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Manuscript title: Sustainability cost curves for urban infrastructure planning

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Abstract

Global urban infrastructure spending is expected to triple by 2050 as cities try to keep up with growing populations and retrofit ageing civil works. But long-lived infrastructure needs to be developed within local and global limits and aspirational targets such as the UN sustainable development goals. This paper presents an approach to measure and prioritise urban infrastructure as it relates to sustainability boundaries and targets. It provides a simple yet powerful tool for public policy and urban infrastructure planning. As an example, the method is applied to nine real transportation projects in Toronto, Canada and these are compared with urban transport projects in Brazil, China, India and Senegal.

Keywords: infrastructure planning/public policy/sustainability

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1. Introduction

The world's largest city-building effort in human history is underway. Many older civil-works are being replaced and retrofitted, and new construction is taking place in fast-growing cities. Cities and their agencies will likely spend at least U$100 trillion on infrastructure and urban service delivery by 2050 (CCFLA, 2015).

While the enormous urban infrastructure rush is underway, planetary boundaries or limits are already severely stressed (Rockstrom *et al.* 2009 and Steffen *et al.* 2015). The drivers of ecosystem degradation are mostly by-products of current urban lifestyles, for example greenhouse gas emissions, water use and land clearing associated with agricultural products. This impact will increase as urban populations double.

In addition to the need to adhere to planetary bio-physical limits, socio-economic targets are proposed, for example through the UN sustainable development goals (SDG). Bio-physical boundaries and socio-economic targets are critical considerations for all urban infrastructure. Sustainability here is defined through seven categories each for bio-physical and socio-economic indicators (Tables 1 and 2).

Marginal abatement cost curves present a set of available options for broad programmes such as greenhouse gas abatement and climate adaptation. marginal abatement cost curves help to understand emission reductions, prioritise investment opportunities and shape policy discussions. McKitrick (1999) highlighted the efficacy of marginal abatement cost curves for individual firms to meet mandated emission reductions through technological changes. Banister (2012) and Hartgen *et al.* (2011), for example, highlight the benefits and challenges of marginal abatement cost curves in evaluating transportation infrastructure options to reduce greenhouse gas emissions.

Building on marginal abatement cost curves this paper introduces the concept of a sustainability cost curve and demonstrates application in evaluating urban infrastructure. The sustainability cost curve estimates the costs and opportunities of increased sustainability accruing from long-lived urban infrastructure.

As an example, the approach is applied to the transportation sector of Toronto in Canada. Sustainability potential is derived from a project's impact on bio-physical limits and socio-economic targets. Bio-physical limits are a city-scale application of Rockstrom *et al.* (2009) and Steffen *et al* (2015) planetary boundaries.

Socio-economic targets are largely derived from the sustainable development goals.

2. Background

Marginal abatement cost curves rose in prominence after the 1997 Kyoto protocol on climate change as countries sought ways to optimise delivery of greenhouse gas emission reductions. Various economists, research organisations, and consultancies produced marginal abatement cost curves, for example Bloomberg New Energy Finance (2010). Ibrahim and Kennedy (2016) provide an extensive marginal abatement cost for greenhouse gas mitigation in Toronto.

Marginal abatement cost curves can present a global suite of possible greenhouse gas mitigation options. Each bar represents a single carbon dioxide mitigation option;

the width of the bar represents the abatement potential relative to business as usual; and the height of the bar represents the abatement cost per year relative to business as usual. The costs are expressed per tonne of carbon dioxide equivalent emissions avoided. The sum of the width of all the bars (X axis) represents the total carbon dioxide reduction potential; the area of each bar represents the marginal cost for that particular mitigation option.

Marginal abatement cost curves can provide powerful public policy tools for climate adaptation. For example, Creyts *et al*. (2007) provide a similar assessment for enhanced adaptation and coastal protection in Florida, USA. A suite of activities and their cost–benefit ratio for coastal protection in a moderate climate scenario are presented.

Advantages and disadvantages of marginal abatement cost curves are widely discussed (Kesicki 2010; Kesicki and Ekins 2012; Vogt-Schilb and Hallegatte 2014). The advantages are a powerful visual display of results, which facilitates consultation with considerable information, such as ‘break-even lines’. The discount rate can be customised by activity. Marginal costs (or benefits) are determined for any given project (or idea), and comparison can be made across sectors and entities (countries, cities, corporations).

Disadvantages include a tendency to favour technological solutions over behavioural change; limitation of analysis to one point in time; path dependency not always represented; and ancillary benefits not considered. Results are sensitive to assumptions, which are not always transparent so that the curves often convey unrealistic certainty.

Actual costs of activities may also vary from those presented due to time dependency. Ekins *et al.* (2011) further discuss the merits and concerns of marginal abatement cost curves and highlight the need to include health and social benefits when evaluating emission-abatement projects. Woodcock *et al.* confirm this approach in their study on the relationship between public health benefits and emission-reduction strategies in urban transportation (Woodcock *et al.* 2009).

3. Developing a sustainability cost curve

Sustainability cost curves can help decision-makers select among a variety of investment options. Policy-makers can apply sustainability cost curves as merit order curves, to prioritise investments for greater sustainability (i.e. progress on the bio-physical and socio-economic indicators). The curves consist of a number of activities along the X axis. Each activity, or wedge, along the curve represents an additional opportunity to increase sustainability.

The width (X axis) of each wedge represents the increase in 'sustainability potential' that the opportunity could deliver to 2050, the wider the wedge, the greater the sustainability potential. Sustainability potential is derived from the aggregate contribution of the 14 bio-physical and socio-economic indicators (Tables 1 and 2). Sustainability potential (SP) is determined by Equation 1.

$$SP = \sum_{i=1}^{14} w_i \Delta SI_i \qquad (1)$$

where ΔSI_i denotes the estimated annual change in a sustainability indicator, weighted by w_i. The values of w_i are determined based on the importance of the activity's sustainability impact. Here, all the activities are weighted equally.
Changes that help to improve sustainability have a positive value for the change in sustainability indicator. Determination of the 14 sustainability indicators is discussed further in Sections 3 and 4 and outlined in Hoornweg *et al* (2016). The area of the wedge represents the activity's total cost, which is the product of sustainability potential and unit cost of sustainability (UCS) – see Equation 2.

$$Total\ Cost_a = SP_a \times UCS_a \quad (2)$$

The height (Y axis) of each wedge represents the average net present cost of that activity per unit of sustainability potential. Net present cost includes capital and operating costs less operating revenues (but not increased land value). Costs include expected expenditures to 2050. Benefits only start accruing from year of commissioning so, on some longer-lived infrastructure, a residual value at 2050 is estimated and discounted to today. A simple 50% discount rate on capital cost is used and operating costs are initially not discounted. The approach closely aligns with public expenditure reviews in local governments and utilities. The curve is ordered left to right, from lowest cost to the highest cost opportunities.
Sustainability cost curves provide an overview of available development alternatives and offer a starting point to prioritise options. They provide a quick way to gauge the relative merits of activities, as well as enable comparisons between sectors and cities. For example, the degree of sustainability potential is consistent if derived for

the transportation or energy sectors and uses a common metric for any evaluated city. Sustainability cost curves can help identify where policy interventions could be particularly effective and can focus discussions among affected stakeholders.

Cost curves require a specific future date to evaluate costs and benefits against; 2050 is selected in this analysis. A relatively long planning horizon of over 30 years is used as this helps evaluate larger-scale, long-lived civil works with longer amortisation periods. The longer time-frame also encourages a more comprehensive analysis of options, combining capital and operation costs. Many of the options evaluated, for example subway lines, can take more than a decade to plan and build. Also, much of the critical infrastructure in today's cities is older than 35 years – roads, rail and ports typically can last more than a century.

Sustainability cost curves are initially proposed for the urban sectors of energy, transportation / connectivity and basic service provision (water and sanitation). In this paper a model cost curve is provide for the transportation sector of metropolitan Toronto, Canada. Many of the investments are large-scale and can be provided through private–public partnerships or directly by the city or its designated utility. In all cases the metropolitan area is evaluated since most large-scale infrastructure such as transportation and energy systems are developed to serve the overall urban agglomeration (and sometimes beyond).

Initially larger cities are targeted for analysis as larger cities have greater global ecosystem impacts. A metropolitan-wide scale is used as ecosystem impacts are influenced by the overall effect of the city and the actions of all of its residents.

Metropolitan-scale programmes in areas such as energy and transportation also offer the greatest opportunity to ameliorate system impacts (Gerst *et al.* 2013).

Each city has a current and target value for each of its sustainability indicators (SI_i and SI_i* respectively). The target value is downscaled (based on population fraction) from global bio-physical boundaries (Figure 1) and socio-economic goals (Figure 2). Fourteen sustainability indicators are used, some with multiple inputs and estimated indices. The limits are roughly half bio-physical and half socio-economic. The basis of the approach is discussed in Hoornweg *et al.* (2016).

Developing sustainability cost curves involves a degree of subjectivity. Initially this is proposed to be undertaken by respective (local) engineering faculties as many of the city-based values should emerge as public indicators and general ‘rules of thumb’ for the engineering community.

4. Global bio-physical limits

Figure 1 and Table 1 present estimated values (current and target) for proposed aggregate bio-physical limits of the world’s largest cities (Hoornweg and Pope 2016). These limits are determined by modifying the global boundaries (or limits) approach of Steffen *et al.* to facilitate a city’s perspective and to focus on integrated aspects of activities, for example greenhouse gas emissions and local air pollution.

The proposed cities-based bio-physical indicators are climate change, rate of biodiversity loss, fresh water use, change in land use, phosphorous and nitrogen cycle, pollution and geophysical risk.

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A boundary (or limit) for geophysical risk is included. This reflects seismic and weather-related risk the city faces, for example earthquake, volcanoes, landslides, storms and flooding. Geophysical risk includes rapid onset events such as typhoons and earthquakes: long-term climate related events, such as drought, pestilence and changes to growing seasons are considered elsewhere.

'Pollution' is included as an estimate of local (and cumulative) air pollution (smog and indoor/outdoor particulate matter), water pollution (chemical oxygen demand, biological oxygen demand, flotsam and heavy metals) and land pollution (solid waste and brownfields). An average overall value is initially used.

5. Global socio-economic limits

The socio-economic targets of sustainability include seven metrics. Where definitive values are not available, values are estimated and, when required, national values used. The targets align with the sustainable development goals.

In an attempt to develop 'contours of a resilient global future', Gerst *et al.* (2013) combine scenario analysis (to 2100), planetary boundaries, and targets for human development. The methodology is sufficiently robust to accommodate dramatic social and technological change. The approach used in this paper is to provide planetary and local boundaries as human development targets that would facilitate a similar application of 'contours of a resilient global future' but provided at a city perspective. Figure 2 and Table 2 provide approximate global socio-economic targets – estimated in relation to existing targets and global boundaries. These targets are mainly a reflection of the UN sustainable development goals. Most of the data is available through data sets such as the World Council on City Data (ISO 37120). However, approximations are needed as values are required for the entire urban area rather than the individual city core alone.

The proposed targets are as follows.

- Youth opportunity: under 5 mortality; gender equity; percent female in schools; youth unemployment rate.
- Economy: unemployment rate; Gini inequality coefficient; percentage of population living in slums; local gross domestic product.
- Energy access and intensity: percentage of city with authorised electrical service; energy intensity.
- Mobility and connectivity: annual number of public transport trips per capita; number of personal automobiles per capita; percentage of commuters using a travel mode other than a personal vehicle to work; commercial air connectivity; transportation fatalities per 100 000 population; number of internet connections per 100 000 population.
- Institutions: ‘ease of doing business’ – World Bank (downscaled from country to city level); number of convictions for corruption by city officials per 100 000 population; tax collected as a percent of tax billed; debt service ratio.
- Basic services: average life expectancy; percentage of population with regular solid waste collection; percentage of city population served by wastewater collection; percentage of population served with potable water supply; percent of houses flooded, by year.

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- Security and public safety: number of fire related deaths per 100 000 population; number of homicides per 100 000 population; violent crime rate per 100 000 population.

Table 2 gives the current values of the global socio-economic indicators compared with the target values or limits. Initial data for all cities (metro areas) over 5 million population are available at city-sustainability.com.

6. Applying the methodology: sustainability cost curves for transportation projects

To illustrate the methodology a detailed assessment of nine possible Toronto transportation projects is provided (Figure 3). For illustrative purposes these Toronto projects are also assessed relative to transportation projects in Dakar, Mumbai, Sao Paulo, and Shanghai (Figure 4; project details in Hoornweg 2015). This cross-city comparison highlights how sustainability cost curves can be used for detailed assessment within a city as well as notionally across several cities.

The following are the nine representative transportation projects (the region-wide bus rapid transit is made up of three inter-connected options).

- 90 min. transfer – Toronto Transit Commission (TTC) plans to allow subway passengers to disembark and return within 90 min. without additional charge. Cost C$12 million a year (TTC 2014).
- Highway 407 extension – privately operated highway 407 express toll road had a 22 km extension in 2016 and a further 43 km extension is due to open in 2020.

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- Union Pearson express – rail link between Union station in central Toronto and Toronto Pearson airport, completed for 2015 Pan-American Games (Kalinowski 2010).
- SmartTrack – regional surface metro in the greater Toronto area due to open in 2021, with 22 stops at major interchanges. Capital cost C$5.3 billion.
- GO electrification – conversion of GO Transit trains from diesel to electric, starting with Union Pearson line. Capital cost C$0.9 billion.
- Pickering airport – proposed international airport 65 km east of Toronto Pearson airport. Cost C$2 billion; with up to 11.9 million passengers a year by 2032.
- Region-wide bus rapid transit and electric vehicles – option 1, 30% more natural gas and electric vehicles; option 2, bus rapid transit system with stops at highway interchanges; option 3, expansion of bus rapid transit system to neighbouring cities.

Table 3 provides values for all transportation projects including three disaggregated options for the region-wide bus rapid transit and electric vehicles. This illustrates how large-scale projects may have several inter-related components requiring assessment of the overall initiative to evaluate sustainability, for example options 1 and 2 with lower factors of sustainability are pre-requisite for the higher-sustainability option 3.

The sustainability factor is derived by estimating project impacts on each indicator (Tables 4 and 5). Only the categories with expected changes are presented for aggregated totals of bio-physical (Table 6) and socio-economic (Table 7) indicators of sustainability of each transportation option. Most categories have zero impact at this time, although they are listed in Tables 4 and 5 as the sustainability assessment is intended to be sufficiently broad to eventually cover all infrastructure services in all cities (Figure 3).

Launching a bus rapid transit system across Toronto and initiating an electric vehicle car-sharing program connected to the bus rapid transit lines has the highest sustainability potential compared to other initiatives. The surface metro has the next highest sustainability potential. Comparatively the 90 min. transfer option provides high sustainability potential at the lowest unit cost.

7. Conclusions

Sustainability cost curves provide a useful tool to assess long-lived infrastructure. For transportation projects, a metropolitan city area – Toronto in Canada – was used to capture intermodal travel options and maximise potential beneficiaries. The optimum timescale for analysis needs to be sufficiently long to encourage alternatives – in this case 35 years has been used.

Urban infrastructure and the shape and size of cities are the key drivers of local and global economy and corresponding environmental degradation. Optimising this infrastructure against a suite of sustainability metrics is shown to be possible. Similar to how major infrastructure works are subject to environmental assessments (as well as economic and technical), they should also be evaluated against sustainability objectives and their relative impact within a suite of possible actions estimated. These curves should be provided for public discourse and policy development purposes.

A 90 min. subway transfer option was found to provide the lowest cost unit of sustainability as only modest infrastructure changes are needed, many people are able to use the option and lost revenues are modest. On the other hand, a tolled highway extension had a relatively high cost per unit of sustainability as few drivers would use the option, greenhouse gas emissions would increase and limited impact on employment was expected. A region-wide bus rapid transit provided significant sustainability potential as many riders were anticipated, significant reductions in greenhouse gas emissions would result and there would be considerable increase in economic opportunity.

Additional sectors to which the sustainability cost curves could be applied include energy, water, wastewater and sanitation. When presented relative to each other, and relative to other cities, cost curves provide a credible tool for local infrastructure planning as well as a method to implement city-based sustainable development.

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Table 1. Bio-physical science Indicators, global average

Physical science indicators	**Unit**	**Global (current)**	**Global (targets/ limits)**	**Source**
Carbon dioxide emissions				
Greenhouse gas emissions/capita	tCO_2/cap. year	4.71	2	Adapted from CCC (2014)
Rate of biodiversity loss				
Ecological footprint	global hectares demanded per capita	2.6	1.7	WWF Living Planet Report (WWF 2014) (down-scaled national values)
Index of biodiversity impact	Low–very high	Very high	Low	Estimated
Fresh water use				
Water consumption	L/cap/day	1148	1546	Rockstrom *et al.* (2009)
Percent of city with potable water supply	%	81	95*	Adapted from Unicef WHO (2012), *estimated value
Index of embodied water consumption (I)	Low–very high	Low	Low	Estimated
Change in land use				
Local land use change (Ha)	% of land converted for cropland	11.7	15	Rockstrom *et al.* (2009)
Population density	person/km^2	3500	TBD	Listed urban areas population density (Demographia 2006)
Index of global land use impact (Ha)	Low–very high	Low	Low	Estimated
Nitrogen cycle				
Per capita values as percent of global values	kg-N_2/cap/yea r	18	5.5	Rockstrom *et al.* (2009)

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based on estimated consumption patterns				
Pollution				
Percentage of city population with regular solid waste collection	%	50	80*	Municipality Waste Management (MSW 2014), *estimated data
Percentage of city population served by wastewater collection	%	76	80*	http://www.worldwaterweek.org/, *estimated data
PM 2.5; PM 10; O3	μg/m^3	20	10	World Health Organization (WHO)
Geophysical risk				
Number of natural disaster related deaths	per 100 000 population	0.134	0.09*	Adapted from Guha-Sapir *et al.* (2013), *(Guha-Sapir and Hoyois 2013)
Percentage of gross domestic product loss due to natural disasters	%	0.2	0.1	b$ 143 in 2012/UCL-WHO (Guha-Sapir *et al.* 2013)
Resilience of city	Low–very high	Medium	High	Estimated
Adapted from Hoornweg *et al.* 2016				

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Table 2. Global social science indicators – current global average values compared to target/limit

Indicators	Current	Target	Comment/source
Youth opportunity			
Under 5 mortality (deaths/1000 live births)	51	17	Millennium development goals (UN 2013)
Gender equity	0.66	1	Millennium development goals (UN 2013)
Percentage of female in schools	85	95	495.9 million illiterate woman in 2007 (UN 2010)
Youth unemployment rate (%)	12.4	12.8	2012 rate and 2018 estimate by ILO (2013)
Average life expectancy (years)	70	70	70 is 2015 target (UN 2014)
Economy			
Unemployment rate (%)	6	6*	ILO (2013), *estimated
Gini coefficient	0.52	0.2*	CBC (2014), *estimated
Percentage of population living in slums	25	18	Millennium development goals (UN 2013)
Gross domestic product ($cap)	10 496	20 000*	b$74910, 7.13 million pop, 2013 (WB 2014), *estimated
Energy access and intensity			
Percentage of city with authorised electrical service	94	100	0.21 million urban residents w/o access (IEA 2011)
Percentage of city with access to clean energy for cooking	88	100	0.43 million urban residents w/o access (IEA 2011)
Energy intensity (MJ/$)	8.9	8.9	Wikipedia: list of countries by energy intensity, 2003
Mobility and connectivity			
Number of personal automobiles per capita	0.15	0.2	1.02 billion in 2010, 1.58 billion in 2020

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Daily number of public transport trips per capita	0.35	0.35*	*Estimated
Number of internet connections (% population)	40	50	ILS (2014)
Percentage of commuters using a travel mode other than a personal vehicle to work	30	50*	*Estimated
Transportation fatalities (per 100 000 population)	17.2	8.6*	World Health Organization (WHO 2013)
Commercial air connectivity (# of destinations)			
Institutions			
Ease of doing business – World Bank (downscaled from country to city level)	95	95	International Finance Corporation (IFC 2014)
Number of convictions for corruption by city officials (per 100 000 population)	42.7	50	TI (2014)
Tax collected as a percentage of tax billed			TBD from GCI
Debt service ratio			TBD from GCI
Basic services			
Percentage of population with regular solid waste collection	50	80*	Urban Solid Waste Management (WB 2011), *estimated
Percentage of city population served by wastewater collection	76	80*	2008, Urban regions, www.worldwaterweek.org, *Estimated
Percentage of population served with potable water supply	81	95*	United Nations (Unicef-WHO 2012), *estimated
Security and public safety			
Number of fire related deaths (per 100 000 population)	3.6	0.5*	265 000 deaths/y (WHO 2014), *Estimated
Number of homicides (per 100 000 population)	6.1	3.05*	437 000 cases in 2013 (UN 2014), *estimated
Violent crime rate (per 100 000 population)			TBD from GCI

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Table 3. Cost estimation and sustainability factors – Toronto's transportation projects

	90 min. transfer	Highway 407 extension	Union Pearson express	Intercity bus rapid transit	GO electrification	SmartTrack	Highway bus rapid transit	Natural gas and electric vehicles	Pickering airport
Cost estimation: C$ billion									
Total cost	0.00	1.00	0.38	14.57	0.86	5.30	1.39	3.40	2.00
Operation cost	0.00	0.60	0.31	0.82	0.42	1.00	0.16	1.00	0.18
Residual value in 2050	0.00	0.00	0.19	7.29	0.43	2.65	0.70	1.70	1.00
Residual value with 50 % discount factor	0.00	0.00	0.10	3.64	0.21	1.33	0.35	0.85	0.50
Revenues from new users	-0.42	1.14	0.00	3.93	0.00	4.52	1.08	0.00	0.30
Users' benefit	2.73	-0.25	0.60	2.84	0.00	3.02	0.47	37.00	0.60
New daily users	100 000	6000	6000	285 640	4617	200 000	5940	1 140 000	32 600
Net cost	0.00	1.60	0.59	11.75	1.06	4.98	1.21	3.55	1.68
Operation starting year	2015	2015	2015	2020	2023	2021	2020	2020	2,030
Sustainability									
Factor	2.02	0.17	0.27	5.38	0.24	3.29	0.29	0.40	0.59
Potential per year	1.50	0.01	0.01	13.33	0.01	5.91	0.02	3.96	0.25
Cost per unit of sustainability	0.00	9.26	2.22	2.18	4.37	1.51	4.13	8.86	2.83

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Table 4. Bio-physical science indicators changes

Physical science indicators	**Unit**	**Estimation method**
Carbon dioxide emission		
Greenhouse gas emissions per capita	tCO2/capita year	No. of users per day * length * 1/3 * no. of days per year / population
Rate of biodiversity loss		
Change in [local] number of native species (ecological footprint)	Number of endangered species	No change
Index of biodiversity impact (number of species)	Very high to very low	No change?
Fresh water use		
Total per capita water consumption	litres/capita/da y	No change
Percent of city with potable water supply	%	No change
Index of embodied water consumption (Litres)	Very high to very low	No change
Change in land use		
Local land use change (Ha)	% of land converted for cropland	Assuming a very small change
Population density	person/km^2	No. of users * 0.0001
Index of global land use impact (Ha)	Very high to very low	No change
Nitrogen and phosphorous cycle		
Per capita values as percentage of global values based on estimated consumption patterns	kgN$_2$/cap/year	No change
Pollution		
Percentage of city population with regular solid waste collection	%	No change

Percentage of city population served by wastewater collection	%	No change
PM 2.5; PM 10; O3	μg/m^3	Assuming a very small change
Index of solid waste (TBD)		
Geophysical risk		
Number of natural disaster related deaths	No./100 000 population	No change
Percentage of gross domestic product loss due to natural disasters	%	Assuming a very small change
Resilience of city	1–5	Assuming a very small change
Critical infrastructure at risk	TBD	

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Table 5. Socio-economic science indicators changes

Socio-economic indicators	**Unit**	**Estimation method**
Youth opportunity		
Under 5 mortality	Deaths per 1000 live births	No change
Gender equity		Assuming a very small change
Percentage of females in schools	%	No change
Youth unemployment rate	%	Assuming a very small change
Average life expectancy	Years	Assuming a very small change
Economy		
Unemployment rate	%	Assuming a very small change
Gini coefficient		Assuming a very small change
Percentage of population living in slums/homeless	%	No change
Gross domestic product	C$/cap	Benefits/population
Access to energy and energy intensity		
Percentage of city with authorised electrical service	%	No change
Percentage of city with access to clean energy for cooking	%	No change
Energy intensity	MJ/C$	Assuming a very small change
Mobility and connectivity		
Number of personal automobiles per capita	Vehicle/capita	No. of users * 5% / Population
Daily number of public transport trips per capita	Trips/capita/day	No. of users * 1% / Population
Number of internet connections	% population	No change

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Percentage of commuters using a travel mode other than a personal vehicle to work	%	No. of users * 50 % / population
Transportation fatalities	No./100 000 population	Assuming a very small change
Commercial air connectivity	No. of destinations and frequency	No change
Institutions		
Ease of doing business – World Bank (downscaled from country to city level)		Assuming a very small change
Number of convictions for corruption by city officials	No./100 000 population	No change
Tax collected as a percent of tax billed	%	No change
Debt service ratio		
Basic Services		
Percentage of population with regular solid waste collection	%	No change
Percentage of city population served by wastewater collection	%	No change
Percentage of population served with potable water supply	%	No change
Security and public safety		
Number of fire related deaths	No./100 000 population	No change
Number of homicides	No./100 000 population	No change
Violent crime rate	No./100 000 population	No change
Index of healthcare (TBD)	Very high to very low	

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Table 6. Bio-physical science indicators – transportation projects of Toronto [need to stitch tables together]

			90 min. transfer		Highway 407 extension		Union Pearson express		Intercity bus rapid transit		GO electrification		SmartTrack	
	Unit	Toronto	Change	Scaled	Change	Scaled	Change	Scaled	Change	Scaled	Change	Scaled	Change	Scaled
Carbon dioxide emissions														
Greenhouse gas emissions per capita	tCO_2/capita year	11.5	-0.051	0.439	0.003	-0.028	-0.001	0.009	-0.144	1.255	-0.002	0.02	-0.034	0.293
Change in land use														
Local land use change	Area of forested land as % of original forest cover	28	-0.001	0.004	0.002	-0.007	-0.001	0.004	-0.001	0.004	0.002	-0.007	-0.001	0.004
Population density	Person/km^2	884	10.0	1.13	-0.6	-0.07	0.6	0.07	28.56	3.23	0.462	0.052	20.0	2.2624
Geophysical risk														
Resilience of city	Low to very High	88	0.0	0.0	0.001	0.001	0.001	0.001						

0.0	0.0	0.001	0.001	0.001	0.001

Highway bus rapid transit		Natural gas and electric vehicles		Pickering airport	
Change	Scaled	Change	Scaled	Change	Scaled
-0.003	0.026	-0.451	3.924	-0.016	0.143
-0.001	0.004	0.001	-0.004	0.001	-0.004
0.59	0.07	-11.40	-1.29	3.26	0.37
0.001	0.001	0.001	0.001	0.001	0.001

Table 7. Socio-economic indicators – transportation projects of Toronto [need to stitch tables together]

		90 min. transfer		Highway 407 extension		Union Pearson express	
	Toronto	Change	Scaled	Change	Scaled	Change	Scaled
Youth opportunity							
Gender equity	0.742	0.0001	0.01	0.0	0.0	0.0001	0.01
Youth unemployment rate: %	18.1	-0.01	0.06	0.0	0.0	-0.01	0.06
Economy							
Gini coefficient	0.33	-0.001	0.012	-0.001	0.012	-0.001	0.012
Energy poverty including access to electricity							
Percentage of city with authorized electrical service	100	9.3	0.0	3.6	0.0	2.4	0.0
Mobility and connectivity							
Number of personal automobiles per capita	0.61	0.01	0.0407	-0.01	-0.0407	0.01	0.0407
Daily number of public transport trips per capita	0.25	-0.0007	0.1154	0.0	-0.0069	0.0	0.0069
Number of internet connections (per 100 000 populaiton)	83	0.0001	0.0563	0.0	-0.0034	0.0	0.0034
Transportation fatalities (per 100 000 population)	2.5	0.0141	0.0612	-0.0008	-0.0037	0.0008	0.0037
Commercial air connectivity		-0.001	0.04	0.001	-0.04	-0.001	0.04
Institutions							
Number of convictions for corruption by city officials (per 100 000 population)	81	0.001	0.0053	0.001	0.0053	0.001	0.0053

Intercity bus rapid transit		GO electrification		SmartTrack	
Change	Scaled	Change	Scaled	Change	Scaled
0.0001	0.01	0.0001	0.0135	0.0001	0.013
-0.01	0.06	-0.01	0.055	-0.01	0.055
-0.001	0.012	-0.001	0.012	-0.001	0.012
31.8	0.06	0.0	0.0	36.62	0.07
0.01	0.0407	0.010	0.041	0.01	0.0407
-0.002	0.3298	0.0	0.0053	-0.001	0.231
0.0004	0.1609	0.0	0.0026	0.0003	0.113
0.0402	0.1749	0.001	0.0028	0.0282	0.1225
-0.001	0.04	-0.001	0.04	-0.001	0.04
0.001	0.0053	0.001	0.005	0.001	0.005

Highway bus rapid transit		Natural gas and electric vehicles		Pickering airport	
Change	Scaled	Change	Scaled	Change	Scaled
0.0001	0.01	0.0001	0.01	0.0001	0.01
-0.01	0.06	-0.01	0.06	-0.01	-0.06
-0.001	0.012	-0.001	0.012	-0.001	-0.012

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7.3	0.01	173.7	0.34	6.3	0.01
0.01	0.0407	0.01	0.0407	0.01	0.0407
0.0	0.0069	0.008	-1.3161	0.0	0.0
0.0	0.0033	-0.0016	-0.6423	0.00005	0.0184
0.0008	0.0036	-0.1606	-0.6981	0.0046	0.02
-0.001	0.04	0.001	-0.04	-0.001	0.04
0.001	0.0053	0.001	0.0053	0.001	0.0052632

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Figure 1. Bio-physical science indicators for cities in a global context

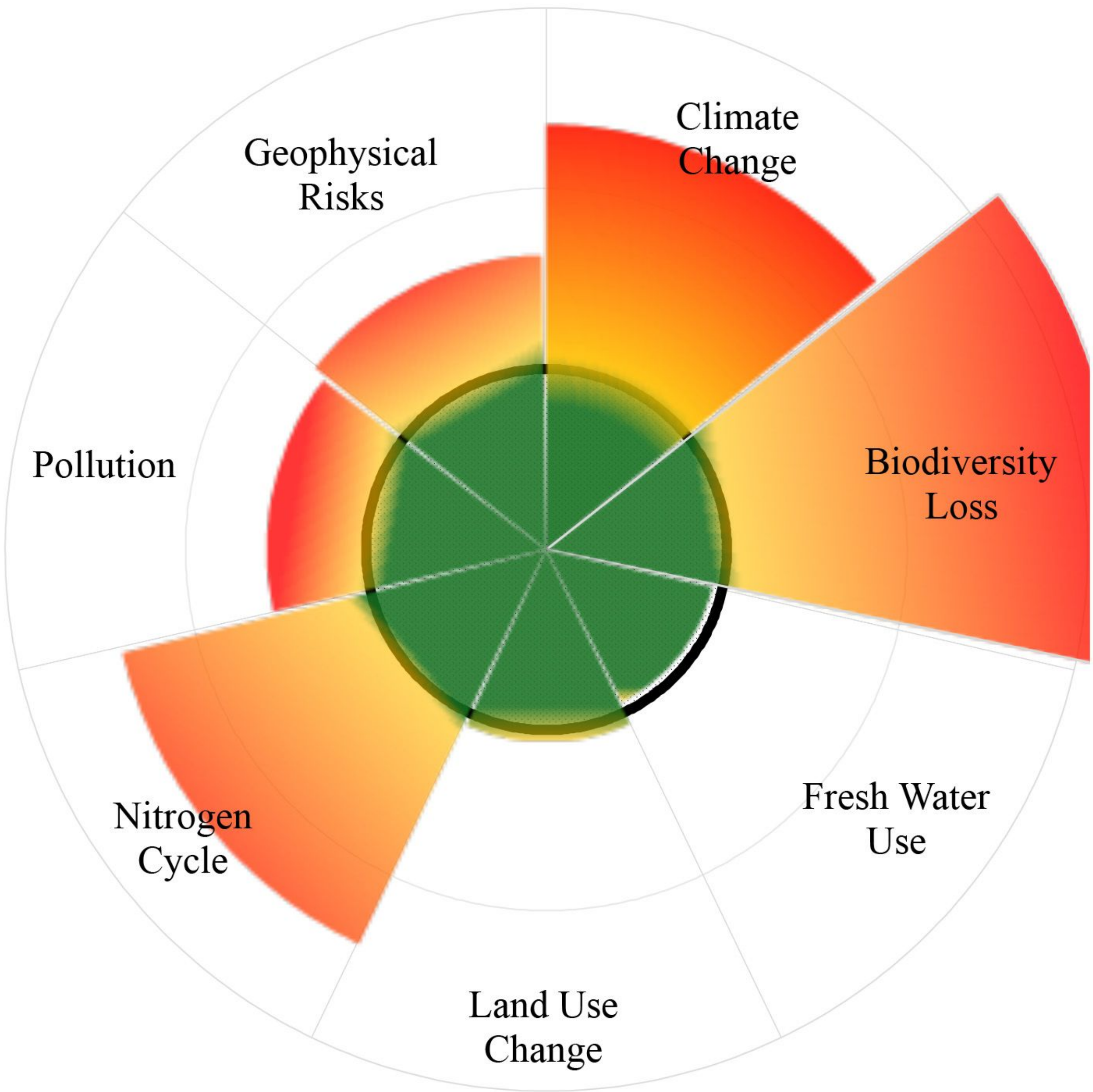

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Figure 2. Socio-economic limits: global situation compared to targets

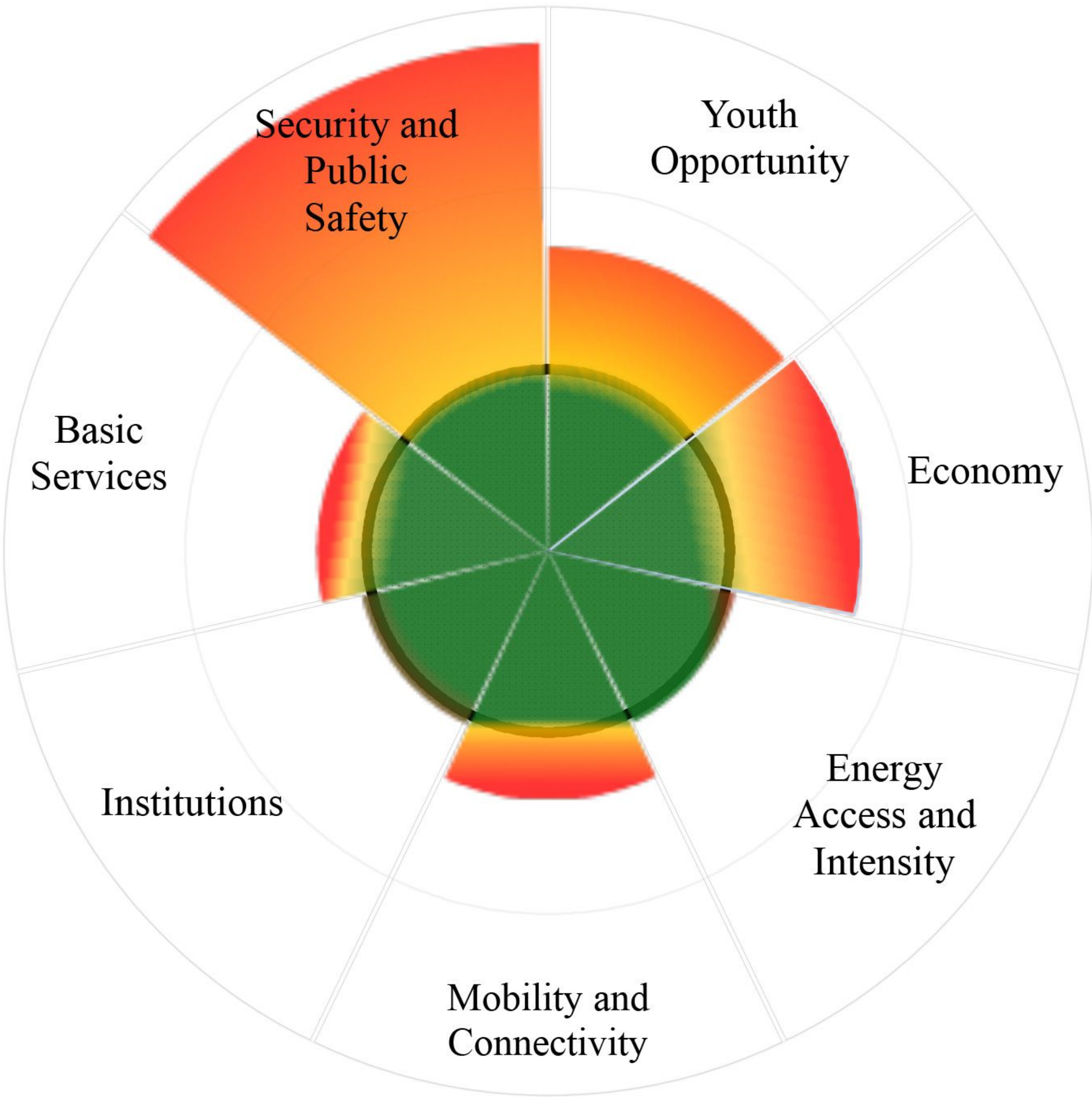

Figure 3. Sustainability cost curve: transportation projects in Toronto

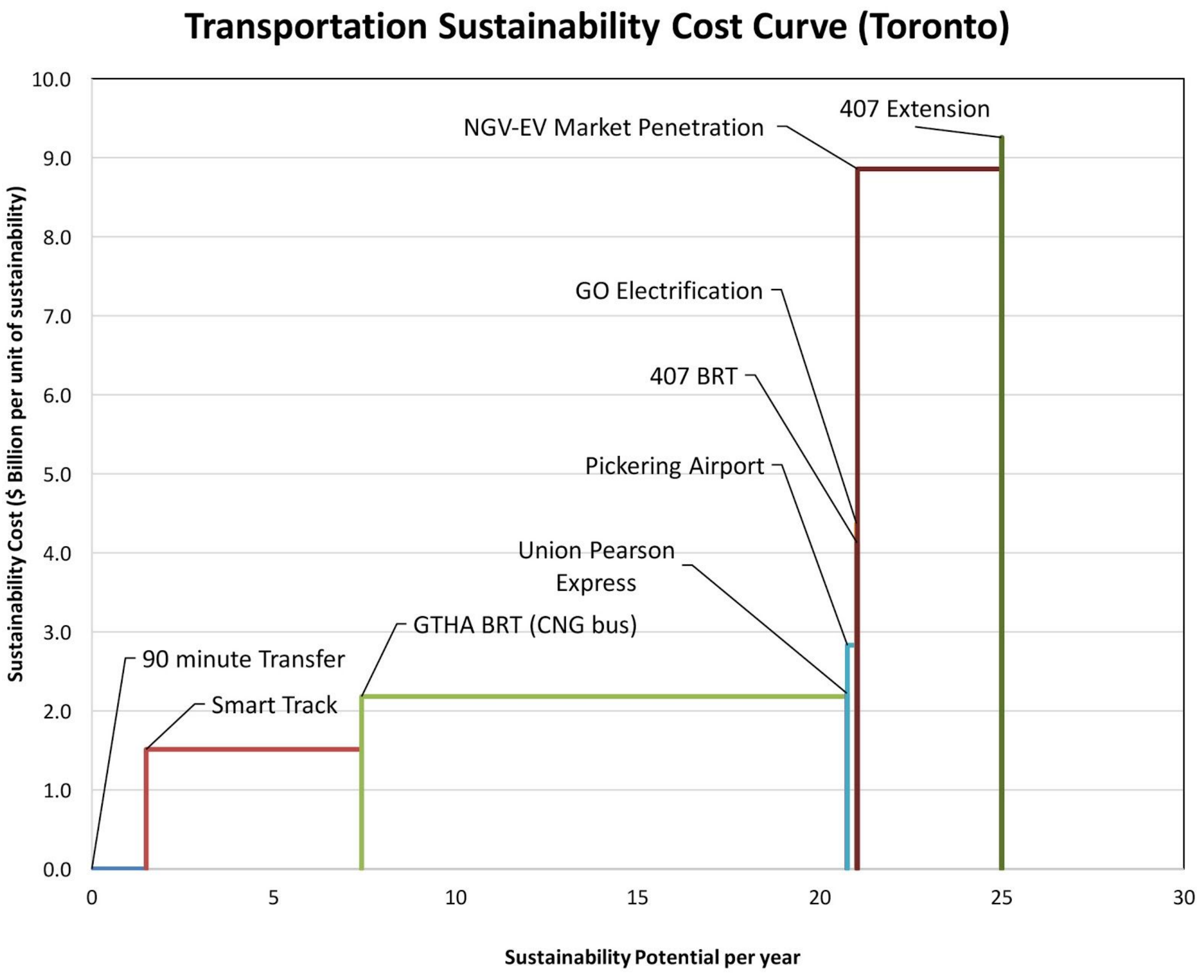

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Figure 4. Sustainability cost curve: transportation projects in five major cities