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Public Transportation and Sustainability: A Review

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Abstract

Public transportation is often framed as a key component of building sustainable cities. Conversely, the social, economic, and environmental impacts of transport are framed as critical issues that can challenge the sustainability of cities and regions. This paper presents a critical literature review of the relationship between public transportation and sustainability. First the paper offers a review of key sustainable transportation concepts and how public transport contributes to sustainability goals. Second, the paper reviews past studies that analyse sustainable transportation in order to develop recommendations for planning, engineering, and researching sustainable public transport. Finally, the paper concludes by offering suggestions for future research into the sustainability performance of public transit.

Keywords: *public transportation, public transit, sustainability, sustainability analysis*

1. Introduction

An effective transportation network is an essential driver for the economic and social development of a city. Transportation systems have been described as the "lifeblood" of cities in recognition this critical role (Vuchic, 1999). As cities grew in the 20th century, expanded transportation networks furthered urban development but also created a series of challenges towards achieving sustainability.

Sustainability is commonly explored in terms of the theories of sustainable development. A commonly used definition of sustainability comes from the Brundtland Commission's report *Our Common Future* - "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

Sustainable development and transport are linked – for example cities around the world experience congested roads due to reliance on automobiles, which leads to emissions and social costs such as accidents (Moavenzadeh *et al.,* 2002). As a result, transportation networks take on a paradoxical role – they drive urban development but at the same time lead to a series of challenges. These challenges include economic, social, and environmental impacts (Banister, 2005). Challenges across these three spheres can be considered as 'sustainability challenges'.

Investing in public transit is often framed as a critical mechanism to reducing auto dependence and lessening the impact of transportation networks on society and the environment, while also enabling transportation to continue to play a critical role in sustainable development.

Ramani *et al.* (2011) proposed a general sustainability assessment framework for transportation agencies along with a review of key sustainable transportation concepts. This framework presents a 5 step process, with feedback loops between each level of the process. The five components of the process are: (1) understanding sustainability; (2) transportation sustainability goal development; (3) development of objectives; (4) development of performance measures; and (5) performance measure application. This paper sets out to clarify the role of public transportation in sustainable urban development through a critical literature review that also provides evidence and information for each of these five steps. This review is divided into three sections. Section 2 presents a review of definitions of sustainable transportation and how public transportation can achieve sustainable transportation goals. Section 3 includes a review of techniques for quantifying and measuring sustainable transportation. Finally, Section 4 contains key conclusions, which summarize the review and note potential future research directions.

2. Sustainable Transportation

2.1 Overview

The analysis of transportation systems is a broad topic with many elements including human behaviour, network configuration, geography of the system, prevailing influences on the system (politics and economics, for example), and the types of mode of

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travel that are available (Manheim, 1979). Sustainability is also a very complex topic that explores all elements of: human welfare (the social aspects of sustainability), economic expansion, and the impacts of human growth and development on the environment. Given the degree of complexity of both topics, combining the two into a common field creates a challenging topic to address (Cidell, 2012). This review seeks to clarify contemporary views on the intersection of these two complex fields: transportation and sustainability.

2.2 Defining Sustainable Transportation

A foundational concept in applying sustainability to transport is the triple bottom line. Theis (2012), Black (2010), Jeon (2007), Kennedy (2005), Newman and Kenworthy (1999), Banister (2005), consider sustainable development issues using three dimensions – environment, economy, and society. These three dimensions are commonly referred to as a 'triple bottom line' (Pei *et al*., 2010). They are defined as follows by Low (2003):

- **Environment:** the environmental or ecological dimension considers the impacts of human activities and developments on changing local and global environments
- **Economy:** the economic development is the process of a community's growth or progress towards economic goals, such as increased wealth, employment, productivity or ultimately welfare
- **Social:** the social dimension of sustainability often is described as dealing with issues of equity and inclusion (Low, 2003).

Before sustainability became a topic of common discourse in the late 1980s, the need to address a variety of impacts of transportation systems was a key component of transportation planning. For example, Manheim (1979) wrote on viewing transportation systems as holistic entities, with a focus on multimodal solutions that take into account social, economic, political, environmental, and other considerations. This approach was written before sustainability became a mainstream research topic, but is in line with the principles of sustainability and the goals set out in the Brundtland report, and other authors who have since studied and expanded upon the sustainability concept.

Schiller *et al.* (2010) suggest that the application and definition of sustainability goes beyond technical progression. Developing sustainable transportation involves society at large – including aspects of planning, policy, economics, and citizen involvement (Schiller *et al.*, 2010). The study highlights the emergence of sustainable transportation in terms of three main concepts: (1) Concerns on transportation's impacts and the counter productivity of conventional highway-oriented planning that emerged from the 1970s onward; (2) Recognition that reducing traffic in cities (either through calming, or pedestrianization) achieved health and environmental benefit; and (3) Increased awareness of sustainability concepts after the Brundtland report was published. These three considerations are positioned as key drivers of the emergent concern for sustainability in transport.

As transportation has a variety of negative impacts, specific focus on environmental, economic, and social issues should be included in a definition of sustainable transportation and its application to decision making (Bongardt *et al*., 2011). Despite an increasing volume of sustainable transport studies, within the literature there is no accepted single definition of sustainable transportation or how to measure it (Bongardt *et al*., 2011).

This review classifies definitions span as aspirational (providing general guidance for sustainability and transport) or objective oriented (outlining specific measurements or considerations for a transport system to be sustainable).

Aspirational definitions include those written by Black (2010). Black suggests that a sustainable transportation system is one that applies the Brundtland definition or simply said "transportation that satisfies the current transportation and mobility needs without compromising the ability of future generations to meet those needs" (Black, 2010).This definition locks sustainable transport in line with broader research on sustainability.

An objective oriented definitions commonly referred to in the literature is the "Centre for Sustainable Transportation definition". It expands on other definitions and outlines three key elements of sustainable transportation: (1)Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations; (2) Is affordable, operates efficiently, offers choice of transportation mode, and supports a vibrant economy; (3) Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise (The Centre for Sustainable Transportation, 2005).

Vreeker and Nijkamp share a similar set of objectives for transportation and identify that these may be difficult to balance: (1) Economic efficiency – reflected in the increased competitiveness of regions through an improvement in connectivity; (2) Social equity – reflected in more equal opportunities for better access to transportation facilities (for different socio-economic groups, for less central areas); (3) Environmental sustainability – reflected in more emphasis on coping with the negative externalities of the transportation sector, such as pollution, noise, landscape decay, congestion, lack of safety (Vreeker and Nijkamp, 2005).

2.3 Frameworks for Understanding Sustainable Transportation

A growing body of research seeks to apply definitions of sustainable transport into applicable frameworks. These frameworks provide understanding for sustainability in two ways: supporting understanding of how projects or programs may make transport more sustainable and frameworks for understanding the impacts of transport.

Banister outlines a sustainable transportation paradigm composed of four aspects: (1) Actions to reduce the need to travel; (2) Encouragement of modal shift; (3) Short trip lengths; (4) Increased efficiency (Banister *et al*., 2008). This framework may be applied to classify policies or projects based on how they

support sustainable transportation.

Another thorough attempt to outline a definition framework to further sustainable transportation comes from Kennedy et al. (2005). Sustainable transportation is framed as a critical urban issue intersecting with complex global issues, such as climate change, as well as local issues like human health. Similar to other frameworks, the authors frame sustainable urban transportation as a balance between economy, environment and society, however the difference is in how this balance is developed. Four pillars are suggested: (1) **Governance**: "the establishment of effective bodies for integrated land-use transportation planning"; (2) **Funding**: "the creation of fair, efficient, and stable funding mechanisms"; (3) **Infrastructure: "**strategic investment in major infrastructure"; (4) **Neighborhoods**: "the support of investments through local design" (Kennedy *et al*., 2005).

A key study on sustainable transportation was conducted by Jeon (2007). This work suggests that all frameworks should consider: (1) How effective the transportation system is; (2) Impacts of the system on economic development; (3) Impacts of the system on social quality of life; (4) Impacts of the system on environmental integrity (Jeon, 2007). This study then presents a framework that is comprehensive and utilizes the three common terms from the triple bottom line framework, but it also explicitly treats transportation effectiveness as a key element of sustainability. The framework suggests that this expanded triple bottom line with four dimensions is a key tool to actively applying sustainability analysis to transport.

2.4 Key Transportation Sustainability Challenges

Transportation intersects with many segments of society and the environment and can create many benefits for human welfare. It can enable economic growth and connect people to necessary services. However, it can also create a number of challenges. A growing body of research suggests that current trends of automobile oriented transportation are unsustainable due to key impacts across environmental, economic, and social considerations as noted in Table 1, drawn from Litman and Burwell (2006).

A key issue in auto dependent cities that greatly impacts their sustainability is congestion. Congestion is characterized by low traffic flow rate, and high density of vehicles and is a key issue associated with auto dependence. Congestion has been deemed a worldwide phenomenon that is caused by increasing automobile dependence (Moavenzadeh and Markow, 2007). Negative impacts include – environmental (increased pollution), loss of economic productivity, and social (human health and equity impacts).

Transportation is a large contributor to pollution and apart from energy generation and industrial processing, transport is the largest contributor to air pollution (Dobranskyte-Niskota *et al.*, 2007). The economic impacts of congestion are explored by Bannister (2005), who suggests that when a system fails to provide acceptable levels of mobility for different trip purposes and different modes it is considered unsustainable from an economic point of view. Auto-dependent transport can be seen as a driver of social sustainability issues including health burden of a sedentary lifestyle (Cidell, 2012).

Schiller *et al.* (2010) and Newman and Kenworthy (1999) provide further context on the unsustainability of auto-dependence beyond the congestion impacts.

Schiller *et al*. (2010) write that due to the decreased travel time and increased personal mobility bestowed by automobiles, cities were able to expand greatly with fewer hurdles than when cities were governed by other modes of travel. While this method of development yielded increased mobility, it also yielded the sustainability challenges as discussed in table 1. The authors suggest that auto-depencen has created environmental impacts including increased emissions for mobility as well as increased land consumption to develop freeways. Schiller *et al.* (2010) argue that economic impacts of auto-dependence are shown in cost of infrastructure development, which are higher for automobile dependent systems than for other modes due to the intense level of freeways required to facilitate movement. The authors suggest that social sustainability issues be explored through the ideas of severance, which occurs where intensive highway development severs communities.

Newman and Kenworthy (1999) also suggest severance is a key social issue that decrease interactions between neighbors and can fragment communities and lead to community deterioration - with sprawl, communities can become bedroom communities with little interaction or sense of community. This growth is most common in North America while in other parts of the world, such as East Asia or Europe, cities are denser and the development patterns are less stratified (i.e mixed use is more prevalent) which makes the automobile a less dominant mode (Newman and Kenworthy, 1999).

2.5 Public Transit Benefits

Public transit is a key driver of sustainability in the transport sector as well as a tool to address the sustainability impacts of

Table 1. Transportation Impacts

Environmental	Economic	Social
Air pollution	Accessibility quality	Equity/fairness
Climate change	Traffic congestion	Impacts on mobility disadvantaged
Noise pollution	Infrastructure costs	Affordability
Water pollution	Consumer costs	Human health impacts
Hydrologic impacts	Mobility Barriers	Community cohesion
Habitat and ecological degradation	Accident Damages	Community livability
Depletion of non-renewable resources	Depletion of non-renewable resources	aesthetics

Adapted from Litman and Burwell (2006)

auto-dependence. This review clarifies the expected benefits of public transit.

Transit can provide energy efficient transportation in an urban setting that competes with the speed of private automobile travel (Schiller *et al*., 2010). This positions transit as a potential competetor to the automobile and a key tool for reducing dependence on automobiles, which in turn can reduce auto-oriented impacts. Given the link between energy consumption and pollution, this positions transit as a key provider of sustainable mobility. Schiller *et al.* (2010) suggest that the space efficiency and social benefits of transit trigger benefits across a suite of sustainability criteria and conclude that transit can be a key factor in reducing auto travel and auto dependence in cities. These benefits could include benefits across all the impacts noted in Table 1, including reduced emissions and consumption of land (environment), improved access (social), increased economic efficiency and contributions to economic activity (economy).

Banister also suggests that a mode shift to transit can achieve sustainable development and urbanization goals, however this mode shift must be accompanied by a reallocation of the public space that was once used for auto travel (Banister, 2008).

Newman and Kenworthy discuss a concept of 'Transit Leverage' – the notion that substituting a transit trip with a car trip has great benefits for the transportation system – in general replacing a car trip with a transit trip greatly reduces the passenger km travelled within a network. They articulate four major points that support transit as a key transportation intervention for promoting sustainability in cities: (1) Good transit options cause businesses and people to adjust their location behaviour; (2) People who take transit combine trips into single trips – rather than separate car trips (reducing the total number of trips); (3) Households that use transit give up a car; and (4) Transit users often use walking or cycling to get to stations or stops. Public transit's benefits exist outside of the realm of direct transportation service – for example, the Canadian Urban Transit Association (CUTA) estimates that there is a $10 billion benefit to the Canadian economy each year due to transit (Canadian Urban Transit Association, 2010).

3. Analyzing the Sustainability of Public Transit

Vreeker and Nijkamp (2005) suggests that transportation planning problems have a degree of complexity that requires the application of both theory and practical policy. This literature review surveys key contributions from research that fills this gap by providing new insights into sustainability and transport for planning, research, and policy development. It focuses on two areas: (1) The development of effective indicators, metrics, and indices to quantify and measure sustainable transportation; and (2) studies of sustainable transportation that have either applied indicators, metrics, and indices, or have utilized another technique to measure sustainable transportation. The focus of this review is on clarifying the studies and tools that have been able to measure sustainability benefits, and assessing their application for public transit analysis.

3.1 Review of Sustainability Indicators/Measurement

The field of public transit performance analysis has an established literature base of theory and applied studies that have analyzed the performance of transit under a variety of lenses including efficiency, effectiveness, economic performance, and environmental impact. While early studies were concerned with operating parameters of transit systems, such as operating expense per passenger, and were developed to understand economic efficiency (e.g. revenue vehicle miles per vehicle) or to understand vehicle utilization, more recent studies have attempted to fill a research gap by assessing transport more holistically

Pope *et al.* (2004) describe sustainability assessment as a process of exploring the implications of existing policies, plans, programmes, projects, or pieces of legislations, or existing practise or activities on sustainability. The authors suggest that while there are many attempts to assess sustainability, many could be declared as extensions of an environmental impact assessment framework, that reflect a triple bottom line conception of sustainability, but do not necessarily truly contribute to sustainable practice by providing an integrated framework (Pope *et al*., 2004). The research suggests that most definitions and approaches to sustainability assessment are generic and describe a suite of processes and that more rigorous approaches are necessary to truly use assessment to promote sustainability.

Analysing and planning transportation systems relies on indicators to understand trends and model or analyse impacts (Sustainable Transportation Indicators Subcommittee, 2009). The Subcommittee also suggests that comprehensive and balanced indicator sets should include indicators from all major categories of issues in order to improve the decision making framework.

Littman and Burwell (2006) suggest that conventional evaluation techniques used in transportation analysis mostly consider motorized travel and may not fulfil sustainable transportation objectives – meaning there is a need for expanded indicators and methodologies for sustainability analysis (Litman and Burwell, 2006). This identifies a clear path for further research into new evaluation techniques that allow for a more nuanced assessment of transport sustainability for other modes – including transit.

To support further research into public transit indicators, a set of studies was reviewed including Bongardt *et al.* (2011), Haghshenas and Vaziri (2012), Dobranskyte-Niskota *et al.* (2007), Litman (2013) and Jeon *et al.* (2009) to develop a set of transit considerations and sustainability objectives, as shown in Table 2. The literature suggests that these are critical considerations for understanding how transit can contribute to sustainability.

3.2 Review of Application of Sustainability Assessment

Sustainability in transportation is a widely acknowledged necessity due to triple bottom line impacts - indicators allow impacts of transportation to be recognized and measured and can be used as a basis for policy making (Bongardt *et al*., 2011).

Table 2 – Sustainability Considerations for Public Transit

	Sustainability Considerations	Objective	Linked to
Environment	Decrease passenger Energy Use	Minimize energy consumed/pkm	(Dobranskyte-Niskota *et al.*, 2007), (Haghshenas and Vaziri, 2012), (Litman, 2013)
	Decrease passenger contribution to climate Change	Minimize ghg emissions /pkm	(Dobranskyte-Niskota *et al.,* 2007), (Haghshenas and Vaziri, 2012), (Bongardt *et al.*, 2011), (Jeon *et al*., 2009),
	Decrease Pollution - Land, air, water	Minimize pollutants or emissions/pkm	(Dobranskyte-Niskota *et al*., 2007), (Haghshenas and Vaziri, 2012), (Jeon *et al.,* 2009)
	Limit Ecological Disturbance	Minimize disruption by right of way and system construction	(Dobranskyte-Niskota *et al*., 2007), (Haghshenas and Vaziri, 2012), (Bongardt *et al.*, 2011), (Jeon *et al.*, 2009), (Litman, 2013)
Economy	Reduce user cost	Reduce Travel Time	(Dobranskyte-Niskota *et al.,* 2007), (Haghshenas and Vaziri, 2012), (Jeon *et al.*, 2009), (Litman, 2013)
		Reduce direct monetary costs	(Dobranskyte-Niskota *et al*., 2007), (Litman, 2013)
	Increase system economic efficiency	Reduce operating cost per unit of travel	(Dobranskyte-Niskota *et al*., 2007), (Haghshenas and Vaziri, 2012)
		Reduce capital cost	(Dobranskyte-Niskota *et al*., 2007), (Haghshenas and Vaziri, 2012)
	Improve System independence	Maximize recovery or reduce required subsidy	(Dobranskyte-Niskota *et al*., 2007)
	Increase demand relative to GDP	Maximize passenger km travelled relative to gdp	(Dobranskyte-Niskota *et al*., 2007), (Bongardt *et al.*, 2011)
Social	Improve affordability	Minimize cost of transit as portion of user or household income	(Dobranskyte-Niskota *et al*., 2007), (Jeon *et al.*, 2009), (Litman, 2013)
	Increase accessibility	Maximize accessibility across multiple dimensions (user, system)	(Dobranskyte-Niskota *et al.*, 2007), (Haghshenas and Vaziri, 2012), (Bongardt *et al*., 2011), (Jeon *et al.*, 2009), (Litman, 2013)
	Limit health impacts	Minimize exposure to and illness/death fro, human health impacting emissions	(Dobranskyte-Niskota *et al.*, 2007), (Bongardt *et al*., 2011), (Jeon *et al.*, 2009)
	Limit safety impacts	Minimize injury and death from system operation	(Dobranskyte-Niskota *et al*., 2007), (Bongardt *et al*., 2011), (Jeon *et al*., 2009), (Litman, 2013)
System Effectiveness	Improve operations and capacity utilization	Maximize reliability and capacity utilization	(Dobranskyte-Niskota *et al*., 2007), (Litman, 2013)
	Shift demand from automobile to transit	Maximize the ridership of transit	(Bongardt *et al*., 2011), (Jeon *et al*., 2009), (Litman, 2013)

Adapted From: Bongardt *et al.* (2011), Haghshenas and Vaziri (2012), Dobranskyte-Niskota *et al.* (2007), Litman (2013), Jeon *et al.* (2009)

While there is much discussion on indicators and their application, it was found that few studies use sustainability indicators to compare systems (Haghshenas and Vaziri, 2012). Recent studies have applied the concept of 'holistic' sustainability including: Jeon (2007), Kennedy (2002), Haghshenas and Vaziri (2012), and Miller (2014). These studies were reviewed to share the state of practice in research. These studies represent a cross section of literature that considers sustainability analysis as a problem with multiple dimensions or criteria that can be quantified and understood. These studies utilize analysis that break down various aspects of sustainable transportation into sets of criteria or accounts of analysis and evaluate these criteria/accounts in order to understand the sustainability implications of the system or problem being explored.

Kennedy (2002) provides an in depth comparison of private and public transportation in the Greater Toronto Region. This study contributes to the field of sustainability analysis by conducting a holistic triple bottom line comparison of the benefits and negative impacts of private and public transportation within a fixed geographic area. A set of indicators are set out and data is collected that combined historical sources with analytical models or estimates where appropriate to conduct a rigorous analysis. Unlike other studies mentioned in this section, there is no effort made to aggregate the data collected or the indicators used for composite indicators or indices, however, the results are clearly explored through in depth analysis. As there are multiple indicators under each category, the potential trade-offs, costs, and benefits within each sustainability category, as well as within each system can be observed and better understood. The key take away from this study is the general approach to setting out indicators and categories for analysis as well as systems being compared as well as setting a clear scope for analysis.

A set of Composite Sustainability Index (CSI) studies was reviewed: Jeon (2007) and Jeon *et al*. (2009), Haghshenas and Vaziri (2012), and Miller (2014). These studies all apply CSI techniques to quantify the sustainability performance of public transit systems. CSIs combine a set of sustainability indicators numerically using normalization and weighting techniques, both

of which impact the final CSI. CSIs are typically a single integer that reflects the overall sustainability performance of a transport system. These techniques were applied uniquely in each study.

Jeon (2007) and Jeon *et al.* (2009) presents a methodology for sustainability analysis that uses multi criteria decision making processes and composite indicators. First, the studies provides a literature review of sustainability based in the triple bottom line paradigm, and sustainability indicator frameworks that reviews common frameworks for utilizing indicators in sustainability analysis. These studies are focussed on applying composite indicator or index techniques to analyzing sustainability plans in a geographic region to both better understand how different plans perform under rigorous sustainability analysis and also contribute to the state of applying holistic sustainability research to decision making problems. These studies break down sustainability into four categories as an expansion of the triple bottom line framework: environmental, social, economic, and system effectiveness. These four categories measure the impacts of different plan alternatives on the city and transportation system, as well as those who live there. Two alternative transportation-network-land use scenarios for the Atlanta Metropolitan region were modelled and the outputs with respect to 30 indicators were analyzed and compared to a 2005 base case scenario. The key takeaways from the Jeon studies is the methodology of how to use composite indices with a modified triple bottom line framework under a MCDM environment in order to compare the overall sustainability of multiple systems or plan alternatives. This technique can be adapted to for public transit analysis by determining appropriate measures or indicators of public transit sustainability and selecting appropriate data.

A second CSI oriented study focuses on the comparison of multiple cities based on their overall transportation systems. Haghshenas and Vaziri (2012) presented a study of cities and their transportation systems from a holistic sustainability lens. Similar to Jeon (2007) and Jeon *et al*. (2009) the study utilized an approach grounded in MCDM with different sustainability categories each with a set of factors represented by an indicator. Also similar to Jeon studies, this study utilized a weighted sum equation to create composite sustainability indices for each city. This study utilized the UITP's (International Association of Public Transportation) millennium cities database for sustainable transportation, which contains 100 cities, along with environmental, economic, and social indicators to rank all cities in the database based on their relative sustainability performance. The overall contributions of the article are oriented around the development of composite indicators using weighed sum techniques, similar to the Jeon (2007), as well as basic insight into denser cities having more sustainable transportation systems.

Miller (2014) applies CSI techniques directly to the question of measuring the sustainability performance of public transit systems, which is at the heart of this review. This analysis develops the public transit sustainable mobility assessment project (PTSMAP) framework to aid in quantifying sustainability and understanding the overall sustainability performance of public transit. The tool outlines two ways to apply CSIs to understand public transit: performance assessment and plan assessment. Performance assessment focuses on characterizing an individual existing transit system's sustainability performance based on historic data. Planning assessment focuses on identifying the potential sustainability benefits of a proposed or planned public transit alternative. The tool was tested against all major LRT and heavy rail systems in the USA using the National Transit Database, as well as a planning study from Vancouver, Canada. The results demonstrated how 16 sustainability indicators could be used to develop a set of composite indicators (environmental, social, economic, effectiveness) and one CSI. The analysis of USA rapid transit systems was used to assess relative comparison of LRT and heavy rail modes – including the

Table 3. Review of Sustainability Studies

Author	Analysis Tool	Key Concepts
Kennedy (2002)	· Multi Criteria Decision Making · Focussed on clarifying key sustainability issues and approaches used for analysis	· Analyzed two different types of travel in the GTA · Developed clear indicators and use them to explore benefits, costs, trade-offs based on triple bottom line · Developed a rigorous analysis for each area of sustainability
Jeon (2007), Jeon, Amekudzi, and Guensler (2009)	· Composite Sustainability Index · Applied to high level transport demand model outputs · Focuses on the transport network/highway expansion scenarios	· Analysed three scenarios in the Atlanta Metropolitan area · Used 30 indicators based on an expanded triple bottom line to understand trade-offs and costs/benefits as well as to develop composite sustainability index · Normalization based on single attribute utility, weights equally assigned
Haghshenas and Vaziri (2012)	· Composite Sustainability Index · Applied to high level travel data to compare cities/regions	· Analysed the transport systems of 100 cities based on a variety of sustainability factors · Used z-score normalization and weights that were equally assigned
Miller (2014)	· Composite Sustainability Index · Built for purpose transit assessment index applied to studies (Vancouver rapid transit expansion) and existing transit (USA systems)	· Adapted CSI techniques for the analysis of rapid transit · Proposed two types of analysis to assess sustainability of rapid transit · Analyzed 32 rapid transit systems in the USA and outlined performance by rapid transit mode (LRT, heavy rail) · Analyzed plan alternatives to demonstrate application of CSIs to planning and policy development

development of performance tier classification for rapid transit sustainability. This analysis also analyzed how three normalization techniques (z-score, min/max, distance to maximum) will impact how CSIs are calculated. Additionally, the Vancouver case study indicated how CSI methodologies can be adapted to existing planning processes to provide new insight into how potential systems can perform.

These studies are summarized in Table 3.

CSI tools have become a key element of sustainability research for transit and transport more broadly due to their flexible nature. Because CSIs have been applied in many other fields there is an existing body of research and practice to draw upon. Nardo et al (2005) provide a guidebook for the application of CSIs and note key pros, such as being able to summarize complex issues into a single value. However, there are also cons, such potential to be misleading if they are not carefully constructed and reviewed (Nardo *et al.*, 2005).

4. Conclusions

4.1 Summary

This paper provides a critical literature review of key topics for understanding the state of research and practice of sustainability analysis for public transit. First, a conceptual base was established by reviewing comparative definitions of sustainable transportation and key sustainability impacts of transport networks. Second a review of public transit's contributions to sustainability and other benefits of transit was presented. Finally, the paper reviewed key studies that provide methodologies to analyze sustainability of transportation systems.

This review, while not exhaustive, reflects the depth of discussion within planning and engineering literature with respect to sustainability and transportation. As noted in the preceding discussion, this is a complex topic that requires further research and development to support understanding how transport impacts urban sustainability and also enable the development of robust research, planning, and engineering support tools that can enrich how transport systems are developed and operated. Because public transport systems offer potential to achieve sustainable urbanization goals, further research into better understanding sustainability benefits will help decision makers and planner/engineers alike in developing optimally sustainable transport interventions.

4.2 Areas for Further Research

As noted in the literature review, the role of multi criteria analysis and CSIs within transport research has grown. These techniques allow sustainability, which is a complex topic, to be explored quantitatively across a large number of indicators Jeon (2007) and Jeon *et al.* (2009), Haghshenas and Vaziri (2012), and Miller (2014) reflect that sustainability performance of a transport system may be assessed with CSI techniques; however, CSIs are dependent on normalization and weighting techniques used. Further research should focus on clarifying how to apply varying weighting techniques to public transit CSIs and the impact of weighting on CSI performance. Similarly, different data normalization techniques may impact the performance of options, as noted in Miller (2014) and further research into characterizing normalization impacts may benefit the application of CSIs. Additional research should also consider the impact of uncertainty on CSIs. Because uncertainty influences CSIs in terms of data inputs, normalization, and weighting, future studies should develop techniques to expand on the CSI processes proposed by Jeon (2007) and Jeon *et al*. (2009), Haghshenas and Vaziri (2012), and Miller (2014) to reduce uncertainty.

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