Policymaking Should Consider the Time-dependent Greenhouse Gas Benefits of Transit-oriented Smart Growth

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ABSTRACT

Cities are increasingly developing greenhouse gas (GHG) mitigation plans and reduction targets based on a growing body of knowledge about climate change risks, and changes to passenger transportation are often at the center of these efforts. Yet little information exists for characterizing how quickly or slowly GHG emissions reductions will accrue given changes in urban form around transit, and whether benefits will accrue quickly enough to meet policy year targets (such as reaching 20% of 1990 GHG emissions levels by 2050). Even more complicated is when cities focus on achieving GHG reductions through integrated transportation and land use planning, as changes in emissions can occur across many sectors (such as transportation, building energy use, and electricity generation). Using the Los Angeles Expo line, a framework is developed to assess how financing schemes can affect the rate of redevelopment and resulting life-cycle GHG emissions from travel and building energy use. The framework leverages an integrated transportation and land use life-cycle assessment model that captures upfront construction of new development near transit and the long-term changes in household energy use for travel and buildings. The results show that for the same amount of development around the Expo line, it is possible to either meet (if aggressive redevelopment happens early) or not meet (if significant redevelopment does not start until decades out) state GHG goals by 2050. The time-based approach reveals how redevelopment schedules should be considered when setting strategies for meeting future GHG emission targets.

INTRODUCTION

Cities across the U.S. and the globe are developing greenhouse gas (GHG) mitigation plans and reduction targets based on a growing body of knowledge about climate change risks (*1*). These plans often focus on emission reductions in cities, where it is expected that 80% of the world's population will reside by 2100 (*2*). Given that automobile transportation is often a large share of a region's GHG emissions, strategies to reduce emissions have now begun to focus on urban form redesign to reduce automobile use, i.e., deploying more public transit and redeveloping neighborhoods around transit. But there is a dearth of knowledge on how GHG emission reductions accrue when urban redevelopment occurs. Robust assessment of future scenarios can help identify the most cost-effective mitigation strategies and advise if current technological changes are strong-enough to meet stringent future goals. Without a framework to assess how GHG emissions reductions accrue at different rates from variations in the aggressiveness of implementing neighborhood redevelopment around high-capacity transit, it is not possible to understand if GHG reduction policy goals set for a particular future year (e.g., 80% below 1990 emissions by 2050) will be met.

California has been at the forefront of GHG mitigation due to mandates set forth in 2006 by Assembly Bill 32 (AB32) and the trickle-down strategies from government agencies and planning organizations to reduce carbon emissions. AB32 and its companion legislation, Senate Bill 375 (SB375), set goals for integrated transportation and land use (ITLU) planning to reduce GHG emissions through shifting to lower (public transit) or no (biking and walking) carbon transport modes and lower building energy use. However, there remains a relatively poor understanding of how benefits from neighborhood redevelopment accrue if changes in urban form and behavior happen quickly or slowly (*3; 4*). Recognizing that ITLU planning is needed for significant and sustained GHG reductions, several cities have encouraged smart growth near activity centers and around transit. California has begun instituting programs to support local planning for urban infill, adaptive reuse of older buildings, local efforts for mixed-use developments around transit, community based transportation planning, and rewards for balancing neighborhood jobs-housing mixes (*5*). AB32 puts in place a statewide goal to reduce GHG emissions to 1990 levels by 2020 and further reduce emissions 80% below 1990 levels by 2050 (*3*). Strategies to meet these time-dependent goals require planning and cooperation from private firms and many levels of government and, therefore, take time to be approved and implemented (*6*). Thus, by delaying changes in urban form or the implementation of transit with incentives for ridership, GHG emissions reductions may occur more slowly and policy targets may not be met, despite reductions being achieved in the long-term equivalent to if these urban changes were to happen immediately. While models have existed for some time to estimate the impacts of transportation and land use changes (*7; 8*), the current state-of-the-art models (*9*) do not provide a robust framework for understanding how the staging of neighborhood redevelopment can result in the desired GHG benefits by a particular policy-relevant period. We develop such a framework by assessing neighborhood redevelopment around Los Angeles Metro's Expo Line.

As cities consider strategies to reduce GHG emissions, it will be important to characterize how quickly or slowly reductions will accrue given changes in urban form and behavior. The creation of mixed use neighborhoods near high-capacity transit can reduce household energy use, shift travel away from automobiles to transit, biking, and walking, and reduce automobile trip distances (*10-13*). The GHG benefits of smart growth, however, are sensitive to a variety of factors including the residential and commercial mix, building size (i.e., single or multi-family), and access to high-capacity transit (*14; 15*). Using Los Angeles Metro's Expo Line as a case-study, a methodology for assessing the time-based benefits of GHG reductions from urban redevelopment is produced. The Expo Line is Los Angeles Metro's most recent light rail line with Phase 1 comprised of twelve stations over 8.6 miles, opening for use in 2012. Because the 6.6 miles and seven stations of Phase 2 are currently under construction and scheduled to begin operation in 2015, the opportunity still exists to recommend specific land use investments for the entire line. The Expo Line is shown in Figure 1 from its Easternmost station in downtown Los Angeles to the current end-of-line in Culver City (Phase 1) and the eventual terminus in downtown Santa Monica (Phase 2).

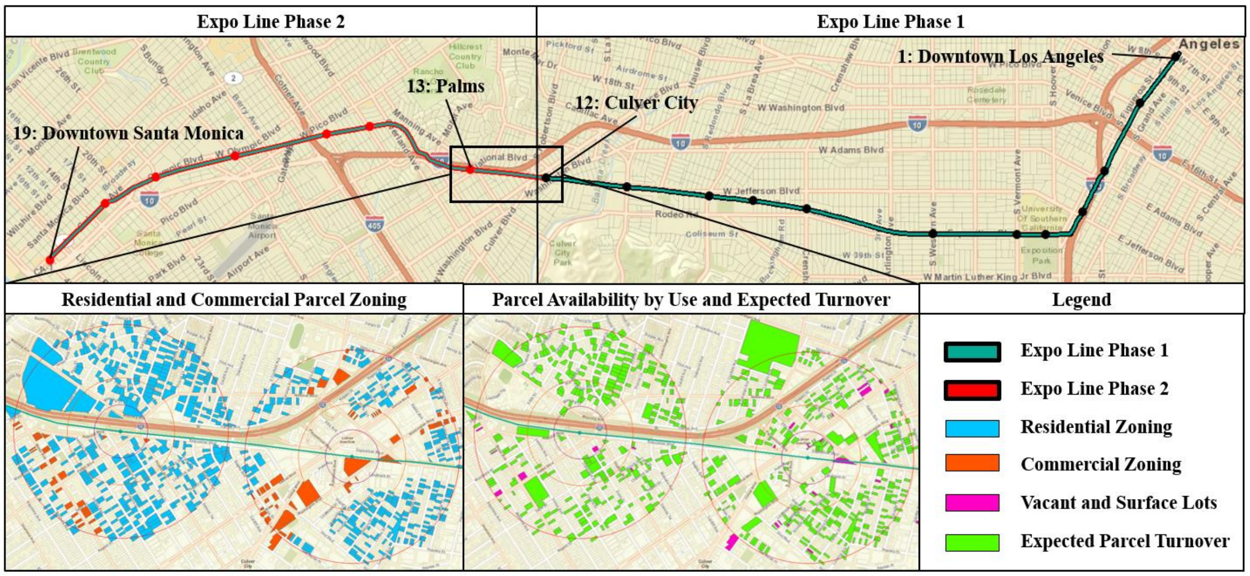

FIGURE 1 Expo Line Map and Station Land Use Analysis. Phase 1 and 2 segments are shown with each of the stations that act as an end-of-line terminus labeled. Sample parcel assessment maps are blown out showing Residential and Commercial Zoning and Parcel Availability opportunities within 0.5 miles (0.8 km) of the station and are further explained in the Methodology.

METHODOLOGY

The time-based framework is developed by i) determining the potential for development around the Expo Line stations, ii) scheduling the deployment of neighborhood infrastructure change to reduce household and transportation energy use, iii) estimating how travel and building energy use change, and iv) assessing how GHG reductions can change by 2050, a future year goal established by AB32. To estimate GHG emission reductions, an integrated transportation and land use life-cycle assessment (ITLU-LCA) framework is utilized building upon previous work (*11; 14; 15*). A life-cycle framework is used to understand how upfront energy, GHG, and cost investments are needed (in the form of new building construction and adaptive reuse) to enable household building and transportation energy use reductions, leveraging existing data developed by (*11*) for Los Angeles. The analysis estimates how TOD around high-capacity transit in Los Angeles produces energy and air emissions changes over business-as-usual (BAU) development where residents do not have walking access to high-capacity transit but still live in the urban core. The residential component of the BAU counterpart is represented in the model as 75% single-family dwelling units and 25% of dwelling units in 3-story apartment buildings. All of the BAU commercial area is in single-story buildings, which is consistent with the building composition within 0.5-2 miles (0.8-3.2 km) from the Expo Line. It is assumed that BAU residents are not able to walk or bicycle to many desired destinations and therefore an opportunity exists to decrease their carbon footprint by moving them closer to high-capacity transit and enabling alternative transportation modes. The life-cycle framework captures energy use and GHG emission changes from household electricity use and transportation fuel use, and also building construction, the production of energy (gasoline production and source fuels for electricity generation) and automobile manufacturing. GHG emissions are characterized as CO_2-equivalents (CO_2e) based on radiative forcing factors with a 100-year outlook (*16*) and all monetary values are presented in 2012 USD.

ITLU-LCA of Los Angeles Urban Redevelopment

Foundational assumptions, methods, and results from (*11*) are used to analyze the impacts of TOD in place of BAU deployment. It is assumed that TOD will be a mixed-use, walkable neighborhood around high-capacity transit that benefits from supportive zoning policies and balanced parking requirements to enable behavioral changes that lead to energy and GHG reductions over BAU transit-inaccessible growth. Future vehicle fuel economy goals of 35 and 55 mi/gal (15 and 23 km/liter) in 2020 and 2050 are assumed to be met, as are goals for removing coal-fired plants from the electricity generation mix by 2030 which will reduce GHG emissions from 520 grams per kilowatt-hour (g/kWh) in 2010 to 230 g/kWh in 2030 (*17; 18*). All impacts from upstream energy production, use-phases, and vehicle manufacturing are estimated using data from the GREET model (*19*). Building construction impacts are estimated using Athena (*20*) and include new construction and adaptive reuse for 7 prototype models of residential and commercial structures. Consumption characteristics for transportation and building energy use are modeled using region-specific data from the 2011 American Housing Survey, Commercial Buildings Energy Consumption Survey, and the 2009 National Household Travel Survey (NHTS) (*21*-*23*). The average dwelling unit size in Los Angeles near high-capacity transit is about 29% smaller than a dwelling unit not near transit and consumes nearly 35% less energy annually (*11*). In addition to shorter trip distances estimated from the NHTS analysis, TOD residents are assumed to shift 25% of their trips to walking, biking, or transit, which is similar to results from (*24*) and (*10*). Households near HCT in Los Angeles drive 11,000 VMT per year, about 48% fewer than households without access to HCT (*11*). The modeling of residential and commercial consumption habits shows that households consume 33% less energy for transportation and household activities while commercial establishments consume an average of only 1% less in a TOD configuration.

Where possible, critical factors were adjusted to be specific for the case of the Expo Line including the use of geo-located NHTS data and recent findings from other research projects on the rail line. An assessment of the availability of land near Expo Line stations was developed using the County Assessor database and is shown in part in Figure 1 (*25*). Residential automobile travel characteristics for TOD and BAU were estimated from a before-and-after study of household travel behavior changes from the new line (*10*). The commercial travel characteristics are estimated from the geo-located NHTS data for i) TOD characteristics from residents residing within 0.5 miles (0.8 km) of stations along the Gold and Red Lines and ii) BAU characteristics considered to be similar to residents located in a buffer that is 0.5-2 miles (0.8-3.2 km) away from all HCT in Los Angeles.

TOD energy use and GHG emissions assessments are compared to BAU development to estimate the net changes that result from neighborhood redevelopment on currently vacant and surface lots and from parcel turnover over time. Parcel turnover is expected to occur when the value of the land is higher than the value of the existing improvements on the land, based on an assessment of the 2012 Los Angeles assessor database. While TOD has been shown to reduce auto dependence (*26*), some literature contends that this is a result of resident attitudes and households self-selecting to live in the walkable neighborhoods rather than attracting households from auto-dependent neighborhoods (*27*). As such, BAU is considered to be development patterns and behavioral characteristics which are located from 0.5-2 miles (0.8-3.2 km) away from HCT in Los Angeles. Residents in this zone are considered to be those who have selected to live in the urban core, but who could further benefit from being located within walking distance of HCT.

Expo Line Land Availability

Spatial analysis is performed using data from the Los Angeles County Assessor's database to determine the land parcels that can be redeveloped around the Expo Line (*25*). There are 6,300 parcels located within one half-mile of the nineteen Expo Line transit stations. The feasibility of parcel redevelopment is considered based on land area, the distance from a transit station, dimensions of the existing buildings, current parcel use classifications, zoning classifications, land value, and the value of existing improvements (see the station map selections in Figure 1). As shown in Table 1, 2,200 parcels were selected under these criteria for use as residential or commercial TOD built by new construction, or adaptive reuse of existing buildings. The comparison between TOD and BAU is based on the number of residential dwelling units (albeit different dwelling unit sizes and different total land consumption) and the total square footage of commercial space (from new construction and adaptive reuse) being equal between the two scenarios as determined by the land availability for proposed TOD. This comparison is chosen because the majority of impacts follow from end-use consumption, which is driven by the number of residential households and the amount of new commercial space that will generate travel and consumption.

TABLE 1 Land Assessment for TOD Construction Potential. The characteristics of usable TOD land within 0.5 mile (0.8 km) of all nineteen Expo Line stations are presented along with the characteristics of an equivalent number of BAU dwelling units and square footage of commercial development.

		Number of Parcels	Total Land Area (acre)	Land Purchase Cost (Billion 2012 USD)	Proposed New Construction Dwelling Units	Proposed New Construction Area (Million ft^2)	Proposed Adaptive Reuse Dwelling Units	Proposed Adaptive Reuse Area (Million ft^2)
Residential	**BAU**	-	1700	$ 2.10	9700	13	-	-
	TOD	1600	880	$ 0.72	6400	7.8	3300	3.3
Commercial	**BAU**	-	510	$ 0.71	-	9.8	-	-
	TOD	560	290	$ 1.10	-	2.5	-	7.3
Total	**BAU**	-	2300	$ 2.80	9700	23	-	-
	TOD	2200	1200	$ 1.80	6400	10	3300	11

The zoning and current use of parcels dictate the type of building that could be constructed and the mixed-use composition of development around the Expo Line. On average, dwelling unit sizes are about 15% smaller in the TOD scenario while the proposed commercial area is the same for both TOD and BAU. Adaptive reuse is determined in this process as a building which already exists on a parcel of land and could become useful for residential dwelling units or commercial space by refurbishing the interior of the building and leaving the supporting structure intact. The proposed TOD redevelopments produce a residential density of 11 dwelling units per acre (26 per hectare), compared to the BAU density of 6 dwelling units per acre (14 per hectare) which is determined as the average residential density for the area 0.5-2 miles (0.8-3.2 km) from HCT in Los Angeles. The TOD smart growth configuration requires only half the land area for construction due to the higher dwelling unit density and can potentially save $1 billion from land purchase costs. Despite higher costs to construct the higher density buildings, developers experience overall savings because less land is purchased to satisfy the 9,700 dwelling units and 9.8 million ft^2 (910 thousand m^2) of commercial space. The parcel assessment is an estimate of available land for urban redevelopment, but the rate of TOD construction can potentially be influenced by many factors; most notably the availability of capital funds.

Neighborhood Redevelopment Financing Schemes

Redevelopment of the urban core is likely to take place over time and will be impacted by local zoning regulations, the availability of land, and financing strategies. Current parcel zoning for commercial and residential types is observed in this model and vacant and surface parking lots are prioritized to allow for immediate construction. Financing strategies are the final obstacle on which TOD construction depends, and the prioritization of redevelopment should focus on the amenity-based elements of land development proximate to transit stations (*28*).

The longer it takes to redevelop neighborhoods to achieve energy use and GHG emissions reductions, the fewer benefits will accrue during a policy-relevant timeframe. Two time periods are considered: i) timelines set forth by AB32 which set a goal of reducing GHG emissions to 80% below 1990 levels by 2050 (*3*), and ii) indefinitely into the future, when GHG reduction benefits are not truncated by policy goals. The 2020 emission reduction goal from AB32 (reduce GHG emissions to 1990 levels) is not considered because land turnover and TOD construction are not expected to significantly occur in the 8 years after 2012 when the transit line opened. Therefore, ITLU policy is better suited for long-term goals like that of 2050.

Because the AB32 reduction goals are based on 1990 GHG emissions, the reduction potential from the time-dependent deployment of TOD is based on 1990 baseline emissions. Annual vehicle travel in 1990 is estimated to be 10% below 2010 levels (*29*) while vehicle fuel economy is unchanged (about 21 mi/gal, 8.9 km/liter). Residential building energy consumption is estimated from the 1989 American Housing Survey and is about 9% greater in 1990 than 2010. The GHG emissions from Los Angeles Department of Water and Power's (LADWP) electricity generation are nearly 14% greater in 1990, due to a larger share of fossil fuels in their mix relative to 2010 (*21*). These estimations form the baseline 1990 GHG emissions which are used to estimate changes from proposed TOD and various capital financing schemes.

Four financing schemes are proposed to estimate how GHG emissions reductions change due to the deployment rate of TOD. The total investment needed for land purchasing and construction costs, $5.2 billion, is estimated from the parcels assessment and each of the four financing schemes amounts to the total investment; equivalent to the area under each curve in Figure 2. The investment schemes are: (1) *Uniform*: $87 million is invested each year for sixty years, (2) *Plateau*: a low initial investment in 2015 escalates to $170 million annually for seventeen years before scaling down again, (3) *Front-Load*: a max investment of $260 million is made annually for five years up-front and gradually scales down, and (4) *Back-Load*: a 20-year delay is followed by a minimal initial investment that escalates to a $290 million annual investment for five years before decreasing. The $5.2 billion of capital can be itemized as $3.2 billion for constructing 9,700 dwelling units as apartment buildings and single-family homes and $2.0 billion for constructing 9.8 million ft^2 of single- and multi-story commercial buildings. Within the proposed commercial construction, 120 buildings are mixed-use with a commercial first floor and three residential upper floors.

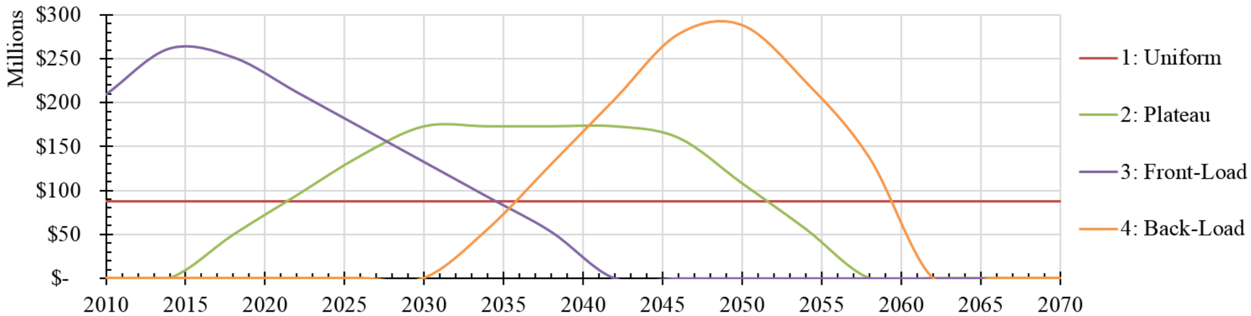

FIGURE 2 Proposed TOD Annual Financing Schemes. Four capital investment schemes are proposed over a 60-year period. The area under each curve is equal to the total cumulative investment needed for TOD around the Expo Line, $5.2 Billion.

While the majority of construction financing is likely to come from private developers based on perceived market demand, the public sector has the potential to influence the rate of funding or composition of construction through strategies such as urban growth boundaries, minimum density targets, required mixes of residential and commercial floor area, and tax incentives. The Uniform investment scheme is representative of higher immediate support for development and the need for predictable financing over time as provided by a bank or private firm. The Plateau scheme shows developer support that is slow to catch on and wanes at the end, but that is high during the middle period, as if responding to market-demand for TOD. The Front-Load depicts very high initial public support that causes a large investment influx from developers upfront, and gradually slows down as less land is available for TOD. The Back-Load investment scheme shows very low initial support for TOD, but then investment begins in 2030 and slowly grows (as residents and developers see benefits from existing TOD) until reaching a peak and scaling down.

Along with the financing schemes, parcel redevelopment prioritization can be implemented to maximize GHG reductions as funds are available. Each of the 2,200 parcels shown in Table 1 that are estimated to fit the profile for urban redevelopment carries unique characteristics for the amount of development that can occur (e.g., a small parcel may only be able to fit a single family home while a larger parcel could fit a higher density mixed use building), cost of development, and GHG emission reductions that are possible from behavior changes. The parcels are first ranked in order of proximity to station (at 0.125, 0.25, and 0.5 mile intervals, 0.2, 0.4, and 0.8 km intervals) and then by the expected GHG emission reductions value (estimated as the cost of development divided by the total expected avoided GHG emissions). Contained within the prioritization method are criteria that a mix of residential and commercial will be constructed annually and that TOD will be constructed around Phase 1 of the Expo Line first before beginning development around Phase 2. These criteria are set because many of the estimated benefits depend on the TOD being a mixed-use, walkable neighborhood which is proximate to active HCT (*30-33*). The effects of the financing schemes and parcel prioritization method are highlighted to show how ITLU impacts can vary depending on the rate of TOD deployment.

RESULTS

Time-independent Environmental Benefits

Based on the available parcel assessment, a time-independent energy use and GHG assessment is first developed to characterize the quantity of reductions that are possible when all land is redeveloped and benefits are counted in perpetuity. With a fixed policy year goal, the avoided GHG emissions will be greatest if all vacant, surface, and low value parcels are developed immediately, the schedule considered by (*14*), (*15*), and (*11*). Figure 3 shows the energy consumption and GHG emissions from the potential redevelopment around the Expo Line if all construction is completed and opens immediately to be used over the next 60 years. The BAU results are the emissions of an equivalent amount of development over the same timeframe, which could have occurred if TOD had not been deployed.

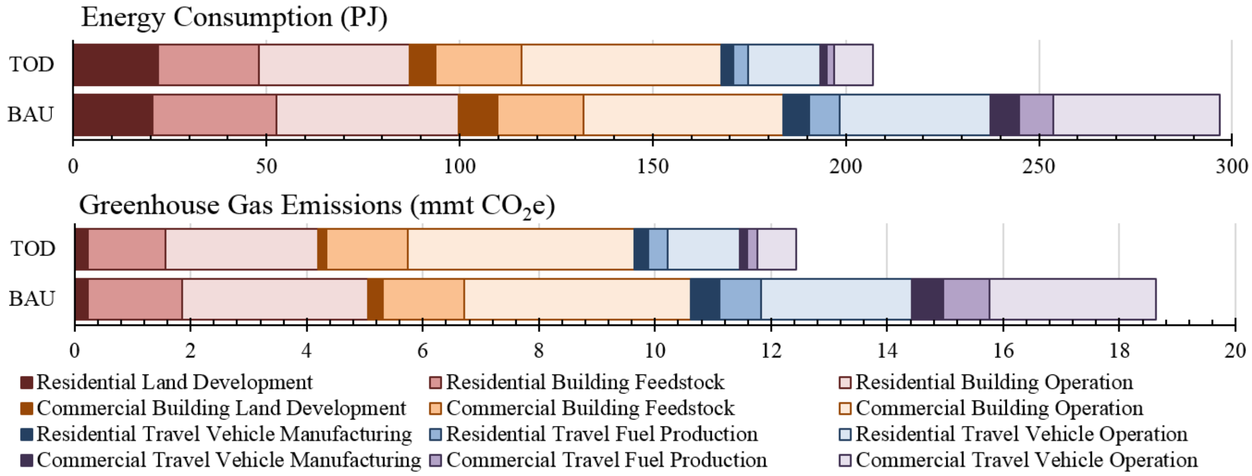

FIGURE 3 Time-independent Deployment Results. Estimated impacts over a 60-year period for TOD and BAU development are shown for residential (reds) and commercial (oranges) buildings and the travel associated with each (blues and purples). Three life-cycle phases are assessed for each: manufacturing or construction (darkest shade), energy production (medium shade), and the use phase (lightest shade). The difference between TOD and BAU shows the potential for avoided impacts.

The results show that up to 33% of the estimated impacts can be avoided over the 60-year period when smart growth development occurs rather than BAU. An upfront energy investment (resulting from the use of more energy-intense construction materials such as steel and concrete) is required to construct the TOD compared to the low-density BAU configurations, but that investment enables resident travel and in-home energy use reductions. End-use energy can be decreased by 30%, or 90 PJ over 60 years, which is enough energy to provide 1.0 million single family homes with power for one year. Up to 6.2 million metric tons of GHG can be avoided over 60 years for a 33% reduction, which is equivalent to the average annual tailpipe emissions of 1.3 million automobiles. Most of the reduced energy consumption and GHG emissions result from shorter travel distances (due to more centrally locating activities) and shifting trips away from personal automobiles, which can reduce impacts locally from tailpipe emissions and nationally from fuel production and the manufacturing of fewer vehicles. Large savings are realized for energy use and GHG emissions from reduced electricity use in homes and fuel consumption for automobile travel. Which are both energy-intensive behaviors. Therefore, an early start redevelopment schedule will allow greater savings to accrue, while a delayed deployment of TOD has the potential to truncate the majority of use-phase savings into a shorter time period.

To most effectively prioritize parcels for redevelopment based on the total time-independent energy consumption and GHG emission results, each parcel must first be individually analyzed to estimate its total purchase and construction costs and potential for avoiding emissions over a 60-year timeframe. Figure 4 shows each of the nineteen stations around the Expo Line and which of the 2,200 potentially usable parcels would provide the best GHG emission reduction value. The highest reduction value parcels tend to be larger in size and located closer to the station, which are characteristics that could enable large mixed-use developments within short walking distance of a station (thereby more likely to shift residents from personal vehicles to transit). Ranking the parcels in this manner provides insights into which redevelopment should be prioritized through developer incentives to most quickly achieve GHG reductions at the lowest upfront cost.

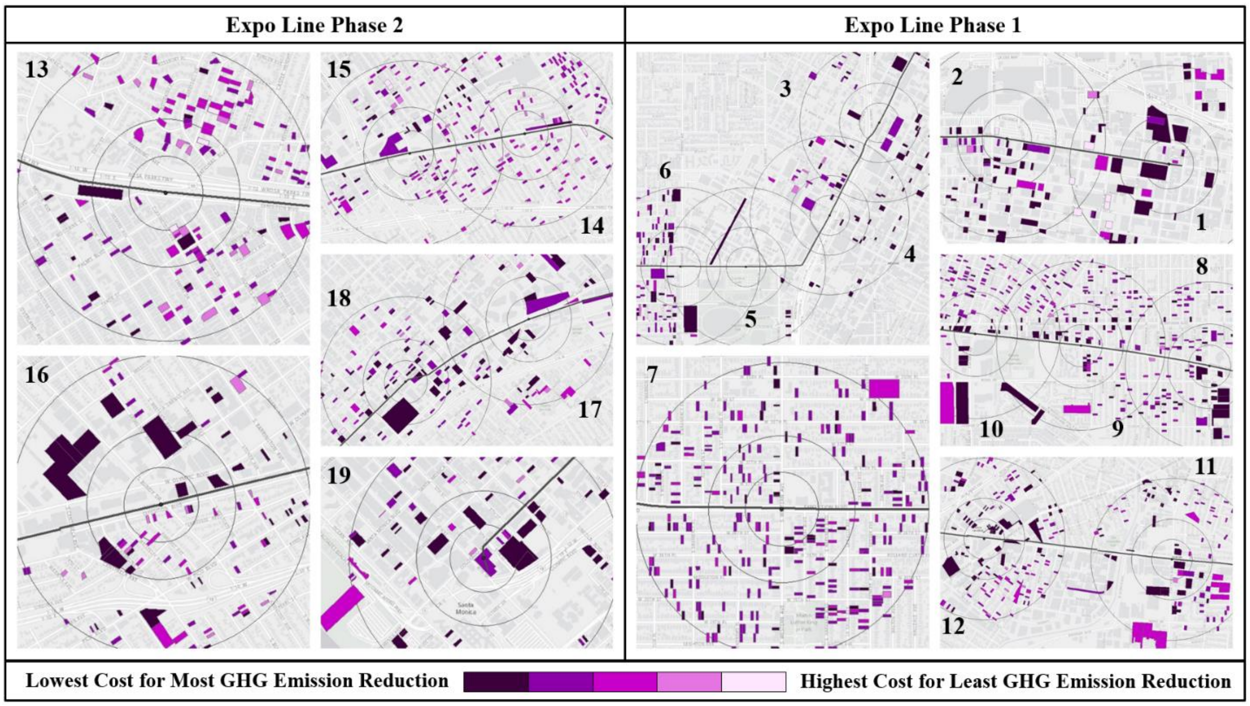

Figure 4: GHG Emission Reduction Value Station Maps. The 2,200 parcels with proposed TOD are shown around the nineteen stations of the Expo Line. The parcels are ranked in order of GHG emissions reduction value with the darkest shade representing the 20% of parcels which provide the greatest value of development cost divided by potential emission reductions over 60 years.

Time-dependent Greenhouse Gas Emission Benefits

The amount of capital made available causes variations in neighborhood redevelopment and large variability in annual avoided energy use and GHG emissions by 2050, which can affect whether or not reduction goals are met. This is shown in Figure 5. The annual GHG emissions savings converge after redevelopment is complete within 60 years, but the differences in the curves show how capital investment schemes could be used to target 2050 GHG emission reduction goals. California's statewide 2050 reduction goal, 80% below 1990 emissions, is 340 million metric tonnes CO_2e for the estimated 50 million residents that year. Allocating a proportion of that to the proposed 30,000 TOD residents that could be housed around the Expo line results in a 200,000 metric tonne reduction for the 9,700 dwelling units and 9.8 million ft^2 (910 thousand m^2) of commercial space. To successfully meet this goal, each investment scheme would need annual

GHG reductions greater than 200,000 metric tonnes by 2050. The Front-Load and Plateau schemes would achieve the 2050 goal at that year, while the Uniform scheme would not meet it until 2058, an 8-year difference. The Back-Load scheme delays the initial TOD construction until 2030 and then peaks in 2048, but that level of urban redevelopment is still not enough to meet the 200,000 metric tonne reduction goal in 2050. All curves converge to 240,000 metric tonnes of annual savings when construction has been completed because the avoided impacts are dependent solely on an equivalent amount of building and transportation energy use from that point forward.

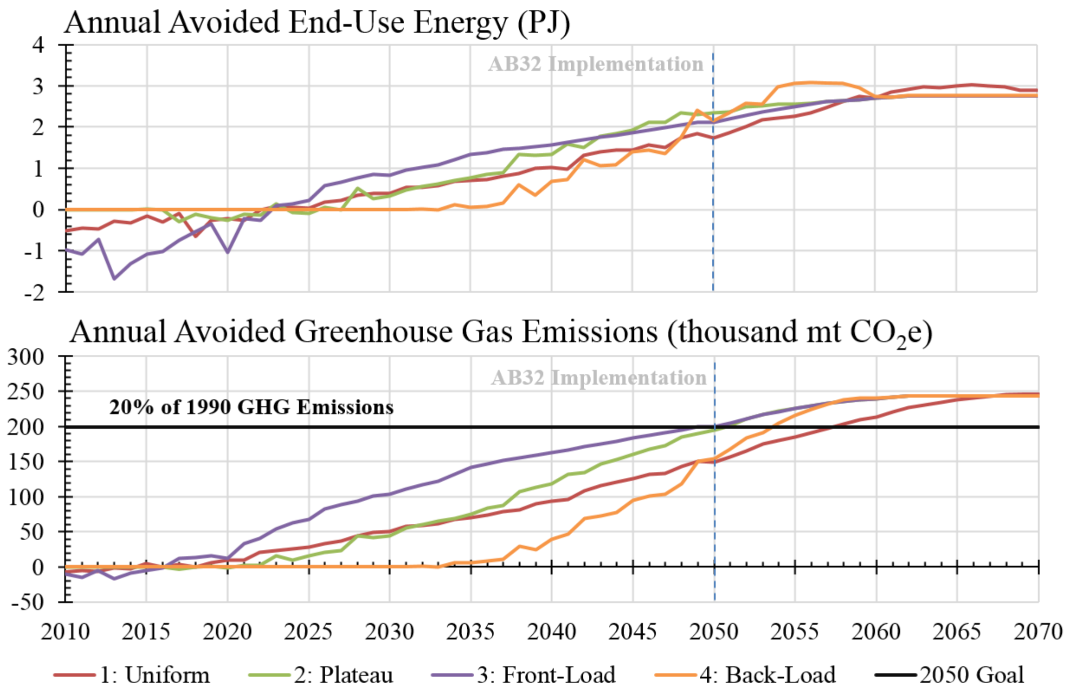

FIGURE 5 Annual Avoided Impacts. The annual avoided impacts for the four investment schemes are shown over the 60-year analysis timeframe with each color corresponding to a scheme.

The cumulative avoided impacts, presented in Figure 6, are sensitive to the variability within the annual avoided GHG emissions and show how the budget curves help meet reduction goals when stated as cumulative targets. The 2050 cumulative GHG reduction goal is estimated to be 4.0 million metric tonnes CO_2e based on reducing emissions to 1990 levels by 2020 and linearly decreasing emissions to 80% below 1990 levels by 2050. GHG emissions reductions diverge for each scenario from 2010-2040 because of the various rates of deployment from the financing schemes. The Front-Load investment scheme shows the greatest cumulative avoided GHG emissions and is the only scenario that meets the 2050 reduction goal on time, because it enables the most construction early in the analysis timeframe and therefore enables households to reduce home and transportation energy use over a longer time period. The Back-Load scenario has the opposite effect, and would not meet the 2050 reduction goal until 2063 because construction is funded late and does not enable benefits to accumulate early in the analysis timeframe. After neighborhood redevelopment is complete in 2070, each of the eight cumulative benefit curves continues to increase at the same rate. Thus, in the long-term, the relative difference in avoided GHG emissions between scenarios will approach zero.

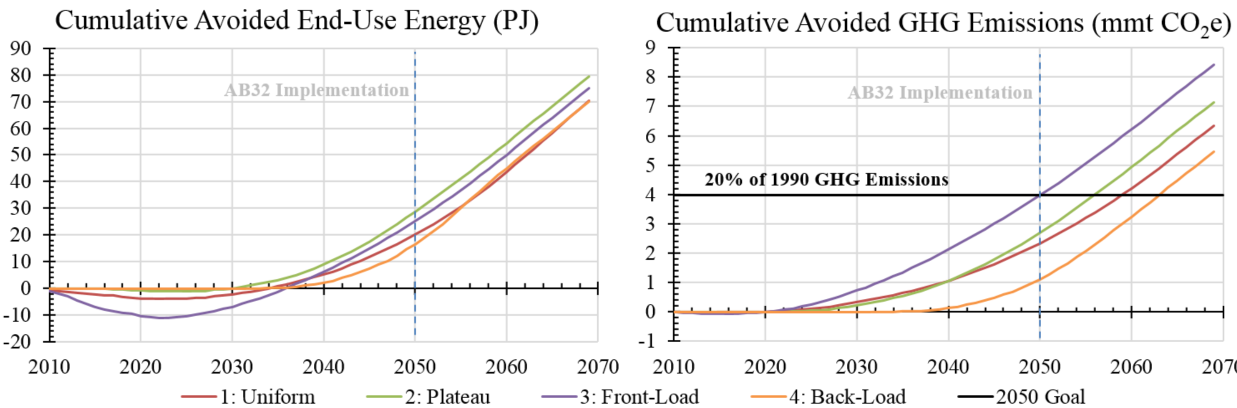

FIGURE 6 Cumulative Avoided Impacts over Analysis Timeframe. Cumulative avoided impacts of the four scenarios are calculated from the annual results of Figure 5. All benefits continue to increase at the same rate after construction is complete.

The four capital investment schemes cause notable variations to GHG emissions reductions, but the results are sensitive to very few other input assumptions because many assumptions affect both the BAU and TOD futures. A second method of parcel prioritization was tested in the model where parcels were sorted only by GHG emission reduction value without the added constraint of developing parcels closest to the stations first. But this method was found to cause less than a 2% change to impacts over time for all four capital financing schemes and illustrates how cumulative benefits are more sensitive to the rate of TOD deployment than the order of parcel development. LADWP's goal to reduce emissions from electricity generation, nationally increasing average vehicle fuel economy, and improving construction methods are likely to reduce the overall GHG emissions from Los Angeles residents regardless of development patterns. The results are most sensitive to the relocation of residents closer to high-capacity transit and enabling them to reduce their carbon footprint by shifting travel to walking, biking, and high-capacity transit use rather than personal automobiles. This case study informs how the rate of TOD deployment can influence potential GHG emission reductions and how to effectively prioritize thousands of available parcels for TOD deployment when aiming for specific reduction goals. Despite setting goals over 35 years in the future, California still may not be able to reach their desired reduction targets if redevelopment action is delayed.

DISCUSSION

The deployment rate of neighborhood redevelopment changes the profile of GHG emissions reductions over time and must be evaluated in addition to technological changes to achieve accurate reduction estimates. The time-based assessment framework provides a foundation to estimate the effects of smart growth around different transit corridors and each corridor is not likely to accrue GHG emissions changes at the same rate. Results should be considered within the local social and developmental context because financing and construction of TOD will likely come from private developers, but a number of factors have the potential to encourage development when used in combination because purely economic incentives are often ineffective (*34*). Cities must recognize that an alignment of non-technical preconditions must occur for GHG emissions reductions to be achieved in a policy-relevant time period. Local political support, interest from urban developers, and the demand for housing around transit will help to determine how aggressively neighborhood redevelopment can occur to meet policy goals. Open land in the Los Angeles area has been disappearing, which has led to increased redevelopment and capitalizing on the few remaining vacant lots in the urban core (*35*). As Los Angeles Metro has rapidly increased their HCT infrastructure, demand for residential and commercial space along these corridors has increased and private developers have begun to shift their focus to these new opportunities. It is this confluence of public sector incentives and private funds that is likely to drive urban redevelopment and may continue to influence future neighborhood form changes.

Land use and transportation are complex and interdependent systems and changes in GHG emissions from neighborhood redevelopment occur due to changes in other sectors across and outside of the city (e.g., electricity generation and fuel economy improvements). The Los Angeles Department of Water and Power is reducing emissions from electricity generation by divesting in carbon-intense plants. At the federal level, a corporate average fuel economy of 55 mi/gal (23 km/liter) based on a goal of 160 g CO_2e/VMT (100 g/VKT) has been set for 2025 (*18*). The confluence of a changing electricity mix and decreasing county travel (*29*) means that neighborhood redevelopment around HCT at any rate is likely to meet interim 2020 AB32 goals. California and local GHG reduction policies, however, tend to ignore the complexity of these systems by establishing sector-specific goals; such as the Southern California Association of Governments setting per capita GHG reductions specifically from transportation in their Sustainable Communities Strategy. As highlighted by the ITLU-LCA framework, transportation and land use systems are interdependent with other sectors and therefore are impacted by changes that occur in these other sectors. The formation of urban GHG reduction policies must acknowledge the interdependencies of complex systems to establish meaningful long-term targets that require innovation and disruption across all sectors. By allowing transportation to, for example, rely on federal fuel economy standards, or smart growth buildings to rely on a greening electricity mix, a city may not reach its full GHG emission reduction potential. Instead, innovative strategies within ITLU systems should be developed to encourage mode shifting and the lowering of household energy use. TOD must exist to enable these resident characteristics which comprise the bulk of GHG emission reductions, and therefore reconstruction of existing TOD during the analysis timeframe is not likely to have a significant impact on GHG emissions (because it would not create new opportunities for residents to reduce their carbon footprint).

The four investment schemes show that prioritizing urban redevelopment upfront and sustaining at least a medium pace of redevelopment is how a city can successfully meet 2050 GHG reduction goals. The Front-Load investment scheme provides enough capital funds to complete construction by 2042 and allows the benefits from transportation and building use to accrue to 80% below 1990 levels in 2050. Policies such as transit-oriented district planning, reduced parking requirements, and ordinances to enable adaptive reuse should be in place to expedite the urban redevelopment process and facilitate private developers to act as soon as possible. Capital funds will ultimately have to be provided by developers who will look to profit from redevelopment and will likely charge higher prices for the new TOD space. But, TOD residents can save money overall by reducing their automobile and building energy expenses despite spending more for rent in smart growth areas (*11*). Public support and consumer demand for walkable mixed-use developments around transit stations is growing in Los Angeles as a number of successful TOD have been constructed on the Gold, Orange, and Red lines. Developers should seek to capitalize on this demand for TOD early and enable residents to change their environmental footprint and work toward meeting California's statewide GHG reduction goals.

Fundamentally, cities must recognize that neighborhood redevelopment takes time, GHG emissions reductions therefore accrue over time, and GHG reduction goals for a specific year must be informed by development schedules and smart growth policy. The current state-of-the-art tends to analyze GHG reductions without considerations for their timeliness. As such, cities are at risk that the policies they set may not be achieved due to a lack of aggressiveness for early implementation. ITLU systems may be particularly sensitive to this effect given how long it takes to implement new mass transit projects and redevelop neighborhoods. Furthermore, a body of research has emerged characterizing how a molecule of GHG emissions not avoided early on has more opportunity to heat the planet (*36*). Therefore, avoiding a GHG molecule early on is more beneficial than avoiding later. Ultimately, cities should adopt time-based assessments of GHG emissions reductions from ITLU systems that consider both household behavioral changes and changes in supporting technological systems (such as electricity generation) to more fully inform policies. The redevelopment of neighborhoods around HCT is a complex challenge in both implementation and GHG assessment, however, it is particularly valuable for cities in that it reduces emissions from changes in behavior and the transportation and household technologies that use energy to facilitate behavior.

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