaeser and Ward 2008). For example, in efficient land markets it would be relatively easy for developers to respond to growing demand for affordable urban housing by converting lower-density single-family homes into larger, taller, multi-family housing, and developers would only build the amount of parking that households demand, but in most cities, development policies and regulations make this illegal or difficult (Bertaud 2014; Lewyn 2005).

Similarly, many current transport planning practices are biased in ways that favor automobile travel over walking, cycling and public transport, reduce affordable mobility options (ADB 2009). For example, current transport planning tends to evaluate transport system performance based primarily on motor vehicle travel conditions, using indicators such as roadway level-of-service and average traffic speed, but gives little consideration to active and public transport travel conditions (DeRobertis, et al. 2014). Most jurisdictions collect extensive data on motor vehicle travel activity, travel conditions and costs (such as fuel prices and accidents), but walking, cycling and public transit travel data are often incomplete, making it difficult for planners to value improvements to these modes. Conventional evaluation recognizes and quantifies motor vehicle congestion delay, but does not generally measure the delays that wider roads and increased vehicle traffic speeds cause pedestrians and cyclists (called the "barrier effect"). As a result, transport planning recognizes the benefits of expanding roadways to reduce motorists' delays, but ignores the costs this imposes on other road users.

Transport project economic evaluation is also biased in favor of automobile travel over other transport options (EVIDENCE 2014). For example, when comparing a highway expansion with a public transit improvement project to improve urban mobility, conventional evaluation assumes that all travelers (at least, all travelers who matter) have an automobile and parking space available and so do not account for vehicle ownership and parking cost savings that result if commuters travel by transit rather than automobile. Conventional planning generally gives little consideration to indirect and external costs, such as the downstream congestion, accident risk and pollution costs that result, if roadway expansions induce additional vehicle traffic.

Transport funding practices also tend to favor the expansion of roads and parking facilities over improvements to other modes (Brown, Morris and Taylor 2009). Various tax policies encourage sprawl and automobile travel. For example, U.S. mortgage interest deductions encourage households to purchase larger homes, which tend to encourage sprawl (AIA 2010), and U.S. income tax policies favor automobile over transit commuting (Dutzik and Inglis 2014). This increases motor vehicle ownership and use beyond what consumers would choose if public policies were more neutral (Kodukula 2011).

Efficient Pricing

In efficient markets, prices reflect marginal costs. An efficient land market would charge development fees, utility rates and taxes that reflect the additional costs of providing infrastructure and public services to more dispersed locations. This is seldom done, which underprices sprawl compared with smart growth (Blais 2010). Efficient pricing would typically reduce development fees, utility rates and local taxes by 10-50% for smart growth compared with sprawl locations.

Similarly, efficient transport pricing would charge travelers directly for the costs they impose, as indicated in Table 21. Currently, many countries subsidize fuel (IMF 2010; Metschies 2013), roads user seldom pay the full costs of roadways and parking facilities (Henchman 2013; Litman 2009), and impacts such as congestion, accident risk and pollution are often underpriced (Clarke and Prentice 2009). More efficient pricing would significantly increase the costs of automobile travel, particularly in urban conditions where congestion, road, parking, accident risk and pollution costs are particularly high (Proost and Van Dender 2008).

Table 21
Efficient Pricing Of Various Transport Costs

Cost	Pricing Method	How Calculated
Congestion	Time and location based road tolls or vehicle fees.	Prices are higher under congested conditions. Price to reduce traffic volume to optimum flow.
Roadway costs	Road tolls or weight-distance fees.	Charge users for most or all roadway costs.
Accident risk	Distance-based fees.	Prorate vehicle insurance premiums by annual mileage.
Parking	Use time and location based fees to charge users directly for parking.	Fees set to recover parking facility costs and maintain 85% maximum occupancy during peak periods.
Pollution Emissions	Time and location based fees (if possible) or distance-based fee.	A vehicle's emission rate (such as grams per mile) times regional pollution unit costs (such as cents per gram).
Fuel externalities	Fuel tax.	Eliminate fuel subsidies. Charge for external costs of producing, importing and consuming fuel.
General taxes	General sales and property taxes.	General taxes should be applied in addition to any special vehicle and fuel taxes and fees.

Source: Litman 2014a; Metschies 2013
This table summarizes efficient pricing of various transport costs.

Summary of Market Distortions and Their Impacts

Table 22 describes various market distortions that encourage sprawl, their impacts, and reforms that can correct them.

Table 22
Sprawl-Encouraging Market Distortions

Distortions	Impacts	Reforms
Restrictions on density, mix, and multi-family housing.	Reduces development densities and increases housing costs.	Allow and encourage more compact, mixed development.
High minimum parking requirements.	Reduces density and discourages infill development. Subsidizes automobile ownership and use.	Eliminate minimum parking requirements, set maxima, require or encourage parking unbundling.
Underpriced public services to sprawled locations.	Encourages sprawl. Increases government costs.	Development and utility fees that reflect the higher costs of providing public services to sprawled locations.
Tax policies that support home purchases.	Encourages the purchase of larger, suburban homes.	Eliminate or make neutral housing tax policies.
Automobile-oriented transport planning.	Favors automobile travel over other modes. Degrades walking and cycling.	More neutral transport planning and funding.
Transport underpricing (roads, parking, fuel, insurance, etc.).	Encourage vehicle ownership and use.	More efficient pricing.
Tax policies that favor automobile commuting.	Encourages automobile travel over other modes.	Eliminate parking tax benefits or provide equal benefits for all modes.

Many current policies favor sprawl and automobile travel over compact development and multi-modal transport.

These distortions have cumulative and synergistic impacts, which significantly increases sprawl and vehicle travel beyond what consumers would choose with better housing and transport options, and more efficient pricing. For example, underpricing parking not only increases parking demand, it also increases traffic congestion, accidents and pollution problems. In a typical situation, with unpriced worksite parking, 80% of employees will drive to work, but if commuters pay directly for parking this declines to 60%, which not only reduces parking costs by 25%, it also causes similar reductions in traffic congestion, accident and pollution costs. Described more positively, more responsive planning and efficient pricing can help reduce a variety of problems and achieve various planning objectives; all of these benefits should be considered when evaluating a particular policy reform.

Table 23 illustrates policy reforms that reflect market principles including consumer sovereignty, efficient pricing and neutral planning. These reforms tend to increase economic efficiency and equity.

Table 23
Examples of Efficient Smart Growth Policies

Improved Consumer Options	More Efficient Pricing	More Neutral Planning
• Improved walking, cycling and public transit in response to consumer demands – such as better sidewalks, bike and bus lanes on most urban arterials. • Reduced and more flexible parking requirements and density limits in urban areas. • More diverse and affordable housing options such as secondary suites. • Improved public services (schools, policing, utilities) in smart growth locations.	• Efficient pricing of roads and parking, so motorists pay directly for using these facilities, with higher fees during congested periods. • Distance-based vehicle registration, insurance and emission fees. • Location-based development fees and utility rates so residents pay more for sprawled locations and save with smart growth. • Vehicle registration auctions in large cities where vehicle ownership should be limited.	• More comprehensive evaluation of all impacts and options in the planning process. • Accessibility- rather than mobility-based planning, so accessibility is given equal consideration as mobility when evaluating transport impacts. • "Least-cost" transport planning, which allocates resources to alternative modes and transportation demand management programs when they are effective investments, considering all impacts.

These smart growth policies reflect market and planning principles such as consumer sovereignty, efficient pricing and neutral planning. This analysis compares current costs with what would occur if such policies were fully implemented.

Some studies have modelled the impacts of comprehensive policy reforms. For example, Gao, et al. (2009) developed an integrated transport and land use mode which evaluated economic impacts, including consumer surplus, of various development scenarios in California. The results indicate that smarter growth options provide significant savings and benefits, including reduced development and transport costs, increased consumer surplus and more equitable distribution of benefits. Litman (2006) identified various transport market distortions which increase automobile travel, and in subsequent analysis (Litman 2014b) estimated that a combination of more responsive transport planning, more neutral development policies, and more efficient transport pricing would reduce U.S. automobile travel 35-50%. This conclusion is supported by international comparisons which indicate that urban residents of affluent European countries such as Germany and Norway travel 35-50% fewer annual motor vehicle kilometers than in North America, apparently due to policies that result in more compact development, and more multi-modal transport systems (Matthews and Nellthorp 2012).

This indicates that market distortions significantly increase automobile ownership and use. The difference in consumer welfare and external costs between current conditions and what would occur in a more efficient market can be considered the economic inefficiency of sprawl. The magnitude of these impacts is affected by consumer demands, including the amount of latent demand for more compact development, and consumers' responsiveness to incentives such as better housing and transport options, more efficient pricing, and urban neighborhood design improvements. The more responsive consumers are to smart growth reforms, the more they increase overall economic efficiency

As described earlier in the "Demand for Sprawl" section, there is evidence of significant latent demand and responsiveness: many households would prefer more compact, walkable and transit-oriented neighborhoods but cannot choose them due to limited supply which increases prices. Modest incentives, such as financial savings or better local services, would attract more households to smart growth (Levine, et al. 2002; Litman 2015b). As a result, full implementation of economically-justified market reforms would result in significantly more compact and multi-modal development than what is occurring in many cities, and like most policies and price changes, their impacts and benefits should increase over time as they influence long-term decisions.

Market Reform Examples

Below are three examples of specific market distortions and reforms.

Example 1
Parking Mandates

Assume that a city's zoning code currently requires developers in urban neighborhoods to provide one parking space per apartment unit. Each space adds $1,200 annual costs per unit. With bundled parking, 80% of occupants own a motor vehicle but if parking is unbundled (i.e., rather than paying $1,000 per month for an apartment that includes a parking space occupants pay $900 per month for the apartment and $100 for each parking space they want to use) only 60% of occupants own vehicles. This allows parking supply to be reduced to 0.6 spaces per unit, which allows 20% more housing units in an area. Under current conditions, the city's parking requirement has the following economic impacts:

- 20% of parking spaces are unoccupied, a wasted resource.
- 40% of occupants are paying for parking spaces they don't need, reducing consumer welfare.
- For occupants that do not need parking spaces, this reduces housing affordability. This tends to be regressive (it burdens lower-income households) since they are most likely to be car-free.
- 20% of occupants own more vehicles, and therefore drive more, and impose more external costs (congestion, accidents, pollution, etc.) than they otherwise would.
- Urban housing supply is reduced 20%, which forces more households to locate in sprawled, urban-fringe locations where they lead more automobile-dependent lifestyles than they prefer. This reduces those households' consumer welfare and increasing motor vehicle external costs.

Such zoning codes are economically inefficient to the degree that some households are forced to pay for parking spaces that they would not otherwise choose. Since this policy reduces development densities which increase sprawl, and leverages additional vehicle ownership and use, it increases various external costs. Reforming this policy would allow developers to decide how much parking to provide, which would increase economic efficiency and help achieve planning objectives such as more affordable housing, and reduced congestion, accidents and pollution.

Example 2
Automobile-oriented Transport Planning

Current transport planning practices often favor motorized over non-motorized travel by devoting more money and road space to accommodate local automobile travel than to comparable trips made by walking and cycling, and by favoring higher traffic speeds on urban arterials, which creates barriers to walking and cycling. This has the following impacts:

- People who rely on walking and cycling are harmed, and become less mobile. Since physically, economically and socially disadvantaged people tend to rely on these modes, this is inequitable.
- Walking, cycling and public transit travel (most transit trips including walking links) declines and automobile travel increases. Residents drive even for short neighborhood trips. This increases automobile external costs.
- The increased vehicle traffic degrades urban environments, which encourages more households to choose sprawled locations, and therefore lead more automobile-dependent lifestyles.

This planning bias is economically inefficient to the degree that some travelers would prefer to walk, bike and use public transit, but cannot due to inadequate facilities. The total inefficiency includes the loss of consumer welfare from people deprived for their preferred travel modes, plus the increased external costs that result from the increased vehicle travel. Reforms that result in more multi-modal planning would increase economic efficiency and help achieve planning objectives.

Example 3
Failure to Apply Location-Based Pricing

Although infrastructure and public service costs tend to be much lower for compact, infill development compared with dispersed, low-density development, these savings are not generally reflected in development and utility fees or local taxes. As a result, smart growth neighborhood residents tend to cross-subsidize the additional costs of residents of sprawled locations, and residents have less incentive to choose smart growth locations. With more efficient pricing, smart growth residents would typically save thousands of dollars annually in housing and utility fees compared with sprawled locations. Pricing differentials of this magnitude are likely to cause a significant portion of households to shift to somewhat more compact housing options, for example, some households would shift from larger- to smaller-lot single-family housing; others would shift from small-lot single-family to adjacent housing; and some would shift from adjacent to multi-family housing.

WHAT ARE THE POLICY IMPLICATIONS FOR RAPIDLY URBANIZING COUNTRY CITIES?

This section discusses the implications of this analysis for developing countries.

A key issue in this analysis is the degree to which these analysis results are transferable to developing country cities. Developing country cities tend to have higher densities, lower automobile ownership rates, and less urban expansion than in North America. Although sprawl costs may be smaller in absolute value in developing compared with developed countries, due to lower incomes and land prices, their magnitude as a portion of household and government budgets, and their impacts on economic development, are often equal or greater.

For example, zoning codes that have high minimum parking requirements are inefficient and unfair because they force residents to pay for parking spaces regardless of whether or not they own a car, reduce housing affordability, reduce development densities and increase total vehicle ownership. Such policies are particularly inefficient and unfair in developing country cities that have low vehicle ownership. Conversely, policy reforms that result in better walking and cycling conditions, and improved public transit services are particularly appropriate in developing country cities as a way to improve travel options for low-income residents and reduce severe traffic and parking congestion, pollution and accident costs.

Because land use development patterns have very durable effects, the decisions that developing countries make now can have large long-term effects. Developing countries now have the opportunity to establish more optimal transport and land use development patterns that help achieve various, economic, social and environmental objectives. For example, by designing walkable and bikeable cities where residents frequently use these modes for local trips, they can avoid future health problems associated with sedentary living. Thus, this analysis indicates the potential future savings and benefits that developing country cities can achieve by implementing smart growth policies, rather than just their current savings.

Many rapidly developing cities include informal settlements occupied by poor people, which over time evolve into more affluent and durable neighborhoods (Arnott 2009). This type of development provides affordable housing and supportive communities, but is often unplanned and unserviced. Governments should recognize the demand for very inexpensive (essentially free) housing, and the benefits to both occupants and the larger community if such settlements reflect smart growth principles, that is, they are located close to services and jobs. There is much that governments can do to support such communities so they are safe and healthy, and to guide such development so it is consistent with a city's strategic goals, including planning for adequate roadways, provision of essential services (water and sewage, electricity, policing, schools and medical services), and mechanisms that allow occupants to obtain legal ownership of land, provided it is in a suitable location (FIG 2008). This requires coordinated planning, engineering, government services and legal practices which are complex and will vary from one city to another.

SMART GROWTH EXAMPLES

This section describes examples of successful smart growth policies and programs.

Infilling Chinese Cities (World Bank 2014)

Chinese cities are rapidly growing, but much of the new development is scattered, and policies favor industrial over residential uses, resulting in urban fringe development and high housing prices. A World Bank report, Toward Efficient, Inclusive, and Sustainable Urbanization (World Bank 2014) recommends land policy reforms to encourage infill development and increase the supply of land available for high quality residential communities.

Urban Intensification Guides (Hamilton 2011)

Various cities have developed guidebooks and websites to help evaluate and implement more intense urban development. These guides include descriptions and illustrations of various buildings and street designs, discuss the advantages and disadvantages of various urban densities, and offer recommendations for maximizing benefits and minimizing problems with higher density development.

Complete Streets Planning

Complete Streets refers to roadway design and operating practices intended to safely accommodate diverse users and activities including pedestrians, cyclists, motorists, public transport users, people with disabilities, plus adjacent businesses and residents. Complete Streets planning recognizes that roadways often serve diverse functions including through travel, recreational walking, socializing, vending, and nearby living, which must be considered and balanced in roadway design and management. Complete streets policies are a practical way to improve walking, cycling and public transit, which increase transport system efficiency.

In recent years many jurisdictions have adopted complete streets policies, and many professional organizations, including some in developing countries, have developed complete streets design manuals which provide guidance on how to integrate motorized and non-motorized modes (ADUPC 2009; ITDP 2011; NACTO 2012; UTTIPEC 2009).

Walkability Improvements (Leather, et al. 2011)

A survey of pedestrians in 13 Asian cities found that:
- 37% of respondents rely primarily on walking for transportation.
- The median walkability rating was 58 out of 100.
- 41% of respondents rate their city's pedestrian facilities "bad" or "very bad."
- 67% of the respondents would shift their walking trips to motorized modes (with 29% shifting to cars and 10% to two-wheelers) if walking conditions do not improve.

The analysis indicates a lack of relevant policies, dedicated institutions, and political support to improve walkability. Proper allocation and use of funds for pedestrian facilities are also identified as major issues throughout Asia. Based on these findings the study made various recommendations for improving walkability and pedestrian conditions. City governments are identified as the key stakeholder group for pedestrian facility development and implementation. National governments and civil society (professional and non-profit organizations) and development agencies can also play important roles. They also recommend changing transport system performance indicators to better evaluate walking conditions, and developing appropriate roadway and pedestrian facility design guidelines, since existing guidelines are often ambiguous, inequitable, or not enforced.

Critical Evaluation of Indian Urban Transport (Mahadevia, Joshi and Datey 2013)

The report, Low-Carbon Mobility in India and the Challenges of Social Inclusion: Bus Rapid Transit (BRT) Case Studies in India critically evaluates the degree that urban transportation systems serve low-income households and other disadvantaged groups. It uses travel demand surveys to evaluate walking, cycling and public transit activity, and consumer expenditure survey data to evaluate transportation affordability. It discusses the quality and utility of Bus Rapid Transit (BRT) systems in various Indian cities, and identifies various problems and potential improvement strategies.

India's National Urban Transport Policy emphasizes the importance of building 'streets for people' rather than simply maximizing motor vehicle traffic speeds. It also emphasizes the need to improve transit service for disadvantaged groups. This offers an opportunity to improve public transit services and develop BRT systems. However, of the 63 cities eligible for national transportation funds, only about 10 built BRT systems, out of which only four have dedicated bus lanes. Some roadway expansion projects that were planned as BRT lanes have been converted to general traffic lanes, and some BRT infrastructure was badly designed, built or maintained, resulting in poor service. Some Indian cities have developed well-used walking and bicycle facilities as part of transportation improvement programs, but others have not, and police often fail to keep motorised vehicles from encroaching on cycle tracks. Sometimes inappropriate design of infrastructure has led to a lack of usage. For example, in Ahmedabad, many roadways lack footpaths and cycle tracks, and some facilities are so poorly designed that cyclists avoid using them. Another common conflict and barrier to efficient urban transportation involves motor vehicles parking on footpaths, cycle tracks and bus lanes. Most vehicle parking is unpriced.

Korean Sustainable Transport and Logistics Development Act (UN 2009)

The Korean Sustainable Transport and Logistics Development Act supports development of sustainable transportation systems. The act:

- Requires national and regional transport agencies to adopt and implement sustainable transportation and logistics' strategies. These must include energy consumption and greenhouse gas reduction goals, transport mode shifts and other related measures, and a financing plan.
- Requires the government to adopt a sustainability management index and standards, and to regularly inspect and evaluate these in order to scientifically and reasonably administrate greenhouse gas reduction, energy use reduction, and green transport.
- Introduces diverse programs to promote the shift to a sustainable transportation and logistics system. One of these programs is the "Total Automobile Traffic Load System by Zones", which sets the total automobile traffic for each zone, and in accordance with a voluntary agreement between local governments and the state, gives administrative or financial incentives to the regional or local governments that successfully reduce the total automobile traffic.
- Provides policy tools to stimulate Non-Motorized Transport (NMT). A comprehensive plan (5-year period) that aims to increase the transport share of NMT is to be devised, and shall consist of an analysis of the present state and prospects of NMT, the objectives and general outline of the policy, and a plan for the increase in the transport share of NMT.
- Provides a support basis to encourage collaboration with non-governmental organizations in developing and diffusing environmentally-friendly transport technology.
- Is implementing comprehensive Transportation Demand Management (Yun and Park 2010).

Improving Urban Walkability in India (CSE 2009)

The report Footfalls: Obstacle Course To Livable Cities (CSE 2009) evaluates walking conditions in Indian cities. Although walking represents 16% to 57% of urban trips in these cities, walking conditions are poor, with little investment, insufficient road space, and inadequate facility design and maintenance standards. The study argues that inadequate support for nonmotorized travel is inefficient and inequitable. The study developed a Transport Performance Index for evaluating urban transportation systems and prioritizing system improvements. It consists of the following factors:

- Public Transport Accessibility Index (the inverse of the average distance to the nearest transit stop or station).
- Service Accessibility Index (% of work trips accessible in 15 minutes time).
- Congestion Index (average peak-period journey speed relative to a target journey speed).
- Walkability Index (quantity and quality of walkways relative to roadway lengths).
- City Bus Transport Supply Index (bus service supply per capita).
- Para-Transit Supply Index (para-transit vehicle supply per capita).
- Safety Index (1/traffic fatality per 100,000 residents).
- Slow Moving Vehicle (Cycling) Index (availability of cycling facilities and cycling mode share).
- On-street Parking Interference Index (1/[portion of major road length used for on-street parking + on-street parking demand]).

Parking Management in Rapidly Developing Cities

The Parking Guidebook for Chinese Cities (Weinberger, et al. 2013) identifies strategies for efficiently managing parking resources in urban areas that are experiencing increased motorization and associated parking problems, in ways that support strategic, long-term goals. It uses Guangzhou as a case study which illustrates how a Chinese city manage parking in the best possible way. It recommends these eight strategies:

1. Establish a centralized management of all parking activities.
2. Implement performance standards for parking management.
3. Use appropriate technology for payment and data collection.
4. Reduce or eliminate parking minimums, establish maximum allowances or area-wide parking caps.
5. Decouple land use from off-street parking requirements and implement shared parking.
6. Price or tax off-street parking according to market cost.
7. Enhance enforcement with electronic technology and physical design.
8. Provide clear information on parking supply to ensure its effective use.

Similarly, collaboration between local and national governments, and international development organizations, had developed parking policy reforms for cities in Mexico which will lead to more efficient management of public parking facilities (ITDP 2014). Mexico City implemented a parking meter pilot project which has proven to be effective at reducing parking problems and generating revenues that are used to improve alternative modes in a busy urban neighborhood. The city is now expanding this program to other areas.

Transport Policy Reforms for Arab Environment and Development (AFED 2011)

The report, Green Economy: Sustainable Transition in a Changing Arab World by the Arab Forum for Environment and Development (AFED) identifies transportation policies that promote sustainable development and reduce poverty. It defines green transportation broadly to mean the provision of safe, affordable, and reliable mobility options that are energy efficient, while minimizing pollution, congestion, and random urban sprawl. It discusses the implications of green transport on economic growth, social cohesion, and environmental sustainability.

Common problems include:

- Government-subsidized gasoline and diesel fuel.
- Poorly maintained and ageing vehicle fleet which increase fuel consumption and emission rates.
- Inefficient and inadequate public transport systems and excessive reliance on private vehicles.
- Government policies that encourage private car ownership
- Inefficient traffic management systems and insufficient public awareness.
- Poor urban and physical planning resulting in rapid sprawling in major urban centers.
- Inadequate governance setup to adequately manage the transportation sector manifested by weak and insufficiently enforced environmental policies and regulations.
- Limited access in rural areas due to poor road networks and the inadequacy of basic transport services.
- Very high road traffic mortality rates.

In response, the report recommends:

- Invest in public transport and non-motorized modes, and provide incentives to promote their use.
- Invest in rail transport to move freight and to transport people within busy corridors.
- Adopt national fuel economy standards for vehicle fleets.
- Remove broad fuel subsidies, while employing targeted subsidies to protect low-income groups.
- Accelerate car replacement programs using incentives to take ageing cars off the road and establish vehicle emission testing.
- Upgrade the quality of fuels, particularly by reformulating gasoline and reducing sulfur content in diesel.
- Introduce and promote through incentives low carbon fuels, such as compressed natural gas.
- Apply mixed-use land management concepts in urban planning to reduce travel distances and protect land from degradation.
- Adopt transportation demand management practices that increase transport system efficiency.
- Accelerate the development of an electrification infrastructure for railway trains and vehicles.
- Improve public transportation planning capacity and technical expertise.
- Design appropriate interventions to reduce traffic fatalities and injuries.
- Raise awareness about fuel-saving purchasing, driving, and maintenance habits among fleet operators.

Developing Country Travel Demand Surveys

Comprehensive and accurate travel statistics are critical for transportation planning. Some developing country jurisdictions have performed travel demand surveys. For example, in 2003 the South African Department of Transportation commissioned that country's first National Household Travel Survey which sampled more than 50,000 residents, a larger than normal sample size for such a survey in order to ensure credible statistical data for all major demographic and geographic groups concerning both motorized and non-motorized travel (SADoT). During April and May 2012, researchers completed 2,068 travel survey interviews in three Rio de Janeiro favelas (informal, low-income communities) which provided information on vehicular ownership, non-motorized transport, modal share, vehicle parking, perception of road safety, plus data on the destination, mode, timing and purpose of 4,336 unique trips (Koch, Lindau and Nassi 2013).

Multi-Modal Planning in Historic Istanbul (Gehl Architects 2013)

Istanbul's Historic Peninsula is one of the most important urban areas in the world: an area of extraordinary beauty where 8,500 years of human history and culture embrace the sea. It is home to tens of thousands of residents and 2.5 million daily visitors including workers, students, business owners, shoppers, tourists and worshippers. This puts undue strain on the area, especially the transport system, which is forced to accommodate more travelers in one day than the total population of most European cities. This area is currently strangled by unsustainable transport infrastructure. The network of old, narrow streets that gives the area its charm also makes it challenging to access the historic sites seashore walkway. EMBARQ Turkey, an international sustainable transportation advocacy group, commissioned Gehl Architects, a world renown urban planning organization, to develop a comprehensive sustainable transportation plan titled, Istanbul: An Accessable City – A City For People which includes comprehensive data on walking, cycling and public transit conditions, detailed analysis, and specific recommendations for creating a more livable, sustainable, and more economically competitive city. It is a beautiful document which could serve as a model for livable community planning in other cities.

EVALUATING CRITICISM

This section evaluates criticisms of sprawl cost studies and smart growth policies.

Criticism of Sprawl Cost Studies

Critics argue that widely-cited studies such as Burchell, et al. (2002) exaggerate sprawl costs (Cox and Utt 2004; Gordon and Richardson 1997). They claim that at most, sprawl costs average households only $80 annually, and cite research concerning the relationships between population density and per capita local government expenditures to claim that sprawl does not significantly increase public service costs. However, their analysis only considers a small portion of total sprawl costs, and their jurisdictional-scale analysis fails to account for important factors such as the type of development that occurs in an area, public service quality (residents in lower-density areas tend to supply their own water, sewage and garbage collection, and often have unpaved roads and volunteer fire departments), incomes (all wages tend to increase with city size), and the additional public service costs borne by cities because they contain more businesses and low income residents (Litman 2015).

Similarly, Fruits (2011), Gordon and Richardson (1997), and Cox (2014) argue that sprawl does not significantly increase transport costs, citing evidence that compact, transit-oriented cities have longer average commute duration than sprawled, automobile-dependent cities. However, average commute duration is an inadequate indicator of overall transportation costs. Various studies indicate that sprawl tends to increase total per capita vehicle travel, travel time, transportation expenditures and associated costs such as traffic fatality rates (Ewing and Cervero 2010; Marshall and Garrick 2012; USEPA 2013; Zhang, et al. 2012). Although more compact cities tend to have more intense congestion (travel speeds decline more during peak periods), residents of such cities drive less during peak periods, which reduces the total time they spend traveling, and their total congestion delay (Ewing and Hamidi 2014; Kuzmyak 2012; Levine, et al. 2012; Litman 2013).

Researchers Melia, Barton and Parkhurst (2011) argue that planning policies which increase population densities tend to reduce overall vehicle use but increase local traffic and parking congestion, and noise and air pollution. They therefore suggest that planners avoid false expectations and implement complementary policies that further reduce local trip generation rates. Although this is sometimes interpreted as a criticism of compact development, it is actually consistent with smart growth, which involves integrated policies to maximize accessibility, minimize vehicle traffic, and mitigate local impacts.

Some critics argue that the amount of land displaced by sprawl is small relative to worldwide supply, and because agricultural productivity is increasing, there is no need to preserve farmland (Cheshire 2009; Gordon and Richardson 2097). However, this ignores many justifications for preserving open space. Many cities are surrounded by valuable farmlands and natural lands, Open space provides important ecological services including wildlife habitat, groundwater recharge, aesthetic and cultural values. As a result, open space displacement often imposes significant costs.

Critics sometimes argue that sprawl provides benefits that offset costs, but most of the benefits they cite (larger homes and gardens, larger play areas for children and pets, reduced exposure to noise and air pollution) are direct benefits to residents; there is no evidence of significant external benefits that would offset external costs. Overall, most sprawl cost study criticism appears to reflect incomplete and outdated information.

Criticism of Smart Growth Policies

Critics raise various objections to smart growth. Some criticism assumes that smart growth consists primarily of regulations that restrict housing and transport options, which increases consumer costs and reduces consumer welfare (Cheshire 2009; Demographia 2012; Mills 1999). This is incorrect. Although some smart growth policies increase regulations and consumer costs, others reduce regulations, improve housing and transport options, increase affordability, and reflect market principles such as efficient pricing, as summarized in Table 24.

Table 24
Smart Growth Impacts

Increased Regulations	Reduced Regulations	Improved Options	Efficient Pricing
Urban growth boundaries Vehicle traffic speed controls Increased parking fees Increased development design standards and review	Reduced and more flexible regulations regarding housing density, size and type Reduced and more flexible parking requirements	Allow more housing options (small-lots, multi-family) Allow more mixed development Improved transport options (walking, cycling, transit, taxi, etc.) Brownfield reclamation	Discounts for more compact development (reflecting their lower public service costs) More efficient transport pricing (cost-based pricing of roads, parking, insurance, fuel, etc.)

Smart growth increases some regulations but reduces others, improves consumer options and applies more efficient pricing which tends to benefit most residents overall.

Critics argue that smart growth contradicts consumer preferences for single-family housing (Kotkin 2013), but as discussed in the Demand for Sprawl section, housing preferences are diverse. Although surveys indicate that most North American households prefer single-family homes, they also value smart growth features such as convenient access to local services and shorter commutes, and many households would choose more compact housing options if given suitable incentives such as better schools or financial savings (Hunt 2001; NAR 2013). Current demographic and economic trends are increasing demand for more compact neighborhoods (Pembina 2014). Smart growth responds to these demands, for example, by expanding affordable housing options and improving public services in accessible, multi-modal neighborhoods.

Contrary to critics' assumptions, smart growth does not usually eliminate single-family housing. Analysis in this report suggests that in unconstrained cities, smart growth can allow more than half of all households to have single-family or attached housing that include private gardens; only highly constrained cities require most households to live in high-rise apartments. It is true that smart growth policies that discourage urban expansion may increase single-family housing prices, making them less affordable to lower-income households, but other smart growth policies reduce the costs of compact housing, as well as infrastructure and transport costs, and so can increase affordability overall. This criticism therefore depends on whether single-family housing affordability is more important than compact housing affordability, and whether house purchase affordability is more important than infrastructure and transport affordability. To the degree that smart growth reduces total resource costs (public infrastructure and service costs, traffic accidents, pollution damages, etc.) it can benefit all residents. All of these impacts should be considered when evaluating consumer welfare impacts.

A related criticism is that smart growth is regressive because it makes single-family housing unaffordable to lower-income households, forcing poor households into inferior, crowded neighborhoods (Kotkin 2013). However, as discussed previously in this report, by reducing restrictions on development density, supporting affordable housing options such as multi-family and secondary suites, and reducing parking requirements, smart growth reduces the costs of compact housing in accessible locations, and so tends to increase overall affordability (Rodier, et al. 2010). Ewing and Hamidi (2014) found that in the U.S., each 10% increase in their smart growth index is associated with a 4.1% increase in residents' upward mobility (probability a child born in the lowest income quintile reaches the top quintile by age 30). In these ways, smart growth tends to benefit most lower-income households.

Critics argue that smart growth causes housing price "bubbles" which increase foreclosure rates, based on the assumption that smart growth consists of urban containment policies that increase prices and speculation (Cheshire 2009; Cox 2011). However, as described in the Household Affordability section, it is the combination of urban containment and restrictions on compact infill development that drive up housing prices. Housing foreclosure rates are lower in more compact neighborhoods, suggesting that smart growth can support stable housing markets (Pivo 2013; Rauterkus, Thall, and Hangen 2010)

In research sponsored by the National Association of Home Builders, Fruits (2011) argues that there is little or no evidence that smart growth policies can reduce climate change emissions and concludes, "regional efforts to slow potential climate change through compact development are little more than showy, but costly, curiosities." However, he relies on outdated and inaccurate analysis. For example, he claims that "some studies have found that more compact development is associated with greater vehicle-miles traveled" citing a 1996 study by Crane which only presented theoretical analysis indicating that under some conditions a grid street system could increase vehicle travel. As previously discussed, extensive, peer reviewed research indicates that smart growth community residents tend to own fewer vehicles, drive less, consume less fuel, and produce less pollution emissions than they would in sprawled, automobile-dependent locations (ATM 2013; D'Onofrio 2014; Ewing, et al., 2009; LSE Cities 2014; UNEP 2011). Subsequent analysis discredited Fruits claims (Litman 2011).

By increasing density and encouraging infill development, smart growth can increases residents' exposure to noise and local air pollutants such as particulates and carbon monoxide. However, by reducing total per capita vehicle travel it reduces the generation of regional and global pollutants such as ozone and carbon dioxide. Targeted efforts to reduce local air pollution, such as policies that encourage use of lower-polluting vehicles and emissions inspections programs, can further improve urban air quality.

Some smart growth criticism reflects local concerns such as fears that more affordable infill housing will increase urban poverty, as discussed in the "Social Problems" section, research indicates that smart growth actually tends to reduce total regional poverty and crime by improving passive surveillance (neighbors' ability to watch out for each other) and economic opportunity for at-risk groups.

Cox (2014) argues that relatively high GDP in some lower density U.S. cities demonstrates that sprawl increases economic productivity, but this evidence is anecdotal and fails to account for other factors that affect productivity. When U.S. cities are compared with each other, there are strong positive relationships between smart growth indicators such as density, transit ridership and walkability, and economic productivity (Abel, Dey, and Gabe 2011; Litman 2014a). The low-density, high GDP cities Cox cites tend to either be small cities that attract affluent households, such as Hartford and Bridgeport, or cities benefiting from a resource booms, such as Houston and Abu Dhabi. As discussed in the Economic Development section, more compact development provides agglomeration efficiencies and cost savings that tend to support economic development (Hsieh and Moretti 2014; Melo, Graham and Noland 2009).

CONCLUSIONS AND RECOMMENDATIONS

The world is experiencing rapid urbanization. How this occurs will have immense economic, social and environmental impacts. To help identify optimal urban development policies, this report investigates the costs of sprawl and potential benefits of more compact, "smart growth" development.

This study builds on an extensive body of previous research. In recent years, there has been significant improvement in the data and tools available for evaluating land use impacts, and several sophisticated studies provide important new insights concerning various economic, social and environmental impacts of urban development patterns. As a result, we now have a far better understanding of development pattern impacts than was previously possible.

However, this type of analysis faces several technical challenges. There are various ways to define and measure urban development patterns, various impacts to consider, various ways to measure impacts, and various scales of analysis. If possible, impact analysis should consider several land use factors including development density, mix, centricity, transport network connectivity and design, the quality of transport options (walking, cycling, public transit, automobile, etc.) and pricing, but in practice, sprawl impacts are often evaluated based only on population density, since this information is easiest to obtain and understand. Some impacts overlap, and some are economic transfers (one group benefits at another's expense), so it is important to avoid double-counting. There are also confounding factors to consider, such as the tendency of residents to self-select neighborhoods, which can confuse our understanding of effects. People sometimes confuse density (people per unit of land) with crowding (people per unit of building space), although they are actually very different. All these issues should be considered when researching development impacts.

This analysis starts by identifying basic physical impacts of sprawl, including increases in the amount of land developed per capita, and dispersion of destinations which increases per capita motor vehicle travel. This indicates that compared with smart growth development (typically more than 30 residents per regional hectare), sprawl (typically less than 6 residents per hectare) increases per capita land consumption 60-80%, and motor vehicle travel by 20-60%.

This provides a conceptual basis for understanding various economic costs of sprawl, including displacement of agriculturally and ecologically productive lands, increased infrastructure costs, reduced accessibility for non-drivers, and increases in various transportation costs including facility costs, travel time, consumer expenditures, traffic accidents and pollution emissions. To the degree that sprawl degrades access by affordable modes (walking, cycling and public transit), these impacts tend to be regressive (they impose particularly large burdens on physically, economically and socially disadvantaged people). To the degree that sprawl concentrates poverty in urban neighborhoods, it tends to exacerbate social problems such as crime and dysfunctional families. To the degree that it reduces agglomeration efficiencies, increases infrastructure costs, and increases expenditures on imported goods (particularly vehicles and fuel), it tends to reduce economic productivity. Sprawl also provides benefits, but these are mostly direct internal benefits to sprawled community residents; there is little reason to expect sprawl to provide significant external benefits to non-residents since rational consumers and businesses internalize benefits and externalize costs.

Table 25 summarizes various sprawl impacts and our current knowledge about them.

Table 25
Sprawl Impacts Summary

Impact	Current Quality of Knowledge
Land development (displacement of farmland and other open space)	This impact is easy to measure, but difficult to monetize.
Public infrastructure and service costs	There is good research on this impact and it can be monetized.
Transportation costs	There is good research on this impact and it can be monetized.
Traffic risk	There is good research on this impact and it can be monetized.
Public fitness and health	There is now research on this impact and it can be monetized.
Energy consumption and pollution emissions	There is good research on this impact and it can be monetized.
Social equity (impacts on disadvantaged populations)	There is research on some aspects of this impact, but it is difficult to monetize.
Social problems (poverty and crime)	Some good research, but it is difficult to quantify and monetize.
Affordability	There is research on this impact, but it is difficult to monetize.
Economic development	There is research on this impact, but it is difficult to monetize.
External benefits of sprawl	There is research on this impact.

This table summarizes the current quality of knowledge concerning the various impacts (costs and benefits) of sprawl considered in this study.

To quantify the incremental costs of sprawl, this study divided U.S. cities into quintiles (fifths) and, using the "smartest growth" quintile as a baseline, estimated the additional land consumption, infrastructure and public service costs, vehicle costs, and health costs of more sprawled development. For example, the research indicates that sprawl increases annualized infrastructure costs from $502 per capita in the smartest growth quintile cities up to $750 annual per capita in the most sprawled quintile cities. Sprawl has similar effects on other cost categories. In total this analysis indicates that sprawl incremental costs average about $4,556 annual per capita, of which $2,568 is internal (borne directly by sprawl location residents) and $1,988 external (borne by other people). Even using lower-bound assumptions, this analysis indicates that sprawl external costs exceed $400 billion annually. Total costs are probably much higher than this estimate since this analysis considered relatively modest development changes (for example, even in the "smart growth" cities most urban residents would live in single-family housing and rely primarily on automobile travel), and excluded some significant costs such as open space displacement and increased social problems, because they are difficult to monetize.

A key question for this analysis is the degree that sprawl is economically inefficient, that is, the amount caused by policy distortions. This study investigated various planning and market distortions which encourage sprawl, such as development practices that favor dispersed development over compact urban infill, underpricing of public infrastructure and services in sprawled locations and underpricing of motor vehicle travel. For example, surveys indicate that many households want to live in more compact, walkable, mixed-use neighborhoods but cannot because current zoning codes discourage such development. Cost-based pricing of utilities and public services would result in 20-40% lower fees and taxes in smart growth locations. For example, if such fees average $1,000 per month, efficient pricing could result in $850 monthly fees in smart growth locations and $1,150 monthly fees in sprawled locations, reflecting the higher costs of providing public services in dispersed locations. Similarly, by charging users directly for roads and parking, efficient pricing would increase the cost of driving an automobile by several hundred dollars annually, and reduce taxes and rents that currently subsidize roads and parking facilities. Consumer preference research suggests that more optimal planning and pricing would cause many households to choose compact communities, drive less, and rely more on alternative modes than they currently do. This suggests that the high degree of sprawl and automobile dependency that occurs in North American cities is an anomaly, resulting in part from planning and market distortions, so this type of development should not be used as a model for cities that strive to be economically efficient and equitable.

Although sprawl costs may be lower in absolute value in developing countries due to lower wages and property values, they are probably similar relative to incomes and regional economies. As a result, smart growth policies that create more compact communities can provide substantial economic, social and environmental benefits in both developed and developing countries.

This study identified various factors to consider when determining how cities should expand. The results are consistent with the conclusions of Angel (2011) and UN-Habitat (2013) that cities should expand systematically along major utility and transit corridors. To help determine the optimal expansion policies, densities and development policies in specific situations, cities are divided into three categories:

1. Unconstrained cities are surrounded by an abundant supply of lower-value lands. They can expand significantly. This should occur on major corridors and maintain at least 30 residents per hectare densities. A significant portion of new housing may consist of small-lot single-family housing, plus some larger-lot parcels to accommodate residents who have space-intensive hobbies such as large-scale gardening or owning large pets. Such cities should maintain strong downtowns surrounded by higher-density neighborhoods with diverse, affordable housing options. In such cities, private automobile ownership may be common but economically excessive vehicle use should be discouraged by applying complete streets policies (all streets should include adequate sidewalks, crosswalks, bike lanes and bus stops), transit priority features on major arterials, efficient parking management, and transport pricing reforms which discourage urban-peak automobile travel.

2. Semi-constrained cities have a limited ability to expand. Their development patterns should include a combination of infill development and modest expansion on major corridors. A significant portion of new housing may consist of attached housing (townhouses) and mid-rise multi-family. Such cities should maintain strong downtowns surrounded by higher-density neighborhoods. In such cities, private automobile ownership should be discouraged with policies such as requiring vehicle owners to demonstrate that they have an off-street parking space to store their car, pricing of on-street parking with strong enforcement, roadway design that favors walking, cycling and public transit, and road pricing that limits vehicle travel to what their road system can accommodate.

3. Constrained cities cannot significantly expand, so population and economic growth requires increased densities. In such cities, most new housing will be multi-family and few households will own private cars. Such cities require strong policies that maximize livability in dense neighborhoods, including well-designed streets that accommodate diverse activities; adequate public greenspace (parks and trails); building designs that maximize fresh air, privacy and private outdoor space; transport policies that favor space-efficient modes (walking, cycling and public transit); and restrictions on motor vehicle ownership and use, particularly internal combustion vehicles.

This analysis indicates that very high regional densities (more than 100 residents per hectare) are only justified in highly constrained cities such as Hong Kong and Singapore. Most smart growth benefits can be achieved by shifts from low (under 30 residents per regional hectare) to moderate (50-80 residents per regional hectare, which is typical of affluent European cities). Although higher densities can provide additional benefits, these are likely to be modest in most cities. However, cities such as Singapore and Seoul demonstrate that with good planning, high density neighborhoods can provide high quality livability, and most cities should have a few districts of very high residential densities around their downtowns and other major transit terminals.

Because motor vehicles are very space-intensive (an automobile typically requires more space for roads and parking than the land used for a typical urban resident's house), a key factor for efficient and livable cities is to manage roads and parking for maximum efficiency, and to limit motor vehicle ownership rates to the capacity of available roads and parking facilities. This requires an integrated program of improvements to space-efficient modes (walking, cycling, ridesharing and public transit), incentives for travelers to use the most efficient mode for each trip, and accessible, multi-modal development which minimizes the need to drive. Since a bus lane can carry far more passengers than a general traffic lane, an efficient city provides bus lanes on most urban corridors. Table 26 summarizes optimal urban expansion, densities and development policies in these various types of cities.

Table 26
Optimal Urban Expansion, Densities and Development Policies

Factor	Un-Constrained	Semi-Constrained	Constrained
Growth pattern	Expand as needed	Expand less than population growth	Minimal expansion
Optimal regional density (residents / hectare)	20-60	40-100	80 +
Housing types	A majority can be small-lot single-family and adjacent	Approximately equal portions of small-lot single-family, adjacent, and multi-family.	Mostly multi-family
Optimal vehicle ownership (vehicles per 1,000 residents)	300-400	200-300	< 200
Private auto mode share	20-50%	10-20%	Less than 10%
Portion of land devoted to roads and parking	10-15%	15-20%	20-25%
Examples	Most African and American cities.	Most European and Asian cities.	Singapore, Hong Kong, Male, Vatican City.

Different types of cities may have different growth patterns, densities and transport patterns.

An important challenge facing growing cities is to provide affordable housing that responds to low-income residents' needs. Lower-priced housing should be diverse, including some larger units for large, extended families, and flexible lofts for households that need workspace for artistic or business activities. Lower-priced housing should be dispersed around the city to avoid concentrating poverty. In some cities, affordable housing policies may include formalizing informal settlements, or making small parcels of serviced land available for sale or lease, on which owners build their houses. In most growing cities, a major portion of affordable housing should consist of mid-rise (2-6 story), wood-framed apartments and townhouses, generally built by private developers with government support. In highly constrained cities, affordable housing may require government subsidy of high-rise apartments.

In all types of cities it is important to ensure that compact urban neighborhoods are very livable and cohesive by designing urban streets to be attractive and multi-functional (including sidewalks, shops, cafes, and attractive landscaping), building public parks and trails, providing high quality public services (policing, schools and utilities), and supporting activities that encourage positive interactions among residents such as local festivals, outdoor markets, recreation and cultural centers, etc.

Some previous sprawl cost studies have been criticized for various reasons. Critics argue that sprawl cost estimates are exaggerated, that such costs are offset by benefits of equal magnitude, or that more compact, smart growth development patterns impose equal external costs. However, much of this criticism reflects inaccurate or outdated research (for example, old studies which suggested that smart growth does not save energy or reduce public infrastructure costs). Although sprawl does provide benefits, these are largely direct, internal benefits to sprawl community residents and there is little evidence of significant external benefits which offset concerns about external costs. Probably the most legitimate criticism of smart growth is that it can reduce single-family housing affordability, but smart growth policies that allow more compact, infill development increase housing and transport affordability, and so are particularly beneficial to low-income households. This criticism therefore depends on whether single-family housing affordability is more important than compact housing affordability, and whether house purchase affordability is more important than infrastructure and transport affordability. To the degree that smart growth reduces total resource costs (public infrastructure and service costs, traffic accident, pollution damages, etc.) it can benefit all residents.

Much of the research in this report is based on North American conditions because that is where the best data are available. However, the basic relationships should be transferable: more dispersed and automobile-oriented development imposes various costs, including external costs, which can be reduced with smart growth policies. These can benefit most overall by improving their housing and transport options and providing new opportunities to save money to households that choose smart growth locations. Smart growth benefits tend to be particularly large:

- In rapidly growing urban areas.
- In urban areas making significant infrastructure investments.
- In cities where urban fringe land has high social or environmental values.
- Where infrastructure and vehicle fuel are costly to produce or import, for example, if a low-income country must import equipment and energy.
- If communities have goals to improve mobility options for disadvantaged populations, improve public fitness and health, or support environmental objectives.

Below are specific smart growth policies that can be implemented by different levels of government.

Municipal and Regional Governments

- Reform zoning codes to allow higher densities and encourage more mixed, multi-modal development within existing urban areas.
- Significantly reduce or eliminate minimum parking requirements in zoning codes, and implement more efficient parking management practices, such as pricing on-street parking, and efficiently enforcing parking regulations.
- Devote special care to planning central business districts and other major activity centers so they are attractive and multi-modal.
- Use regulations or pricing to manage road space to favor higher value trips and more space efficient modes over lower value trips and space intensive modes.
- Apply complete streets policies which insure that urban roads are designed and managed to accommodate diverse users and uses, including pedestrians (including those with disabilities and special needs), cyclists, public transit travelers, businesses, customers, tourists, delivery vehicles and residents.
- Ensure that any new "greenfield" development is well planned, creating complete communities (housing, shops, schools, parks, etc.) with good walking, cycling and public transit access.
- Structure development fees, utility rates and taxes to reflect the higher costs of providing public services in more dispersed locations.
- Support professional development programs for planners, engineers, developers and public officials to introduce smart growth concepts.

National Economic and Finance Ministries

- Reduce and eventually eliminate motor vehicle fuel subsidies, and implement regularly scheduled fuel tax increases.
- Apply comprehensive and multi-modal urban transportation planning. Ensure that all urban roadway projects reflect "complete streets" principles which accommodate diverse users and uses.
- Provide diverse and stable urban transportation funding options, including optional regional fuel taxes, road tolls, special property taxes (for land value capture), vehicle fees, employee levies, emission fees, and parking taxes.
- Establish national transportation and land use data programs to collect standardize GIS and transportation statistics.
- Provide a regional planning framework that encourages municipal governments to cooperate on transportation and land use planning.

Of course, these issues are complex. Urban planning decisions involve numerous trade-offs between various planning objectives, so many different factors must be considered when evaluating policies and projects. More research is needed to better understand the full benefits and costs of specific policy and planning decisions and determine the best policies to implement in a particular situation.

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