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USING SUSTAINABILITY COST CURVES TO EVALUATE URBAN INFRASTRUCTURE IN CANADA

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Abstract: Worldwide about $15 trillion is expected to be invested in urban infrastructure over the next 15 years. In Canada alone, the national government committed $180 billion in infrastructure funding for 12 years. This increased investment is taking place while governments commit to reduce greenhouse gas (GHG) emissions and meet the Sustainable Development Goals (SDG). New approaches, in addition to existing cost benefit analysis and factor of safety, are needed to broaden the assessment of urban infrastructure. This paper introduces sustainability cost curves as a means of 'applied sustainable development' to define and prioritize urban infrastructure. Sustainability cost curves rely on an open source sustainability assessment for the city or region. The sustainability assessment is dynamic and globally consistent, encompassing planetary boundaries, SDGs, urban resilience, and equity considerations. In this paper, sustainability assessments are provided for Montreal, Toronto and Vancouver. The sustainability assessments facilitate the introduction of sustainability cost curves for transportation projects in Montreal, Toronto and Vancouver. The approach enables definition of sustainable ('green') infrastructure. We propose to begin this in Canada, with a view to launch the approach globally so that all major cities (urban regions) consider sustainability cost curves to better define urban infrastructure priorities and public policy options.

1. Introduction

The practice of making infrastructure investment decisions based on cost-benefit analysis dates back to 1848, when Jules Dupuit, determined the merits of a new bridge in Paris. For 170 years cost benefit analysis, along with a 'factor of safety' have underpinned infrastructure decisions. Today however, these tools need to be complemented with a preliminary assessment of how the proposed investment or policy meets broader objectives such as urban resilience, GHG mitigation, and equity. Globally, ambitious development efforts are underway. Infrastructure planned for urban areas over the next 15 years could be greater than the $50 trillion value of today's existing urban infrastructure (CCFLA, 2015). This comes while concerns rise whether this new infrastructure can adapt to a changing climate, and when the construction sector is under increasing scrutiny for particularly poor productivity. McKinsey (2017), for example, identified an annual global productivity shortfall of $1.6 trillion in the construction industry.

Meanwhile, the 193 member states of the United Nations unanimously adopted in 2015 the 17 Sustainable Development Goals (SDG) of the 2030 Agenda for Sustainable Development. The SDGs include ending poverty and hunger, and ensuring gender equity, education, health, water and sanitation, clean energy, and employment for all. Additional goals include infrastructure and innovation, sustainable cities, responsible consumption, climate action, protection of the oceans and land, peace, justice, strong institutions and partnerships.

Most countries repond to these at a national level, e.g. Intended Nationally Determined Contributions (INDCs) for GHG emission reductions under the United Nations Framework Convention on Climate Change (UNFCCC). The SDGs are predicated on the earlier Millennium Development Goals, which in turn were built upon 'Agenda 21' that emerged from the 1992 Rio Conference. Similar to how local governments prepared 'Local Agenda 21s' post-1992, cities are now defining their own approaches to sustainable development. Cities, and particularly the residents of cities with purchasing power, need to assess direct impacts as well as those impacts driven from product supply (that eventually makes its way to city residents).

An urban, or cities, approach to SDGs (and planetary boundaries) must strive for several inter-related considerations and objectives. For example, a systems approach (the urban region) is needed, especially for services like transportation and local air quality that typically transcend municipal boundaries. Emissions inventories, and global impacts on biodiversity, need to consider all contributions, including embodied emissions, aka 'consumption' – therefore Scopes 1, 2 and (eventually) 3 need to be accounted for. National trends and contributions are critical; however, where possible, they should be differentiated by city. Urban resilience is a key consideration in the development agenda of cities. A sustainable development agenda in cities may warrant a longer time frame than the SDGs, as 15 years is usually insufficient to fully amortize infrastructure investments. A planning horizon to 2050 provides a broader suite of investment and policy options.

2. The difficulty in defining the sustainability of urban infrastructure

Defining 'green' or sustainable infrastructure is challenging. Sustainability is measured in many ways. For example, Poveda and Lipset (2014) outline more than 600 existing approaches to sustainability assessment. The two most common global approaches are planetary system boundaries (Rockstrom *et al* 2009, updated by Stefen *et al* 2015) and the sustainabale development goals (SDGs).

There is little agreement of what constitutes 'green' in "green infrastructure". 'Green', or sustainable, infrastructure, typically includes low-carbon options, but should also include issues particularly relevant to cities, as well as those espoused through national commitments such as the SDGs and the Paris Climate Agreement. Definitions of sustainable infrastructure should include enhancements to ensure 'value for money' and prioritization of objectives such as reduced greenhouse gas emissions, increased urban resilience, reduced local air pollution, equity and social-support.

In the last ten years, several infrastructure-rating tools emerged to better quantify infrastructure sustainability. Two methods particularly relevant to assessment of civil works are Engineering Canada's Public Infrastructure Engineering Vulnerability Committee (PIEVC, https://pievc.ca/protocol) and ASCE's 'Envision' (https://www.asce.org/envision/). PIEVC is a detailed climate vulnerability assessment of discrete infrastructure, e.g. a wastewater treatment plant. Envision is a comprehensive sustainability assessment using 60 criteria, called 'credits', in five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. Both of these approaches provide a broad assessment of the infrastructure in question (all sustainability in the case of Envision, climate vulnerability in the case of PIEVC); costs and data requirements for the evaluations are considerable (typically more than $50,000 per evaluation).

Prior to detailed evaluation of infrastructure (and policy initiatives), e.g. through PIEVC and Envision, a contextual, 'order of magnitude' dynamic assessment may be warranted. In other words, what policy-makers need is a heuristic for "green" that is directionally correct and allows them to select between infrastructure plans without running a full assessment.

3. Sustainability assessment of cities

Building on planetary boundaries, Raworth (2012), Dearing *et al*. (2014), and O'Neill *et al.* (2018) state that ensuring a safe and just operating space for human wellbeing (i.e. sustainability) requires appreciation of both bio-physical and socio-economic boundaries (or targets). They propose frameworks that integrate these operating spaces. Levels of sustainability are usually defined at the national scale through various metrics published annually by census and international agencies (e.g. GDP, PM10, unemployment rate, gini coefficient) and as global (all country) assessments by various agencies (e.g. WWF's Living Planet; World Bank's Ease of Doing Business; and indices such as resilience, energy intensity, health care).

Cities are both impacted by, and drive, global trends. For example Montreal, Toronto and Vancouver urban regions account for more than half of Canada's economy (GDP). Similarly China's three-largest urban areas, the Yangtze and Pearl River Deltas and Beijing-Tianjin corridor, provide a combined GDP in excess of $5.25 trillion (~60% of all China in 2015). Globally, residents of cities account for more than 80% of the world's GHG emissions (Hoornweg 2015). Similarly, the majority of infrastructure threatened by a changing climate is urban based (Hallegatte *et al* 2013).

Accounting for city (and corporate) GHG emissions presents unique issues, not experienced in national inventories. The full life cycle of activities must be considered, for example the emissions associated with the food grown, or items manufactured, overseas. Recognizing the need for emissions inventories that reflect vicarious or embodied emissions (generated on behalf of the entity but done so through a third party or in another area) the World Business Council for Sustainable Development and World Resources Institute began in 1997 to develop a standard methodology consistent with national GHG inventories. 'Scopes 1, 2 and 3' were defined to account where the emissions were generated while ensuring globally consistent national, local, and corporate emissions inventories (ISO 14064-I, 2016).

The initial work by WRI-WBCSD (ISO 14064), efforts by researchers (Kennedy *et al* 2010), the World Bank, and a common global protocol by C40-ICLEI-WRI led to a city-wide GHG emissions inventory now widely accepted and included within the recent ISO 37120. Cities, and individual residents and businesses, can credibly measure their GHG emissions, relative to national inventories. Sudmant et al (2018) illustrate how cities need to focus on both production (scope 1 and 2) and consumption (scope 3) GHG emissions, while countries typically only provide inventories of production emissions.

The concept of scope 1 (direct emissions/impacts from owned or controlled sources), scope 2 (indirect emissions from the generation of purchased energy) and scope 3 (embodied or indirect emissions, not included in scope 2, that occur in the value chain) provides a precedent for other activities with potential planetary impacts. Sustainability measures for cities, that quantify local and global impacts, could similarly include biodiversity, water use, nitrogen and phosphorous use, and solid waste generation.

Sustainability assessments for Montreal, Toronto and Vancouver are measured through bio-physical and socio-economic indicators. Bio-physical and socio-economic data estimates for Montreal, Toronto and Vancouver are provided at city-sustainability.com. These estimates are aggregated and compared to global targets. Key differences between Canada's three largest cities include: higher GHG emissions in Toronto; more remaining cropland in Toronto region; slightly better air quality in Vancouver; less resilience in Vancouver (higher seismic threat); slightly less unemployment in Vancouver; more inequality in Toronto; higher GDP in Montreal; less energy intensity in Montreal (likely reflecting the lower cost of electricity); and higher reliance on personal automobiles in Toronto. Values are presented as a starting point, to be updated annually, and are consistent with findings from Mohareb and Mohareb (2014), Ibrahim and Kennedy (2016, Toronto) and Moore et al (2013, Vancouver).

Indicators are presented with a confidence levels ranging from 1 (broad estimate, often down-scaled national value) to 5 (third-party audited or peer reviewed for the entire urban area). While some indicators for Canadian cities may have little immediate relevance, e.g. solid waste collection rates, all values are provided to ensure a common approach globally (initial data for the world's 122 largest cities is provided at city-sustainability.com). Discussions are underway with groups like Engineers Without Borders (EWB) and local researchers to refine data and provide annual (or biennial) assessments.

For Montreal, Toronto and Vancouver the census metropolitan area as defined by Statistics Canada is initially used, although in the case of Toronto for example, the area will be refined in future, to fully capture the commuter-shed of urban Toronto. The larger urban area is used as this better reflects potential impacts of large-scale long-lived urban infrastructure.

Bio-physical indicators are modelled after planetary boundaries with seven key sectors: climate change, biodiversity loss, fresh water use, change in land use, nitrogen use (and phosphorous), chemical pollution, and urban resilience. Urban resilience is specific to infrastructure and economy of the assessed city. For several sectors, such as biodiversity and resilience, indices comparing cities globally are used. Initially these are national values, although discussions are underway with agencies such as WWF (biodiversity) and Notre Dame GAIN (resilience), to provide their national values disaggregated for the world's larger cities.

Socio-economic indicators capture aspects of the SDGs at an individual city level with broadly available data, e.g. ISO 37120 sustainable development of communities. Seven sectors are proposed: youth opportunity, economy, energy access and intensity, mobility and connectivity, institutions, basic services, security and public safety.

4. Sustainability cost curves as a possible heuristic for "green"

One possible solution to the challenge of defining sustainability of infrastructure is the marginal abatement cost (MAC) curve. The MAC rose to prominence after the 1997 Kyoto Protocol agreement to reduce GHG emissions and can provide policy-makers with a means to visualize and prioritize initiatives – which is precisely what they need.

MAC curves help to understand emission reductions, prioritize investment opportunities, and shape policy discussions. The curves can present a global, national or local suite of possible greenhouse gas emissions (GHG) mitigation options. Each bar represents a single carbon mitigation activity; the width of the bar represents the abatement potential; the height of the bar represents the abatement cost per year (all relative to business as usual). Costs are expressed per tonne of emissions avoided.

Variations on the MAC curve are common. For example, Creyts et el (2007) provide a similar assessment for enhanced adaptation and coastal protection in Florida. Woodcock et al. use a MAC curve to highlight the relationship between public health benefits and carbon emissions reduction strategies in urban transportation (Woodcock et al. 2009). Ibrahim and Kennedy (2016) provide a comprehensive MAC for GHG mitigation in Toronto.

Advantages and disadvantages of MAC curves are widely discussed (Kesicki and Ekins 2012; Vogt-Schilb and Hallegatte 2014). Advantages include a powerful visual display of results to help facilitate consultation. Discount rates can be customized by activity with marginal costs (or benefits) determined for any given project (or policy). Comparisons are made across sectors and entities (countries, cities, corporations). Disadvantages include the 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 and are not always transparent, and might convey unrealistic certainty. Actual costs of activities may also vary from those presented due to time dependency (Hoornweg, 2015).

5. Applying MAC curves to infrastructure projects in Montreal, Toronto and Vancouver

With sustainability assessments serving as a baseline, impacts of infrastructure options can be evaluated over the life of the activity (here, estimated to 2050). The 'factor of sustainability' for proposed infrastructure or policy incorporates costs (capital, operating, residual values, and user benefits), number of users (or persons directly impacted by the policy), and change against the 7 bio-physical and 7 socio-economic sectors used to define the city's sustainability (Figure 1).

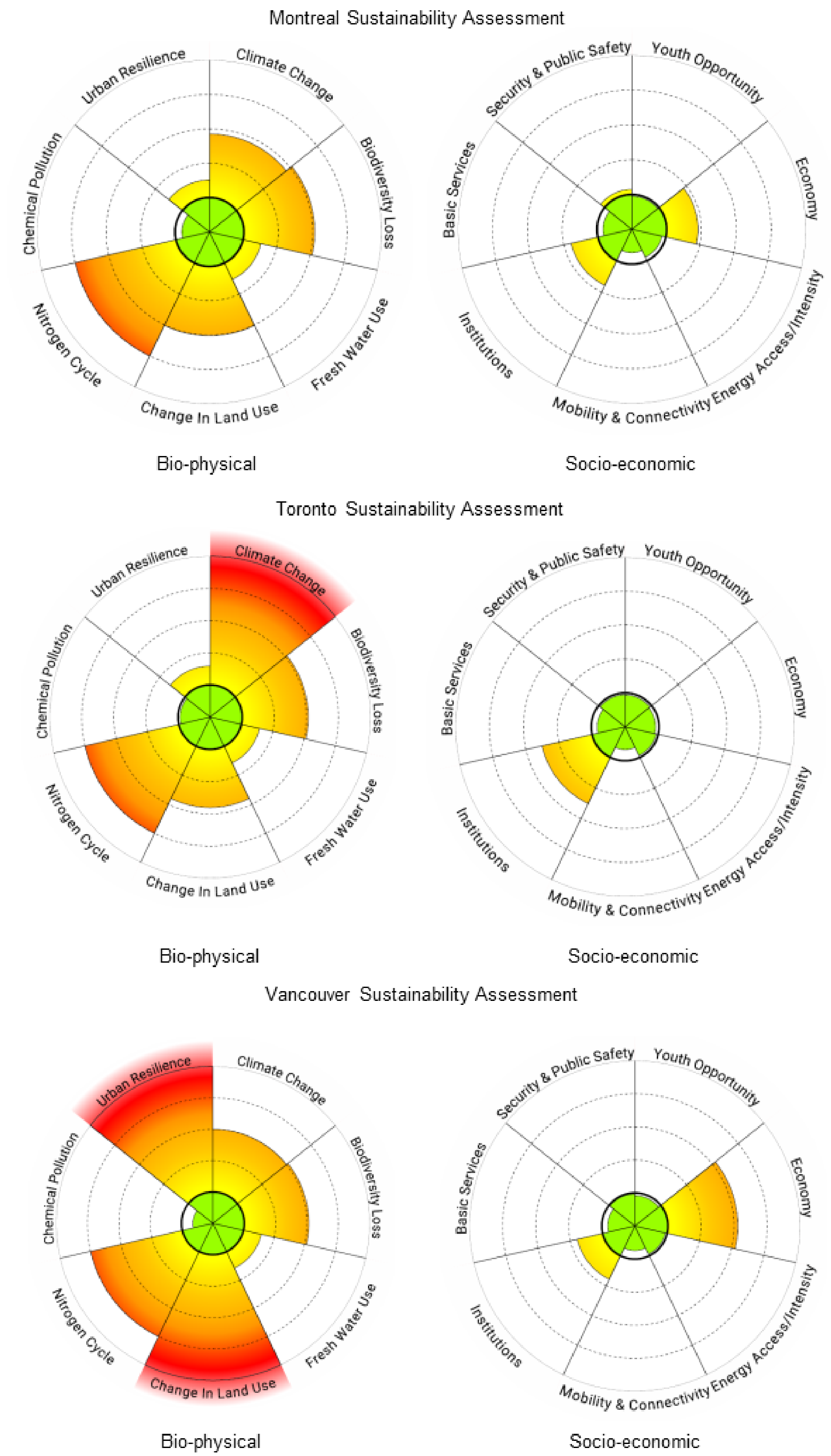

Figure 1: Sustainability Assessments: Montreal, Toronto and Vancouver

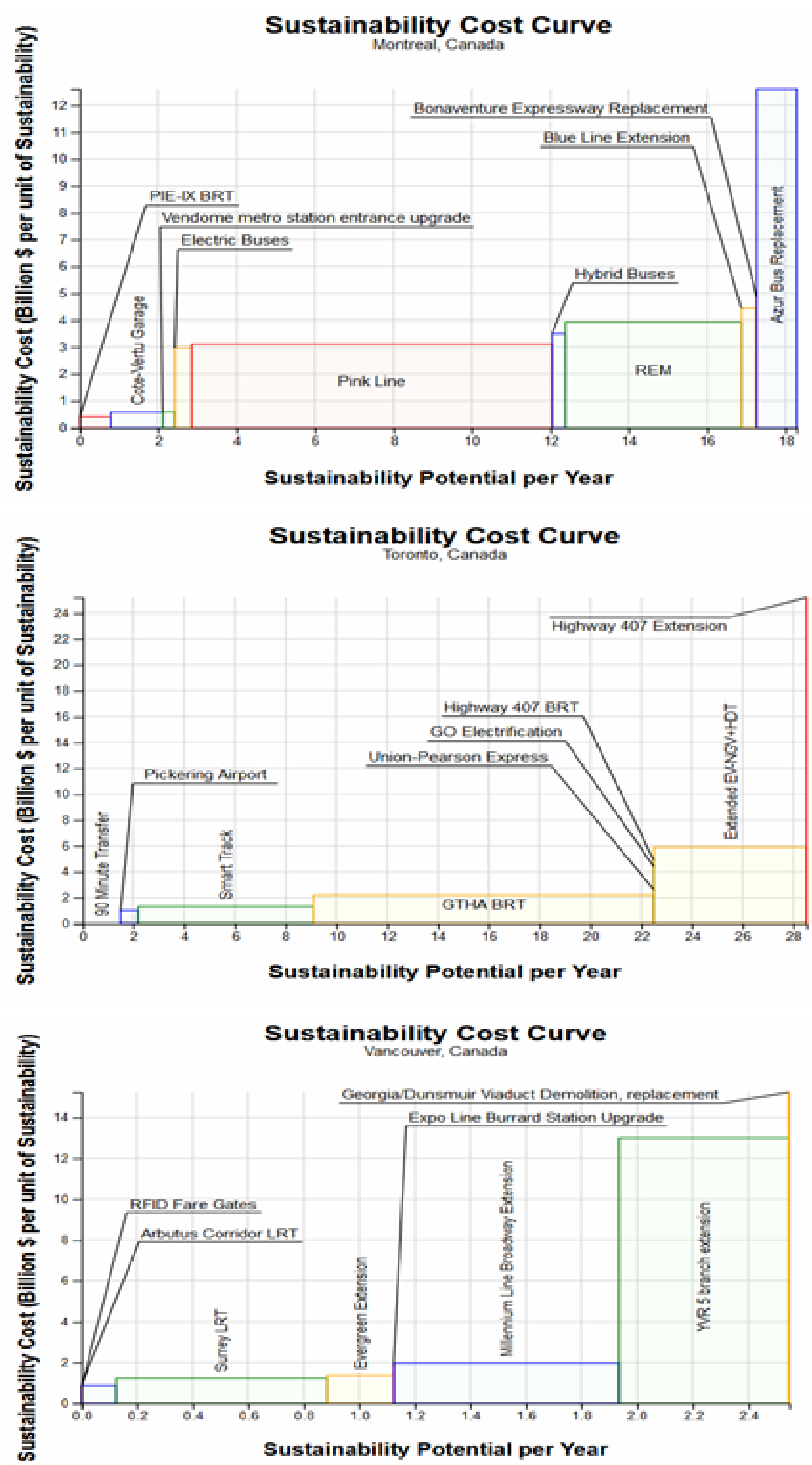

Figure 2: Sustainability Cost Curves: Transportation projects in Montreal, Toronto and Vancouver

Table 1: Transportation projects assessed

Project	Est. capital cost	Operating cost per year	Operation starting year	Number of new users
Montreal				
REM rapid transit	$5.5 billion	$0.19-$24/ person/km	2020	167,000/day
Pink Line	$5.9 billion	$172 million	2028	250,000 new riders
Blue Line	$3 billion	$30 million	2025	45,000 new riders
Hybrid buses	$225 million	$75 million	2020	300 new buses
Electric buses	$2.8 billion	$85 million	2025	<500
Côte-Vertu Garage	$440 million	$10 million	2022	Wait time reduced; expected ridership increase
PIE-IX BRT	$300 million	$7 million	2022	70,000
Azur Bus Replacement	$1.2 billion	$405 million	2018	8% more per bus (1104)
Vendôme métro entrance	$76.5 million	$10 million	2019	Increase by 18M in 2021
Bonaventure Ex. Upgrade	$142 million	$20 million	2017	5,000
Toronto				
90 minute transfer	$10 million	$12 million	2015	100,000/day
Pickering airport	$2 billion	$180 million	2030	32,600
Smart Track	$5.3 billion	$1 billion	2021	200,000
GTHA BRT	$14.6 billion	$820 million	2020	285,640
Union Pearson express	$380 million	$310 million	2015	6,000
GO electrification	$860 million	$420 million	2023	4,617
Highway 407 BRT	$1.39 billion	$160 million	2020	5,940
Highway 407 extension	$1 billion	$600 million	2015	6,000
Extended NGV-EV Market	$3.4 billion	$1 billion	2020	1,140,000
Vancouver				
Pattullo Bridge Replacement	$1 billion	$20 million	2023	10% increased capacity, 25-35% reduction @peak hours (77,000/day)
Surrey LRT	$2.1 billion	$22 million	2023	2040 passengers/hr/direction
Millennium Line Broadway Extension	$1.98 billion	$22.3 million	2025	67,000/day
YVR 5 branch extension	$5.6 billion	$275 million	2037	accommodate 35 million/yr (vs 22.3 in 2016)
Georgia/Dunsmuir Viaduct Demolition, replacement	$200 million	$25 million	2025	5,000/day
Expo Line Burrard Station Upgrade	$61 million	$10 million	2021	need to support 25,700 pphpd by 2041
RFID Fare Gates	$9 million	$2 million	2018	1,000/day
Arbutus Corridor LRT	$1 billion	$10 million	2040	50,000
Evergreen Extension	$1.35 billion	$10 million	2016	30,000
George Massey Tunnel Replacement	$3.5 billion	$20 million	2022	11,200

Detailed methodological discussions, and an initial Toronto transportation cost curve is presented in Hoornweg, 2015. Updated Toronto estimates, and a similar suite of transportation projects for Montreal and Vancouver, are presented in Table 1. Figure 2 provides sustainability cost curves for possible transportation projects in Montreal, Toronto and Vancouver. The x-axis provides the sustainability potential per year while the y-axis measures sustainability costs per unit of sustainability. Projects on the left-hand side of the curve provide lower cost initiatives (compared to those on the right). The length of the activity along the x-axis indicates its overall contribution toward sustainability (the wider the activity the greater the benefit).

Projects considered initially for Toronto include: 90 minute transfer (on TTC), Smart Track, GTHA Bus Rapid Transit (BRT) with electric vehicles, Union Pearson Express, Pickering Airport; GO Electrification, Highway 407 BRT, natural gas and electric vehicles market penetration, Highway 407 extension.

The proposed 90-minute transfer provides the greatest degree of sustainability for lowest cost while extension of Hwy 407 provides the least. Degree of sustainability is measured based on number of users impacted, costs and environmental/social impacts. The activity with the most sustainability potential is the integrated Highway 407 BRT with electric vehicles linkages. This reflects the high number of potential users and significant GHG reductions.

Projects considered for Montreal include: Réseau électrique métropolitain, Pink Line, Blue Line extension, hybrid buses, electric buses, Côte-Vertu Garage, PIE-IX BRT, Azur bus replacement, Vendôme metro station upgrade, Bonaventure Expressway upgrade.

Projects evaluated do not necessarily reflect overall feasibility and provide an order-of-magnitude for illustrative purposes. Cost curves are derived directly from the website city-sustainability.com and are able to facilitate changes to inputs as more information is available. The Pink Line, for example, provides significant sustainability potential although the project is still notional. The PIE-IX BRT provides the most cost-effective sustainability while the Azur bus replacement has the highest cost.

Projects considered for Vancouver include: Pattullo Bridge, Surrey LRT, Millennium Line, YVR 5 branch extension, Georgia/Dunsmur viaduct replacement, Expo Line Burrard Station upgrade, RFID fare gates, Arbutus Corridor LRT, Evergreen extension, George Massey tunnel replacement.

Similar to Montreal and Toronto, large sustainability potential accrues from transit lines such as the proposed Surrey LRT and expanded Millennium Line extension. Relatively low-cost investments such as RFID readers provide high sustainability potential (far-left of the curve), while the Georgia/Dunsmur viaduct replacement provides at relatively high cost (right side of the curve). This illustrates the need to maintain a broad overview of the overall transportation system, since individual projects may appear unduly pessimistic (or optimistic) if viewed in isolation. However, through the MAC a preliminary assessment readily emerges to help focus discussions.

For illustrative purposes, selected projects provide a suite of possible options where basic information is readily available. Sustainability cost curves are dynamic and are expected to be regularly updated as data is refined (especially, costs, numbers of user and start-up date). Projects can also be modified to provide greater sustainability potential, e.g. the GTHA 407 BRT expanded with widespread adoption of electric vehicles.

6. Discussion

Urban infrastructure, especially in the transportation sector, has notoriously low levels of productivity. While the manufacturing sector enjoyed an eight-fold increase in productivity since 1950 (economic value per financial input), productivity in the construction sector has not increased (McKinsey, 2017). Infrastructure projects are often subject to interference by interest groups and changing political imperatives, e.g. Subway lines and station locations. These pressures will likely remain a function of these activities – as high costs and long timeframes are involved. However, sustainability cost curves that are regularly updated and widely understood by the community, can significantly enhance prioritization and comprehensive assessment of potential investments. Sustainability cost curves can assist in enhancing productivity in the infrastructure (construction) sector.

Sustainability cost curves provide an accessible way to compare investments within a city (urban area), and across cities. Values can be quickly adjusted as new information warrants. Through a comprehensive assessment that includes local and global priorities, the degree of sustainability, or level of 'green', for infrastructure can be assessed and readily communicated.

As shown in Figure 2 for Montreal, Toronto and Vancouver, the cost of sustainability and annual sustainability potential for an activity, provides an order of magnitude assessment to facilitate planning discussions. As the engineering community relies on cost-benefit analysis and factors of safety to assure project practicality, a 'factor of sustainability' should similarly be calculated and communicated as a typical engineering assessment.

As illustrated, sustainability cost curves can be developed with open-source information. Similar to convergence on the mean for a sporting event's betting-line, or as Galton (1907) showed at London's Fall Fair, 'guess the weight of the ox', accurate estimates can emerge for activities investigated through sustainability cost curves. Once publicly available, and regularly updated, these curves will be sufficiently robust to withstand manipulation or unsubstantiated criticism (or championing) by affected stakeholders.

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