A Review of Integrated Urban Planning Tools for Greenhouse Gas Mitigation

Linking Land Use, Infrastructure Transition, Technology, and Behavioral Change

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Global Platform for Sustainable Cities

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Abbreviations

CIFAA	City Infrastructure Footprinting and Action Analysis
CO_2e	carbon dioxide equivalent
CSTC	China Sustainable Transportation Center
CUD	compact urban development
CURB	Climate Action for Urban Sustainability
CyPT	City Performance Tool
GEF	Global Environment Facility
GHG	greenhouse gas
GIS	geographic information systems
GPC	Global Protocol for Community-Scale Greenhouse Gas Emission Inventories
GPSC	Global Platform for Sustainable Cities
GSURR	Global Practice for Social, Urban, Rural, and Resilience
KPI	key performance indicator
MMT	million metric tons
RF	RapidFire
SDG	Sustainable Development Goal
TOD	transit-oriented development
UF	UrbanFootprint
UP	Urban Performance
USF	Urban Sustainability Framework

Executive Summary

Achieving the Sustainable Development Goals (SDGs) over the next 30 years will critically depend upon urban land use and infrastructure development actions taken across multiple sectors (buildings, energy, transportation, water-sanitation, and waste) in global cities. Integrated urban planning addresses a multiplicity of urban sustainability objectives (e.g., economy, environment, inclusivity, and resilience) (GPSC, World Bank 2018), including cross-sectoral and cross-scale linkages (Ramaswami et al. 2016) and connection of physical planning with social, cultural, behavior, and policy dimensions.

Urban land use is foundational to integrated urban planning. Grounded in urban land use, four key levers have been identified that have significant potential to result in resource-efficient, inclusive, and low-carbon cities (IRP 2018):

1. Compact urban development (CUD) and land use
2. Single-sector infrastructure and technology innovations
3. Cross-infrastructure interventions
4. Policy and behavior change

Together, these four levers shape how urban land use and infrastructure provisioning will impact the SDGs, in particular the goal of reducing greenhouse gas (GHG) emissions associated with cities—which is a key objective of the Global Platform for Sustainable Cities (GPSC).

Together, the four levers can have a multiplicative effect that maximizes GHG mitigation potential and thus helps achieve the targets of the Paris Agreement. For example, an inclusive compact urban form (Lever 1) can reduce travel demand, reduce material use (via high-rise construction versus single-story homes that are typical of urban sprawl), and lower the cost of physical infrastructure networks. Building upon this compact urban form, additional efficiencies and low-carbon trajectories can be achieved both within individual sectors (Lever 2, e.g., by making each building more energy efficient or supplying it with renewable energy) and across sectors (Lever 3, e.g., by having a network of buildings dense enough to reuse waste heat through district energy systems). Human behavior is critical to ensure that resource-efficient technologies and urban form are deployed in a manner that reduces energy use overall (Lever 4).

The objective of this report is to review the state of knowledge (science) and the state of practice (models actually used by cities for policy) for modeling the GHG mitigation benefits achievable through integrated urban planning across the four levers, with attention to the foundational Lever 1, CUD.

Although the field of urban sustainability is relatively young, and the availability of robust data is uneven across world cities, our review found that significant scientific advances have occurred in modeling the four levers representing integrated urban planning in the context of GHG mitigation. Within each of the four levers, more than 30+ strategies were identified in the literature. For all the strategies, the GHG mitigation potential can be modeled using the same structure of algorithms, which is computed by multiplying two key parameters:

1. The first parameter is the strategy effect per unit of an intervention, i.e., the reduction in demand or resource use per unit of intervention. Examples include reduction in travel demand per unit increase in transit provision, or reduction in energy use per unit of green building constructed. The strategy effect is bounded on one hand by a maximum upper limit (e.g., best-case travel demand reduction for a CUD zone is about 25 percent of the baseline for that zone in U.S. cities). There may also be minimum thresholds before a strategy takes effect (e.g., transit is not considered to be effective at densities less than ~35 dwelling units per acre (Santasieri et al. 2014). Depending on the sector, the strategy effect is represented in the form of elasticities in demand, and resource efficiency improvements per unit of intervention (such as energy reductions per unit area from building retrofits or energy reductions per mile driven in efficient cars).
2. The second parameter is the penetration rate or adoption rate of each intervention in the strategy scenario. Examples include the percentage of households experiencing CUD improvements or purchasing energy-efficient cars compared to the baseline. This rate has a high impact on the citywide potential for GHG mitigation from implementing a strategy and is shaped by human behavior and policy.

Each of the strategies can be characterized systematically by these two component parameters. It is important to use context-specific data or knowledge to inform both strategy effect and participation rates in baseline versus scenario cases. If an intervention with a high strategy effect (GHG reduction per unit intervention) is carried out in a context with limited prospects for extensive penetration, it may have limited GHG mitigation potential, while an intervention with a relatively low strategy effect (GHG reduction per unit intervention) but with extensive penetration could in fact represent an overall high-impact intervention. Both the strategy effect and penetration rate for a given intervention can vary substantially across urban contexts.

Focusing on compact urban development, a "5D" framework is widely cited in the scientific literature to represent various land use parameters that describe compact urban form in the context of travel demand (NRC 2009; Cervero and Kockelman 1997). The 5Ds refer to articulated and accessible **d**ensity; **d**iversity of use and income; **d**esign of neighborhoods and streets; **d**istance to transit; and **d**estination access. Elasticities for travel demand with respect to the 5Ds, any threshold densities for effect, and maximum bounds (best-case travel demand reductions) have been well established, but mostly for U.S. cities.

The science review does not recommend translating the quantification of strategy effects (i.e., travel demand elasticities) from one national context to another. Further, for some levers, such as compact land use development, it is not known if all of the 5D parameters (developed for car-dominated cities) are important in developing countries, where vehicle ownership is more limited and can, by itself, shape travel demand. Lastly, transparent penetration rates and adoption rates, grounded in locally derived data, are recommended both to track GHG mitigation over time, and learn from real-world experiments occurring across cities.

The review of the state of practice evaluated six integrated planning models that have been used by several cities to inform their urban development or climate action plans. These include

1. RapidFire/Urban Footprint: Chongqing, China; and various U.S. cities
2. Urban Performance: Amman, Jordan; and various global cities
3. City Performance Tool (CyPT): Los Angeles, California (United States); and various global cities
4. Climate Action for Urban Sustainability (CURB): Oakland, California (United States); and various global cities
5. ClearPath: Portland, Oregon (United States); and various U.S. cities
6. City Infrastructure Footprinting and Action Analysis (CIFAA): Denver, Colorado (United States) and various U.S. cities

Among the six models, only two models (ClearPath and CIFAA) integrated across all four levers, and these models have to date mostly been applied in U.S. cities. Most models are not tracking all the determinants relevant to all the strategies, including the 5Ds. There is an opportunity in the future to develop more robust integrated models across the four levers, along with associated tracking metrics, to represent the full multiplicative impact that is necessary to get a factor of 10 energy use reduction and achieve the Paris climate goals.

Focusing on the models that assess GHG benefits of CUD models, this review identifies three broad categories:

- Models that use locally derived elasticities to represent GHG benefits of compact urban form (RapidFire/UrbanFootprint)
- Models that apply U.S. field data–derived 5D elasticities to U.S. cities (ClearPath, CIFAA)
- Models that apply North American field data–derived 5D elasticities to world cities, given the absence of local data (CyPT, CURB)

Among these, the development of RapidFire in Chinese cities presents a very promising and robust method to model GHG mitigation in world cities, although it also relied on extensive field research (done with a local institution) to derive the elasticities, using new informatics and big data approaches (Jiang et al. 2017).

The six available models can be used in different city contexts to address different policy questions (as described in section 4 of the main report); while no single model to date integrates all the levers together, certain models are better suited to specific levers. While all four levers are important, they vary in degrees of critical relevance across city contexts. Understanding which levers are most important for certain types of city contexts and which models provide particularly strong coverage of which levers can help decision makers prioritize the modeling tool that is most appropriate for their specific urban context and policy goals.

This report makes four key recommendations:

1. Concerning CUD models, models such as RapidFire and Urban Performance are stronger than models that use U.S.-derived elasticities broadly across city contexts globally. This is because RapidFire and Urban Performance are developed using in-country data and elasticities, and CUD model selection is recommended to take these considerations into account. New big data approaches have much potential to be applied in world cities to develop locally specific data. Opportunities to apply big data locally highlight the importance of local capacity. In addition, RapidFire and Urban Performance produce results apart from GHG impact alone, including land savings, reduced water and energy usage, mobility optimization, and lower infrastructure cost. The co-benefits generated from integrated land use and planning provide an important basis for policy dialogue with political leadership around developing a compact urban spatial strategy.
2. Longitudinal data on key performance indicators should be gathered from a wide range of cities and be used to report elasticities and baseline adoption/penetration rates publicly. A network of cities, such as GPSC, has an unprecedented opportunity to gather data to improve scientific knowledge and develop more robust CUD models going forward.
3. In the context of fully integrated urban planning models, there is a need and an opportunity for future model development and benchmarking that connects all four levers in diverse world cities. Given the growing pressures of rapid urbanization on natural resources and ecosystems, future models should consider the equity and distribution of scarce resources (e.g., the growing cross-sectoral competition for scarce water and land resources) in order to bring enhanced relevance of GHG mitigation strategies into the context of the SDGs and local policy goals.
4. All models should be developed so that all their underlying assumptions and algorithms are transparent and available in the public domain. This type of transparency is critically important for the ability of decision makers and technical specialists to (i) judge the fit of a particular model for a specific context, based on existing algorithms; and (ii) allow for algorithm modification using more locally, regionally, or urban typology–specific data that may be more suitable for a specific context. Overall, it is important to start co-developing consensus on the acceptable level of uncertainty and accuracy that will result from the use of the recommended tool(s).

Section 1. Introduction and Objectives

More than half the world's population lives in urban areas, and based on current urbanization rates, it is projected that two-thirds of the world's 9.8 billion people in 2050 will live in urban areas (UN DESA 2013). Urban areas are estimated to account for more than 70 percent of global energy-related GHG emissions when accounting for direct fuel and electricity use (Hoornweg, Sugar, and Gomez 2011). Cities are a crucial action arena for sustainable development, as they respond to issues of population growth, infrastructure needs, and development, while also addressing issues such as pollution, resource sustainability, and climate change (IRP 2018; United Nations 2017; UN Habitat 2018).

The World Bank's Global Platform for Sustainable Cities (GPSC) is designed to "assist cities in tapping into cutting-edge knowledge and expertise on topics ranging from urban planning to low-carbon strategy, transit-orientated development, and sustainable financing" (GPSC, World Bank 2018). This report supports that goal by assessing available tools for evaluating integrated urban GHG mitigation strategies that incorporate land use in support of compact urban development (CUD).

The GPSC's Urban Sustainability Framework (USF) lays out two enabling dimensions by which to achieve four key outcomes related to a sustainable city (see table 1). The first enabling dimension relates to governance and integrated urban planning. This report focuses on integrated urban planning relating to all four outcome dimensions (economy, environment, climate resilience, inclusivity), with particular attention to quantification of GHG mitigation potential, which is of specific interest to the GPSC.

Drawing upon the USF, we define integrated urban planning as planning that addresses multiple city objectives (e.g., economy, environment, inclusivity, and resilience) (GPSC, World Bank 2018) by focusing on the design of a city's physical infrastructure as a whole (i.e., including cross-sectoral and cross-scale dependencies and linkages) (Ramaswami et al. 2016), and by connecting physical infrastructure planning with social, cultural, behavior, and policy dimensions. Linking in-boundary urban planning with a transboundary, cross-scale perspective (as discussed in Ramaswami et al. [2012]) is important because cities rely on imported electricity, fuel, water, and other key basic services for their functioning, and these are increasingly being quantified in city GHG accounting methods.

Urban land use patterns are foundational to integrated urban planning. Grounded in urban land use, four key levers have been identified by the United Nations (IRP 2018) as interacting with each other to support resource-efficient, inclusive, low-carbon, and climate-resilient cities:

1. CUD and land use
2. Single-sector infrastructure and technology innovations
3. Cross-infrastructure interventions
4. Policy and behavior change

Together, these levers shape how urban land use and infrastructure provisioning will impact the Sustainable Development Goals (SDGs), in particular how they support climate action by reducing greenhouse gas (GHG) emissions associated with cities—which is a key objective of the GPSC.

The four levers together have a multiplicative effect, maximizing GHG mitigation potential. For example, inclusive CUD (Lever 1) can reduce travel demand, reduce material use (e.g., via reduced material use per housing unit in high-rise construction versus single-story homes), reduce land expansion and urban sprawl, and lower the cost of physical infrastructure networks. Upon this compact urban form, additional efficiencies and low-carbon trajectories can be achieved, both within individual sectors (Lever 2; e.g., by making each building more energy efficient or supplying it with renewable energy) and across sectors (Lever 3; e.g., by having a network of buildings dense enough to reuse waste heat through district energy systems). Human behavior and associated policy changes (Lever 4) are critical (e.g., to ensure that efficient buildings and technologies are actually used in a manner that reduces overall energy use).

The objective of this report is to review the state of knowledge (science) and the state of practice (models actually used by cities for policy analysis) for modeling the GHG mitigation benefits that are achievable through integrated urban planning across the four levers, with attention to foundational compact urban development (Lever 1).

We use the 5D framework to assess GHG mitigation arising from CUD. The 5D framework includes consideration of **d**ensity, **d**esign (multi-modal and human scale), **d**iversity of use and income, **d**istance to transit, and **d**estination access (NRC 2009; Cervero and Kockelman 1997). It lays the foundation for encouraging built environments that minimize dependence on personal motorized vehicle travel (IRP 2018). Together, the 5Ds (discussed in greater detail in section 2) represent an urban form in which human-scale design, an appropriate mix of land uses, and strong mobility connections across the city can shrink the distance between key daily destinations (e.g., housing, jobs, commerce, services, etc.) *and* facilitate transit or nonmotorized modes of travel between those destinations as desirable and accessible travel defaults.

Infrastructure transitions on the horizon such as electricity-based mass mobility systems, the renewable energy grid, and green building design paradigms (e.g., passive design) can dramatically transform resource efficiency and the way in which infrastructure services are provided in cities. The GHG mitigation potential of these infrastructure transitions is closely linked with how infrastructure and buildings are spatially laid out across an urban fabric (i.e., spatial land use patterns).

Ongoing projects in several GPSC cities demonstrate a commitment to pursuing the development of more sustainable urban form through principles of compact urban development. For example, projects in the seven GPSC cities located in China—Guiyang, Shenzhen, Ningbo, Nanchang, Beijing, Tianjin, and Shijiazhuang—focus on compact, mixed-used, and transit-oriented development (TOD) encouraging a shift toward walking, biking, and high-quality transit. The project in Abidjan, Côte D'Ivoire, supports improved spatial planning informed by a mobility plan as well as an intelligent transport system plan. Asuncion, Paraguay, is making investments in CUD via actions supporting sustainable mobility, including investments in bus rapid transit, bike paths, and a traffic management plan.

Table 7: Enabling and Outcome Dimensions as Identified in the GPSC's Urban Sustainability Framework

ENABLING DIMENSIONS		GOALS
1.	Governance & integrated urban planning	Achieve integrated, well-planned urban development
2.	Fiscal sustainability	Ensure accountable governance and fiscal sustainability

OUTCOME DIMENSIONS		GOALS
1.	Urban economies	Attain sustainable economic growth, prosperity, and competitiveness across all parts of the city
2.	Natural environment & resources	Protect and conserve ecosystems and natural resources into perpetuity
3.	Climate action & resilience	Work toward mitigating greenhouse gas emissions while fostering the overall resilience of cities
4.	Inclusivity & quality of life	Work toward creating inclusive cities and improving cities' livability, focusing on reducing poverty levels and inequality throughout cities

Source: GPSC, World Bank 2018.

Using the above discussion of integrated urban planning and CUD as a launching point, this report focuses on the following key questions:

1. **State of knowledge:** How are the relationships between CUD policies (density and strategic intensification actions) and GHG emissions being quantified in the literature? How are compact urban development strategies incorporated with other levers, such as infrastructure, technology, and behavior?
2. **State of practice:** How do current tools treat the complexity of CUD (Lever 1)? How are CUD models used in future urban development scenarios within the broader landscape of integrated urban planning (the multiplicative effect of Levers 1–4)?
3. **City context:** Are integrated tools sufficiently developed to represent likely outcomes in different city and country contexts? Are some strategies/levers more likely to be impactful in certain city contexts?

The remainder of the report addresses these questions and is organized as follows:

- **Section 2** describes the review methodology and assessment criteria, including a discussion of operationalized CUD in the form of the 5D framework.
- **Section 3** gives the results of the model analysis relative to each model's general orientation, data requirements, transparency of algorithm assumptions in assessing CUD impacts on GHG emissions, and broader linkages to overall integrated urban planning levers.
- **Section 4** discusses city context factors relevant to the process of translating models across contexts.
- **Section 5** offers conclusions and recommendations.

The models shown in table 2 are assessed in the context of the four levers (discussed above) that together improve urban resource efficiency (energy and materials) and reduce GHG emissions. Additional benefits of integrated urban planning, such as reduction in air pollution or infrastructure costs, are represented as co-benefits. The models were selected based on having been applied in cities to inform planning. The set of models were identified during the initial formulation of this report, with additional models identified in the literature and through interviews with practitioners at institutions including the World Resources Institute, World Bank, and ICLEI.

Table 8: Models Selected for Review

Primary focus on urban form and land use (Lever 1)	**Primary focus on technology (Lever 2)**
Urban Performance (UP)—developed by CAPSUS	City Performance Tool (CyPT)—developed by Siemens
RapidFire/UrbanFootprint (RF/UF)—developed by Calthorpe Analytics	LEAP—developed by Stockholm Environment Institute[a]
	TRACE—developed by ESMAP[a]
Multiple focuses (includes at least three of the four levers with varying levels of integration)	
Climate Action for Urban Sustainability (CURB)—developed by World Bank	
ClearPath—developed by ICLEI USA	
Open source models such as City Infrastructure Footprinting and Action Analysis (CIFAA)[b]	

a. These models are not assessed because they focus on future energy planning and energy efficiency strategies only.
b. Model evaluation focuses on the CIFAA tool, developed by researchers at the Sustainable Healthy Cities Network (SHC), which models GHG mitigation strategies across land use, infrastructure technology, and behavior-policy linkages in U.S. cities (Ramaswami et al. 2012), and cross-infrastructure assessments for Chinese cities (Ramaswami et al. 2017). Evaluation of other open source, university-developed tools, such as PURGE, is based on Canadian studies (Kennedy et al. 2015; Mohareb and Kennedy 2012; Ibrahim and Kennedy 2016) with sectoral focus.

Section 2. Compact Urban Development: First among Four Key Levers for GHG Mitigation

2.1 Four Key Levers for GHG Mitigation

Integrated urban planning for resource efficiency has been defined in relationship to sustainable urban infrastructure transitions for GHG mitigation as spanning four key levers of action (IRP 2018). These are listed below and shown in figure 1.

Lever 1: Compact urban development–land use strategies

Lever 2: Infrastructure technology strategies, covering the individual sectors of buildings, energy, transportation, water, wastewater, and solid waste management
- **Lever 2a:** Infrastructure—demand reduction technologies
- **Lever 2b:** Infrastructure—supply technologies

Lever 3: Cross-infrastructure strategies, leveraging systemic efficiencies across infrastructure sectors

Lever 4: Policy and behavior change strategies, impacting the behaviors of individuals (and businesses)

Figure 1: High GHG Reduction Potential of Integrating the Four Levers

<table>
<tr><td rowspan="2">Lever 1: Compact urban development–land use strategies reducing demand for infrastructure services</td><td>Lever 2: Infrastructure technology strategies making demand and supply more efficient</td><td rowspan="2">Lever 4: Policy and behavior change strategies affecting behaviors of individuals (and businesses) using infrastructure services</td></tr>
<tr><td>Lever 3: Cross-infrastructure strategies leveraging circular economy strategies enhanced by compact development</td></tr>
</table>

Up to a factor of 10 GHG reduction potential (IRP 2018)

Lever 1, CUD, is seen as the foundational lever, but the four levers are considered to be multiplicative and interconnected, as the GHG mitigation potential of infrastructure technology strategies depends on the policies that support adoption of the technology by the homes, businesses, and industry the technology serves (IRP 2018; Salat 2009).

The following example illustrates the envisioned multiplicative effect of the four levers. Compact urban form reduces travel demand in the best case by 25 percent in U.S. cities. This means that vehicle miles traveled (VMT) could now be 75 percent of the baseline in the compact city scenario, assuming the influence is equivalent across all households. Electric vehicles with an electric drive train further reduce energy use at the engine by ~80 percent. Therefore, energy requirements for motorized transportation (75 percent x 20 percent) now become 15 percent of the base case, i.e., an 85 percent reduction. Beyond urban form, there are driver behaviors that can result in further energy efficiency improvements (better vehicle maintenance, trip chaining, stop-start behavior) and reduce energy use by 10–20 percent (often stimulated by price signals). If these further reductions are applied on top of the first two levers, the potential exists to reduce energy to 12 percent of the baseline. This is almost a factor of 10 reduction from the base case and exemplifies the multiplicative impact of the four levers. In contrast, if cities try to shape driving behaviors only through price signals, the reduction will be only ~10 percent.

2.2 Structure of Algorithms to Model GHG Mitigation

The current state of the science across all four levers and their interactions was reviewed (see appendix A). In general, there is an emerging literature that is able to quantify the resource/demand/GHG mitigation (Ramaswami 2013; Ibrahim and Kennedy 2016) associated with various strategies that can be implemented for each of the levers.

The science of quantifying the impact of these strategies can be represented by two key dimensions:

- The first dimension quantifies the strategy effect per unit of intervention—that is, the **reduction in demand/resource use/GHG per unit of intervention.** The strategy effect is represented with different terminologies for different strategies across the four levers. For example, the reduction in travel demand due to a doubling of any of the 5D parameters is called elasticity in travel demand with respect to land use parameters, and similar elasticities have also been reported for price signals (e.g., VMT reduction for an increase in price of gasoline). In the resource efficiency literature, the strategy effect is represented as the resource savings per unit of intervention—e.g., energy or water use reduction for a green building compared to a conventional building. The GHG intensity for that unit of energy can be high or low depending on the proportion of the energy supply that is carbon-free. In addition to elasticities or resource efficiency estimates, the models should clarify two limits:
    - Minimum thresholds for interventions to yield GHG mitigation, such as average density measures. These have been cited for car-sharing and transit to be cost effective. For example, the U.S. Federal Transit Administration recommends that densities exceed 35 dwelling units/acre (Santasieri 2014) to yield cost-effective investments in transit and foster measurable VMT reductions; car sharing has also been documented as being financially viable at densities above a minimum threshold of 5–10 dwelling units/acre in the United States (Millard-Ball et al. 2005).
    - Maximum limits for a particular strategy's effect. For example, the 5D literature suggests that doubling all the 5D parameters will reduce travel demand by no more than 25 percent in the affected zone (Bento et al. 2005; NRC 2009).
- The second dimension quantifies assumptions of **penetration rates or adoption rates of the intervention**—for example, for a CUD intervention, the percentage of the population living in areas where all 5Ds are improved; for a single sector technology intervention, the percentage of buildings being retrofitted wit energy efficient light bulbs. The penetration or adoption rates depend significantly on culture, local practices, and policies. Further, it is important to establish clear benchmarks of current participation rates/adoption rates against which the future

scenarios are assumed. Without clarification of the current baselines, it is difficult to determine the GHG mitigation potential of strategies in modeled scenarios based on projected penetration or adoption rates.

City carbon mitigation potential is defined to include reducing infrastructure service demand (which may be considered an avoidance strategy) as well as reducing the carbon intensity of service supply (e.g., renewables in the electricity grid). It is important to note that in many developing countries a significant portion of the population may not have access to several key infrastructure sectors; new models for reducing service demand must therefore also address equity and inclusion (e.g., CUD that maintains easy access to destinations through nonmotorized travel or transit). The overall GHG mitigation potential is then computed using model algorithms similar to those shown in equation 1:

Equation 1

$$Potential\ for\ City\ GHG\ Mitigation = \left(\frac{Demand\ Reduction}{Unit\ of\ Intervention}\right) \times \left(\frac{Energy\ or\ Carbon\ Intensity}{Unit\ of\ Demand}\right) \times (\%\ Adoption\ of\ Intervention)$$

These two dimensions are detailed below for Lever 1. A description of the other levers can be found in appendix A.

2.3 Algorithms for GHG Mitigation in Compact Urban Development: The 5D Framework

The literature frequently cites a 5D framework to denominate the reduction in motorized travel stemming from more compact urban form. When looking at CUD as a mechanism for achieving sustainable urban form, it is important to note that measures of high average density alone do not necessarily provide a meaningful measure of sustainable urban form. TOD is often a key strategy for realizing the 5D framework in actual urban development practice at the project level.

The 5D framework originated in U.S. cities as a key land use parameter for understanding what CUD means in actual practice (NRC 2009; Cervero and Kockelman 1997). Its key indicators are these:

- **Density:** Population density, jobs density, housing density; measures of polycentrism for nodal development configuration
- **Design (human scale, multi-modal):** Intersection density, distance between intersections, building set-back length, pedestrian infrastructure, bicycle infrastructure, tree cover
- **Diversity (income and use):** Commercial/residential floor area ratio, jobs-housing balance, housing type and tenure split, neighborhood-level race and income diversity indexes
- **Distance to transit:** Share of population within radius of transit access
- **Destination access:** Distance/travel time between core-service destinations (e.g., jobs, health care, schools)

CUD strategies focus on increasing one or more of these Ds—and ideally should consider all 5Ds together—for achieving density that is accessible, livable, resource-efficient, and equitable. An increase in one or more of the 5Ds is anticipated to reduce demand for infrastructure services (e.g., reduce demand for travel, floor space, or horizontal infrastructure such as pipes and roads). The 5Ds are often represented as articulated density. Articulated density emphasizes nodes of well-connected high-density development around transit stations surrounded by sloping gradients of medium- to high-density development. Accessible density emphasizes convenient access via transit and non-motorized personal travel to key daily destinations for housing, jobs, education, commerce, and services (ESMAP 2014). Transit-oriented development—undergirded by density, non-motorized and transit mobility options, and key destination access—is a concept often used to operationalize principles of articulated and accessible density at a project level. Ensuring that 5D-focused development is operationalized at the level of a city as a whole requires a larger perspective for understanding how various TOD zones or projects operate together and interact with each to support holistic CUD policies.

The strategy effect per unit of intervention (dimension 1) has been most discussed in the literature for travel demand with a focus historically on density (Newman and Kenworthy 1989); see table 3.

Table 9: Strategy Effect on Travel Demand with Maximum Limits and Minimum Thresholds

a. Elasticities of 5Ds on per capita motorized VMT reduction in the United States			
Study	**5D built environment feature**	**Scale**	**VMT reduction (%)**
Ewing and Cervero 2010	Density	Neighborhood	5%
	Diversity (land use mix)	Neighborhood	5%
	Design	Neighborhood	3%
	Density, diversity, and design	Neighborhood	13%
	Accessibility	Regional	20%
Bento et al. 2005	City shape, jobs-housing balance, road density, rail supply	Regional	Less than or equal to 7% per variable
	Population centrality alone	Regional	15%
	All variables together	Regional	25%
Brownstone and Golob 2009	Density	Regional	12%

b. 5D upper limits or minimum thresholds (based on U.S. cities)
Upper limit for VMT reduction in the best case of doubling all 5Ds = 25%
Minimum density threshold for CUD to be effective = 35 dwelling units per acre

Source: NRC 2009. Adapted and reprinted with permission of the National Academy of Sciences. Courtesy of the National Academies Press, Washington, DC. © National Academy of Sciences.

As shown in equation 1, the GHG mitigation potential of each strategy depends heavily on assumed participation rates (dimension 2). Different models are transparent to varying degrees toward these assumptions. For example, some models allow users to input assumptions, and those assumptions are then made transparent: the CURB model is transparent in assuming 40 percent of households in a particular case study are in TODs, and projects an increase to 65 percent in future scenarios (Bloomberg Associates 2018). Other models may measure baseline using empirical data and then model future scenarios: CIFAA, for example, measured the number of transit riders at present in Denver and then estimated the impact of tripling this population in a future CUD scenario (Ramaswami et al. 2012).

2.4 Application of 5Ds to City Context

We can classify three types of compact urban development models based on their algorithms and the context they are applied to: (i) models that apply U.S. field data–derived 5D elasticities to U.S. cities; (ii) models that apply U.S. field data–derived 5D elasticities to world cities, given the absence of local data; and (iii) models that use locally derived elasticities to represent GHG benefits of compact urban form.

The first type of model uses the average best-case strategy effect of the 5Ds in the United States found over several decades of empirical research (summarized in table 3) to represent the best-case reduction in travel demand possible. These models are very well-suited to the U.S. context (e.g., CIFAA, ClearPath, CURB). However, these assumptions may not translate to other cities, such as those in developing countries with a very low rate of vehicle ownership. Therefore, CUD models that use country-specific empirical data to quantify elasticities (e.g., UrbanFootprint/RapidFire in Chongqing) would be the best for non-U.S. contexts.

It should be noted that many integrated land use/transport models exist to predict transportation behavior at the macro level (regionwide) and micro level (individual trips) based on different land use patterns (Southworth 1995; Miller et al. 1999). These models are computationally complex, and new models are being developed as more spatial and big data approaches become available. But there is hope that the scientific community will create more open source and operational models (Moeckel et al. 2018) that could be used for city-specific estimates of compact land use patterns' effect on travel demand. There is much debate in the urban planning literature on which 5D variables play the largest role in reducing travel demand (represented via elasticities) in the United States. Further, there are also questions on whether the 5Ds translate to developing countries with low levels of car ownership and whether the magnitude of these effects seen in developed nations (United States, EU nations, Canada, and Australia) are applicable to developing nations and cities that are yet to be built.

Cities in Developed Countries

CUD and travel demand studies in the United States suggest that regional accessibility—measured as distance from job centers and central business districts and as jobs-housing balance—may be the most important among the multiple 5D variables (Boarnet 2011; Boarnet and Wang 2016). This finding highlights the importance of not focusing on density alone (Handy 2017; Duranton and Turner 2017). The impact of regional accessibility in terms of employment access (i.e., jobs within five miles of residence) is found to be more influential than density, with per capita VMT elasticities ranging from 20 percent to 30 percent (Boarnet and Wang 2016; Salon et al. 2012) and similar to those noted in table 3 (Ewing and Cervero 2010). Empirical studies exploring the relationship between CUD and travel demand in other developed nations (EU, Canada, and Australia) do not use all components of the 5D framework. However, elasticities with respect to population density are reported to be of the order of 7 percent to 10 percent in Canadian and Australian cities (Choi 2018; Stanley, Hensher, and Loader 2011) and 5 percent in the United Kingdom (Echenique et al. 2012)—indicating that when country-specific data are available, they should be used. Furthermore, many EU countries measure other outcomes (beyond personal VMT per capita) such as transit ridership.

An analysis of population density and per capita personal motorized VMT across 26 developed world megacities (in the United States, Western Europe, Canada, and Australia, controlling for regional variation) and across city archetypes (strong center, weak center, full motorization) reports long-run elasticities (per capita VMT reductions) with respect to average density of 15 percent to 35 percent over the 40-year period 1960–2000 (McIntosh et al. 2014). Thus, the literature seems to suggest that average density is an important consideration for the long term, but that in the near term, factors like regional accessibility and jobs-housing balance will likely be more critical and influential in a planner's strategy list. These insights may be useful to inform the development of new cities; they cannot be independently assessed in other countries where cities regularly exceed the minimum densities. All the reviews suggest that the 5Ds concept is a useful one, and yields better sustainability outcomes overall—considering equity, livability, and reductions in demand for infrastructure services. Given that several cities in developed countries have been studied, we recommend using available country-specific elasticities where possible and explicitly citing the sources and studies used in the model for developed country cities.

Cities in Developing Countries

Empirical studies for cities in developing country contexts are limited, and hence quantifications of elasticities are not available in the literature. Still, many of the developing country urban studies also highlight the importance of not considering average population density alone as a key representation of compact urban development (Brown 2017, UN Habitat 2014). Human settlements in developing nations typically exhibit average population densities double or triple those in developed nations, and interventions should therefore be designed carefully to retain the accessible and mixed-use nature of such density. For example, when existing mixed-use development was transformed in Shanghai to a superblock design with large distances between street intersections, a study of 900 households showed a 50 percent *increase* in VMT (Cervero 2013), thus emphasizing the importance of human-scale street design as part of the 5D framework.

Many developing country studies recognize the importance of tracking other variables beyond motorized VMT demand per capita, such as personal vehicle ownership and transit use, as additional measures of CUD impacts on travel demand (Poudenx 2008; Guerra et al. 2018; Cervero and Dai 2014). Little is known about which of the 5Ds, individually or in combination with one another, have a relatively larger impact on motorized personal travel in developing nations. In Indian cities (Cervero, 2013; Munshi 2016), distance from jobs to homes was a significant variable influencing motorized travel demand—more so than population density (given current household wealth and vehicle ownership trends). Case studies in Jinan (Jiang et al. 2015; Jiang et al. 2017; Ohshita et al. 2015) indicate that land use diversity (jobs-housing balance) and design (neighborhood walkability/permeability) reduce household VMT, while destination access appears to have less influence. Given the already high average densities in Chinese cities (Darido, Torres-Montoya, and Mehndiratta 2009) and concerns over rapid urban expansion, land use patterns related to shape and fragmentation of urban areas need to be optimized to promote compact urban development (Wang et al. 2017). Zhao (2014) emphasizes the need for nationwide empirical studies, as the literature is dominated by individual case studies with mixed conclusions. In summary, while the 5D framework appears to be broadly applicable in developing nations, the quantification of elasticities and the understanding of which "Ds" are critical—again individually or in combination with each other—is still nascent. Thus, empirical observations, such as new informatics and big data approaches taken by the China Sustainable Transportation Center (Jiang et al. 2017; CSTC 2016), are recommended for use in developing cities.

Concerning CUD's impact on other infrastructure demand measures, there is limited converging evidence that increasing density of development reduces floor area per person, or that energy use in buildings is reduced per unit area. However, savings in the cost of horizontal infrastructure requirements (streets and pipes) can reliably be estimated with knowledge about the geometries and spatial layout of street networks, as can savings on construction materials per square foot when transitioning from single-story to high-rise construction. These are documented in multiple countries and literatures (Nagpure, Reiner, and Ramaswami 2018).

Due to this uncertainty in the literature and in translation of models to cities in developing countries, models should make their algorithms and assumptions transparent. GPSC has an excellent opportunity to document such data as these models are applied to GPSC member cities.

2.5 Which Levers Dominate in Different Global City Contexts?

Although all the levers are important, certain levers are likely to be more important in certain city contexts. For example, while the GHG mitigation potential of Lever 1 (CUD) and Lever 2a (infrastructure—demand reduction technologies) may improve efficiency and reduce demand across all city contexts, Lever 2b (infrastructure—supply technologies) may be particularly useful in cities in developing economies lacking access to clean fuels. Further, the mitigation potential of Lever 3 (cross-infrastructure strategies) will likely be highest in highly industrial cities, while Lever 4 (policy and behavior change) strategies will be most effective in cities with already high levels of infrastructure demand. Section 4 provides further details on the prioritization of levers in different city contexts with key points summarized below.

- In fast-growing cities, it is critically important to implement CUD and adopt new cutting-edge infrastructure and leapfrogging technologies for new construction (Levers 1 and 2). A significant opportunity will be missed if these levers are ignored in new or fast-developing cities. In contrast, in slow-growing cities, retrofits of existing buildings and infill development are particularly important.
- Certain economic structures are more conducive to cross-infrastructure strategies. For example, in industrial cities, urban planning that co-locates industries in eco-industrial parks and promotes sufficiently dense centers that are well suited for district energy systems are particularly important (Lever 3).
- City extent (built area footprint) and population size can guide particular strategies around CUD (i.e., transit); it is important to preserve walkability and non-motorized modes of transit in smaller cities while also investing in mass transit in larger cities (Shastry and Pai 2016).
- Cities with large proportions of their population in informal settlements should consider the importance of accessible and livable urban form in these areas (Lever 1). In addition, they should consider infrastructure and technology leapfrogging from conventional centralized infrastructure configurations to radically different infrastructures like distributed and renewable energy (Lever 2). Policies to shape behavior change, responding to equity considerations, may focus less on energy conservation and more on adoption of these alternative infrastructures.

Section 3. Model Evaluation Methods and Results

3.1 Model Evaluation Methods

This section presents the methodology and results of a review of the models identified in table 2; specifically, it assesses the degree to which they quantify the four integrated urban planning levers discussed above. This list is not meant to be comprehensive, as certain strategies (e.g., carbon/fuel tax, construction material reduction) may not be covered by the tools. We recognize that there is a suite of specialized tools available for local energy planning (Cities-LEAP 2016) and for customizing GHG mitigation planning to individual cities (CityInSight 2017). However, the models on this list are well known by experts in the field, incorporate multiple cities in multiple countries, and are most likely to assess the urban GHG mitigation potential of CUD–land use strategies.

The models are reviewed according to five criteria, as follows:

1. The specification of a baseline community-wide GHG accounting methodology
    a. What accounting methodology is referenced?
    b. Are there baseline energy efficiency indicators identified?
    c. Are transboundary, life-cycle GHG emissions included to prevent burden shifting (for electric power plants, transportation fuels, construction materials)?
    d. Can baseline data from a similar city be estimated as a proxy?
2. Coverage of different strategies within the four integrated planning levers
3. The transparency of the algorithms and the case studies from which algorithms were derived (including specifications of resource efficiency/GHG impact per unit with thresholds and upper limits, as well as adoption rates), and discussion of the uncertainty in translation of these algorithms to other city contexts
    a. Is the menu of strategies discussed in the context of suitability for different city types?
    b. Are the model algorithms/calculations for various strategies clearly documented and linked to literature or empirical data analysis? If based on data analysis, from which region of the world?
    c. Are the model algorithms for future scenarios modified or flagged when applied to a different context (nation, region, city type, etc.)? Is uncertainty represented in assessing the impact of interventions?
4. Discussion of costs and benefits of each lever
5. Discussion of co-benefits of GHG mitigation (e.g., effect on air pollution, health, livability, etc.)

The first criterion, the **baseline accounting methodology**, involves assessing the model's interaction with the accounting approaches for quantifying GHG emissions at the community-wide scale. Certain accounting methods are better suited for determining the potential for GHG mitigation actions, depending on the strategy's spatial scale (within jurisdiction boundaries or spanning jurisdiction boundaries) and on the actors being targeted (households, businesses, industry, government). Most cities have adopted the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories

(GPC) to facilitate standardized reporting on emissions inventory to the Global Covenant of Mayors for Climate and Energy and to allow cities to connect their community GHG mitigation actions to national and international targets. Therefore, this criterion assesses how easily the model can integrate with GPC inventories and whether alternative accounting approaches are utilized. Table 7 in appendix B shows the key performance indicators (KPIs) being utilized by the models to determine future GHG mitigation potential based on projections of baseline GHG inventories for future emissions scenarios.

The second criterion, **coverage of levers and strategies***,* is focused on how extensively each of the models addresses each of the four levers. While no model fully covers all four levers, it's important to note which levers are covered and the strength of the coverage based on the strategies and the transparency of their assumptions. Levers covered and strength of coverage are shown in the figure that accompanies each model description (in sections 3.4, 3.5, and 3.6). Some models may be useful without full coverage because the strategies covered by the model may be well suited to a specific city context. Details on each individual strategy and the models covering them can be found in table 8 in appendix B.

The third criterion examines **transparency** and documentation of the elasticity (strategy effect) and participation rate for each strategy modeled. The strategy effect may include the elasticity, or the algorithms used to calculate the effectiveness of each strategy. Assumptions surrounding adoption rates and participation rates are evaluated based upon change in the current and future participation rate of each strategy. Knowing the assumptions behind both the effectiveness and adoption rate assumed for each strategy modeled is important for understanding whether the model's projected GHG emission reduction will be consistent with future monitoring, reporting, and verification.

The fourth criterion, **cost and benefits evaluation**, involves moving beyond the carbon reduction potential of each strategy to determine the economic cost and benefits. Each model may choose a different method, but most models address the economic efficiency of each strategy either qualitatively or quantitatively. The description of each model documents the cost metrics used to compare strategies, including cost/ton CO_2 reduced, benefits ($) of energy savings, payback period, capital/operations and maintenance costs for infrastructure, and employment benefits. Given the limited fiscal capacity of local governments, cities want to understand which strategies are most effective per unit cost and how certain strategies may pay off in the short or long term.

The fifth criterion, **co-benefits coverage**, addresses the extent to which models evaluate co-benefits of carbon mitigation in terms of infrastructure and environmental benefits that can occur because of interventions addressing the four levers. GPSC pilot cities may have related concerns beyond carbon mitigation, including air pollution, land conservation, water/wastewater treatment, and livability concerns, such as infrastructure reliability and service coverage along with informal settlement growth. Ideally, the co-benefits addressed by the model would align with goals of the pilot city, but here we evaluate the co-benefits addressed by each model and whether the estimates of these benefits are quantitative or qualitative.

3.2 Model Evaluation Results

The extent to which each lever is covered by each model is summarized in table 4. Specific coverage of 23 broad strategies is summarized for each model in the bar charts (figures 3, 6, 8 , 10, & 12), while detailed breakdown of coverage of an expanded list of 34 strategies is provided in table 8 of appendix b. Using the five criteria identified in section 3.1, each model is evaluated below. Case studies and model descriptions accompany each evaluation to explain how the model has been used in practice.

In addition, each model evaluation is accompanied by a figure describing the coverage of each strategy as well as the transparency of assumptions and uncertainty in translation based on table 8 in appendix B. Along the vertical axis in each figure, strategies are sorted based upon the four levers to demonstrate the coverage of each model. Transparency of each strategy is evaluated on a 0 to 0.5 scale based upon whether the model algorithms/calculations are clearly documented and linked to literature or empirical data analysis. Uncertainty in translation of each strategy is also evaluated on a 0 to 0.5 scale based upon whether model algorithms and assumptions are modified or flagged when applied to different contexts (as described in section 4), which may vary by country, geographic region, or city typology. Evaluation of model transparency and uncertainty is combined into one bar for each strategy.

Table 10: Model Review of Lever Coverage

Levers	UP	RF/UF	CURB	CyPT	ClearPath	CIFAA
Lever 1: CUD-land use	Yes	Yes	Yes	No	Yes	Yes
Lever 2: Infrastructure technology	Yes	Yes	Yes	Yes	Yes	Yes
Lever 3: Cross-infrastructure	No	No	No	Yes	No	Partial[a]
Lever 4: Policy and behavior change						
a. Behavior: Are participation baseline rate and target rate explicit?	No	No	Target rate only	No	Target rate only	Yes
b. Policy: Is there an explicit assumption of policy enforcement?	Yes	Yes	Yes (saturation)	Yes	Yes	Yes

a. Cross-sector model was developed for Chinese cities (Ramaswami et al. 2017), while other levers are for U.S. cities.

3.3 Model Evaluation Summary

The majority of the models (CyPT, CURB, ClearPath, and CIFAA) subscribe to a particular community-wide GHG accounting methodology, normally compliant with the GPC. Cities interested in the emissions of transboundary supply chains of goods and materials used by the city require a model that has a specified life-cycle-based methodology. The models that are primarily focused on land use (UP and RF/UF) calculate community-wide emissions but do not specify an accounting methodology and likely cannot account for emissions outside of the city.

Only two models (ClearPath and CIFAA) integrated across all four levers, but they have mainly been applied to U.S. cities and require locally derived elasticities in order to be translated to global cities. Table 4 shows that Lever 1 (CUD) and Lever 2 (infrastructure technologies) are generally covered across all models, but there is limited coverage of Lever 3 (cross-infrastructure strategies) and Lever 4 (policy and behavior change). Critically, table 6 in section 4 shows which models have stronger coverage of each lever and how lever coverage relates to high priority contexts based on city type.

Because this report is focused on CUD, we have reviewed all the models and classified them into three types based upon the underlying data used to estimate the travel demand elasticities of CUD and how they have, to date, been translated to different city contexts. The results are shown in table 5. Although ClearPath and CIFAA tools were developed for U.S. cities and use U.S. elasticities, their algorithms can readily be translated to other contexts by updating the models with locally relevant elasticities. In contrast, other models (CURB, CyPT, UP) appear to apply North American elasticities to developing countries, an approach that is not recommended; moreover, their assumptions of elasticity are not transparent. Only RapidFire appears to use locally derived elasticities in China and Mexico through long-term agreements with local agencies and consultancies to collect local-level data.

Although all models make an effort to quantify costs of the strategies modeled, the costs and benefits that these models account for are inconsistent. Land use models generally account for reduced infrastructure and transportation costs in order to quantify the benefits of more compact urban development. The other models account for the costs of each strategy in order to compare their feasibility based on the potential costs of implementation compared to the potential energy savings.

CyPT and RapidFire/UrbanFootprint have begun estimates of the air pollution co-benefits of the urban GHG mitigation strategies modeled, but they have used simplified estimates that do not involve air pollution modeling. CIFAA has quantified these co-benefits in Chinese cities but has not yet integrated this functionality into the full model. It is critical that future modeling efforts attempting to quantify these air pollution co-benefits use air pollution models or advanced satellite/monitoring data-based algorithms to quantify the impacts of transboundary air pollution that affect many global cities.

Table 11: Model Translation of CUD Elasticities

	UP[a]	RF/UF	CURB	CyPT[a]	ClearPath	CIFAA
Type 1: Uses U.S.-based elasticities, applied to U.S. cities					X	X
Type 2: Uses elasticities derived from North American cities, applied to global cities	X		X	X		
Type 3: Uses country-specific elasticities derived from primary data/in-country research		X				

a. Algorithm assumptions not transparent.

3.4 Models Primarily Focused on Land Use

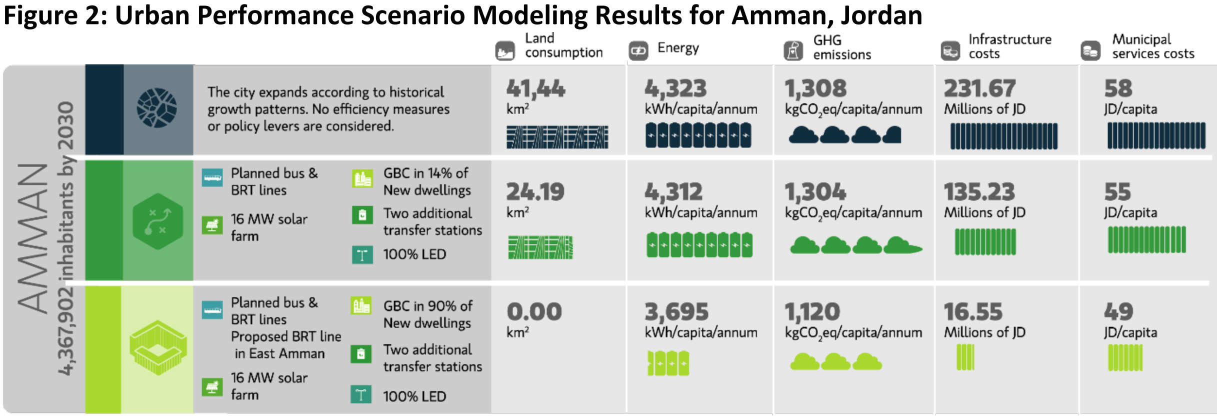
Urban Performance (UP)

- ***Highlights:*** Specifically tailored to predict land use development patterns in fast-growing cities (in Jordan, Gaza, Cote d'Ivoire, and Indonesia) and assess how these growth patterns impact infrastructure indicators (cost, energy, GHGs, and water).

Box 1: Case Study: Five Cities in Jordan (Amman, Irbid, Mafraq, Russeifa, and Zarqa)

Project highlights: The Urban Performance tool was adapted to model five cities in Jordan through a collaboration between the Ministry of Planning and International Cooperation, CAPSUS, and the World Bank Group. The team modeled urban expansion through 2030 based on current land use patterns under proposed policies and master plans. Three scenarios—Business as Usual (historical growth patterns), Moderate (city master plan), and Vision (compact urban growth)—were evaluated across 17 environmental, social, and economic indicators. The results of these scenarios are shown in figure 2 for the case of Amman; across the five cities modeled, the compact growth scenario annually reduces 1.1 MMT CO_2e and 20 percent of the annual cost of municipal services, while increasing by almost 40 percent the proportion of the population that can walk to work (World Bank 2018).

Figure 2: Urban Performance Scenario Modeling Results for Amman, Jordan



Source: World Bank 2018.
Note: The rows from top to bottom correspond to the three scenarios (Business as Usual, Moderate, and Vision. BRT = bus rapid transit; GBC = green building code.

- ***Developed by:*** CAPSUS.

- ***Objective:*** The UP tool provides a flexible, easily replicable, and scalable platform for modeling urban growth scenarios. It can be used at a national level to evaluate multiple urban areas at a time or at the local level to estimate the potential impacts of specific initiatives. Using a common methodology across countries, this model aims to assist local governments in decision making and acquiring finance for proposed infrastructure projects. By measuring indicators for climate, energy, infrastructure cost, and accessibility (distance to work, hospital, education, etc.), the model assesses how future urban development will occur based on policy, infrastructure, and land use planning interventions across multiple scenarios.

- ***Summary of levers covered:***
    - *Lever 1 (CUD–land use):* Comprehensive coverage of the impact of land use/development patterns on transportation and physical infrastructure requirements.
    - *Lever 2 (infrastructure technology):* Moderate coverage of infrastructure technology improvements in building sector, solid waste, renewable energy, and improvements to public transportation systems.
    - *Lever 3 (cross-infrastructure):* Not covered.
    - *Lever 4 (policy and behavior change):* Moderate coverage of policy and behavior change lever, documented assumption of policy enforcement in building codes with unclear coverage of behavior change interventions; does not provide context of current participation and policy options that would achieve future participation.

- ***Specified GHG accounting methodology:*** Life-cycle emissions are not assessed, only per capita GHG emissions based upon energy use in public lighting, water supply, transportation, and waste management.

- ***Monetary cost and benefits:*** Assesses infrastructure costs (transportation, water supply, wastewater, waste) and municipal operations and maintenance costs.

- ***Co-benefits:*** Tracks metrics such as water consumption, proximity to health facilities, proximity to schools, infrastructure costs, and municipal service maintenance costs across scenarios.

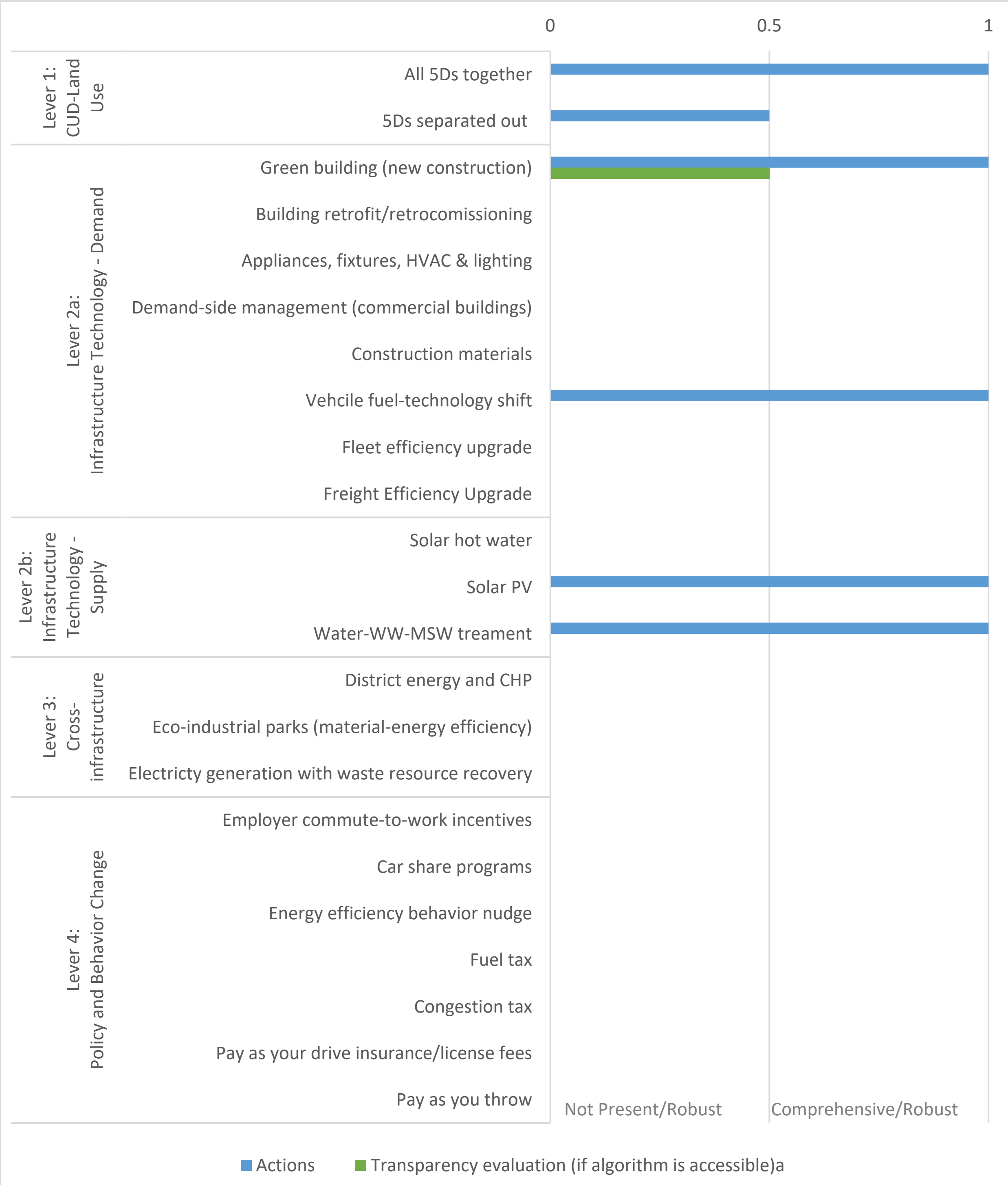
- ***Advantages:*** Strategies modeled for each set of cities within country are tailored to context based upon focus groups/workshops with local policy makers. KPIs and model architecture are customized for developing areas expecting rapid population growth and urbanization.

- ***Potential limitations:*** Model assumptions and translation across countries are not transparent since only Jordan (urban growth scenarios) has been documented; requires significant land use data to transform scenario modeling based on regionally specific land use and development patterns.

- ***Transparency and uncertainty*:** Model algorithms are available in technical appendix; elasticities are not documented. This is a new model, so only assumptions for Jordan have been documented; therefore it is not possible to evaluate translation across countries.

- ***Cities/world regions applied to:*** Being applied to cities in Asia, Africa, Latin America, and the Middle East in countries such as Indonesia (Semarang, Denpasar), Côte d'Ivoire (Abidjan), Mexico (Merida, Colima, etc.), Jordan (Amman, Russeifa, Zarqa, Mafraq, Irbid), and the West Bank and Gaza (Nablus, Ramallah, Bireh, Bethlehem, Hebron).

Figure 3: Urban Performance: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are not transparent and may be developed in North America, but applied to global cities.

RapidFire/UrbanFootprint (RF/UF)

- ***Highlights:*** RF and UF have been applied to cities in the United States, Mexico, and China; both have the ability to represent land use and development in a way that explicitly addresses the 5Ds and includes three additional Ds (see table 7 in annex B). The RF travel model applies factors that are developed based on running local transportation demand models and applying research-based elasticities. The UF travel model is dynamically responsive to characteristics of the built environment and the location of jobs. RapidFire/UrbanFootprint are based on place types that are strategically distributed across the urban region, with different proportions and distribution of types depending on the scenarios. Types are defined mainly by jobs-housing balance, access to structured public transport, density, and scale (size of urban blocks).

Box 2: Case Study: Chongqing, China

Project highlights: RF/UF was developed to quantify benefits of compact urban development, including reductions in land use consumption, building energy use, water use, infrastructure costs, household utility and driving costs, and air pollution/health impacts. RF/UF was adapted, through collaboration with the China Sustainable Transportation Center (CSTC) and the World Bank's Global Platform for Sustainable Cities, to model the impact of CUD on Chongqing in 2035. The Chongqing 2035 scenarios focus on a Trend scenario using current land use patterns and a Compact Growth scenario using infill-focused, compact land use patterns. The Compact Growth scenario enables shorter travel distances, more efficient infrastructure networks, and building forms that reduce land use consumption and infrastructure cost (figure 4). New greenfield land consumption by sub-area is a pivotal measure of future development. The Trend scenario requires 553 km^2 of new land for development—195 km^2 more than the Compact Growth scenario (figure 4, left). Cumulative infrastructure costs in 2035 are ¥34 billion less under the Compact Growth scenario than under the Trend scenario because the former requires less road, water, and sewer infrastructure (figure 4, right) (World Bank 2019).

Figure 4: RapidFire/UrbanFootprint Selected Scenario Modeling Results

Source: World Bank 2019.

- ***Developed by***: Calthorpe Analytics (now known as UrbanFootprint).

- ***Objective:*** UF and RF are two related modeling tools that focus on land use planning and modeling the impacts of varying development patterns, alone or in combination with policy-based performance assumptions, on building and transportation energy use, emissions, and costs. RapidFire is a programmatic spreadsheet-based tool first developed to evaluate climate policy in California and the United States, and since adapted for use in Mexico City and Chongqing, China. UrbanFootprint is a web-based geospatial platform that is pre-populated with extensive geographic information system (GIS) data for the United States, where it is currently being used by public agencies and private practitioners.

- ***Summary of levers covered:***
    - *Lever 1 (CUD–land use):* Comprehensive coverage of 5Ds, evaluated individually rather than as aggregate measure.
    - *Lever 2 (infrastructure technology):* Moderate coverage of energy efficiency improvement for transportation and buildings.
    - *Lever 3 (cross-infrastructure):* Not covered.
    - *Lever 4 (policy and behavior change):* Moderate coverage of policy and behavior change lever. The model documented assumptions of policy enforcement in buildings and transportation, but it is unclear about the current coverage of behavior change interventions.

- ***Specified GHG accounting methodology***: GPC compliance is not specified; Scope 1 and 2 building and transportation energy/emissions are quantified.

- ***Monetary cost and benefits***: Assesses infrastructure costs (transportation, water supply, wastewater) and municipal operations and maintenance costs; includes household benefits from building/transportation energy savings.

- ***Co-benefits:*** Addresses transportation-related health impacts and costs; water and water-related energy use, costs, and emissions; infrastructure needs and costs; and land consumption.

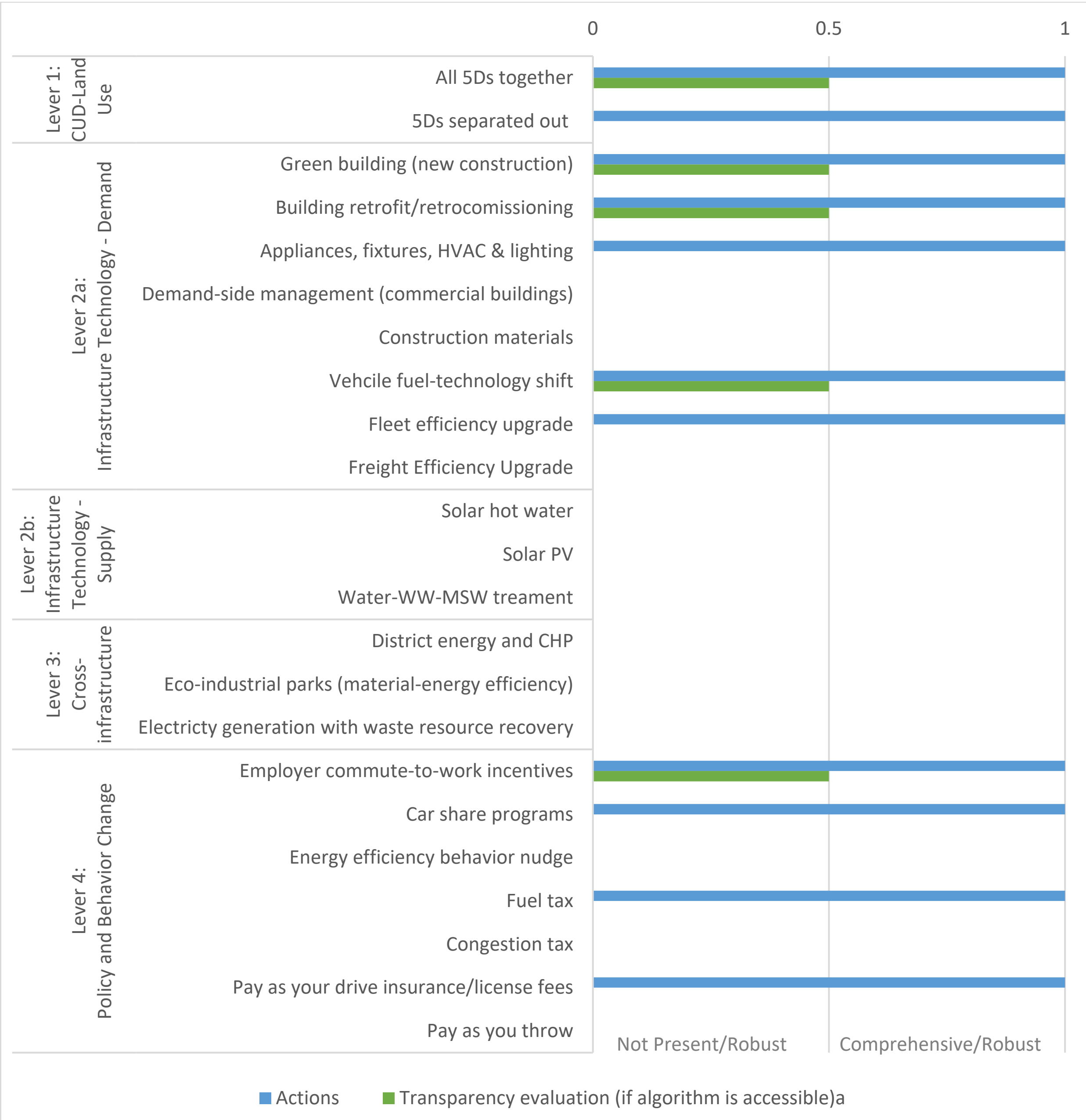
- ***Advantages:*** Clear assessment of land use change and development patterns on building and transportation energy and GHG emissions. As a web-based tool, UF is relatively much lighter than any tools requiring GIS software.

- ***Potential limitations***: Requires significant land use parcel-level data (or access) and existing research or technical capacity to calibrate the travel model to local conditions. Open source or crowdsourced data can be used to fill data gaps (e.g., point location data linked to cell phone use in Chongqing).

- ***Transparency and uncertainty:*** Travel demand elasticities and algorithms are transparent; growth scenarios and building energy models are documented but not descriptive. There is clear translation between U.S. cities and other countries given the land use data and modeling requirements.

- ***Cities/world regions applied to***: RapidFire and UrbanFootprint initially focused on California cities and later expanded to other cities in the United States and Mexico. The RF model is now being applied to Chongqing, China.

Figure 5: RapidFire/UrbanFootprint: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are transparent and developed based on country-specific empirical data.

3.5 Models Primarily Focused on Technology

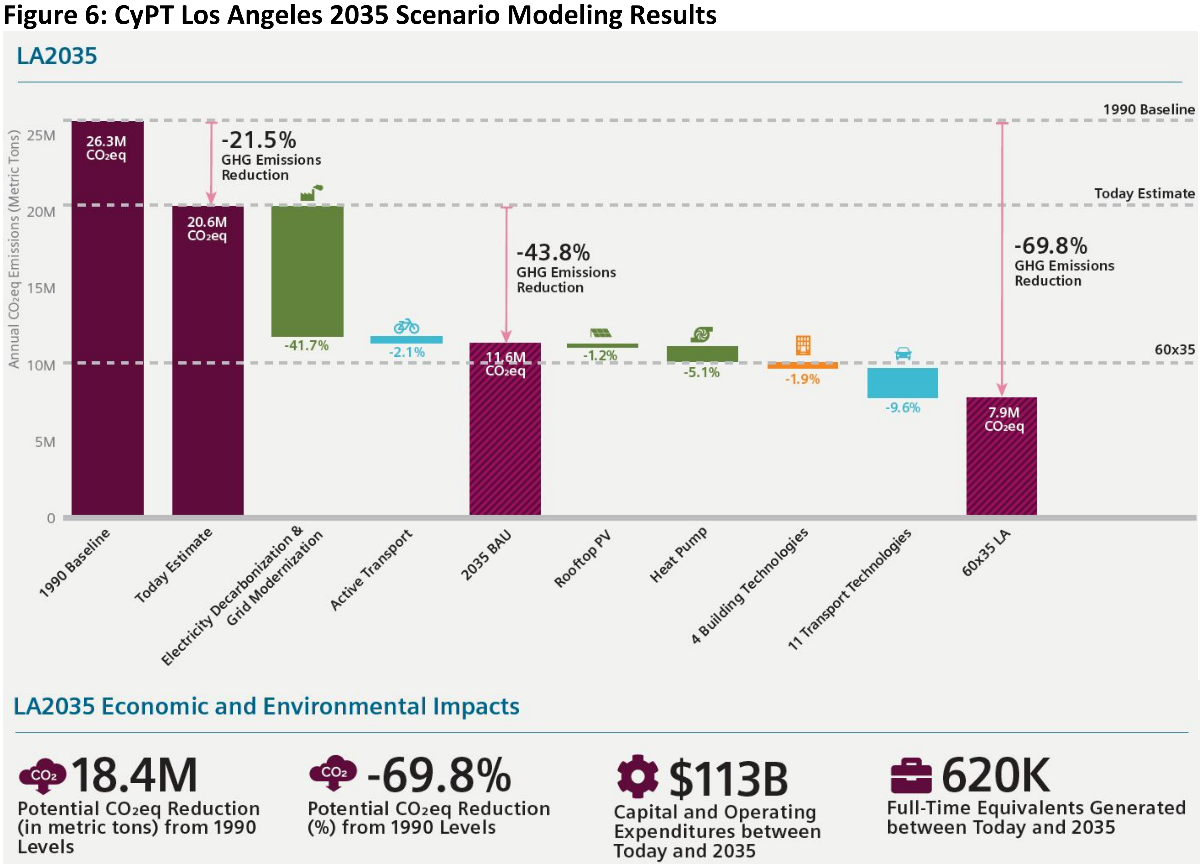
City Performance Tool (CyPT)

- ***Highlights:*** Technology-focused model covering many Lever 2 strategies in buildings, transportation, and energy generation; built-in capacity to address infrastructure demand strategies for cities in Asia, Africa, Europe, and North America.
- ***Developed by:*** Siemens.

Box 3: Case Study: Los Angeles, California (United States)

Project highlights: Siemens's Cities Center of Competence worked with the City of Los Angeles to collect more than 350 data inputs from the city's transport, energy, and buildings sectors. These were used to establish baseline community-wide emissions and model deep decarbonization pathways related to clean energy, improved energy efficiency in buildings and transport, and modal shift in transportation. Siemens modeled emissions reductions for 19 technologies to determine how Los Angeles could meet its reduction targets of 60 percent by 2035 and 80 percent by 2050 in buildings and transportation energy use. The model results for 2035 are shown in figure 6, with a focus on GHG emissions reduction, cost, and job creation (Siemens 2018b).

Figure 6: CyPT Los Angeles 2035 Scenario Modeling Results



Source: Siemens 2018a.

Note: BAU = business as usual; PV = photovoltaic; 60X35 LA = GHG emissions reduction target of 60 percent by 2035.

- ***Objective:*** With the goal of supporting cities in infrastructure-related decision making, CyPT uses Siemens' technology expertise and life-cycle management approaches to develop city-specific technology-based scenarios for meeting GHG mitigation targets while connecting to cost and air quality KPIs.

- ***Summary of levers covered*:**
    - *Lever 1 (CUD–land use):* Potentially covered through Lever 2 transportation scenario modeling.
    - *Lever 2 (infrastructure technology):* Comprehensive coverage of technology interventions in individual infrastructure sectors of buildings energy, transportation, and energy generation.
    - *Lever 3 (cross-infrastructure*): Potential coverage of cross-infrastructure strategies involving district energy and combined heat and power.
    - *Lever 4 (policy and behavior change*): Moderate coverage of policy and behavior change lever. Assumptions of policy enforcement in buildings and transportation are documented, but with unclear links to current behaviors and behavior change interventions.

- ***Specified GHG accounting methodology*:** Ability to track with GPC Basic because energy, buildings, and transportation sectoral emissions are calculated using GHG protocol.

- ***Monetary cost and benefits***: Local job creation potential and implementation cost.

- ***Co-benefits*:** Quantified by KPIs in air pollution emissions by sector and technology.

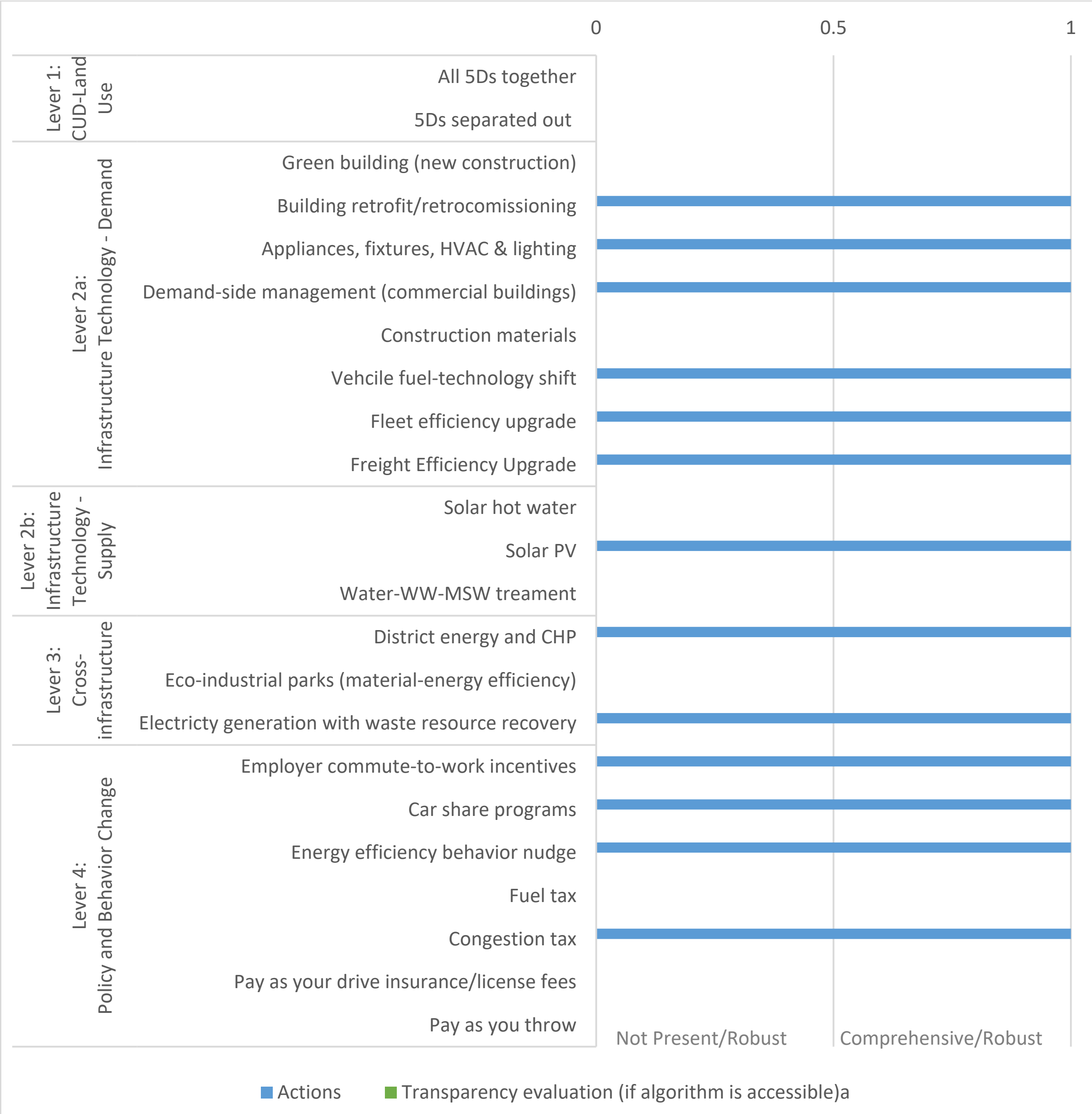
- ***Advantages:*** Siemens consults with local governments to get accurate local data (over 300 data inputs) and demand projections while supplementing missing data with national/regional data proxies based on expert knowledge in regional offices (Asia, Africa, United States). Siemens uses standardized methodology and life-cycle assessment software for 70+ technology levers across buildings, energy, and transportation sectors.

- ***Potential limitations*:** Assessment of local data limitations and methodology translation across cities requires Siemens consultants to work with local municipal governments; assumptions are not clearly documented and are therefore difficult to verify against literature. Model quantifies emissions in only three sectors—energy supply, transportation, and building energy demand.

- ***Transparency and uncertainty***: Scenario development and estimates of activity demand (using local government data) are transparent; model elasticity and algorithms are embedded in software and are not publicly available. Translation of model assumptions between countries is not documented.

- ***Cities/world regions applied to:*** Forty-five cities in Asia, Europe, Africa, and the United States.

Figure 7: City Performance Tool: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are not transparent and may be developed in the United States or Europe but applied to global cities.

3.6 Models with Multiple Focuses

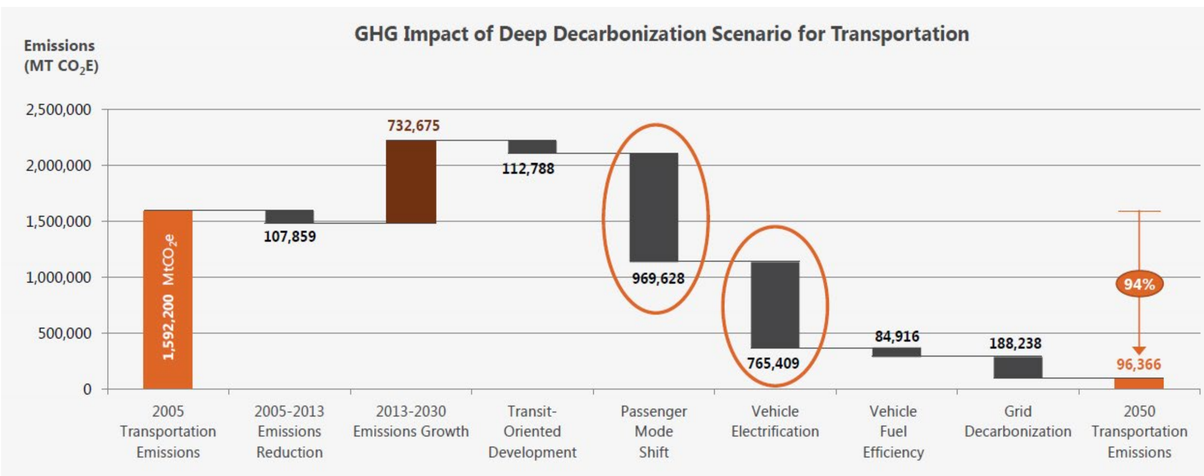
Climate Action for Urban Sustainability (CURB)

- **Highlights:** Focuses on land use (Lever 1) and some technologies (Lever 2). Levers 3 and 4 not included. Proxy data available for cities without data; most KPIs are transparent; model assumptions are embedded within the model with economic costs of each strategy clearly documented.

Box 4: Case Study: Oakland, California (United States)

Project highlights: Bloomberg Associates and the City of Oakland used the CURB model to estimate deep decarbonization pathways in order to achieve 83 percent GHG emissions reductions by 2050. Two scenarios, a Projected Trajectory based on current climate action plans and a Deep Decarbonization scenario, were created to assess the impact of 60 distinct actions that could reduce emissions in the buildings and transportation sectors, including transit-oriented development. CURB defines TOD based upon the proportion of households located within a quarter-mile of a transit station that has service every 15 minutes or less. In both scenarios, CURB projects that Oakland's proportion of TOD will increase from 43 percent to 65 percent, resulting in 10 percent GHG emissions reduction in the transport sector due to trip reduction (Bloomberg Associates 2018).

Figure 8: CURB Oakland 2050 Deep Decarbonization Scenario Modeling Results



Source: Bloomberg Associates 2018.

- ***Developed by***: World Bank, C40, Bloomberg Philanthropies, Global Covenant of Mayors for Climate and Energy, and AECOM.

- ***Objective***: CURB was developed to help cities identify and prioritize deep decarbonization action and meet climate action plan targets. CURB is utilized by Bloomberg Philanthropies and others to quickly determine which GHG reduction actions will be most cost-effective in meeting emissions targets.

- ***Summary of levers covered***:
    - *Lever 1 (CUD–land use):* Coverage of CUD presents broad aggregate VMT reductions, but does not discuss specific 5D interventions, such as transit, design, etc.
    - *Lever 2 (infrastructure technology):* Comprehensive coverage of infrastructure sectors noted in the GPC Basic inventory.
    - *Lever 3 (cross-infrastructure):* Not covered.
    - *Lever 4 (policy and behavior change):* Coverage of Lever 4 is mostly based on user input of strategy effect and participation/adoption rates that could impact infrastructure demand levels; model does not provide context of current participation rates and policy options that would achieve higher future participation rates.

- ***Specified GHG accounting methodology*****:** Consistently tracks with GPC accounting methods through CIRIS (City Inventory Reporting and Information System).

- ***Monetary cost and benefits*****:** Includes quantification of economic costs of various interventions as a key component for differentiating between interventions.

- ***Co-benefits:*** Air quality, public health, ecological health, deferred infrastructure, local economy, energy independence, public services, and social equity co-benefits qualitatively discussed for each strategy.

- ***Advantages:*** Addresses short-term and long-term strategies that would enable target GHG reductions from present trajectories; identifies cost and jurisdiction requirements of high/medium/low implementation. Proxy data are available from national data sets when local city data are unavailable.

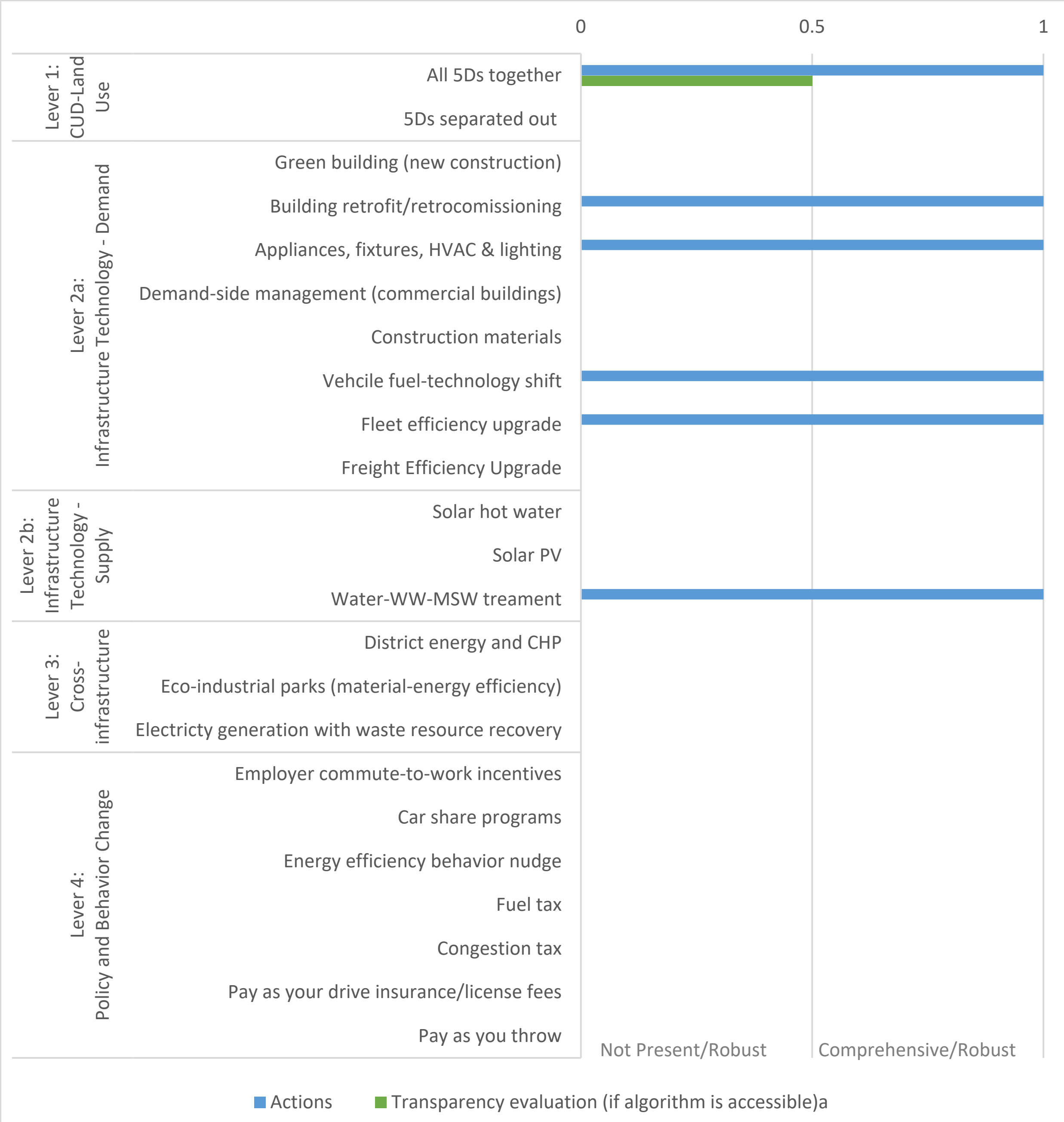
- ***Potential limitations*****:** Transportation strategies are grouped together based on mode shift away from private vehicles (difficult to separate between mode shift and electrification or fuel switching); combination of 5D parameters makes it difficult to determine the individual impact of any single CUD determinant. Policy and behavior change strategies are not linked to current quantitative participation data.

- ***Transparency and uncertainty*****:** Activity data and KPIs are transparent. Assumptions underlying elasticity are not clear because they are embedded within the spreadsheet; rationale for participation rates is not transparent, as many are based on user input without guidance on underlying context.

    - One documented elasticity is for smart growth (25 VMT reduction/percentage of TOD adoption).
    - Difficult to assess translation to other contexts because 5D elasticities are not delineated.

- ***Cities/world regions applied to*****:** Global.

Figure 9: CURB: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are not transparent and may be developed in United States or Europe but applied to global cities.

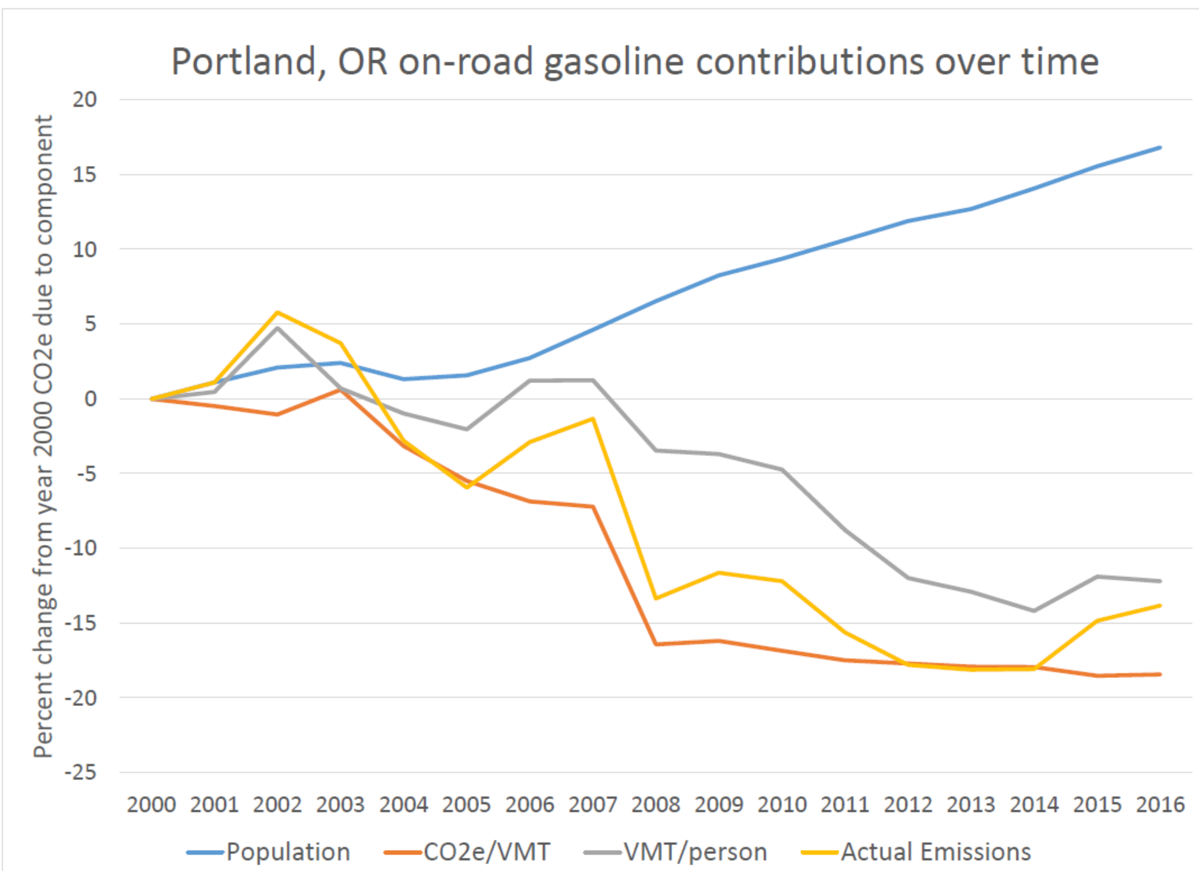
ClearPath

- ***Highlights:*** Transparent modeling assumptions for many strategies, covering three of four levers (Lever 3 not currently covered); tailored for use by ICLEI USA cities but available globally; direct linkage with GHG inventory in web interface. KPIs and reporting benchmarks explicitly tracked.

Box 5: Case Study: Portland, Oregon (United States)

Project highlights: ICLEI's ClearPath tool allows cities to both project future emission reduction strategies and consistently track city inventory data. ICLEI's 16 years of work with Portland, Oregon, have resulted in a rich data set and enabled ICLEI to develop a separate Contribution Analysis tool to analyze emission drivers (results for Portland are shown in figure 11). The tool will likely be integrated into future versions of ClearPath. Communities using ClearPath can report their annual GHG emissions inventories to CDP, Carbonn, and the Global Covenant of Mayors for Climate and Energy, while tracking progress toward their climate action goals. Portland's effort to meet its climate action planning target of reducing per capita VMT by 30 percent from 2008 levels can be tracked over time to determine if its CUD and smart growth strategies are being implemented effectively (ICLEI 2018).

Figure 10: ClearPath Portland Contribution Analysis Results

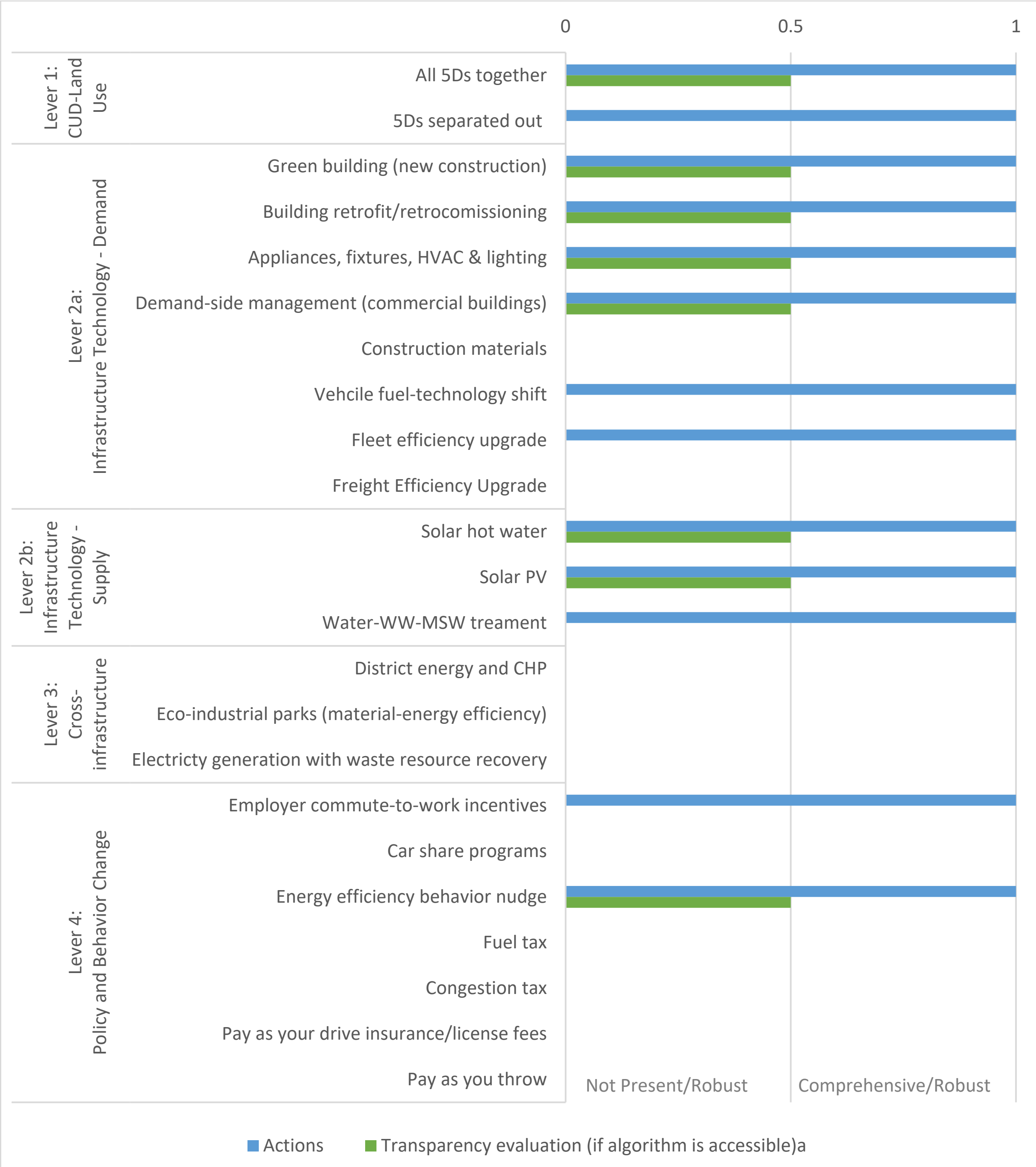


Source: ICLEI 2018.

- ***Developed by:*** ICLEI USA.
- ***Objective:*** ClearPath is intended as a long-term performance-monitoring tool that integrates periodic community-wide GHG inventories with mitigation planning to monitor plan performance and recalibrate climate action plans.
- ***Summary of levers covered:***
    - *Lever 1 (CUD–land use):* Comprehensive coverage of the impact of land use/development patterns on transportation energy and emissions.
    - *Lever 2 (infrastructure technology):* Moderate coverage of single-sector efficiency improvements in buildings energy/water use and transportation in U.S. cities.
    - *Lever 3 (cross-infrastructure):* Module for waste recovery and waste-to-energy is in development.
    - *Lever 4 (policy and behavior change):* Moderate coverage of strategies that would affect infrastructure demand; mostly based on user input of participation rates; model does not provide context of current participation and policy options that would achieve future participation.
- ***Specified GHG accounting methodology*****:** Compliant with U.S. Community Protocol and used for reporting to GPC.
- ***Monetary cost and benefits*****:** Direct financial costs are covered within an advanced cost-benefit analysis framework incorporating the cost of implementation compared to energy savings.
- ***Co-benefits:*** Sector-specific co-benefits are recognized, and measures can be identified that improve public health, advance equity, conserve water, etc.
- ***Advantages:*** Model has been utilized by 300 cities across the United States with levers and strategies tailored to meet the needs of U.S. communities based on transparent literature-based assumptions.
- ***Potential limitations*****:** Strategies and assumptions are not easily translatable outside the United States, and communities seeking to model strategies across multiple sectors for climate action planning targets may choose to select other tools tailored to their unique situation.
- ***Transparency and uncertainty:*** Most strategies have documented assumptions of elasticity and participation rate (model also gives flexibility for user-defined actions/elasticities). Translation between California-specific assumptions and other U.S. cities is not well documented.

Cities/world regions applied to**:** Previously applied to 300 U.S. cities and local governments; international inventory-only version exists that supports translation (five languages currently); awaits support to expand mitigation planning capabilities globally.

Figure 11: ClearPath: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are transparent, but have been applied only to U.S. cities, and there has been no attempt to quantify uncertainty in translation.

Community Infrastructure Footprinting and Action Analysis (CIFAA) Model

- ***Highlights****:* Publicly available/transparent model assumptions co-developed and tested with 20+ U.S. cities. Model covers all levers with citywide focus; Levers 3 and 4 receive more comprehensive coverage. Health co-benefit estimates with air quality models ($PM_{2.5}$ concentration/exposure modeling). KPIs and reporting benchmarks specified across many of the levers to track progress.

- ***Developed by****:* Researchers at the Sustainable Healthy Cities Network (SHC).
- ***Objective****:* Determine how unique actions taken at the urban scale can be quantified in the context of GHG mitigation (within the boundary as well as from a transboundary/life-cycle perspective), in a manner compliant with GPC and the U.S. Community Protocol. Strategies are modeled based upon the levers available to each city or each regional set of cities.

- ***Summary of levers covered:***
    - *Lever 1 (CUD–land use):* Comprehensive coverage of 5Ds; citywide estimation of land use/development pattern impacts on transportation energy and emissions; acknowledgement of uncertainty on buildings energy use.
    - *Lever 2 (infrastructure technology):* Comprehensive coverage of efficiency improvements in individual infrastructure sectors.
    - *Lever 3 (cross-infrastructure)*: Moderate coverage of material and heat exchange strategies across Chinese cities.
    - *Lever 4 (policy and behavior change):* Comprehensive coverage of policy and behavior change strategies, with emphasis on the differences in participation rates and enforcement potential across voluntary and regulatory actions.

- ***Specified GHG accounting methodology*****:** Compliant with GPC methodology.

- ***Monetary cost and benefits:*** Marginal abatement cost of implementing each strategy is assessed based on capital cost, operations and maintenance costs, and energy savings (Ibrahim and Kennedy 2016); cost per unit of GHG mitigated is provided for U.S. cities, with payback periods noted.

- ***Co-benefits*****:** Quantified based upon air pollution exposure and health impacts related to reductions in $PM_{2.5}$ emissions. Other studies expand additional co-benefits to health and well-being.

- ***Advantages:*** Strategies modeled are based upon the national/state/local policies proposed for reducing urban GHG emissions and potential future cross-infrastructure interventions uniquely available to cities. Models are peer-reviewed, and algorithms, assumptions, and participation data are transparent so that models may be translatable across contexts with attention to the assumptions embedded in the models. KPIs are reported and used by cities for future tracking.

- ***Potential limitations*****:** Levers 1, 2, and 4 are integrated in models applied to U.S. cities (Ramaswami et al. 2012). Cross-infrastructure strategies (Lever 3) have been developed for Chinese cities (Ramaswami et al. 2017) and will be integrated into CIFAA in the future. Cost data and marginal cost curves have been applied only for Toronto (Ibrahim and Kennedy 2016).

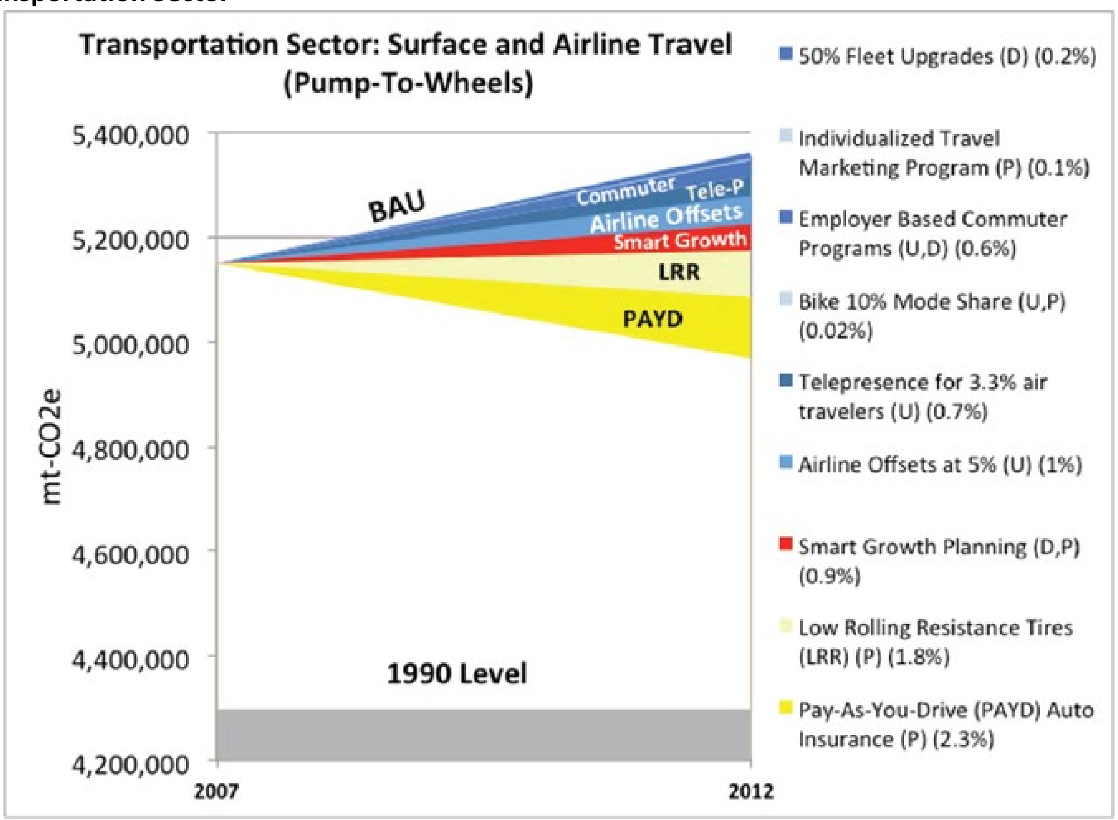
- ***Transparency and uncertainty****:* Model elasticity and algorithms are publicly available and documented in literature; participation rates are explicitly tied to targets drawn from current baselines in each city.

- ***Cities/world regions applied to*****:** Global: specifically United States (20 Colorado cities and 8 other U.S. cities), China, Canada, and some Indian cities.

Box 6: Case Study: Denver, Colorado (United States)

Project highlights: CIFAA utilizes transparent elasticities and participation rates available in scientific literature to model the GHG emission reductions that can be expected from land use, technology, cross-sector, and behavior change strategies in individual cities. Modeling results for various near-term transportation strategies and building strategies are shown for Denver in figure 12 and figure 13, respectively. Particular attention should be paid to the Smart Growth Planning strategy (figure 12, in red), which assumes CUD will impact 3.4 percent of Denver's 2012 population, resulting in 0.9 percent reduction in GHG emissions from the transportation sector (Ramaswami et al. 2012).

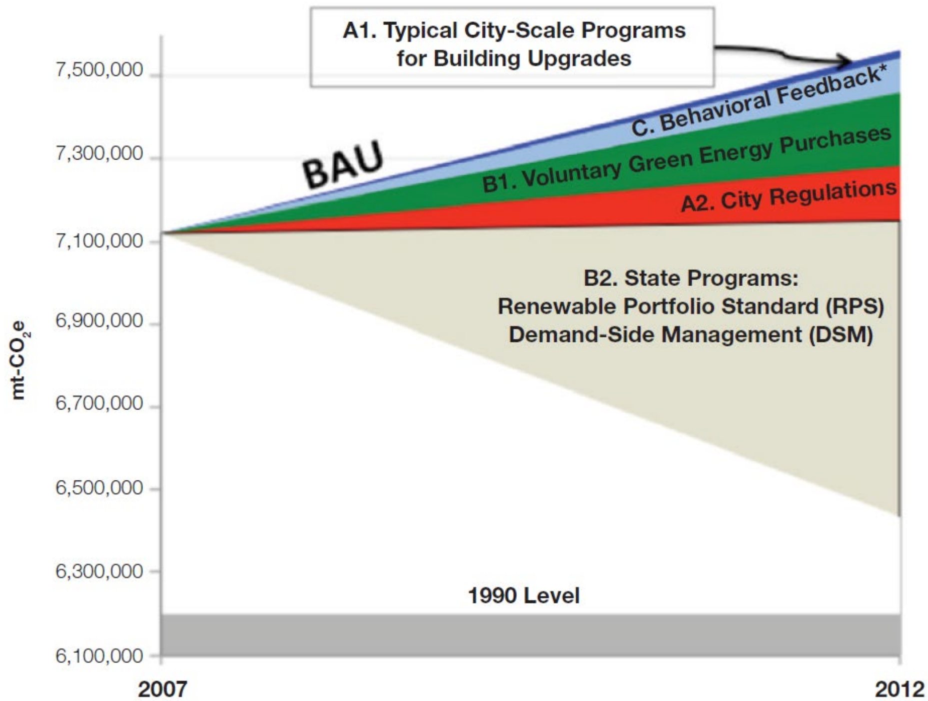
Figure 12: CIFAA Short-Term GHG Mitigation: Denver 2007–2012 Scenario Modeling Results for Transportation Sector



Source: Adapted and reproduced with permission from Ramaswami et al. 2012. Original image © Ramaswami et al. 2012.
Note: BAU = business as usual; D = action by infrastructure designer-operator; P = policy action; U = action by individual user.

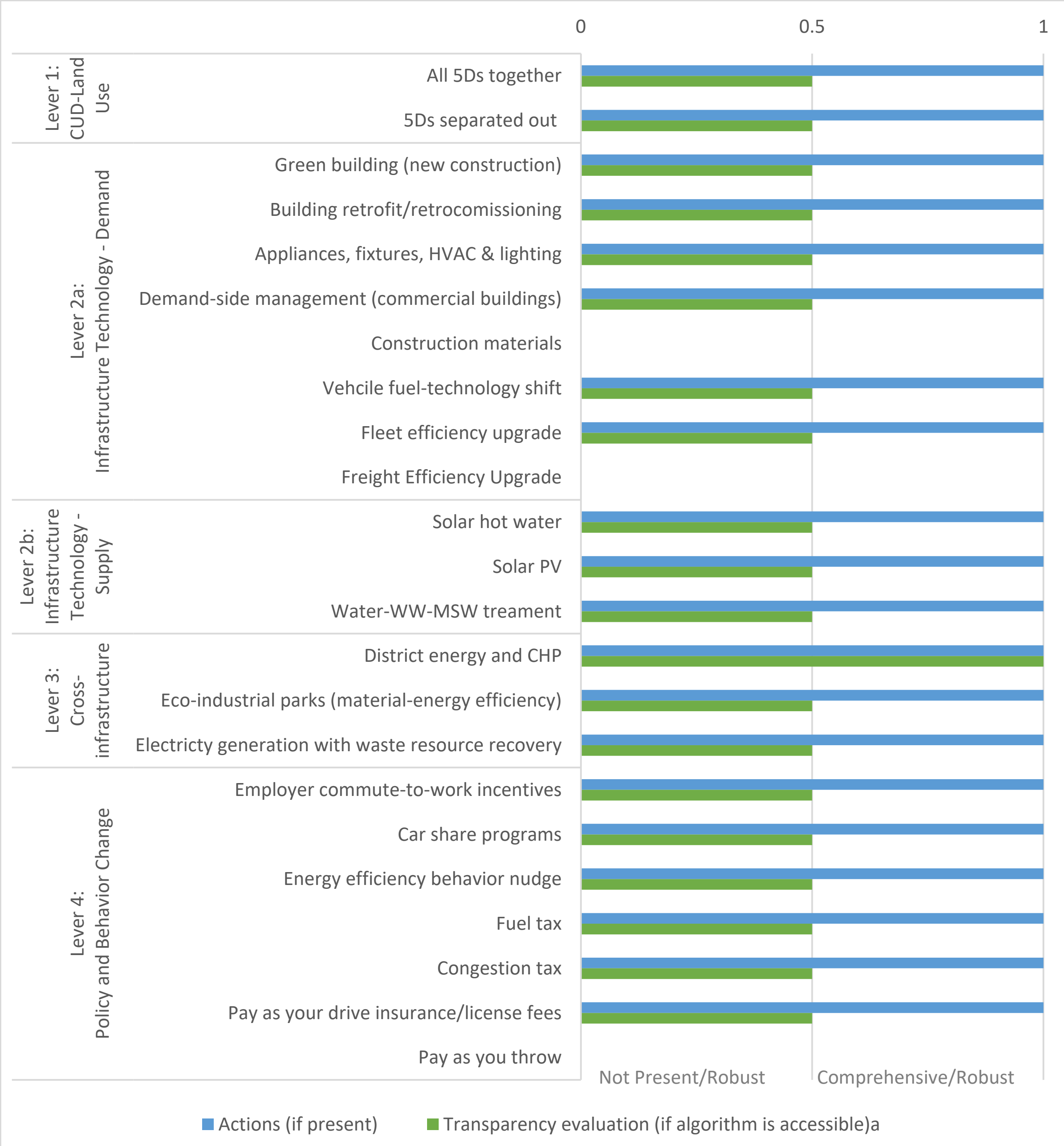
Box 6 (continued)

Figure 13: CIFAA Short-Term GHG Mitigation: Denver 2007–2012 Scenario Modeling Results for Building Sector



Source: Adapted and reproduced with permission from Ramaswami et al. 2012. Original image © Ramaswami et al. 2012.
Note: BAU = business as usual.

Figure 14: CIFAA: Evaluation of Lever Coverage, Model Transparency, and Uncertainty in Translation



Note: PV = photovoltaic; WW = wastewater; MSW = municipal solid waste; CHP = combined heat and power.

a. Model algorithms and assumptions are transparent, but have been applied only to U.S. cities, and there has been no attempt to quantify uncertainty in translation.

Section 4. Model Translation Considerations across Diverse City Contexts

Although all the levers are important, and notwithstanding the need for a fully integrative model, certain levers are likely to be more important in certain city contexts, as explained in section 2.5. Decision makers in a given city might draw on the additional information in this section to assess which of the models analyzed most appropriately responds to the needs, priorities, and constraints of their specific context. More detailed context analyses for specific GPSC cities, undertaken with locally specific data and insights into the five city-context factors presented below, could be an important next step but are beyond the scope of this report.

As shown in table 6, cities can ascertain which levers are most impactful based on context/city type, and which models have greater coverage of each lever based on the model evaluation described in sections 3.4, 3.5, and 3.6. For the six models analyzed in those sections, Lever 1 (CUD) coverage exists across all the models, with more comprehensive coverage in three models (UP, RF/UF, CIFAA). Lever 2a (infrastructure technology—demand efficiency) is covered across all the models except for UP; but Lever 2b (infrastructure technology—low-carbon supply) receives more comprehensive coverage only in the sector-based models (CyPT, CURB, ClearPath, CIFAA). Lever 3 (cross-infrastructure strategies) is currently covered only in two models (CIFAA, CyPT), while Lever 4 (policy and behavior change) is particularly well covered in only three models (RF/UF, CyPT, CIFAA).

Table 12: Lever Prioritization under City Context/City Type and Model Coverage

Lever	High-priority context based on city type	Particularly strong coverage
Lever 1 (CUD –land use)	Fast-growing cities accommodating new growth	UP, RF/UF, ClearPath, CIFAA
Lever 2 (infrastructure technology—demand reduction and low carbon supply)	All cities	CURB, CyPT, ClearPath, CIFAA
Lever 3 (cross-infrastructure)	Cities with significant industrial activity	CIFAA
Lever 4 (policy and behavior change)	Wealthy cities with high levels of consumption	RF/UF, CyPT, CIFAA

The sections below describe which levers are likely to be most relevant in terms of impact or opportunities missed in different city contexts. We consider city contexts in terms of (i) population growth rates and new construction; (ii) built environment area and activity density; (iii) economic structure of cities; (iv) prevalence of informal settlements; and (v) governance context.

4.1 Growth Context: Fast-Growing Cities and New Construction

Whether a city's population is growing quickly will affect the participation/adoption rates of individual strategies encompassed by levers in a given time period, and not necessarily strategy effect per unit. For example, the elasticities of the percentage of energy reduction per green building constructed remains the same in both slow- and fast-growing cities, but the number of new buildings that could be reached by green building standards is much greater in fast-growing cities with significant new construction. In general, fast-growing cities experiencing substantial new construction have the unique opportunity to impact large shares and perhaps all of their population through early integrated urban planning action. This is particularly true of Lever 1 (CUD) and Lever 2 (infrastructure technology) strategies, where participation rates can be profoundly impacted by the design of policies—i.e., policies that require compact development across the city or implementation of green building standards for all new buildings (which then last for the next ~30 years).

Fast-growing cities will have more opportunities to affect new construction and will be able to see greater impacts for all the levers in a shorter period of time. It is very important to consider policy design and regulation at this crucial stage of early development—making all options purely voluntary will represent a large missed opportunity. On the other hand, strategies will have to be vetted and contextualized to local context before being scaled up through regulation that targets 100 percent adoption; this step avoids locking in unintended consequences that emerge as a function of contextual differences. Governments must also have the capacity to implement urban plans and building codes, which can be challenging when population is increasing rapidly: in many cities in developing countries, population and GDP growth rates are between 5 percent and 10 percent a year, while fast city growth in developed countries often means only ~1 percent growth. In already developed slow-growing cities, a priority should be to focus on "areas of change" within cities and on the relatively small number of new buildings that are built to accommodate new population growth. In such cities, building retrofits and infill development to enhance 5D-informed CUD will be more important.

4.2 Built Environment Context: Land Area and Activity Density

A city's existing land footprint and baseline average activity density (population and jobs) can affect the strategies chosen to achieve the accessible and livable density embodied in the 5D framework.

For developing world cities where average densities are generally already very high, particularly in informal settlements, merely focusing on increasing population density is not meaningful and can also have the unwanted effect of inducing further travel demand. In such contexts, an increase in density could actually result in increased GHG emissions, as it could exacerbate congestion such that shared and private vehicles spend substantially more time idling in traffic. Additionally, quality of life concerns associated with very high levels of density (congestion, poor access to green space, noise, air pollution, etc.) may encourage outward sprawl and enclave township development. Thus in already dense cities (> 3,000 inhabitants/km^2), rather than simply trying to increase densities, it is more important to focus on street design, jobs-housing balance, and diversity of transit options (including emphasis on non-motorized travel) (UN Habitat 2013). Studies in India suggest that small cities with land footprints of less than 50 km^2 and populations of ~500,000 or fewer may be particularly well suited for mobility investments in bus transport and non-motorized modes (walking and cycling), rather than the mass transit system investment that will be needed in cities with larger populations and more extensive land areas (Shastry and Pai 2016).

In low-density cities (e.g., many developed world cities), attention to density thresholds is important. Some early studies in the United States suggest that a minimum threshold density of 35 dwelling units/acre is necessary to make mass transit investments cost-effective (Santasieri et al. 2014), and they also suggest that car-sharing programs appear to be cost-effective only at densities above 5–10 dwelling units/acre. Density thresholds are important because they represent the minimum point at which the reduced infrastructure demand effects of 5D-based CUD will start to accrue. Focused interventions to increase density in targeted areas, along with the other 5Ds, will be needed in larger but less dense cities.

Moderate density and co-location are also important for Lever 3 interventions (cross-sector strategies), such as district energy systems that specifically leverage waste heat from industry and that generally need to be located within 30 km of the industry site before system heat losses begin affecting the viability of the system (UNEP 2015).

4.3 Economic Structure: Industrial, Commercial, and Hybrid Economies

The economic structure of a city—whether mainly industrial, commercial, or mixed—substantially affects the economic activities that take place within that city, in turn influencing the participation/adoption rates, as well as feasibility, of multiple cross-infrastructure strategies. While industries are increasingly "zoned out" of cities, co-location of industries in eco-industrial parks can leverage heat or material exchanges between industries. Co-location and heat recovery from industries (even located 30 km from residential and commercial central business districts) can provide substantial heating and cooling by recycling waste heat. Such systems can provide high levels of energy efficiency and are particularly important to consider in industrial cities.

Strategies for Lever 1 (CUD) and Lever 2 (infrastructure technology—demand and supply) would not generally be substantially impacted by economic structure.

4.4 Infrastructure Access and Consumption: Informality, Access, and Baseline Consumption

Multiple GPSC pilot cities are characterized by national urban contexts in which sizable segments of the population are not formally connected to infrastructure networks. GPSC pilot cities also span multiple national per capita income profiles. Per capita income is a key driver of infrastructure consumption levels, with high-income earners generally consuming more than low-income earners. Cities with large informal populations and challenging governance environments highlight the limited potential to provide centralized and conventional western-style infrastructure in such contexts. Lever 2 strategies (infrastructure technology—demand and supply) and novel infrastructure transitions present opportunities for cities to leapfrog to new infrastructures and configurations that can help correct for existing service provision deficits. The wide proliferation of cell phone use in developing country contexts (skipping any period of widespread use of land lines) exemplifies the potential for leapfrogging past certain infrastructure stages; it thus highlights the importance of considering technology innovations and new infrastructure configurations to address infrastructure access in cities with large informal populations.

Baseline consumption and infrastructure access also inform equity considerations in that it may not be equitable to ask all households to reduce their consumption by a specific percentage when some households (often the wealthiest) are consuming at per capita levels that are much higher than other households. Moreover, in low-consuming environments, Lever 4 strategies (policy and behavior change) may not be about changing *current* unsustainable behavior, but rather about avoiding the adoption of *future* unsustainable behavior. For example, in contexts with limited personal vehicle ownership, the broad behavior challenge may be to convince those without vehicles not to purchase them as their incomes rise (by providing attractive mobility alternatives). This is in contrast to the challenge of convincing those who already own vehicles to give them up or use them less (i.e., change their existing behavior). Both challenges can be targeted via policy and behavior changes, but the directional changes themselves are somewhat different, and may require different suites of strategies.

4.5 Governance Context: Regulatory Control and Compliance Enforcement

Regulatory control and compliance enforcement capacity will affect participation rates across all four levers. Without mandates for compact urban development, infrastructure technology upgrades (demand and supply), cross-infrastructure strategies, and policy/behavior change, the adoption or deployment of any of the encompassed levers and strategies within this model review will likely remain limited, due to considerations of up-front cost, convenience, or path dependency. The effectiveness of regulations and policy mandates is explicitly premised on the ability to widely enforce meaningful penalties for noncompliance. In governance contexts with low levels of regulatory control and compliance enforcement capacity, incentives—either direct financial incentives or indirect incentives via efforts to highlight a strategy's associated co-benefits—are the primary tool that cities have at their disposal to encourage voluntary adoption until market forces encourage wider adoption as a function of demand and price signals.

Section 5. Conclusion and Recommendations

This report reviews the state of knowledge (science) and of practice (commercially available models) for modeling the GHG mitigation benefits achievable through integrated urban planning across the four levers, with attention to the foundational Lever 1, CUD. The report uses a 5D framework to represent various land use parameters in developing compact urban form: articulated and accessible **d**ensity, **d**iversity of use and income, **d**esign of neighborhoods and streets, **d**istance to transit, and **d**estination access.

A review of the knowledge base (section 2; see also appendix A) finds that quantitative algorithms drawn from theory (engineering calculations or transportation demand modeling studies) as well as empirical observations are available to quantify the anticipated GHG mitigation benefits that could be achieved by implementing each of strategies spanning the four identified levers. These algorithms are developed in particular city or country contexts, and this review highlights when and how they might be translated globally (section 4).

As explained in section 2.2., the algorithms consist of two dimensions: (i) the strategy effect per unit of an intervention (i.e., the reduction in demand or resource use per unit of an intervention), which is represented in the form of elasticities in demand and resource efficiency improvements per intervention; and (ii) the penetration rate or adoption rate of each intervention in the strategy scenario. Each of the strategies can be characterized systematically by these two component parameters. It is important to use context-specific data or knowledge to inform both strategy effect and participation rates in baseline versus scenario cases.

Our review of the state of practice comparing six tools (see section 3) found the following:

- Only two models (ClearPath and CIFAA) integrated across all four levers, and these models to date have mostly been applied in U.S. cities.
- Focusing on the models that assess GHG mitigation potential of Lever 1 (CUD), we identified three broad categories of models:
    - Models that use locally derived elasticities to represent GHG benefits of compact urban form (RapidFire/UrbanFootprint)
    - Models that apply U.S. field data–derived 5D elasticities to U.S. cities (ClearPath, CIFAA)
    - Models that apply North American field data–derived 5D elasticities to world cities, given the absence of local data (Urban Performance, CyPT, CURB)
- Due to the intrinsic local nature of elasticities, the only valid methodology to apply in various rapidly growing cities, such as those in China, is RapidFire/UrbanFootprint, which uses locally derived elasticities. ClearPath and CIFAA are scientifically sound when their application is limited to the U.S. context, while the use, so far, of CyPT and CURB is not advisable due to the current need to extrapolate elasticities outside their geographical domain of validity.

Among these tools, the development of RapidFire in Chinese cities presents a very promising and robust method to model world cities: it relies on extensive field research to derive the elasticities (Jiang et al. 2017) using new informatics and big data approaches (CSTC 2016). Among urban form and land use models, those developed using in-country data and elasticities, such as RapidFire, are better than models that use elasticities derived from North American cities broadly across city contexts. The approaches taken by RapidFire in Chongqing and Urban Performance in Jordan have much potential to be applied to world cities. These approaches also indicate the importance of local capacity. In addition, these two models quantify multiple benefits that go beyond GHG impact, including reduced land use, reduced water and energy use, lower infrastructure cost, and the potential for mobility optimization. The multiple co-benefits generated from integrated land use and planning provide an important basis for local policy dialogue with political leadership around developing a compact urban spatial strategy.

Most models are not tracking all the determinants relevant to all strategies, including the 5Ds. Given that the field of integrated urban planning is relatively young, there is an unprecedented opportunity to gather longitudinal country-specific data on KPIs from GPSC member cities and to publicly report elasticities and baseline adoption/penetration rates of modeled CUD mitigation potential to improve the scientific knowledge and develop more robust models going forward.

Future work should adopt a robust set of indicators that represent multiple CUD metrics as well as indicators across all four levers. Applying these models across different city types and world regions in the GPSC pilot cities provides an invaluable opportunity to develop KPIs across all four levers. Very few of the models have KPIs for compact urban development, which is foundational for integrated urban land use and infrastructure planning. Having a consistent framework for KPIs is essential, not only for tracking progress within cities but also for developing and extrapolating key lessons across cities moving forward. In particular, the experience of the GPSC pilot cities could inform other cities on the average budgetary, institutional, and staff-time requirements associated with collection, interpretation, and management of context-specific data.

Further, in the context of fully integrated urban planning models, there is a need and an opportunity for future model development and benchmarking connecting all four levers in diverse world cities. GPSC may have an opportunity to develop a more robust integrated modeling platform with its member cities, along with associated tracking metrics, to represent the full multiplicative impact across the four levers that is necessary to achieve a factor of 10 energy use reduction and, more generally, the Paris climate goals. Given the growing pressures of rapid urbanization on natural resources and ecosystems, future models should consider the equity and distribution of scarce resources (e.g., the growing cross-sectoral competition for water and land) in order to highlight the relevance of GHG mitigation strategies in the context of the SDGs and local policy goals. Models that are able to measure the co-benefit outcomes (e.g., land use savings, water and energy savings, mobility optimization, lower infrastructure costs) could be especially attractive to clients.

Overall, it is important to start building consensus on the acceptable level of uncertainty and accuracy that will result from the use of the recommended tool(s). The model algorithms, assumptions, and any empirical data should be made transparent by those implementing any model applied to GPSC member cities. Very few of the models reviewed were transparent about policies and participation rates, or about the basis upon which future participation rates are assumed. Current and future participation rates and policies are among the most important factors that affect GHG mitigation potential, making documentation of them essential. Care should be taken in translating models and algorithms developed for cities in advanced economies to cities in the Global South; this guidance is especially relevant for 5D elasticities (which may not apply) and for the percentage of energy reduction possible through various interventions, given that the explicit preservation of existing efficient vernacular technologies and sustainable consumption behaviors may constitute an important GHG avoidance strategy.

Lastly, in the absence of tools integrating across all four levers, certain levers are likely to be more important in certain city contexts. GPSC member cities interested in a specific lever or set of strategies can consult section 2.5 on which levers should be prioritized given their context and section 4 on the levers covered by each model as well as what context considerations should be emphasized by the modelers during implementation.

Appendix A. Description and Quantification of Four Key Levers for GHG Mitigation

Lever 1: Compact Urban Development–Land Use Strategies

CUD strategy effects on transportation service demand represented as elasticities: The effect of each of these land use strategies, and in theory their combined effect, on the demand for infrastructure services (e.g., travel demand) is often modeled through the use of elasticities, or the per unit effect that could be anticipated for a specific intervention. Elasticities in the context of CUD represent the percentage reduction in infrastructure demand (e.g., travel demand) that may arise due to a percentage increase of each of the CUD variables (the 5Ds). Elasticities with respect to specific 5D strategies have been recorded in the United States and are summarized in table 3. Notice that each of these elasticities refers to short-run elasticities (VMT demand reduction per capita). These elasticities have been developed for U.S. cities and have been controlled for by age of population, family size, and self-selection bias in comparing less dense and more dense developments. Some researchers have noted a minimum threshold for some CUD land use strategies before their effects can be seen—e.g., minimum threshold densities of 35 dwelling units/acre for effective public transit in the United States (Santasieri et al. 2014). The elasticities also level off, revealing a maximum impact "ceiling"—i.e., the best case possible after which additional increases yield minimal returns. For example, the best-case scenario for implementing all five CUD strategies (all 5Ds together) in the United States finds no more than 25 percent per capita VMT reduction is possible. In all cases it is important to note that these VMT reductions apply only to those populations exposed to or experiencing some or all of the CUD-land use interventions.

CUD strategy effects on other infrastructure service demands: Compact Urban Development-Land Use strategies could also affect housing floor area by reducing living space per capita, and also potentially reducing energy use intensity per unit of floor area, given that single-family housing may be less energy efficient (have greater heat loss) than attached or multifamily housing, in which homes may share one or more common walls. However, the data on both these effects is inconclusive. In general, the science to date indicates that while dwelling area per household may be smaller in dense urban centers than in suburban areas, these differences may become less significant when evaluated on a per capita basis. In terms of building energy use, the literature is inconclusive, with some research finding that high-density high-rise buildings require more energy per floor area (Du and Wood 2017).

CUD can also reduce the magnitude of demand for horizontal infrastructure services from reduced road and pipe networks requirements. For example, in the United States, documented benefits include 12 percent reduction in road network capital costs in compact urban developments and on average 38 percent capital cost savings through reduced roads, sewers and water pipes, and other infrastructure in CUD areas (Burchell et al. 2000; Smart Growth America 2013; Rode et al. 2014). Similar influences in developing economies such as China and India have also been documented in a few cases. For example, moving from single-story to high-rise construction in India can result in material use reduction of around 30 percent; infrastructure pipe network requirements in Delhi range from 1.4 m to 5.2 m sewerage piping per household in various neighborhoods based on density and spatial arrangements (Nagpure, Reiner, and Ramaswami 2018). A single study in China has found that horizontal infrastructure costs may be reduced by 50 percent in a compact growth scenario. However, specific elasticities could not be drawn from these studies. Detailed case study data with known geometries of spatial arrangements and road and pipe network design can more directly yield reductions in horizontal infrastructure requirements and costs. Such an approach is translatable across all city contexts.

The extent to which CUD–land use travel demand elasticities are translatable across cities and countries is unsettled. There is much debate in the urban planning literature on which CUD variables (representing the 5Ds) play the largest role in reducing travel demand (represented via elasticities), and whether the magnitude of these effects seen in developed nations (United States, EU countries, Canada, and Australia) are applicable to developing nations and cities that are yet to be built. Details are presented in section 4.

In summary, our review of the literature leads us to the following conclusions:

- The 5D framework is broadly applicable in diverse city contexts, but the impact of CUD on infrastructure demand (e.g., travel demand) has been quantified in only a few cities and countries. Additional work to better quantify the effect of CUD on infrastructure demand in diverse cities and regions globally is needed.
- Models that seek to quantify the impact of CUD–land use parameters on infrastructure service demand should be transparent and explicit as to the underlying algorithms applied (including details on the assumptions around elasticities, any density thresholds, and maximum anticipated benefit, along with the population experiencing CUD interventions).
- Models should clarify the literature source and/or the empirical data upon which the VMT and other infrastructure use reductions are modeled, noting the country and city context from which they are derived, including the policy context, so that judgments can be made about whether the model is translatable to other countries and other city contexts.
- All models should use indicators—not only for the CUD–land use metrics, but also for associated metrics related to infrastructure service demand, current and future technology performance, current and future infrastructure/technology adoption rates, and any overall policies that influence such adoption (such as gas taxes, license plate policies, etc.). Examples of suggested KPIs across all urban planning levers are shown in table 7 in appendix B.
- Whenever possible, the effects of CUD interventions should be quantified by looking at the 5Ds together, rather than individually, as CUD concepts explicitly emphasize interaction effects among the 5Ds as potentially being greater than the sum of isolated 5D-derived interventions.

Lever 2: Infrastructure Technology Strategies in Individual Sectors

Key sectors and strategies of interest for infrastructure technology interventions include the following:

- **Building sector efficiency strategies**, with a focus on strategies that reduce demand for energy, water, and materials through high-efficiency technologies and appliances (Lever 2a)
- **Transportation sector efficiency**, with a focus on vehicle fuel shifts, mode shifts, and fleet fuel efficiency upgrades that reduce the energy intensity of motorized travel (Lever 2a)
- **Energy sector supply-side strategies** that are valuable in reducing GHG emissions and relate to urban form, including installation of solar water heaters and/or photovoltaic (PV) solar generation on rooftops (with sky view factors applied in dense urban areas to determine the maximum potential area that can be used for PV generation) (Lever 2b)
- **Water, wastewater, and solid waste management efficiency**, with a focus on treatment plant efficiency, pumping efficiency, and leakage reduction as well as methane capture (Lever 2b)

Quantifying strategy effect of technology interventions in individual sectors: Several algorithms have been identified in the literature to estimate the impacts of these single-sector strategies (Ramaswami et al. 2012). Algorithms may estimate reductions in energy use per unit of intervention, based on multiple factors and data sources, including theoretical energy use reductions, real-world case study and analysis of outcomes, and assessment of current building use behaviors. The following considerations should be kept in mind for modeling technology transitions:

- **Theoretical potential for energy-efficient appliances and implementation case studies:** Algorithms based on theoretical calculations can be applied to many interventions (e.g., energy savings through switching from incandescent light bulbs to CFL or LED lamps, or through increasing insulation). Such theoretical potentials should be translatable to all city contexts assuming identical human behavior and technology performance. These estimates can be improved upon with regional implementation case studies that provide a better understanding of actual energy savings in real-world conditions to estimate impacts of building efficiency retrofits and appliance upgrades (for example, evaluating strategy effects across several hundreds of households to quantify energy use reduction potentials for each appliance upgrade).
- **Ranges of energy use reductions from green building upgrades**: Energy efficiency gains from whole building design changes are more complex, as they represent energy saved compared to a reference building and are also influenced by occupant behaviors. Such energy reduction estimates should be handled with care, and a range of expected energy use reductions should be used drawing upon real-world case study results. For example, one recent study (IRP 2018) used maximum energy use reductions of 50 percent against a reference building, as reported in U.S. studies; but many studies show the impact of green building interventions must be evaluated in context, as real-world studies have shown that energy performance improvement varies widely.
- **Possible resource efficiency of existing vernacular and ordinary "non-green" buildings:** City context is important, and vernacular buildings must be considered in addition to western green building norms. In many countries, existing vernacular buildings may use less energy than contemporary green building construction (Zhang et al. 2010) because of the way their occupants use energy (for example: they use air conditioning sporadically, leave doors and windows open, and dry clothes outside). Existing GHG mitigation tools need to recognize the existing efficiencies achievable in vernacular buildings and exercise caution in recommending strategy scenarios that replace all such buildings with tight-envelope buildings that are heated and cooled mechanically (UNEP 2018).
- **Impact of deprivation and lack of infrastructure services in the water/wastewater sector:** Algorithms should recognize the impact of deficits in this sector—for example, untreated sewage that is diverted to rivers results in methane generation. Sewage treatment should be a first priority for certain countries to invest in, as it has the capacity to capture methane, which is 28 times more potent than CO_2. Even where there is a wastewater treatment plant, methane may still be discharged to the atmosphere.

KPIs that reflect these considerations in the built environment include the following:[1]

- Households lacking various basic services (across all services)
- Energy use per capita (city average) and by income levels of housing
- Energy use intensity (per square area) comparing interventions and controls
- Energy use by various sub-activities (if available), e.g., for water heating, space heating/cooling to model transitions
- Construction material use per capita
- Water use and wastewater generated per capita

See also table 7 in appendix B for further details.

Broadly, care should be taken to understand the performance of single-sector infrastructure technology interventions in local context. Current emerging technologies show potential for recovering energy from various waste streams such as municipal solid waste, sewage, and food waste. These emerging interventions in single infrastructure sectors set the stage for discussing cross-infrastructure strategies that can create systemic circular economy benefits.

Lever 3: Cross-infrastructure Strategies

Recent studies have shown that there is high potential for cities to decarbonize through urban planning that facilitates cross-infrastructure exchange of waste heat and materials. For example, low-temperature waste heat that has no other use can be piped up to 30 km from industry fence lines to urban residential and commercial buildings for district heating and cooling (UNEP 2015), offering cost efficiency and displacing fossil fuel use for heating and cooling purposes. These cross-infrastructure strategies enabled by district energy systems that use waste heat as well as bio-resources can be an important decarbonization strategy that is further enhanced by CUD. Recent studies of more than 600 Chinese cities have indicated that cross-infrastructure efficiency strategies, such as using low-grade waste heat in district energy systems and exchanging waste materials (fly ash to cement, steel slag to cement), can contribute to as much as two-thirds of single-sector efficiency strategies established by the Chinese national government (Ramaswami et al. 2017; Tong et al. 2017). Each city, based on its mix and structure of industrial, commercial, and residential activities, will show different potential for implementing cross-infrastructure solutions. Thus, algorithms that can estimate the potential of these cross-infrastructure strategies should be customized to each city (Tong et al. 2017).

Lever 4: Policy and Behavior Change Strategies

This lever refers to tracking both behavior change in voluntary programs and the number of people encouraged to participate in mitigation strategies through regulatory action. Many studies recognize that while the strategy effect—i.e., the technological potential for GHG mitigation—can be high for light bulbs, individual appliances, and individual green buildings, citywide GHG mitigation is strongly influenced by the level of participation in energy efficiency programs or level of adoption of high-efficiency appliances achievable in cities. In other words, the maximum penetration of these new technologies limits the reach or potential for GHG mitigation. For example, Ramaswami et al. (2012) working with the City of Denver showed that voluntary adoption of green building standards would reach only 5–7 percent of newly constructed buildings. However, policies that require compliance with green building standards, such as those put in place in Boston for large-floor-area commercial buildings,

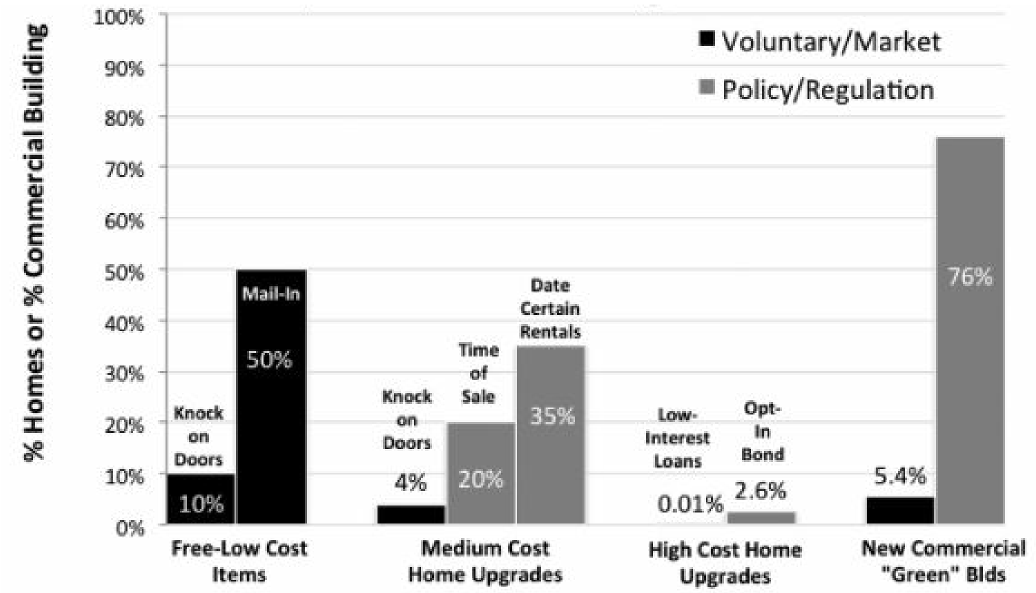
[1] More detailed examples of such KPIs with specific city applications can be found by referencing the Global City Indicators Facility and ISO 37120; see also Hillman and Ramaswami (2010) addressing eight U.S. cities; and Nagpure et al. (2018) addressing inequality in Indian cities.

would address more than 70 percent of newly constructed buildings. Similarly, knocking on doors as part of energy-efficiency campaigns can reach only about 5–6 percent of households, while time-of-sale regulations for household energy-efficiency upgrades could reach a much larger percentage (>25 percent) of the housing stock over a five-year period (see figure 15).

More recently, efforts such as bill feedback and price signals have also proven to be important policy levers for behavior change. For example, real-world implementation in U.S. cities has shown that targeted messaging and feedback through utility bills can save up to 12 percent of energy use in participating households (Dietz et al. 2009). Understanding the implementation context of these strategies is important. Thus for cities in a developing country context, where residents may already be consuming less electricity than minimum standards suggest is necessary for meeting basic needs, the focus should be on providing clean electricity to meet basic minimum consumption thresholds for the under-consuming population rather than on energy efficiency among that same population. Understanding the segments of a population that consume the most energy is also important for targeted energy-efficiency campaigns.

In general, the percentage adoption of various strategies influences the reach of all the strategies, and hence models must specify the basis for assumptions about strategy reach. Certain policies—such as mandatory regulations, gas taxes, and driver's license fees—should by design impact all (100 percent) of the population, assuming a robust enforcement environment. In modeling Lever 2 technologies, models should state their assumptions about the level of adoption/penetration expected based on realistic estimates. Any user inputs about the amount of participation should be guided by existing participation levels in similar programs, as seen in Denver's Climate Action Plan (Denver 2015), where all participation data were determined on the basis of existing participation rates. Creating a database on participation in various voluntary and mandatory programs in various world regions would be very valuable, as participation rates can affect GHG mitigation potential of certain strategies by orders of magnitude; this is shown in the difference in participation rates of commercial "green" buildings in figure 15.

Figure 15: Five-Year Participation/Adoption Rates for Programs Observed in Denver, or Modeled After Regions in Other Cities in the United States



Source: Adapted and reproduced with permission from Ramaswami et al. 2012. Original image © Ramaswami et al. 2012.
Note: New commercial green buildings show that the adoption rates can increase tenfold, based on the design of the policies.

Across all levers, the model review presented in section 3 focused on evaluating whether available integrated urban planning models explicitly clarify their assumptions, both in quantification of the strategy effect and participation/adoption rates of each strategy. It is important to call out the potential reach of each strategy in Lever 4 because mandatory and voluntary policy actions will have large differences in adoption or participation rates. As Ramaswami et al. (2012) did for green building policy design in Denver (figure 15), Boarnet and Handy (2017) qualitatively assess statewide transportation policies in California (fuel/congestion pricing, infill development, transportation investment, and transportation demand management strategies) to evaluate the strategy effect of each policy on VMT and to illustrate potential participation/adoption rates, with some policies applying to all users statewide and others applying only to metropolitan areas or small subsets of the population. Likewise, it is important to note that interventions related to the 5D elasticities noted in Lever 1 will apply only to the subset of populations who are experiencing the improvements in compact urban form and will often be limited to areas undergoing change. Lastly, it is important to consider that pricing strategies (fuel taxes, pay-as-you-go insurance, etc.) may have immediate effects on the whole population; this is in contrast to land use and infrastructure investment (transit, bike/pedestrian investment), whose effects become visible over longer time horizons by steadily impacting subsets of the population and growing their impact over time.

Appendix B. Model Review Tables

Table 7: Model Review: Baseline GHG Accounting and KPIs

	UP	RF/UF	CyPT	CURB	ClearPath	CIFAA
1. Empirical data for proxy city	Jordan, Indonesia, Mexico, etc.	California Metropolitan Planning Organizations, selected U.S. cities, Mexico City, Chongqing	45 cities and regional data	National proxy: 150+ countries City proxy: variable count	300 U.S. + global cities	10 global and Canadian cities, 20+ U.S. cities (Colorado and Minnesota), 600+ Chinese cities[a]
2. GHG accounting methodology	No	No	GHG protocol	GPC compliant	U.S. Community Protocol & GPC compliant	U.S. Community Protocol; GPC Basic +
3. Life-cycle emissions included?	No	No	Yes	Yes	Yes	Yes
4. Population growth rate	Yes	Yes	Yes	Yes	Yes (user-input)	Yes
5. Economic growth rate	Yes	Yes	Yes	Yes	Yes (user-input)	Yes
6. City type by economic structure	No	No	No	No	No	Yes
7. KPI: CUD–land use determinants (5Ds)		8Ds[b]	City-dependent			
a. Density (of population, jobs, etc.)	Yes	Yes (population/jobs density)	No	No	Yes	Yes (population density)
b. Diversity (mixed-use floor area ratio, mixed-income)	No	Yes	No	No	Yes	Yes
c. Design (multi-modal)	No	Yes	No	No	Yes	Yes
d. Destination access (distance to job centers)	Yes	Yes	No	No	Yes	Yes

e. Distance to transit	Yes	Yes	No	No	Yes	Yes
8. KPI: Infrastructure demand by sector						
a. Household floor area/person	Yes	Yes	Yes	Yes	Yes	Yes
b. Commercial floor area	Yes	Yes	Yes	Yes	Yes	Yes
c. Energy use intensity ○ Residential ○ Commercial	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes	 Yes Yes
d. VMT per capita	Yes	Yes	Yes	Yes	Yes	Yes
e. VMT modal share	Yes	Yes	Yes	Yes	No	Yes
f. Automobile ownership per capita	No	Yes	Yes	No	No	No
g. MSW per capita	Yes	No	No	Yes	Yes	Yes
h. Construction materials per capita	No	No	No	No	No	Yes
i. Water use per capita	Yes	Yes	No	Yes	Yes	Yes
j. Sewage generated per capita	No	No	No	Yes	No	No
9. KPI: Slum/underserved						
a. Percentage without access to infrastructure	No[c]	No	No	Yes	n.a. (U.S.)	Yes[d]
b. Percentage consuming less than basic needs thresholds	Yes[e]	No	No	Yes	n.a. (U.S.)	Yes

10. KPI: Policy and behavior change						
a. Price of fuel	No	Yes	No	Yes	Yes	Yes
b. Pay as you drive (license fees, insurance fees, parking costs)	No	Yes	No	No	No	No
c. Cordon/ congestion tolling price	No	Yes	No	No	No	No
d. Cost of land	No	No	No	No	No	No

Note: n.a. = not applicable.

a. For Lever 2, see Kennedy et al. (2015); Mohareb and Kennedy (2012); Ibrahim and Kennedy (2016); LoGoPEP (2017). For Levers 1, 2, and 4, see Ramaswami et al. (2012). For Lever 3, see Ramaswami et al. (2017).

b. 8Ds are 5Ds plus development scale (critical mass and magnitude of compatible uses), demographics (household size, income level, auto ownership), and demand management (pricing and travel disincentives).

c. Tracks vacant housing rates and proximity to amenities such as schools, hospitals, places of worship, etc.

d. See Nagpure et al. (2018) for a discussion of basic infrastructure provision and energy access in India.

e. Tracks per capita residential water and energy use only.

Table 8: Model Review: Strategy Coverage and Evaluation of Transparency/Translation

	UP	RF/UF	CyPT	CURB	ClearPath	CIFAA
Lever 1: Compact urban development–land use strategies						
Land use and transport						
1. CUD (5D) VMT demand reduction a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	Yes Yes No	No	Yes Yes No	Yes Yes No	Yes Yes No
Land use and buildings						
2. CUD building floor area reduction per capita a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	Yes No No	Yes No No	No	No	U.S. data show no significant decrease in per capita floor area
3. CUD and energy demand intensity reduction a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes[a] No No	Yes No No	No	No	Too uncertain to quantify
4. CUD infrastructure network costs/use a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	Yes No Yes	No	No	No	No
Lever 2: Infrastructure technology strategies						
Building efficiency strategies						
5. Green building code for new construction a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes Yes No	Yes No Yes	No	No	Yes Yes No	Yes Yes No
6. Whole building retrofit/efficiency for existing structure (weatherization, code enforcement, etc.) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	Yes No No	Yes No No	Yes Yes No	Yes Yes No
7. Heating/cooling efficiency upgrade a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	Yes No No	Yes No No	No

8. Appliances/lighting efficiency upgrade a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	Yes No No	Yes Yes No	Yes Yes No
9. Water fixtures upgrade (e.g., low-flow toilets) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	No	Yes No No	Yes Yes No	Yes Yes No
10. Commercial/multi-family building retro-commissioning a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	Yes Yes No	No
11. Utility demand-side management for commercial/industrial operations a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	Yes Yes No	Yes Yes No
12. Low-carbon and recycled construction materials a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	No	No
13. Streetlighting efficiency upgrade a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	No	Yes No No	Yes No No	Yes Yes No	No
Transportation Efficiency						
14. Private vehicle and fleet fuel technology switch of fossil fuel to biofuel, electric vehicle, or hybrid a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	Yes No No	Yes No No	Yes No No	Yes Yes No
15. Mode shift to transit through policy/programs a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	Yes Yes No	Yes No No	(Program not specified) No No	(Program not specified) No No	No
16. Mode shift to cycling through policy/programs (bike share, etc.) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	Yes No No	No	Yes No No	Yes Yes No

17. Private vehicle and fleet fuel efficiency upgrades (increase in miles per gallon) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No Yes	Yes No No	Yes No No	Yes No No	Yes Yes No
18. Freight: Efficiency or mode shift a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	No	No
Energy supply						
19. Building-scale solar hot water heaters a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	Yes Yes No	Yes Yes No
20. Building-scale solar PV (rooftop) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	No	Yes No No	No	Yes Yes No	Yes Yes No
Water/wastewater/solid waste management						
21. Service expansion for underserved to avoid methane emissions from untreated sewage a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	No	No
22. Treatment plant (or pump) efficiency a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	Yes No No	No	No
23. Methane capture from wastewater treatment plant a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	Yes No No	No	No
24. Pipe leakage reduction a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	No	No	Yes No No	No	No
25. Waste management: Municipal solid waste a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	Yes No No	No	No	Yes No No	Yes Yes No	Yes Yes No

26. Waste management: Construction and demolition waste a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	Yes Yes No	No
Lever 3: Cross-infrastructure strategies						
27. District energy with waste heat and bio-resource reuse options a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	No	Yes Yes Yes
28. Materials exchange via eco-industrial parks a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	No	Yes Yes No
29. Waste heat reutilization for electricity supply a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	No	Yes Yes No
Lever 4: Policy and behavior change strategies						
30. Car sharing/carpooling (including commuter programs) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes[b] No No	Yes[c] No No	No	No	Yes Yes No
31. Energy behavioral nudges (bill feedback, messaging, real-time energy displays, etc.) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	Yes No No	No	Yes Yes No	Yes Yes No
32. Carbon or fuel tax a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	No	Yes Yes No
33. Congestion/time of use pricing a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	Yes No No	No	No	Yes Yes No
34. Pay as you drive tax/parking/license costs a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	Yes No No	No	No	No	Yes Yes No

35. Pay as you throw tax (solid waste management) a. Model algorithm and underlying case transparent b. Uncertainty in translation explicit	No	No	No	No	No	No

Note: For each numbered strategy in boldface, "yes" or "no" answers the question "Is the strategy present?" For "a. Model algorithm and underlying case transparent," "yes" or "no" answers the questions, "Are the model algorithms/calculations for various strategies clearly documented and linked to literature or empirical data analysis? If based on data analysis, from which region of the world?" For "b. Uncertainty in translation explicit," "yes" or "no" answers the questions, "Are the model algorithms for future scenarios modified or flagged when applied to a different context (nation, region, city type, etc.)? Is uncertainty represented in assessing the impact of strategies?"

a. See DiStefano and Lew (2016).

b. UF addresses autonomous vehicles and transportation network companies.

c. Electric car sharing and eco-driver training/consumption awareness.

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Achieving the Sustainable Development Goals by 2030 will depend upon cities making critical land use and infrastructure development decisions across multiple sectors—including buildings, energy, transportation, water-sanitation, and waste. The Technical Paper “A Review of Integrated Urban Planning Tools for Greenhouse Gas Mitigation: Linking Land Use, Infrastructure Transition, Technology, and Behavioral Change” is the outcome of an Expert Meeting convened by the World Bank’s Global Platform for Sustainable Cities (GPSC) in May 2018. It analyzes a range of tools that cities can use to measure the impact of different urban planning scenarios on their greenhouse gas emissions, with the objective of helping cities adopt compact urban development and integrated urban planning strategies that are beneficial for their sustainable futures.

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