VALIDATING ALTERNATIVE CONCEPTUALIZATIONS OF SUSTAINABLE TRANSPORTATION

A Dissertation

by

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ABSTRACT

This study explores how the concept of sustainable transportation relates other broad and overarching concepts that have emerged recently in the transportation sector, such as livability, health, and resilience. This study uses the term "alternative conceptualization" of sustainable transportation to collectively reference discourse in the transportation sector that *explicitly* purports to promote sustainability, as well as discourse (such as the examples of livability, health, and resilience) that addresses aspects of sustainability *implicitly.* The primary goal of the study is to assess these alternative conceptualizations of sustainable transportation in relation to each other.

First, the study undertook a qualitative analysis of alternative conceptualizations of sustainability, on the basis of their scope, coverage of sustainability dimensions, and acknowledgement of inter- and intra-generational equity issues. The analysis demonstrated that there are overlaps, as well as significant differences between the various concepts.

Second, the study used transportation planning data to conduct an indicator-based case study for the El Paso metropolitan area. Data from the regional travel demand model and other sources were used to quantify a sustainability index, livability index, and health index for individual traffic analysis zones in the region, for four analysis years (2010, 2020, 2030 and 2040). Each index was comprised of representative indicators, which were normalized and aggregated in accordance with common multi-criteria decision-making methods. The analysis results demonstrated little correlation

between the quantified livability, sustainability, and health indices developed for the El Paso region. The indices also showed relatively low levels of change over time for a location. That is, the relative performance of a traffic analysis zone tended to stay the same, despite the modeled changes to the transportation system, demographics, and land use.

The main implication of the research findings is that despite overlaps at a theoretical level, concepts such as livability and health cannot necessarily serve as proxies for sustainability when implemented in practice. The study also provides insight into the challenges of making meaningful change in the area of sustainability over time and highlights the influence of factors beyond transportation, such as land use and socio-economic issues.

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1. INTRODUCTION

1.1. Background

Sustainable transportation is a term that is widely used to denote how concepts of sustainability and sustainable development are applied specifically to the transportation sector. These concepts are generally rooted in concerns about the impact of humans on the environment, and have evolved to cover the "triple bottom-line" of environmental, economic and social considerations.

Transportation is a major contributor to greenhouse gas emissions, affecting climate change and the environment; Transportation is also inextricably linked to people's daily lives, including access to jobs and other critical destinations. It also supports trade, commerce, and the economy, and is an important element for economic growth. Thus, "sustainable transportation", or "sustainability in transportation" has emerged as a vast area of research, planning, and policy. Despite this focus on sustainable transportation, there are several challenges that have limited or constrained progress toward sustainability. These stem from the broad nature of sustainability, and the resulting lack of consensus on what sustainable transportation means. Questions remain about how sustainable transportation principles are operationalized in the transportation sector, and how they can be evaluated rigorously through the use of frameworks and indicators.

Furthermore, recent years have seen the emergence of other broad and overarching concepts in the transportation field, such as health, livability or resilience. Discourse in these areas is seen to overlap with sustainability, raising questions about the relationship between these concepts, and whether they can be viewed as alternatives or competitors to sustainability; it is unclear whether they support or hinder progress toward sustainable outcomes.

1.2. Objectives

This study contributes to the understanding of how sustainable transportation as a construct is applied - specifically in light of challenges faced with overlapping and conflicting discourse around the subject. The overall goal is to validate *implicit* and *explicit* frameworks and discourse related to sustainability in transportation (termed here as “alternative conceptualizations” of sustainable transportation), using indicators. Specific objectives of the study are as follows:

1. Conduct a *qualitative analysis* of relationships between alternative conceptualizations of sustainable transportation.
2. Conduct a *quantitative analysis* using sustainability indicators to investigate the impact of alternative conceptualizations of sustainable transportation on measured outcomes.

The research results can help address questions about whether alternative conceptualizations of sustainable transportation are substitutable, i.e. can serve as proxies for each other. Further, the study can provide insight into the value of indicators in providing an accurate picture of the issue at hand, and the extent to which the overall evaluation framework affect the outcomes observed from indicators. These findings will also allow for a better understanding of how sustainability can be addressed in the U.S.

transportation planning context, where sustainability issues tend to be addressed both implicitly and explicitly.

1.3. Scope

The focus of this study is on transportation planning, where "planning" is used as a general term to denote activities related to the provision of transportation infrastructure and services to the public. The specific context of the discussions of policy and practice is what is broadly viewed as surface transportation planning in the U.S. It covers the planning activities conducted by metropolitan planning organizations, state departments of transportation and their partnering agencies in line with federal mandates, covering roadway transportation, transit and bicycle and pedestrian programs. The study is designed with the use of indicators (also known as performance measures or metrics) as the basis for a quantitative analysis. Data from the El Paso metropolitan area is used for a case study analysis conducted to validate the concepts that are developed.

1.4. Terminology

In this study, the terms sustainability and sustainable development are generally used interchangeably – though slight distinctions can be made between these two terms, as explained in the literature review. Similarly, the term "sustainable transportation" is used in this study to refer to efforts that apply sustainability-related concepts to the transportation sector. As discussed in the literature review, the term sustainable transportation is sometimes viewed as being more narrow or limiting than the concept of "transportation in support of sustainability". However, the term sustainable transportation is primarily used in this study, for clarity and convenience.

Finally, this study introduces the term "alternative conceptualization" of sustainable transportation as a collective term to reference implicit and explicit discourse related to sustainability. By including discourse that implicitly addresses sustainable transportation the term encompasses other broad and holistic frameworks that have recently emerged in the transportation sector, such as the concepts of livability, resilience, or health in transportation. Further discussion and justification of this is provided in Section 5.

1.5. Organization

Following this introductory section, Section 2 provides a literature review covering key concepts related to sustainable transportation, alternative planning frameworks and discourse related to sustainability, and the use of indicators as a means of assessing sustainability concepts. Section 3 draws on the literature review findings to frame the issues related to sustainable transportation, and make a case for needing a nuanced research approach to address the same. Section 4 provides an overview of the conceptual framework and research design for the qualitative assessment and quantitative analysis. Section 5 presents a qualitative assessment of alternative conceptualizations of sustainable transportation, and Section 6 presents the results from the quantitative analysis conducted for the El Paso metropolitan area in Texas. Section 7 then provides a discussion of conclusions and key findings.

2. LITERATURE REVIEW[*]

This section summarizes major literature relevant to this research, organized into five subsections. The topics covered include sustainability and sustainable development, sustainable transportation, alternative discourse related to sustainability, sustainability-related aspects of transportation planning practice in the U.S., and the measurement and evaluation of sustainability through indicators.

2.1. Sustainability and Sustainable Development

Several authors have traced the emergence of the concept of sustainability over the years, from early efforts in the 1950s and 1960s related to environmental issues, through various global conferences, events, and legislation, to more recent developments such as the United Nations (UN)'s move to adopt a set of Sustainable Development Goals in 2015 (*1; 2*). Sustainability is recognized today as a broad concept that can hold several meanings (*3*), and the most widely-cited definition of "sustainable development" remains that of the Brundtland Commission. In a report titled *Our Common Future* (*4*), the commission defined sustainable development as "*development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*". The terms "sustainability" and "sustainable development" are often used interchangeably – a distinction is made that sustainability is an idealized end state, while sustainable development can be viewed as the process of working towards sustainability (*2; 5*).

[*] Sections of this material are reprinted with permission from: Ramani, T. L. and J. Zietsman (2016). "Sustainable transportation – alternative perspectives and enduring challenges." International Journal of Urban Sciences: 1-16.

The roots of sustainability thinking, however, are based on concerns regarding the environment and the earth's carrying capacity. Hardin's *Tragedy of the Commons* (*6*) is often referenced as a foundational document on the origins of sustainability thinking. While not explicitly using the term "sustainability", Hardin's work spoke to the growing concerns regarding the impact of human activity and overpopulation on the environment and ecosystems. Kidd traced the evolution of sustainability from these environmental/ecologically-focused roots, crediting biologists, ecologists and environmental planners for taking leadership in the area. He also acknowledged that the concept now signifies something much broader, "*encompassing a wide range of economic, political and social goals"*(*7*). The definition of sustainability under these circumstances is no longer purely tied to the environment. For example, Solow (*8*) speaking from an economist's perspective, states that while the notion of sustainability is rooted in an obligation to the future, it does not necessitate "*leaving the earth as we found it*". He instead advocates for a more flexible view on sustainability, defining it as "*…an obligation to conduct ourselves so that we leave to the future the option or the capacity to be as well off as we are."*

Current discussion of sustainability, in line with this evolution, often refers to the three "dimensions" or "pillars" of sustainability – namely the environment, the economy, and society/social equity (*9*) , also sometimes referred to as the "3Es" (*10*). A majority of literature defines elements of sustainability along these lines – with some viewing equity as separate from the social dimension, and instead as an overarching inter- and intra-generational issue (*2; 5; 11*).

2.1.1. Frameworks for Sustainability

A framework is a means of structuring information to understand and further study a specific concept. Frameworks are particularly useful to help understand and communicate broad concepts such as sustainability – and several examples exist in the literature of sustainability frameworks and assessment methodologies. Several of these are rooted in systems analysis-based approaches, that take into account the complexities, conflicts, interrelationships and feedback loops involved in assessing progress toward sustainability (*12-14*).

Gasparatos et al defined a set of criteria for "holism" in sustainability assessment methodologies and frameworks – which included being integrated, predictive, participatory, precautionary, and taking equity into consideration. A review of various approaches to assessing sustainability found that none of the popular sustainability assessment approaches met these criteria, and that more work was required in the area of sustainability assessments and frameworks (*15*) . Applications of sustainability frameworks specifically to transportation are discussed in the next section of the literature review.

2.1.2. Strong and Weak Approaches to Sustainability

As mentioned previously, while sustainability originally derived from the environmental movement, the concept in recent years has expanded to a framing that covers the environmental, economic, and social dimensions. In this view of sustainability, it is seen that the three dimensions inherently conflict with each other. A widely-cited description of these conflicts is to describe them as the "property conflict" that exists between the economic and social dimensions, the "development conflict" that exists between the social and environmental dimensions, and the "resource conflict" that exists between the economic and environmental dimensions (*10*). It is also acknowledged that while there are conflicts, there are also complementarities between these dimensions.

In balancing the dimensions of sustainability, another issue to deal with is the relative importance given to each. This is linked to what is commonly termed as "strong" or "weak" sustainability – in simple terms, weak sustainability allows for tradeoffs between the three sustainability dimensions, while a strong approach does not allow for this (*16*). "Weak" sustainability can be viewed as an economic principle, in that natural capital can be traded-off with economic or human capital, whereas "strong" sustainability can be viewed as a physical principle that requires certain natural resources or environmental conditions to be maintained, i.e. rooted in environmental conservation (*17*). Weak sustainability is also sometimes termed as "Solow Sustainability", based on Solow's perspective that preserving individual species or natural resources is not necessary for sustainability, as long as the capability for performing the functions of those same resources remained in the future, through the use of substitutes or by other means (*8*).

While the Brundtland definition of sustainable development is the most commonly occurring, it has also been criticized for being anthropocentric in nature, i.e. placing human needs over environmental or ecological concerns and subscribing to a weak approach. Another related classification of sustainability perspectives is to distinguish anthropocentric views from an eco-centric or techno-centric approach; however, authors have noted concerns with this classification, given that any framing of sustainability is inherently anthropocentric to some degree (*10; 18; 19*) . Others have argued that sustainability can even be viewed as an environmental paradigm ("sustaincentrism") that is distinct from ecocentric and technocentric approaches (*20*).

Alternative approaches to sustainability that provide an eco-centric perspective to the Brundtland view of sustainability include concepts such as natural capitalism (*21*) and ecological footprinting (*22*), which put environmental concerns at the forefront. These discussions have looked at the carrying capacity of the earth, for example in terms of planetary boundaries that are under threat from human development (*23*) . The ecological footprint model, however, has also been criticized for not accounting for factors such as population density, land degradation and per capita income/consumption in its definition of sustainability (*24*).

2.1.3. Criticism of Sustainability as a Concept

The examples cited so far approached the concept of sustainability from the perspective of it being something that is important, and of value and relevance. At the same time, there are perspectives that question the utility of sustainability. Extending Wildavsky's critique of planning " *If Planning is Everything, Maybe it is Nothing*" (*25*) to sustainability, several authors have questioned the value of the concept (*26; 27*) . Others have derided sustainability as an "empty signifier" and a "fantasy" (*28*). Gunder discussed the Brundtland approach of the "northern elites" coopting the discussion to focus on growth at the expense of social and environmental issues/injustices (*29*).

An acknowledged weakness of sustainability as a concept is that it serves as a catch-all descriptor for any desirable attribute for the system or society as a whole (*30*). As stated by Marcuse, "*sustainability is both an honorable goal for carefully defined purposes and a camouflaged trap for the well-intentioned unwary"* (*26*).

2.1.4. Sustainability as a Wicked Problem

The characteristics of a "wicked problem" discussed by Rittel and Webber in the context of planning are highly applicable to sustainability as well. Some of these characteristics include having no definitive formulation, no objectively "true" or "false" answers, are unique to a context, and do not have a set of enumerable solutions. (*31*). Their main thesis is that problems dealt with in the planning context, including most social and public-policy issues are inherently "wicked", i.e. marked by characteristics that make them unsolvable, unlike purely scientific/engineering problems. This is in line with the description of "problems with no technical solution" alluded to in the *Tragedy of the Commons* (*6*). Sustainability as a wicked problem has also been discussed by others in different public policy contexts – see for example (*32*-*34*). This perspective explains, to a certain extent the vast variations seen in how sustainability is understood and applied.

2.1.5. Analyzing Discourse on Sustainability

Previous sections discuss definitions and approaches to the concept of sustainability. Some literature also specifically explores sustainability-related discourse. As noted by Jamieson (*35*), a weakness of discourse on sustainability is its open-endedness, "*…(the) language of sustainability can draw diverse parties into the* *conversation. But since we can always ask what should be sustained, for what period, in what region; and even why sustainability is good, and if it is good, how good it is; the discourse of sustainability as it is practiced is not likely to bring us to closure with respect to important, long-term issue*". Similarly, Baumgartner and Korhonen identify reductionism in dialogue around sustainability as a shortcoming that limits progress in this regard (*36*).

There are several efforts that have tried to address this issue by putting forward frameworks or core principles needed for discourse on sustainability to unify toward a common goal. The Framework for Strategic Sustainable Development (FSSD) developed from the work of Robert and others proposes a five-level model to address sustainability, covering system level, success level (vision), strategic guidelines, actions, and tools (*37*). Kates et al put forward a set of core questions for sustainability science (*38*). Despite these attempts to standardize discourse around sustainability, the arbitrary nature of the subject was still noted as a weakness by Christen and Schmidt (*39*). They proposed a modular framework identifying core criteria for what are termed as "conceptions" of sustainability, which covered foundational and practical aspects (*39*).

2.2. Sustainable Transportation

The previous section of the literature review provided a brief overview of concepts and terminology related to sustainability and sustainable development. This section expands on the concepts introduced, specifically focusing on the transportation sector. Transportation is a derived demand, and an integral part of human life. Transportation is also a major consumer of fossil fuel energy and is similarly responsible for a large share of global greenhouse gas emissions. Thus, progressing toward sustainability in the transportation sector is very important if progress is to be made in sustainability in general.

2.2.1. Definitions and Frameworks for Sustainable Transportation

There are differing perspectives on what sustainable transportation means. It has been described as "*an expression of sustainable development in the transportation sector*" (*40*). Some authors are of the view that "sustainable transportation" in and of itself is not a meaningful concept, but that a shift is required instead to view it as "*transportation in support of a sustainable society*" (*41*), or as *"… a transportation system that contributes to sustainable development of the community that uses and owns the system"* (*42*). The contrasting approaches of considering transportation as the main focus for sustainability efforts, versus considering transportation's role in broader sustainability are respectively termed as "transportation-centric" and "holistic" view of sustainability (*2; 43*).

Similar to discussions of sustainability or sustainable development, literature on sustainable transportation tends to define elements of sustainability along environmental, economic and social dimensions – with some viewing equity as separate from the social dimension, and instead as an overarching inter- and intra-generational issue (*2; 5; 11*). Several authors have put forward frameworks and approaches for sustainable transportation, including in policy and planning frameworks (*43*), performance-measure based approaches and frameworks (*5; 44; 45*), as well as the application of popular generalized ecological and sustainability frameworks to transportation (*46; 47*).

There are many operating definitions for sustainable transportation, many of which either look at sustainability policy as a pathway, or an end state vision. However, as with the literature on general sustainable development, authors emphasize the need for a systems-based approach to sustainable transportation (*48*).

Other authors have produced classification of sustainable urban transportation practice by scale – global, regional, national, local scale (*49*). The ecological footprinting approach (*22*) , though the subject of criticism (*50*), has also been adapted to the transportation sector in the form of a "sustainability footprint" framework (*51*). It has also been adapted for similar applications in urban transportation systems, considering fleet composition and the footprint needed to travel a certain distance per year (*52*).

After tracing the history of sustainable development – from its roots in fields as diverse as ethics and environmental economics, Hall presented a framework for applying sustainable development to transportation at the policy level in the US. He contrasted a "sustainability approach" with the current approach to planning (*43*). Similarly, others have explored current practice in terms of definitions and frameworks in the transportation field, including the application of popular generalized ecological and sustainability frameworks such as the Pressure-State-Response framework, and the Driving Forces-Impacts-Pressure-State-Response Framework (*46; 47*).

Richardson conducted an extensive mapping exercise to develop frameworks and linkages for factors affecting sustainability both in terms of passenger and freight transportation (*53*). Zietsman and Ramani also developed a generally applicable framework for sustainability centered on non-negotiable principles of sustainability, from which transportation-sector specific goals and performance measures are derived (*5; 44*). Similarly, Litman also put forward a set of goals, objectives and indicators for sustainable transportation, also covering the environmental, economic, and social dimensions (*45*).

2.2.2. Alternative Perspectives on Sustainable Transportation

Several of the examples of frameworks explained above take a broad view of sustainable transportation, putting forward the need for a balance between environmental, economic and social factors. This then generally translates to goals and objectives relevant to the transportation sector, covering each of those elements.

A perspective held by some is that this approach leads to a dilution of the concept of sustainability, with the term becoming a catch-all descriptor for any desirable attribute for the system or society as a whole. For example, if sustainability is taken to mean being able to meet mobility needs in the future, short-term issues such as noise pollution, water pollution, etc. should not form a part of sustainability, if they do not tangibly affect the future capacity to provide transportation (*30*). In such a perspective, depletion of fossil fuels and climate change impacts will take a primary role over other more immediate concerns.

Similarly, Holden et al. stressed that sustainable transportation is often misinterpreted in current practice, and that going back to the roots of the Brundtland report implied a focus on meeting basic mobility needs, protecting the environment, and on inter-and intra-generational equity. Contrary to many others who stress the importance of local context and stakeholder input of developing strategies for sustainability, the authors contend that this is not necessary, and that instead focus must be on the four equally important elements outlined previously (*11*).

Low et al discussed barriers to sustainable transportation in terms of discourse used by engineers, economists and urban planners, to justify the status quo or certain preferred actions (*54*). Gudmundsson and Hojer also caution that the framing of sustainable mobility (sustainable transportation), as with sustainable development, can impact results. Sustainability and development can be viewed as a single-directional (corresponding to weak sustainability), dichotomous (corresponding to strong sustainability), or a multi-directional concept, and each approach may result in different outcomes. To quote the authors, *"in the best case, sustainable mobility expresses intent to reconsider the balance between positive and negative, long- and short- term effects. In the worst case, it implies that the overall goal for transport policy is maximized mobility."* The principles put forward for sustainability, similar to Holden et al., focus on preservation of natural resources for future generations, preserving the option value of human and man-made capital for future generations, improving the quality of life for individuals, and ensuring a fair distribution of life-quality (*55*).

2.2.3. Sustainable Transportation and Technological Advancements

Another factor to consider in the sustainable transportation debate is the changing nature of transportation in the face of technological advancements and social change. While some authors have posited that technological advancements such as shared-use mobility and autonomous vehicles have the capability to drastically change mobility patterns and support sustainability goals (*56*), others have been skeptical of these impacts, and cautioned about the potential to increase the demand for travel and transportation (*57*). Authors have cautioned of a “rebound effect” that increases overall energy use due to introduction of new technologies (*58*). Writing in *Nature*, Bruun and Givoni discuss two aspects with regards to the intersection between technology and sustainability in transportation – firstly, that the long-term impacts of new technologies should not be viewed as unanimously positive or sustainable. Secondly, governance and planning systems have been ill-equipped to handle advancements in the transportation sector, and must evolve to better address their impacts (*59*).

2.2.4. Discourse on Sustainable Transportation

There are limited examples in literature that explicitly offer analysis of sustainable transportation discourse. However, different approaches to sustainable transportation emerge from the literature, often reflecting dichotomies seen in general discussions of sustainability. Sustainable transportation has been classified as holistic or transportation-centric (*2; 43*), somewhat aligned with the weak versus strong positions on sustainability. Another reflection of the weak versus strong sustainability approach (also reflecting anthropocentric/eco-centric perspectives) is the extent to which environmental considerations, especially the issue of climate change and greenhouse gas emissions, are addressed (*30; 55*). An added dimension in relation to sustainable transportation is the extent to which transportation system performance takes prominence (*46*). Based on these findings, this study classifies discourse related to sustainable transportation into three perspectives – an anthropocentric view, which acknowledges three sustainability dimensions but tends to focus on the transportation system and human needs, an eco-centric view that emphasizes aspects such as climate change, and a holistic view that extends the discussion of the sustainability dimensions and places constraints in the form of equity considerations and natural capital.

2.3. Alternative Discourse Related to Sustainability

Until now, this literature review has focused on cases where the primary interest is in pursuing or achieving predefined goal of "sustainability" in transportation. Sustainability itself can be viewed as one of many environmental discourses, and under sustainable development itself, there are differing discourses and viewpoints (*60*). Further, while sustainability may be a common policy goal, transportation planning and policy can also be driven by other goals and priorities. This can include "traditional" transportation planning paradigms which focus more on basic mobility, to other paradigms that are somewhat related to sustainability, such as livability, resilience, smart growth, public health, climate adaptation, etc.

This section covers three such examples that have emerged as important concepts guiding transportation planning and policy discourse in recent years – namely livability, resilience, and health. These three areas were selected for further study for the following reasons: 1) They are generally defined in a broad and overarching manner, similar to sustainability; 2) they tend to promote a more holistic approach to transportation planning, i.e. focus beyond basic mobility issues, and 3) they are noted for having varying degrees of overlap/complementarity with sustainability considerations.

2.3.1. Livability

Livability is sometimes conceptualized as a “subset” of sustainability (*45*) , focused on more localized and immediate elements, i.e. spatially and temporally localized. Chazal distinguished livability and sustainability as follows: “*In the simplest sense, livability can be seen as a pure expression of values or desires. I see sustainability, whilst also involving values, implying an ecological constraint on the realization of those desires.”*(*61*) . This brings up conflicts between livability and sustainability, or as noted by Chazal (2010), “the sustainability of livability”.

The conflicts between livability and sustainability were discussed by Godschalk, who presented a “sustainability-livability prism” that extended Campbell’s analysis of conflicts in sustainability to livability (*10; 62*). Thus, addressing both livability and sustainability requires an understanding of similarities, tensions and complementarities between the two concepts (*63*). Appleyard et al examined various definitions of livability in detail, discussed relationships to sustainability, and put forward a set of “livability ethics” to guide planners (*64*).

2.3.2. Resilience

Resilience is focused on a system’s ability to cope with changes, especially climate and ecological change, or disruptions due to natural disasters or catastrophic events. As in the case of livability, resilience and sustainability also have several similarities, as well as potential conflicts (*65*). Coaffee discusses resilience as being the integration of security concerns with environmental concerns (*66*).

Adger distinguishes social and ecological resilience and emphasized that social resilience has an institutional context relating to social capital of societies and communities. He states that institutional structures govern the use of natural resources, creating incentives for sustainable or unsustainable use. Thus, sustainability concerns can be viewed as a linking social and ecological resilience (*67*). Adger also cites Common in emphasizing that from an ecological economics perspective resilience is key to sustainability (*68*). This is similar to Folke et al's view that "*The goal of sustainable development is to create and maintain prosperous social, economic, and ecological systems. These systems are intimately linked: humanity depends on services of ecosystems for its wealth and security. Moreover, humans can transform ecosystems into more or less desirable conditions. Humanity receives many ecosystem services, such as clean water and air, food production, fuel, and others. Yet human action can render ecosystems unable to provide these services, with consequences for human livelihoods, vulnerability, and security. Such negative shifts represent loss of resilience" (69).*

Wang noted that while originally rooted in ecological studies (*69; 70*), in transportation, the concept of resilience generally takes on two aspects – ecological resilience, and engineering resilience, though it is observed that current practice seems to value the latter over the former (*71*). It was also observed that the current status quo in terms of investments and priorities for transportation in the US is not really cognizant of resilience in the decision-making process (*72*).

Cox et al proposed a framework and metrics for transportation system resilience derived from economic resilience theories – resilience was viewed as a function of system vulnerability (robustness), system wealth (redundancy) and system flexibility (responsiveness) (*73*). Litman identified components of resilience as diversity, redundancy, efficiency, autonomy and strength (*74; 75*) .

2.3.3. Health

Public health (health) is an emerging paradigm in contemporary U.S. transportation planning. There has been increasing collaboration between public health agencies and transportation agencies, as they recognize linkages between the two areas. There is limited literature exploring parallels and conflicts between health and sustainability in the transportation context. However, there are examples of more general discussions on human health/public health in relation to sustainability/sustainable development as a whole.

The general consensus in this area is that health is a sustainability issue, though there are potential conflicts between purely ecologically-focused sustainability, and views of public health that focus mostly on the present human condition, or on that of an individual. McMichael discusses these issues in two papers – one that addresses a new vision for sustainability, and another on population health as a bottom line for sustainability (*76; 77*). As stated. "…*public health researchers have a responsibility to ensure that their societies understand that, in the final analysis, sustainability is about ensuring positive (and equitable) human experience – of which health is fundamental…"*(*77*) . Similarly, King, writing in *The Lancet*, made the case for health as a sustainable state. He traced how concepts of health broadened from being an individual concern, to a family concern, and finally a social issue (*78*).

Additionally, in the context of climate change as a sustainability issue, a vast body of literature has also emerged on the effects of climate change on human health, which range from heat and cold-related illnesses and deaths, air pollution effects, spread of infectious diseases, flood and drought-related death and diseases, etc. (*79-81*) .

Early discussions of health as it relates to transportation focused mostly on the relationship between active living, the built environment, and health (*82; 83*), with the discussion sometimes also expanding to cover air quality and safety considerations (*84-86*). Environmental justice, health disparities, and the need for collaborative research between the transportation and health disciplines were also noted (*87*).

In the U.S., the focus on active living as the primary linkage between health and transportation was also reflected in case studies of collaborative planning efforts among health and transportation professionals (*88; 89*). However, the health in transportation planning framework from the Federal Highway Administration (FHWA) also introduced a concept for a holistic approach to health and transportation that covered four main elements 1) active transportation, 2) safety, 3) air pollution, 4) access to opportunities for healthy lifestyles (*89; 90*). The equity element, in terms of impacts on vulnerable populations, was also discussed as being of cross-cutting importance (*89*).

Other practitioner-based guidance has also put transportation and health in the context of sustainability. For example, the California Department of Public Health listed key connections between transportation, health, and sustainability covering direct effects (such as physical activity, air pollution, safety, etc.) and indirect effects (including access to jobs, services, medical care, etc) (*91*). The Transportation and Health tool developed by the U.S. Department of Transportation (USDOT) and the Centers for Disease Control (CDC) similarly cover a broad range, from alcohol-impaired fatalities, to commute mode shares, to land use mix, seat belt use, and housing and transportation affordability (*92*). If we consider these indicators to be reflective of priorities in terms of health and transportation, we again see that it represents a holistic view, covering traffic and roadway safety, to proxies for land-use and built environment factors that could affect active living elements.

Tools and criteria that can be used to evaluate healthy places in relation to transportation and land use – including walkability audits, health impact assessments (HIAs), and certifications such as the Leadership for Energy and Environmental Design (LEED) for neighborhood development (*93*). Brownson et al discussed frequently-assessed built environment-related health measures, with data sources and examples from studies. These included metrics such as population density, land-use mix, access to recreational facilities, street pattern, sidewalk coverage, vehicular traffic, crime (*94*). Davis described a study of opinions on health and transportation among practitioners in the UK. The three most important health-related transportation issues were traffic casualties, air quality and walking/cycling, followed by social inclusion. (*95*). In a more transportation agency-focused approach, Amekudzi-Kennedy et al. developed a framework for Transportation System Health that considered a hierarchy of needs analogous to Maslow’s hierarchy of needs (*96*). However, this approach attempts to combine both system/infrastructure health along with community or public health into a single framework, unlike the other literature which focused purely on public health impacts.

2.4. Sustainability-Related Aspects of U.S. Transportation Planning Practice

The previous section discussed examples of sustainability-related discourse that have emerged in recent times, often in the context of the transportation sector in the U.S. Since this study is focused on the U.S. context, this section provides further discussion of how sustainable transportation is currently being addressed, specifically with regards to surface transportation.

Transportation planning in the U.S. is devolved to state and local agencies, which follow a federally-mandated process with federal oversight (*97*). Every area with a population of over 50,000 is required to have a Metropolitan Planning Organization (MPO). MPOs may sometimes exist within a Regional Planning Organization or a Council of Governments and may also be referred to as such. Transportation planning for these metropolitan areas is led by MPOs, with State Departments of Transportation (DOTs) being responsible for nonmetropolitan areas and for statewide planning efforts.

There is no comprehensive approach to implementing sustainability in transportation in the U.S., though several programs and initiatives exist at the state and federal level. There are challenges associated with promoting policies aligned with triple-bottom-line sustainability in the largely auto-oriented context on the U.S. (*98*). It is generally seen that individual states and metropolitan regions drive sustainability initiatives based on local needs and priorities (*99; 100*). Research on how sustainability is addressed in the US transportation planning context has also discussed the lack of a social and quality-of-life focus and emphasized the need for the same (*101; 102*).

A review of various programs and initiatives in the U.S. at a federal level indicated that there are several programs that address sustainability considerations in transportation both explicitly, as well as implicitly (*98*). As shown in Table 1, there are sustainability-related aspects to several key guidebooks, programs and initiatives. Explicit sustainability initiatives include programs such as the Federal Highway Administration‘s INVEST tool (*103*). Other initiatives and policies that implicitly address sustainability considerations include the *Beyond Traffic* framework that addresses land use and multimodal transportation issues (*104*), the “Ladders of Opportunity” policy initiative which focuses on community revitalization, access to jobs, and multimodal transportation,(*105*), as well as the previously-discussed initiatives geared toward health in transportation (*89; 90; 92*), climate change and resiliency initiatives (*106*), livability initiatives (*107*), smart growth (*108*) , and context sensitive solutions (*109*). These examples from practice support the findings from the literature, and demonstrate the prevalence of sustainability-related discourse in various forms.

Table 1. Sustainability Aspects of Selected Programs, Policies, and Documents [Source: (*98*)]

Item	Description
Advancing a Sustainable Highway System – Highlights of FHWA Sustainability Activities	This report (*103*) provides an overview of how sustainability is incorporated into a variety of FHWA's programs and policies. It includes descriptions of specific initiatives such as the creation of a sustainability working group, linking asset management and planning, sustainable pavements, climate change, and air quality.
Climate Change and Transportation	FHWA has compiled a resource page (*106*) that features information and several publications regarding adaptation and mitigation programs and related research. Recent reports and initiatives include those focused on infrastructure resilience, FTA's Climate Change Adaptation Assessment Pilot, a Climate Change and Extreme Weather Vulnerability Assessment Framework, etc.
Context Sensitive Solutions (CSS)	Over the years, CSS has evolved into a set of guidance and best practices aimed primarily at the highway engineering sector. It is defined as "*a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting. It is an approach that leads to preserving and enhancing scenic, aesthetic, historic, community, and environmental resources, while improving or maintaining safety, mobility, and infrastructure conditions*" (*109*).
Health and Transportation Initiative	The FHWA commissioned the USDOT's Volpe National Transportation Systems Center to develop two reports to provide guidance on linking public health and transportation – titled *Metropolitan Area Transportation Planning for Healthy Communities(89)* and *Statewide Transportation Planning for Healthy Communities(90)*. These reports put forward a holistic view of health in transportation that overlaps heavily with sustainability principles – consideration of a) active transportation b) safety for all, c) air pollution reduction, and d) access to opportunities for healthy lifestyles. The USDOT also collaborated with the Centers for Disease Control on the development of a Transportation and Health Tool(*92*) that provides a range of transportation, land use, and health indicator data for regions in the US.
INVEST Program	Web-based, voluntary sustainability rating tool that has a triple-bottom-line approach to sustainability. Contains modules for system planning, project development, operations and maintenance (*110*).
Ladders of Opportunity	Recent policy initiative termed as a "Transportation Empowerment Pilot" (*105*). Focuses on community transportation projects with an aim to revitalize neighborhoods and improve transportation connectivity, especially in urban downtown areas. While this is a new initiative with no concrete outcomes to date, it may address social sustainability elements in terms of access, jobs, and equity.
Livability Initiative (Partnership for Sustainable Communities)	Also called the Partnership for Sustainable Communities, this is collaboration between the USDOT, the Environmental Protection Agency (EPA) and the Department of Housing and Urban Development (HUD) to promote livability. The partnership put forward a set of "livability principles (*107*)that touch upon several sustainability-related elements. FHWA also developed a Livability in Transportation Guidebook (*111*)that presents projects, planning approaches, and case studies focused on promoting the livability principles.

Table 1. (continued)

NCHRP Report 750 Foresight Series	A set of six reports dealing with the future of transportation was published by the National Cooperative Highway Research Program (NCHRP) under the umbrella of "Strategic Issues Facing Transportation". One of these reports was on *Sustainability as an Organizing Principle for Transportation Agencies.* Other topics investigated in the series included freight, climate change, technology, energy, and socio-demographics. (*41*)
Smart Growth	The EPA maintains a clearinghouse to support its Smart Growth program (*108*). Smart Growth is defined as "*range of development and conservation strategies that help protect our health and natural environment and make our communities more attractive, economically stronger, and more socially diverse*". EPA conducts research, provides funding and technical support for implementation smart growth projects. The activities are linked to the Livability/Sustainable Communities initiative. EPA also maintains a Smart Location Database that provides a rich dataset of transportation, demographic and built environmental data relevant to sustainable transportation(*112*).
Transportation Planning for Sustainability Guidebook	This guidebook was prepared for the FHWA (*42*) as a means to compile current knowledge on sustainable transportation to serve transportation planning agencies in the US. It contains compilation of sustainability practices, tools and evaluation methods from across the US and around the world.

2.5. Measuring and Evaluating Sustainability – Indicators

Measuring and evaluating sustainability (as well as related concepts such as livability, resilience and health) is a key part of operationalizing the concepts, and allowing for them to be appropriately considered in transportation decision-making. This is especially true since sustainability and related constructs tend to be broad concepts that are not always clearly defined.

From the perspective of implementing policies and programs to promote a transition towards sustainability, Sorenson et al noted three related but distinct aspects (dimensions) need to be addressed – namely, the normative, analytic, and governance dimensions (*113*) . Evaluating sustainability through indicators plays a direct role in the analytical dimension, and is also relevant to the normative and governance aspects.

In terms of technical approaches or analysis tools, one classification of methods for assessing sustainable transportation as follows (*49*):

- Descriptive statistics – including exploratory and graphical methods
- Spatial mapping
- Spatial statistics
- Travel preference functions
- Regression analysis
- Predictive models based on time-series census data
- Travel demand modeling/scenario planning with land use

At the very basic level however, most qualitative, analytical, or modeling approaches still utilize the concept of *indicators*. Indicators are a very useful tool for the understanding and assessment of broad, multi-dimensional concepts such as sustainability, and can range from simple values to complex indices/functions, and can be non-numerical. The term indicator is often used interchangeably with other terms such as parameter, measure, proxy, value, variable, performance measure, etc (*2; 114*).

2.5.1. Selecting and Using Indicators for Sustainability

Since indicators have a wide range of uses outside of the context of sustainability, a question arises about what makes an indicator an indicator of sustainability. Maclaren distinguishes sustainability indicators from regular planning indicators as being 1) integrating, 2) forward looking, 3) distributional, and 4) developed with input from multiple stakeholders in the community. (*115*). Others emphasize the need to focus on outcomes, as opposed to inputs/processes and outputs for sustainability indicators (*5; 116*). There are several compilations of sustainable transportation indicators available in the literature, a majority of which identify and classify indicators based on specific goals or areas of interest relevant to sustainability (*5; 46; 117-119*). Others also focus on the urban scale, quantifying sustainable transportation indicators for the comparison of cities (*120; 121*) .

The actual application or implementation of these indicators generally follows approaches based in the field of multi-criteria decision making (MCDM) or multi-criteria decision analysis (MCDA), including approaches such as the Analytic Hierarchy Process (AHP) and pairwise comparisons to elicit priorities and values. Examples include the use of MDCM to obtain priority weights for environmental outcomes (*122*), to select appropriate measures from a long-list, and for identifying desirable attributes of an indicator (*118*), and for developing composite sustainability indices(*123; 124*). Other approaches to assess sustainability in the transportation context include sustainability rating systems (*125; 126*), monetization of dimensions into a single value, similar to a benefit-cost analysis (*127*) .

2.5.2. Do Indicators Make a Difference?

Despite a sizeable body of work focused on assessment of sustainability, and the use of sustainability indicators, questions remain as to whether these have actually made a difference to outcomes. For example, Berke and Conroy (2000) found that explicit inclusion of "sustainability" in community plans did little to tangibly improve sustainability outcomes measured against normative definitions of sustainability. However, they also acknowledge that this could be due to the "narrow" definition of sustainability that was taken into account (*128*). Even when sustainability indicators are found to be in use by practitioners, it was seen that the depth of their influence, as a whole, could not be judged (*129*).

Some of the issues with this are arguably due to how sustainability was defined and the indicators that were used. For example, an analysis of six sustainability rating systems showed that to what extent sustainability was addressed was not clear, given the differing values and definitions and weights assigned to criteria (*130*). According to Marsden et al. (*131*) there is a "definition deficit" that hinders the ability of sustainability indicators to have a tangible effect on decision-making. This deficit (lack of clear definition of what sustainability is) makes it harder to generate meaningful information in the form of appropriate sustainability indicators that can be applied in decision-making.

2.5.3. Criteria for Assessing and Selecting Appropriate Indicators

A means of improving how indicators perform (and how they are used to affect decisions) is for the development of a more rigorous approach to the development and selection of sustainability indicators. An important part of this is to select valid and relevant indicators. As described by Innes (*132*), validation of indicators is very complex, especially when measuring a theoretical construct. Validation depends on "*analysis, judgement, intuition, professionally acquired understandings and skills, feedback from applications, and social and political processes*".

Several authors have discussed criteria to take into consideration for selection of indicators. For example, emphasizing internal consistency, transparency, and external validity (*133*), or considering theoretical basis, operationalization, interpretability and communicability, and data requirements (*134*).

A systematic approach to select appropriate indicators is provided by Joumard and Gudmundsson (*135*). They list criteria under three categories - representational criteria (referring to how accurate an indicator is in representing the problem at hand), practical criteria (dealing with the ease with which the indicator can be made operational), and contextual criteria (which relates to the suitability of indicators in the context of application).

2.5.4. Spatial Data and Sustainability Indicators

Spatial mapping and spatial statistics were previously discussed as methods of assessing sustainable transportation (*49*). With advancements in Geographic Information Systems (GIS), the use of spatial data to quantify sustainability-oriented transportation and land use indicators at the disaggregate level has become increasingly common. These analyses often make use of data from travel demand models, censuses, travel surveys, transit providers, and similar sources. Applications found in the literature range from understanding accessibility (*136; 137*), pedestrian connectivity (*138*), equity and environmental justice analyses(*139; 140*) and emissions estimation (*141*). Increasingly, as noted by Malczewski (*142*) GIS-based analyses are also used in combination with multi-criteria decision analysis methods to reflect composite results for multiple indicators or attributes. The term GIS-MCDA is used broadly to cover these types of applications. Transportation-related examples include Jeon's computation of sustainability indices in the Atlanta metropolitan region (*124; 143*), and work by

Jakimavicius and Burinskiene on the ranking of zones in a city on the basis of transportation sustainability criteria (*144*).

3. FRAMING THE ISSUES FACING SUSTAINABLE TRANSPORTATION*

The literature review brought to light several issues that complicate the advancement of sustainable transportation as a research or policy agenda. This section of the dissertation organizes these into a systematic listing of six main issues and challenges, which are mapped to three key areas related to sustainability – namely its definition, measurement, and implementation. The categorization of key areas is consistent with other literature, such as the classification of normative, analytical, and governance dimensions (*113*). Figure 1 provides a graphical summary of the issues and challenges, which are discussed in the remainder of this section.

3.1. Unclear Definition/Misuse of the Term

The broad nature of sustainability makes it hard to define, and therefore easy for any practice related to planning and delivery of transportation services to be termed as "sustainable". This also ties in to the fundamental criticisms of sustainability discussed previously (*27*-*29*). As noted in a recent book on the subject , "…*sustainable transportation is broadly defined, which permits policies and practices to be labeled as 'sustainable' while pursuing business-as-usual approaches*" (*2*).

3.2. Cross-Cutting Nature of the Problem

Sustainability issues in transportation cannot be viewed in isolation. They affect other sectors, and are affected by other sectors, thereby cutting across organizational silos(*45*). For example, sustainable transportation also depends on factors such as land

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use, economics and demographics. This makes it difficult for transportation agencies to create meaningful change on their own, without collaboration with other agencies and sectors (*53; 145*).

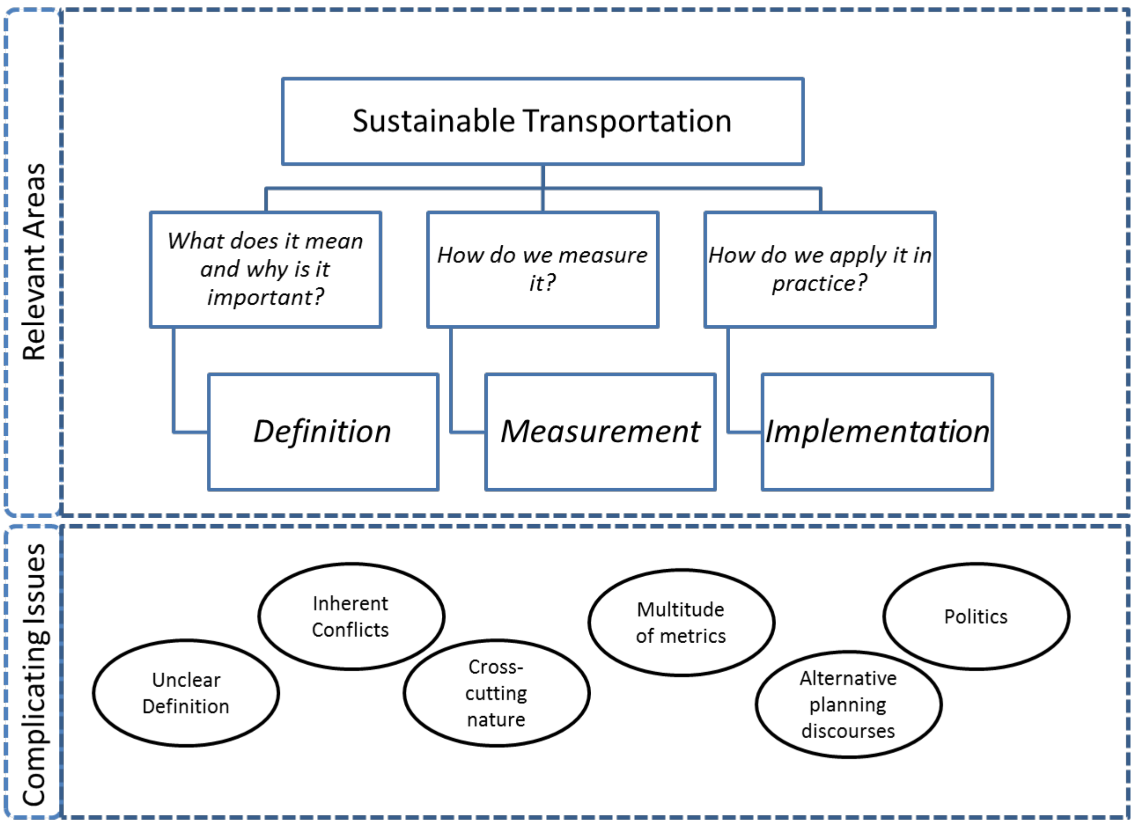

Figure 1. Framing Issues Related to Sustainable Transportation

3.3. Inherent Conflicts

There are inherent conflicts when it comes to the three pillars of sustainability itself (*10*). For example, economic growth and progress may conflict with environmental needs and the depletion of natural capital, and some interpretations of sustainability can result in environmental and social issues being ignored at the expense of economic growth or to preserve the status quo(*26; 29*) . While a “strong” conceptualization of sustainability provides primary importance to the environment, a “weaker” approach to sustainability allows for tradeoffs that may heighten conflicts in this regard.

3.4. Multitude of Frameworks and Metrics

While there is broad consensus in literature and practice regarding what sustainable transportation means, there are a multitude of conceptual frameworks and indicators applied to the subject (*46; 47*) . Thus, sustainable transportation still remains a somewhat nebulous concept, especially in the policy and implementation realm, and in whether outcomes have been affected through the application of these frameworks and indicators.

3.5. Politics of Sustainability

While not always the case, in many areas, the political acceptability of the “sustainability agenda” can become an issue, for example when sustainability is discussed in the context of greenhouse gas emissions and climate change. For example, Banister et al (*99*) discuss this in the U.S. context, where the U.S. was leading the world in the implementation of environmental regulations in the 1960s and 70s, but is comparatively lacking in progress on greenhouse gases and climate change. The term continues to be polarizing to some, especially in conservative contexts (*146*). Further, there are large differences between states, and local and regional governments in terms of actions taken towards sustainability in the U.S (*99*). All these can affect how sustainability is addressed in policy and practice.

3.6. Alternative Discourse in Transportation Practice

In recent years, there has also been a proliferation of other concepts or frameworks driving policy and practice of transportation. Some examples include a focus on livability, resilience and climate adaptation, public health, smart growth, etc. While not always explicitly aligned with sustainability, there are significant overlaps and complementarities between these concepts, as well as occasional conflicts.

3.7. Interrelationship Between Sustainability Issues and Challenges

The six issues discussed above are often interrelated and overlapping. For example, how sustainable transportation is defined will affect the overall framework and metrics used for assessment; similarly, the local political context may drive whether sustainability is a goal for transportation policy, or whether alternative discourses such livability or resilience are pursued instead. On reviewing the six complicating issues discussed above, it is seen that they address, to varying extents, the three main elements mentioned at the outset, i.e. the definition, measurement and implementation of sustainable transportation.

From a definitional perspective, contributing issues include unclear definition of the term, conflicts between the three dimensions of sustainability, and a lack of clarity about what sustainable transportation is (for example, holistic versus sector-specific approaches). From a measurement perspective, there are a multitude of potential frameworks, approaches and indicators that can be implemented. At a practical level, challenges include the fact that sustainability considerations often span the responsibility of different sectors (cross-cutting), and that there may be other planning goals or paradigms in place, or political issues that can hinder progress. Table 2 provides a summary of how the sustainability issues and challenges relate to the definition, measurement, and implementation of sustainable transportation.

Table 2 Categorizing the Complicating Issues for Sustainable Transportation

Item	Summary	Contributing Issues
Definition	Relates to how sustainable transportation is conceptualized and defined, usually as a starting point to a sustainable transportation initiative or program	Affected by unclear definition and misuse of the term. Also affected by inherent conflicts between sustainability dimensions, political factors, and alternative discourses.
Measurement	Relates to how progress toward sustainable transportation is assessed, usually through the use of indicators.	Primarily affected by the multitude of frameworks and metrics present; It is also affected by the cross-cutting nature of sustainability which may limit the scope of what is measured.
Implementation	Relates to how policies and programs for sustainable transportation are implemented in practice.	Political issues, and alternative discourses can affect how programs and policies are implemented.

3.8. Summary

This section highlights the complexities and interrelationships in sustainable transportation, and establishes the need for a nuanced research approach. It sets the stages for a systematic understanding of the challenges faced, which were accounted for in the research design. While the focus of the research is specifically on the issue of alternative discourse in sustainability, there is a need to understand other issues and how they fit together in influencing the use of specific discourse. The findings lead to the conclusion that there is no “one-size-fits-all” approach to sustainable transportation, which must instead be approached from the perspective of both theory or discourse, and the resulting impacts on practice.

4. RESEARCH DESIGN

Section 2 covered a broad range of literature on sustainable transportation and related topics. Section 3 built on the literature review to frame complexities and interrelationships in how sustainable transportation is defined, measured, and implemented. These findings support the need for a study that takes into account the broad and overarching nature of sustainability concepts, which cannot necessarily be reduced to a conventionally testable hypothesis. This section describes the two-part research design developed to address the study objectives.

4.1. Research Objectives and Conceptual Framework

As mentioned in the introductory section, the overall goal of this research is to assess the validity of *implicit* and *explicit* frameworks and discourse around sustainability in transportation. The specific objectives include:

1. Conducting a qualitative analysis of relationships between alternative conceptualizations of sustainable transportation.
2. Conducting a quantitative analysis using sustainability indicators to investigate the impact of alternative conceptualizations of sustainable transportation on measured outcomes.

Figure 2 shows the conceptual framework that the study is based on, along with elements of the study design. As seen in the figure, differing strains of discourse on sustainable transportation (each termed as an alternative conceptualization of sustainable transportation) can be contrasted with each other at a qualitative level to identify their scope, stated values, and goals. At the quantitative level, these goals and values can be used to derive representative indicators quantifiable for a common transportation and land use test case. These findings will provide insight into how the root conceptualization of sustainable transportation can impact measured outcomes.

4.2. Research Hypothesis

This study builds on the premise (as demonstrated in the literature), that several planning discourses exist that can be loosely viewed as “alternative conceptualizations” of sustainability in transportation. Building off this premise, the main research hypothesis is as follows:

“Alternative conceptualizations of sustainable transportation promote complementary goals and values and can serve as proxies for each other.”

Testing a hypothesis of this scale and scope is not straightforward and necessitates the following steps that align with the previously-stated objectives:

- Identifying alternative conceptualizations of sustainable transportation that exist in policy and practice.
- Understanding their key goals and values, and identifying appropriate indicators that can be used to operationalize the measurement of each of these concepts.
- Quantifying these indicators in a case study analysis to assess results and draw conclusions.

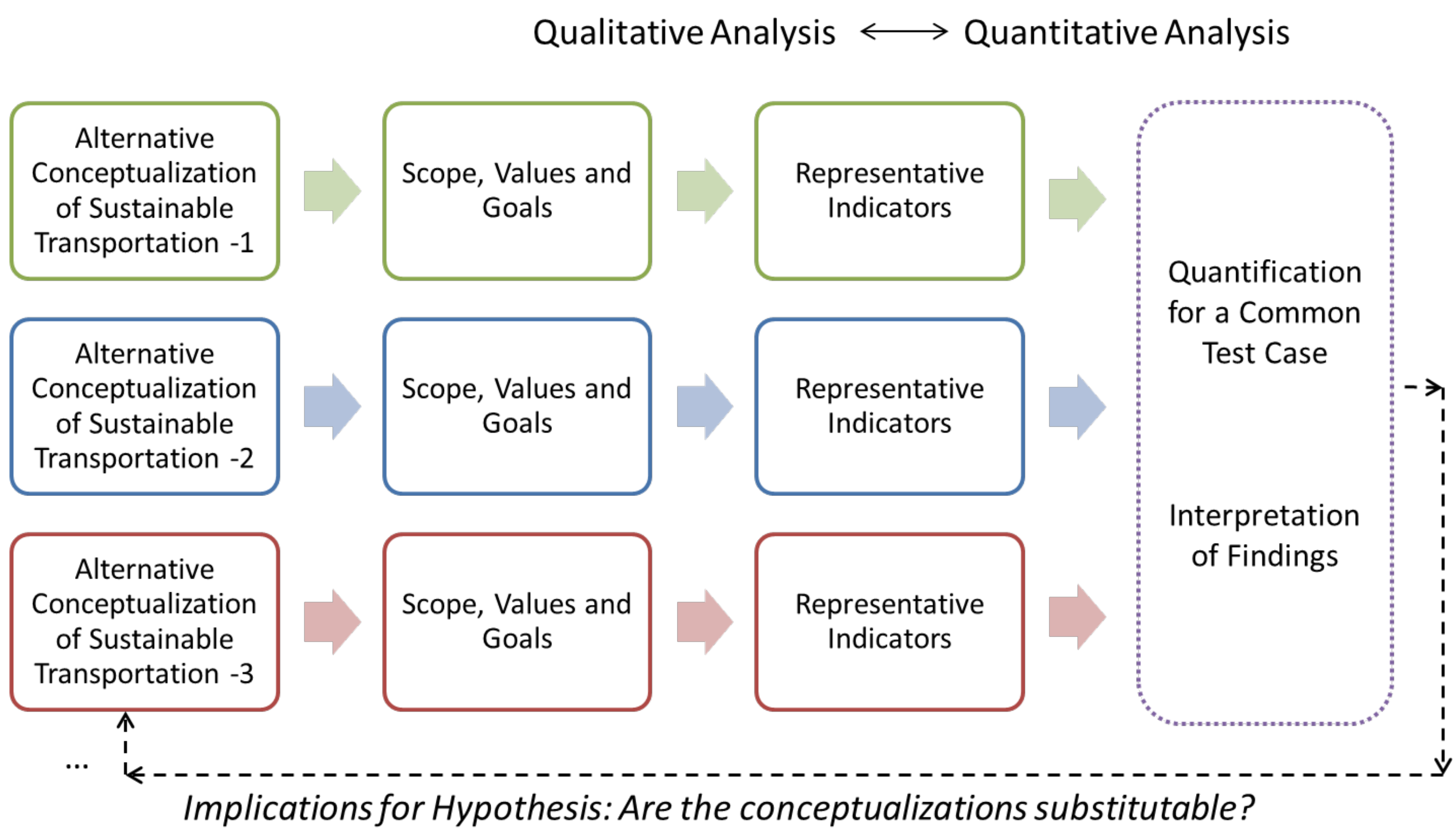

Figure 2. Conceptual Framework and Overview of Research Design

4.3. Research Approach

The study approach involves a combination of assessment and analysis, centered on the use of indicators. As discussed in the literature review section, indicators are commonly used to measure and manage policy outcomes, and are generally constructed to reflect the values of a broader conceptual framework. This research is divided into two main phases – a qualitative analysis focused on understanding and mapping out the key components of various alternative conceptualizations of sustainable transportation, and the quantitative analysis in which sustainability indicators are identified, quantified, and analyzed to assess linkages between the foundational concepts and measured results. The qualitative and quantitative components are discussed in the following sections.

4.3.1. Qualitative Component - Analysis of Alternative Conceptualizations of Sustainable Transportation

This part of the study aims to assess how sustainability is approached in the transportation planning context. The focus is on discourse that explicitly purports to address sustainability, as well as discourse that addresses sustainability implicitly in stated values and goals. For purposes of this study, these are collectively termed as "alternative conceptualizations" of sustainability.

The objective is achieved through a systematic review of literature and other written content to parse key concepts relating to sustainability in transportation. The approach is broadly based on methods of content analysis, i.e., an examination of the contents of a particular body of material for the purposes of identifying common patterns or trends (*147*). The analysis took into account what are generally thought of to be normative principles of sustainable transportation, along with work examining discourse-related aspects of sustainability thinking, and meta-frameworks developed to analyze the same (*36-38*). Further details of the methodology used and results obtained are provided in Section 5.

4.3.2. Quantitative Component - Case Study Analysis Using Indicators

The aim of this phase is to conduct an assessment of how different conceptualizations of sustainability, when translated into quantified indicators, differ in terms of results or observed outcomes. It is acknowledged that indicators have different definitions and applications (*135; 148*), but for purposes of this study, the term is used to denote *"a variable, or a combination of variables, selected to represent a certain wider issue or characteristic of interest"* (*2*). A subset of the alternative conceptualizations was selected from those covered in the qualitative analysis. Representative indicator sets relevant to transportation planning were developed for each, and quantified for a test case, namely the El Paso metropolitan area in Texas. Data from the El Paso MPO's regional travel demand model and other sources were used for this analysis. Further details of the methodology used and results obtained are provided in Section 6.

4.4. Summary

The design of this study attempts to validate alternative conceptualizations of sustainable transportation through a qualitative analysis of discourse, and the translation of findings from the qualitative analysis into an indicator-based quantitative analysis that is applied to a test case. The results from both the analyses provide insight into the key research question of whether alternative conceptualizations of sustainable transportation are interchangeable, both when viewed at the level of discourse, and when applied in the form of indicators. The following sections of the dissertation describe each part of the research in further detail.

5. ANALYSIS OF ALTERNATIVE CONCEPTUALIZATIONS OF SUSTAINABLE TRANSPORTATION

This qualitative analysis is driven by the simple premise that the root conceptualization of sustainability (or any similar broad concept) can be used to identify key goals and values that reflect the overarching construct. These, in turn, can be used to derive representative indicators, which can be used for quantitative assessment of the differences between the various concepts of interest.

The overall approach is to review relevant literature and documents to systematically assess how various “alternative conceptualizations” of sustainability in transportation stack up against each other. The focus is on the application to transportation planning, though the content analysis and review of foundational concepts necessitates going beyond transportation-specific applications.

The assessment is done in the context of transportation planning, (where the term is used in a general sense to denote activities related to the provision of transportation infrastructure and services to the public). While not solely applicable to the U.S., the paper does take into account the U.S. context, in which transportation planning discourse sometimes addresses aspects of sustainability under the areas of livability, health and resilience.

5.1. Defining Alternative Conceptualizations of Sustainable Transportation

A first step in conducting this assessment is to define what constitutes an “alternative conceptualization” of sustainability. As mentioned previously, the term is used to collectively reference discourse (in the form of planning frameworks or recommended approaches) that either purport to advance sustainability, or overlap with sustainability considerations on examination of stated goals/values. By this definition, it includes “sustainability-based” and “alternative” discourse, as defined below:

- Sustainability-Based Discourse – relates to transportation goals and priorities that explicitly reference sustainability as a primary motivation.
- Alternative Discourse – relates to situations where transportation goals and priorities do not explicitly align with sustainability, though overlaps and commonalities are noted. This category covers frameworks that are seen to be more “holistic” and cross-cutting than traditional transportation practice, such as the examples of livability, resilience, and health discussed previously.

It is acknowledged not everyone will agree with this characterization of “alternative conceptualizations” of sustainability, which takes the view of sustainability as a broad “catch-all” concept. For example, some authors discuss sustainability as paradigm that is distinct from technocentrism (or anthropocentrism) and eco-centrism (*20*). However, one can also view the “ecocentric” and “technocentric” aspects of environmental discourse as analogous to “strong” and “weak” sustainability, rather than distinct from it. This research takes the latter view, which is supported by most of the examples cited in the literature review discussing sustainable transportation.

5.2. Qualitative Analysis Approach

The concepts of sustainability and sustainable transportation are broadly defined and can take on multiple meanings. The analysis of the subject therefore requires a nuanced approach, and cannot be boiled down to a checklist or a set of "yes/no" questions. At the same time, standard reference points are desirable to allow for comparisons. As noted in the literature review, examples exist of meta-frameworks or approaches that can be used for the analysis of general sustainability discourse (*36-38*), though these frameworks tend to be more globally-focused and not directly applicable to sustainable transportation. Similar examples pertaining specifically to sustainable transportation are limited, and mostly deal with discussions contrasting strong and weak sustainability approaches, or holistic and transportation-centric approaches (*2; 30; 43; 46; 55*).

Keeping in mind the scope of this study (which is sector-specific), a set of reference points for analyzing sustainable transportation discourse was developed, reflecting the various aspects of sustainability and sustainable transportation discourse that emerged from the literature. The aim was to identify elements that emerged as areas in which different approaches to sustainable transportation can be contrasted with one another. The set of reference points developed in this study cover three main elements, as follows:

- <u>Scope of the Discourse</u>
    - What are the stated values and goals?
    - What is the scale/level of applicability?

    - Is the view more globally-focused (transportation in support of sustainable development) or sector-specific (sustainable transportation)?
    - To what extent is transportation system performance a consideration?
- <u>Coverage of Sustainability Dimensions</u>
    - How are the environmental, economic, and social dimensions addressed?
    - What is the approach to tradeoffs/substitutions between the dimensions – i.e., strong versus weak sustainability approach
- <u>Treatment of Equity Issues</u>
    - To what extent is equity addressed, in terms of:
        - Intra-generational equity – equity across different population groups and regions at a point in time (current generations)
        - Intergenerational equity – equity considerations over time (i.e., for future generations)

5.3. Identification of Discourse for Assessment

The scope of this assessment includes both implicit and explicit discourse related to sustainable transportation. Consistent with the discussion in the literature review, the following were identified as distinct approaches meriting further analysis:

- Sustainability-Based Discourse

    - Eco-centric sustainability
    - Anthropocentric sustainability
    - Holistic sustainability
- Alternative Discourse
    - Health
    - Livability
    - Resilience

The literature review findings were then used to develop a working definition for each of the above. The definitions, along with additional notes and considerations about each framework are shown in Table 3.

5.4. Qualitative Analysis Results

Each of the frameworks identified were then systematically assessed using the reference points identified – i.e. in terms of scope, coverage of sustainability dimensions, and treatment of equity. The results of this assessment are shown in Table 4.

Table 3 Characterizing Sustainability-Related Discourse in Transportation

Item	Working Definition	Additional Notes
Eco-Centric Sustainability	Discussions of sustainability in transportation that are centered on long-term environmental and ecological considerations, most notably climate change.	While the environmental dimension of sustainability covers broader issues such as ecosystems, wetlands, and habitat protection, it is generally seen that greenhouse gas emissions/energy consumption is used as the primary indicator of sustainability to reflect climate change as the main consideration. Can make a case for this as a "strong" sustainability – even though the economic and social dimensions are not considered.
Anthropocentric Sustainability	Discussions of sustainability in transportation that reference the environmental, economic and social dimensions, but do not specify a hierarchy between the various dimensions or explicitly reference equity issues.	Tends to be the most common approach seen in how transportation agencies address sustainability issues – i.e. acknowledgement of broader social, economic and environmental issues. While not explicitly mentioned, the emphasis in practice tends to be on social and economic elements over environmental aspects, often coupled with discussions of transportation system performance and linkages to transportation agency strategic goals. Conforms to traditional notions of "weak" sustainability.
Holistic Sustainability	Discussions of sustainability in transportation that reference the environmental, economic, and social dimensions, and also place constraints or limitations in terms of distributional effects/equity, and an acknowledgement of limits to natural capital.	Can be viewed as an extension of the above discussion of "weak sustainability" – i.e. a more rigorous application with added qualifiers on the same spectrum. Can also make a case for this being "strong" sustainability, since it places constraints.
Livability	Discourse that is generally concerned with transportation as it relates to community-scale impacts, primarily on human well-being.	Can be viewed as spatially and temporally localized application of sustainability Focus tends to be on socio-economic aspects.
Health	Discourse organized around transportation's relationship to human health, especially in relation to four key elements – safety, air quality, active living opportunities and access to critical destinations.	The holistic view of health that has emerged in recent discourse demonstrates overlaps with livability as well as with sustainability.
Resilience	Discourse related to transportation's ability to continue functioning when faced with disruptive events.	While disruptions are generally viewed as sudden shocks to the system (e.g. natural disasters and terrorism), it is sometimes viewed as encompassing longer-term impacts of climate change. When viewed from a sustainability perspective, it is important to note conflicts between ecological and system/engineering resilience.

Table 4 Assessment of Frameworks as Applied in Transportation-Related Discourse and Practice

Framework	Scope	Coverage of Dimensions	Treatment of Equity
Eco-Centric Sustainability	Globally focused, and often specifically oriented towards climate change considerations.	Focuses solely on environmental dimension, primarily greenhouse gas emissions and fossil fuel consumption.	Emphasis on intergenerational equity (i.e. future aspect).
Anthropocentric Sustainability	Promotes consideration of multiple environmental, economic and social goals. Transportation system effectiveness/performance is often a consideration given equal or greater importance.	Environmental, economic, and social aspects are considered. Weak approach is usually implicit – tradeoffs are acceptable between environmental and other dimensions.	The intergenerational equity aspect is often given some emphasis (i.e. acknowledgement that sustainability requires thinking about the future); intra-generational equity, if discussed, is usually under the "social" dimension.
Holistic Sustainability	Promotes consideration of multiple environmental, economic and social goals. Broader approach promoting sustainable outcomes beyond transportation.	Environmental, economic, and social aspects are considered. Limits placed on tradeoffs from perspective of environmental dimension (natural capital) and social dimension (equity).	Emphasis on both intergenerational and intra-generational equity.
Livability	Limited spatial and temporal scale Transportation is viewed primarily in relation to providing access and opportunities for the public.	Economic and social dimensions are emphasized. Environmental dimension may be addressed in the context of detrimental environmental impacts experienced by the public.	Intra-generational equity considered in terms of access/opportunities for population subgroups.
Health	Scale may vary in terms of geography, but tends to be limited temporally Transportation is viewed primarily in relation to 1. Impacts on human health and 2. Opportunities for healthy living.	Primarily focused on one aspect of the social dimension, i.e. human health, and environmental considerations from perspective of health impacts.	Intra-generational equity considered in terms of health impacts on populations subgroups.
Resilience	Transportation-centric Usually focused at a system level.	Social and economic dimensions addressed in relation to transportation system impacts. Environmental dimension addressed when resilience is in the context of climate change and adaptation	Intergenerational equity is a consideration when it comes to maintaining resilience into the future (esp. in the face of climate change) Intra-generational equity may be considered in how system performs for vulnerable users.

5.5. Mapping Relationships to Holistic Sustainability

The results from the assessment of six alternative conceptualizations demonstrate overlaps and differences between the various concepts. Of the six, the holistic sustainability framework is seen to have the broadest scope, taking into consideration five key elements – the three sustainability dimensions, and inter- and intra-generational equity concerns. This five-pronged conceptualization of holistic sustainability can therefore serve as a baseline to "map" the coverage of the other frameworks - as shown in Figure 3. The mapping exercise provides a useful means of understanding how the relative values of the different conceptualizations stack up against each other. While it can be argued that the holistic sustainability definition is in one sense almost "utopian", and practically unachievable, it provides a good frame of reference to visualize relative priorities of others, for example in contrasting against priorities of eco-centric and anthropocentric sustainability.

Figure 3 was developed by assessing the extent to which each discourse emphasized the five elements (on a high-medium-low scale) as shown in Table 5, based on the observations from the analysis documented in Table 3 and Table 4. These ratings were then assigned a score on a three-point scale (3 for high, 2 for medium, and 1 for low) and mapped against each other. An analysis of this kind does involve an element of subjectivity, and its intent is to demonstrate the relative priorities of various perspectives on sustainability. Opinions may vary regarding the relative emphasis among the different elements for each discourse, and for the purposes of this analysis, the ratings were assigned to be consistent with the working definitions developed (Table 3) and the assessment results (Table 4). The holistic sustainability perspective, as explained previously, was considered to place high, and equal emphasis on all five elements, and serves as the analysis baseline. Further elaboration of the other ratings in Table 5 is as follows:

- The eco-centric sustainability perspective for transportation was rated as having a high emphasis on the environmental dimension and intergenerational equity, given its primary focus on climate change, which is a future-oriented environmental issue. The social, economic, and inter-generational equity aspects were rated low as they are usually not emphasized in this perspective.
- The anthropocentric perspective on sustainability was rated as placing a high emphasis on the economic aspect, due to its implicit acceptance of trade-offs i.e., having a weak sustainability perspective that generally favors the economic dimension. Further, the emphasis on balancing the sustainability triple-bottom-line with transportation system performance also tips the scale towards the economic dimension, over the social and economic dimensions (which are rated as having a medium level of emphasis). Between inter- and intra-generational equity, intergenerational equity is assigned a medium score, due to the acknowledgement of sustainability as needing to address needs of the future. Intra-generational equity is rated low, since if acknowledged, it is usually as part of the social dimension.
- Livability emphasizes near-term social and economic issues, and is therefore rated high on the economic and social dimensions. The environmental

dimension, on the other hand is rated as medium, since the emphasis on the environment from a livability perspective is mostly in how it impacts human health or the human experience (similar to anthropocentric sustainability). Since livability takes into considerations aspects such as access to opportunity for all, it is rated as medium for intra-generational equity, and low for intergenerational equity due to the near-term focus of the concept.

- The concept of health is a more narrow application than livability, in that it addresses one part of social considerations (i.e. human health). It is therefore classified as having a medium emphasis on the social dimension, and a low emphasis on the economic dimension. The concept of health is similar to livability in terms of environmental considerations (focused on impacts on human health), and on equity issues (with some emphasis on health impacts for disadvantaged subgroups [intra-generational equity] and less emphasis on future generations [intergenerational equity]).
- Resilience, on the other hand, is seen to touch on all aspects, though with lowest emphasis on the social dimension - social considerations related to resilience are primarily reflected in concern for intra-generational equity (i.e. impact on vulnerable users of the transportation system). Environmental and economic considerations are reflected in climate change and asset management/system performance aspects, respectively, which are seen to have medium emphasis. The climate adaptation element is also seen to provide a medium level of emphasis on intergenerational equity.

Table 5. Emphasis of Each Discourse on Dimensions and Equity Elements

Framework	Emphasis on Element				
	Environmental	**Economic**	**Social**	**Equity - Intra-generational**	**Equity - Intergenerational**
Holistic	High	High	High	High	High
Eco-centric	High	Low	Low	Low	High
Anthropocentric	Medium	High	Medium	Low	Medium
Livability	Medium	High	High	Medium	Low
Health	Medium	Low	Medium	Medium	Low
Resilience	Medium	Medium	Low	Medium	Medium

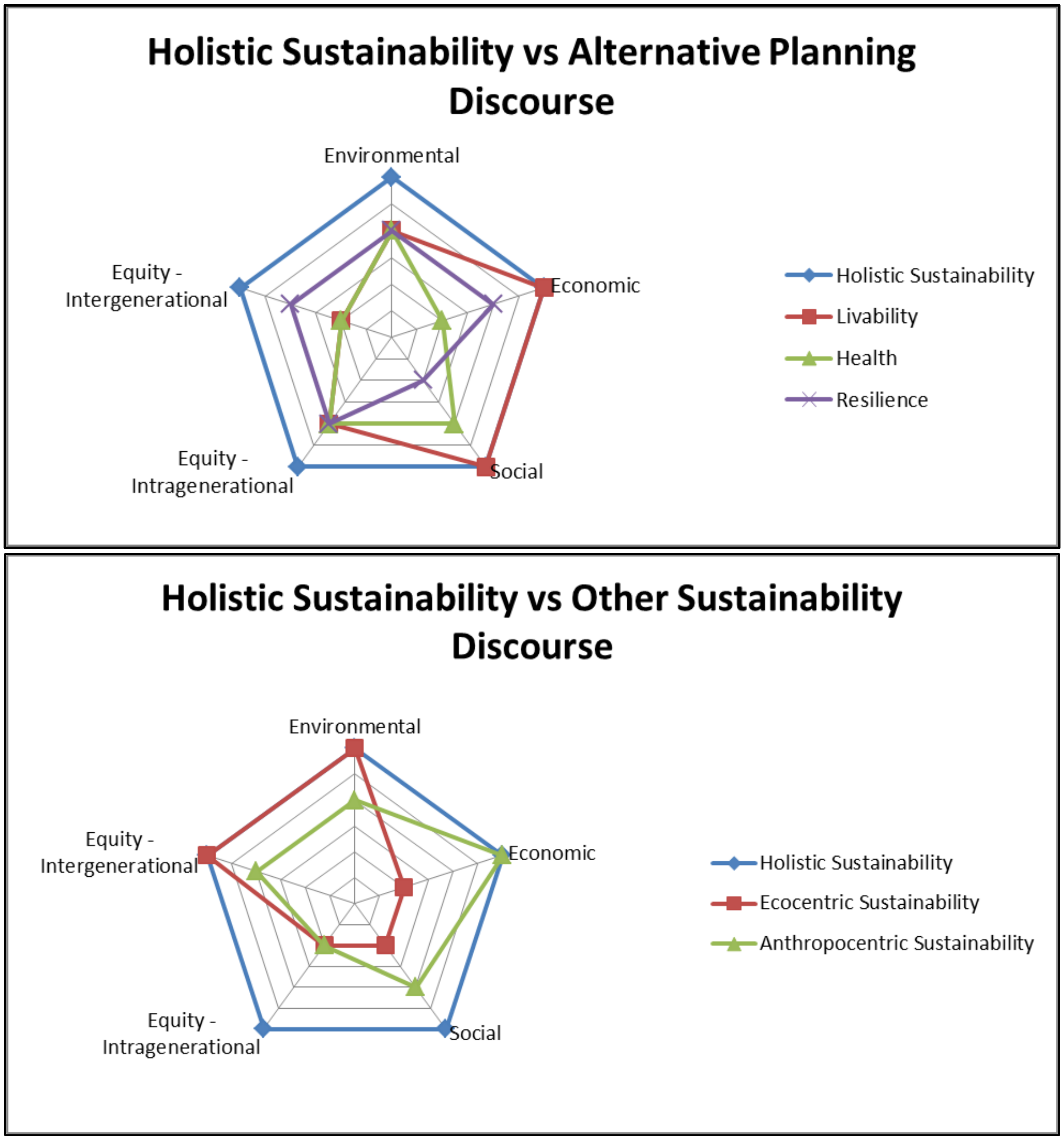

Figure 3 Mapping Sustainable Transportation-Related Discourse.

This mapping exercise also helps visualize what is lacking from certain discourse relative to holistic sustainability. For example, resilience almost mirrors holistic sustainability in terms of relative balance of priorities, with the exception of the social dimension. This leads to questions about whether “social-resilience” can be viewed as being similar to holistic sustainability. In the case of livability, the findings reflect the literature on the subject, which view it as a temporally- and spatially- limited application of sustainability. Health, similarly, also occupies a relatively small area when mapped against holistic sustainability.

5.6. Livability, Resilience and Health against Sustainable Transportation Considerations

One of the questions raised in this study is whether alternative frameworks such as livability, health or resilience can serve as proxies for sustainability. As another means of investigating this issue, an established set of sustainability considerations, in the form of goals for sustainable transportation from Zietsman et al (*5*) were selected as a baseline. Table 6 discusses how each of these goals is addressed in livability, health, and resilience discourse. As seen in the table, while some goals are not explicitly addressed, several others are addressed either fully or partially by health, livability and resilience frameworks. The ecosystems and waste-generation goals, specifically, are not addressed by any of the three frameworks.

Table 6 Sustainability Goals Addressed in Other Frameworks

Sustainable Transportation Goal – from (*5*)	**Addressed in a Health and Transportation Framework?**	**Addressed in Livability Framework?**	**Addressed in a Transportation Resilience Framework?**
Safety	Addressed.	Addressed partially – in relation to societal impacts.	Not addressed explicitly.
Accessibility	Addressed partially – in terms of access to destinations that promote health and access in terms of alternative modes.	Addressed.	Not addressed explicitly.
Equity/Equal Mobility	Addressed partially – in terms of mobility by non- motorized and alternative modes from an equity perspective and emissions reduction perspective.	Addressed partially – in terms of mobility by non- motorized and alternative modes from an equity perspective.	Addressed partially – in terms of system functioning for all users in the face of catastrophic events.
System Efficiency	Not addressed explicitly.	Not addressed explicitly.	Addressed.
Security	Not addressed explicitly.	Not addressed explicitly.	Addressed.
Prosperity	Addressed partially - in terms of equity, health, etc.	Addressed.	Addressed partially– from perspective of maintaining transportation system functioning as a social and economic support.
Economic Viability	Not addressed explicitly.	Not addressed explicitly.	Addressed partially - in relation to asset management considerations.
Ecosystems	Not addressed explicitly.	Not addressed explicitly.	Not addressed explicitly.
Waste Generation	Not addressed explicitly.	Not addressed explicitly.	Not addressed explicitly.
Resource Consumption	Not addressed explicitly.	Not addressed explicitly.	Addressed partially – in terms of fossil fuel consumption/climate change considerations.
Emissions and Air Quality	Addressed partially – in terms of health impacts	Addressed partially – in terms of air pollution impacts directly experienced by the public.	Addressed partially – in terms of greenhouse gas emissions.

5.7. Summary

This section analyzed how sustainable transportation is addressed *implicitly* and *explicitly* in current transportation planning practice. Following an extensive literature review, six types of discourse related to sustainable transportation (termed as alternative conceptualizations of sustainable transportation) were identified. Each of these alternative conceptualizations were defined, and assessed in terms of their scope, coverage of sustainability dimensions, and treatment of equity.

The results of this analysis indicated overlaps, as well as significant differences between the alternative conceptualizations of sustainability. It was also seen that the "holistic sustainability" approach was the most comprehensive in addressing sustainability considerations by tackling five key elements – three sustainability dimensions and inter- and intra-generational equity considerations. The alternative conceptualizations were then assessed against these five elements, as a means of visually mapping overlaps and gaps in coverage.

Finally, the alternative (or implicit) sustainability frameworks were compared against a set of established sustainability considerations. It was seen some sustainability considerations were addressed by the alternative frameworks, while others were not addressed explicitly.

The findings from this study are a first step in understanding how sustainability is applied in the transportation sector in the U.S., especially in the context of sustainability "competing" with other policy goals or frameworks such as resilience, livability or health. The results from this assessment indicate the potential for these concepts to work toward complementary goals, or to serve as proxies for each other. At the same time, there is a danger associated with certain aspects of holistic sustainability being neglected when other frameworks are applied.

A quantitative analysis using sustainability indicators, described in the next section, addresses some of the issues raised. It also provides further insight into how the overall framing of sustainability issues affects the outcomes observed from indicators.

6. CASE STUDY ANALYSIS USING SUSTAINABILITY INDICATORS

The previous section of this research focused on a qualitative assessment of frameworks and discourse related to sustainable transportation. In this section, a quantitative analysis using indicators is conducted. As described in the study design section, the aim of this phase is to conduct an assessment of how different conceptualizations of sustainable transportation, when translated into quantified indicators at the transportation planning level, differ in terms of results or observed outcomes. This analysis is conducted for a subset of the alternative conceptualizations of sustainable transportation discussed in the previous section for a case study in the El Paso metropolitan region in Texas, United States.

6.1. Study Area

El Paso is located in West Texas, at the U.S.-Mexico border, across from the city of Ciudad Juarez in Mexico. El Paso is also adjacent to the city of Las Cruces, New Mexico. The entire binational region is home to over 2 million people, and the ports of entry at El Paso receive a large volume of cross-border freight and trade. Per the 2010 US Census, the El Paso-Las Cruces Combined Statistical Area had a population of over a million residents (*149*). The El Paso MPO is responsible for transportation planning in this region, and it covers a regional planning area that includes El Paso county in Texas and portions of Dona Ana and Otero counties in New Mexico, as shown in Figure 4.

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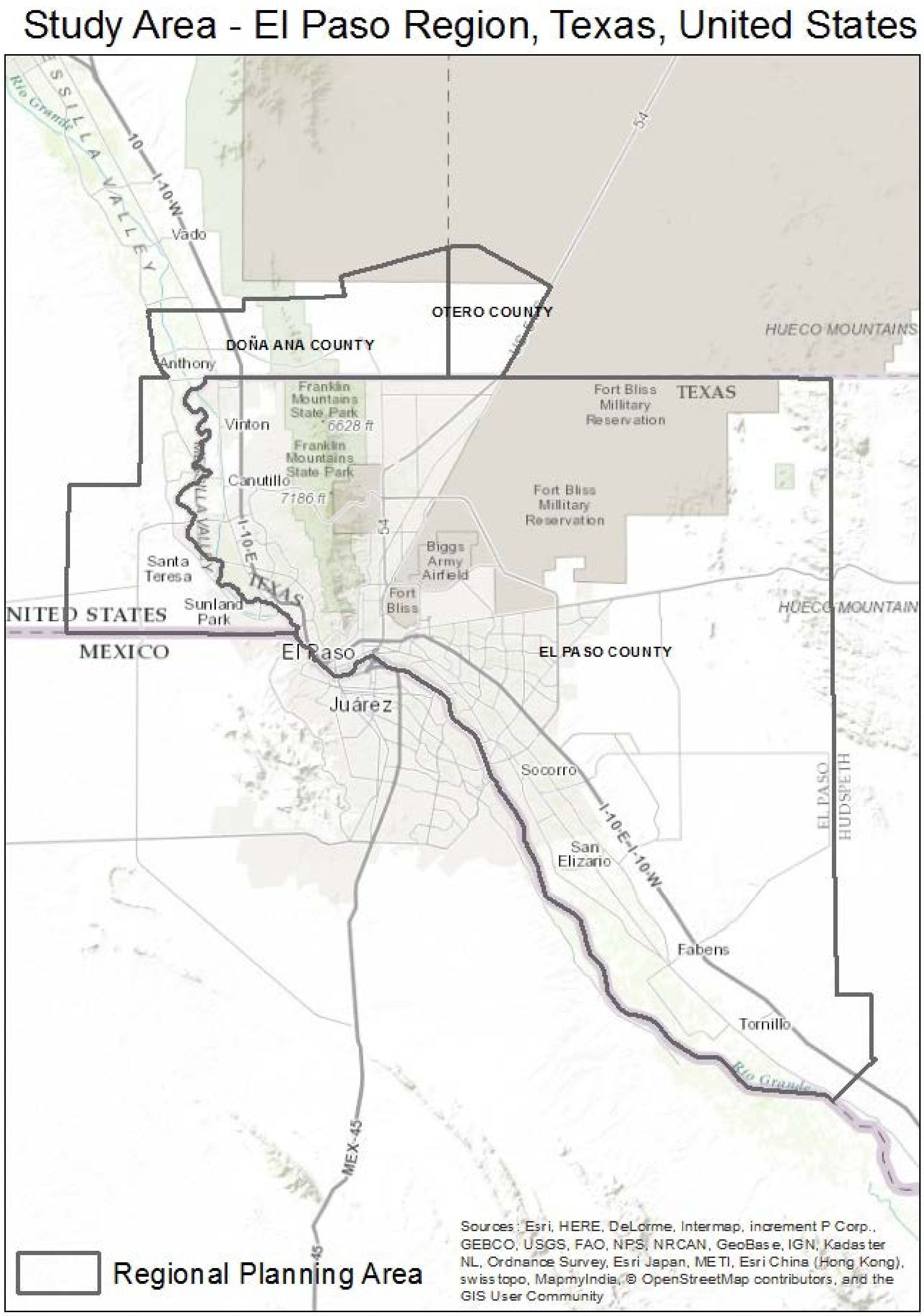

Figure 4. Map of Study Area

6.2. Quantitative Analysis Approach

As stated previously, the analysis aims to assess how conceptualizations of sustainable transportation differ when translated into quantified indicators applied to a common test case. From the conceptualizations identified in Section 5, the following were selected for the quantitative analysis:

- Anthropocentric sustainability (termed in this section as Sustainability) – to be representative of "baseline" sustainability considerations as commonly applied in the area of transportation planning.
- Livability and Health – as the alternative conceptualizations of sustainability, that represent emerging alternative discourse in transportation planning that are sometimes replacing sustainability considerations.

As seen in Section 5, anthropocentric sustainability represents the predominant approach to sustainability in the transportation sector. It was therefore selected to represent the baseline to be contrasted against alternative approaches. From among the alternatives of livability, health, and resilience explored in Section 5, it is seen that resilience is slightly different from livability and health in terms of the scope (being more system focused), and consequently in terms of a possible scale of analysis and relevant indicators for the same. Thus, livability and health were selected as the additional alternative conceptualizations of sustainable transportation, allowing for comparison of representative indicators for each of the concepts using common approaches and data sources.

The analysis approach is summarized in Figure 5. It involves the identification of representative indicators for the three conceptualizations being compared, namely, sustainability, livability, and health. These indicators are then quantified using spatially-disaggregated data (reflecting land use, demographics, transportation, etc.) for areas within the study region. The indicators are also combined into composite sustainability, livability, and health indices, using a simplified aggregation method based on multi-criteria decision analysis methods. This approach is consistent with what are broadly viewed as GIS-MCDA analyses, as discussed in Section 2.5.4.

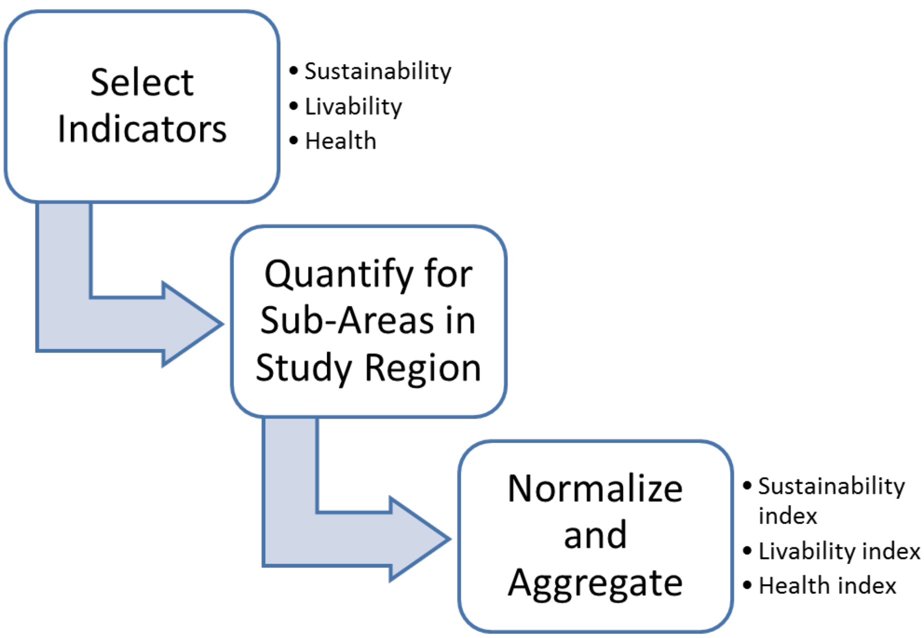

Figure 5. Overview of Analysis Approach

6.3. Data Sources and Unit of Analysis

The primary data source for this analysis is the El Paso MPO's regional travel demand model (TDM). As part of the federally-mandated transportation planning process, MPOs use travel demand modeling (or travel demand forecasting) to estimate future travel demand and assess the compatibility of transportation plans with future land use and demographic patterns, and for purposes such as transportation conformity analyses (*150*). The most common model used for this purpose is known as the "four-step" model, which includes the steps of trip generation, trip distribution, mode choice, and trip assignment (*150; 151*) .

Traffic analysis zones, or transportation analysis zones (TAZs) are considered to be the building blocks or unit of analysis for the four-step mode. They contain demographic and land use data that are used in the estimation of travel between the zones (*150; 152*). The design of TAZs is not an exact science, though existing literature discusses different approaches to TAZ development, and rules of thumb for appropriate TAZ size and scope (*150; 152; 153*). In general, TAZs are constructed to be relatively homogenous in terms of land use and demographic characteristics, and the density of TAZs (number of zones per unit area) increases in areas of greater population density such as city centers or highly urbanized areas. In line with several examples from the literature that use TAZs as the unit of analysis in quantifying sustainability-oriented transportation and land use indicators (*136; 139; 143; 144*) , this study also uses TAZs as the basic unit of analysis in the indicator and composite index calculations.

The El Paso MPO provided data from their current version of the travel demand model for this study. The model, called the 2040 Horizon model is a four-step transportation model that utilizes the TransCAD software package. Data in the form of TransCAD files and supporting documentation (*154; 155*) were obtained from the MPO. The data included transportation network data (network files) and demographics and land use information (TAZ files) covering four analysis years - 2010, 2020, 2030 and 2040. Figure 6 shows the layout of the study area TAZs, along with an example network for 2010. Both the TAZ files and network files have a range of spatially-linked attribute information that was used for calculating TAZ-level indicators.

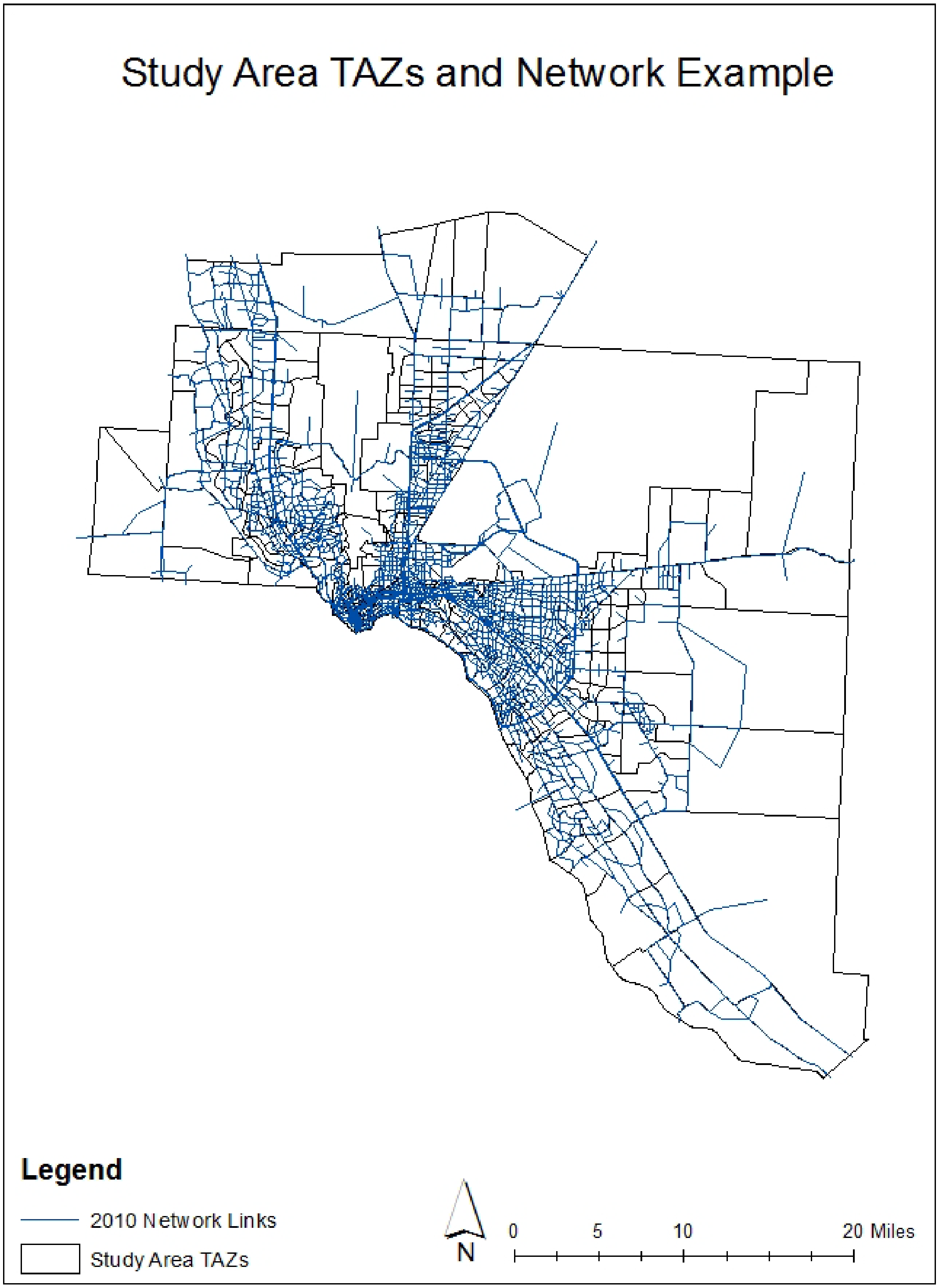

Figure 6. TAZ Boundaries and 2010 Network

Other data such as GIS maps containing locations of sites such as transit stops and bicycle lanes were also used in the analysis, obtained from a web repository of GIS datasets maintained by the University of Texas at El Paso, in collaboration with public agencies in the region (*156*). Individual data elements for each indicator and details of their computation are discussed in later subsections.

6.4. Indicator Selection

The selection of indicators for analysis was conducted taking into account the following considerations:

- The indicators selected should be based on examples from the literature.
- The indicators should reflect the particular discourse under consideration (sustainability, livability, or health), consistent with findings from the qualitative analysis.
- The indicators should be of appropriate scale for quantification using transportation planning data, and have available data for their quantification.

Table 7 summarizes the indicators selected, along with considerations that governed the indicator selection, relevant literature sources reviewed, and additional clarifying notes. As seen in the table, the sustainability indicators selected were reflective of what could be considered an anthropocentric or weak approach to sustainability, and included a set of indicators reflecting social, economic, and environmental aspects. The greenhouse gas and criteria pollutant emissions cover the environmental aspects; the safety measures address social considerations, while the land use measure and mode split measure can be viewed as addressing both the social and economic dimensions. This is consistent with several sources that discuss sustainability indicators (*5; 46; 117; 120; 121*). Table 7 also provides additional discussion of moving toward holistic sustainability through the use of additional equity-focused indicators (*139; 157*), or looking at a subset of greenhouse gas/energy focused indicators for an eco-centric perspective (*30; 55*) . The livability indicators were selected to reflect community-scale impacts, primarily on human well-being/quality of life, consistent with livability indicators from the literature (*45; 63; 111; 158-161*). These include measures of proximity to bicycle routes, transit facilities, and parks and recreation, along with the employment-population balance which is a common measure akin to the jobs-housing balance measure, and aims to assess how close people are to jobs and economic opportunity. While there are limitations to this indicator(*160; 161*), it was selected over alternatives such as commute times or distances due to considerations of data availability for future years. The health indicators were selected to reflect four key elements – safety, air quality, active living opportunities and access to critical destinations, consistent with literature on the subject (*89-92*). This included a measure of traffic intensity used as a proxy for exposure to traffic related emissions (*140; 162*), as well as the safety indicator, and proximity to parks and recreational facilities (active living opportunities) and to clinics and hospitals (critical destinations).

Table 7. Summary of Indicator Selection Process

Discourse	Considerations for Indicator Set	Indicators Selected	References/Sources and Additional Notes
Sustainability (Anthropocentric)	Indicators reflecting environmental, economic, and social factors. *<u>Notes regarding other sustainability discourse:</u>* *- Holistic sustainability can be represented by including an equity dimension.* *- Eco-centric sustainability can a greenhouse gas/energy focused metric or subset of metrics*	• Mode split • Greenhouse gas emissions • Criteria pollutant emissions • Land use mix • Safety	• General sustainability indicators - Jeon and Amekudzi 2005(*46*); Litman 2007(*117*); Zietsman et al. 2011(*5*); Haghshenas and Vaziri 2012 (*120*); World Business Council on Sustainable Development, 2015 (*121*) • Perspectives on strong vs weak sustainability (anthropocentric vs holistic) - Gudmundsson and Höjer 1996 (*55*); Black, 1996 (*30*) • Equity element – Karner 2016(*157*); Golub and Martens 2014 (*139*) • Eco-centric perspective – Amekudzi et al 2009(*51*); Black 1996(*30*); Wackernagel and Rees 1997 (*22*)
Livability	Indicators concerned with transportation as it relates to community-scale impacts, primarily on human well-being/quality of life	• Employment-population balance • Proximity to bicycle routes • Proximity to transit facilities • Proximity to parks and recreation	• Livability indicators - Gough 2015(*63*) Litman 2010 (*45*); USDOT 2010 (*111*) • Employment-population balance as a variation of jobs-housing balance - California Planning Roundtable (*158*); Horner and Murray 2003 (*159*); Limitations of measure discussed by Guiliano 1991 (*160*) and Cervero 1996 (*161*), but was selected due to extensive use in literature as a livability measure.
Health	Indicators reflecting transportation's relationship to human health, especially in relation to four key elements – safety, air quality, active living opportunities and access to critical destinations.	• Traffic density • Safety • Proximity to clinics and hospitals • Proximity to parks and recreation	• Health indicators – California DPH 2013 (*91*); USDOT 2015 (*92*); Lyons et al 2014 and 2012 (*89; 90*) • Traffic density or intensity measure – defined as vehicle miles of travel per unit area - is used in literature as a proxy for exposure to traffic related emissions – Rioux et al 2010 (*162*); Rowangould 2013 (*140*)

6.4.1. Overlaps in Indicator Sets

As seen in Table 7 there is one indicator (proximity to park and recreation facilities) overlapping between the health and livability indicator sets, and one indicator (safety) overlapping between health and sustainability indicator sets. This is expected, and representative of reality, given the overlaps between the concepts seen in the literature review and in the qualitative analysis. At the same time, the number of overlapping measures was intentionally limited to a single measure between any two indicator sets.

It is also seen that some of the measures between the indicator sets represent similar considerations, but at a different scope/scale. For example, the traffic density measure looks at exposure impacts of traffic emissions, from an air quality and health perspective. The criteria pollutant emissions measure, in the sustainability indicator set also addresses the air quality issue, though at a different scale, focused on absolute emissions levels for a TAZ. Similarly, mode split in the sustainability indicator set, and transit or bike lane access in the livability indicator set, each address similar issues (of alternative transportation modes) at different levels. Again, these conceptual overlaps do not detract from the main study objective, which is to investigate whether the prevailing notions of sustainability, livability, and health differ significantly when quantified using indicators. While a case can be made for some of the non-overlapping indicators in one indicator set to also be included in the other, this study is focused on identifying a limited set of the most representative indicators for each concept, as described in the previous section. It does not imply that the indicators represent the entirety of important sustainability, livability and health considerations – they instead signify a representation of key considerations when quantified as indicators at the transportation planning level.

6.4.2. Indicator Definitions, Computations, and Desired Direction

Table 8 provides a summary of the indicators used, specific definition and computation, desired direction of the indicator, and the discourse (sustainability/livability/health) that it is applicable to. More detailed description of the measures and their computation at the TAZ level is provided below.

6.4.2.1. Mode Split

In this study, mode split is defined as the ratio of non-single occupant vehicle (SOV) trips to SOV trips originating from a TAZ. From a sustainability perspective, higher ratios of non-SOV trips (defined as passenger vehicle trips with 2 or more persons in the vehicle, as well as transit trips) to SOV trips are desirable, indicating larger number instances of transit use, carpooling, or trip chaining. The El Paso TDM data contains trip tables with origin-destination (O-D) pairs covering all TAZs. Trips originating from one TAZ to all others are aggregated by mode to calculate this indicator.

Table 8. Summary of Indicators

Measure	Computation	Desired Direction	Relevant Discourse		
			Sustainability	Livability	Health
1. Mode Split	Ratio of Non-SOV Trips to SOV trips originating from the TAZ	Higher			
2. Emissions - GHG	Total CO_2 emissions from TAZ	Lower			
3. Emissions – Criteria Pollutants	Total NOx and PM_{10} emissions from TAZ, in tons of NOx equivalent weighted by damage costs	Lower			
4. Land Use Mix	Aggregated area type for TAZ from TDM	Closer to 1 on 1-5 scale			
5. Employment-Population Ratio	Ratio of employment to population in a TAZ	As close to 1 as possible			
6. Proximity to Bicycle Routes	Distance of TAZ centroid to nearest bicycle route	Lower			
7. Proximity to Parks and Recreation	Distance of TAZ centroid to nearest park or public recreation facility	Lower			
8. Proximity to Transit Facilities	Distance of TAZ centroid to nearest transit facility	Lower			
9. Proximity to Clinics and Hospitals	Distance of TAZ centroid to nearest clinic or hospital	Lower			
10. Safety	Uncalibrated total annual crashes per TAZ using PLANSAFE model estimate	Lower			
11. Traffic density	VMT/square mile	Lower			

6.4.2.2. Greenhouse Gas (GHG) Emissions

This indicator is defined as the total carbon dioxide (CO_2) emissions (in lbs per day) from the TAZ. CO_2 is the primary transportation-related GHG, and of importance from a sustainability/climate change perspective. Lower CO_2 emissions are desirable for this indicator. The estimation of TAZ-level CO_2 emissions was based on computed vehicle miles of travel (VMT) by roadway type and emissions factors from United States Environmental Protection Agency (EPA's) Motor Vehicle Emissions Simulator (MOVES) emission model. Appendix A provides further details of the emissions estimation methodology, which was implemented in the form of an emissions analysis tool developed for the El Paso MPO (*163*).

6.4.2.3. Criteria Pollutant Emissions

The criteria pollutants reflected in this indicator are oxides of nitrogen (NOx) and particulate matter (PM_{10}), since they are of relevance to the El Paso region. The El Paso region is currently in violation (classified as being in nonattainment) of the National Ambient Air Quality Standards (NAAQS) for PM_{10}. The region has also been proposed for designation as a nonattainment area for the 2015 ozone NAAQS, and NOx is an ozone precursor generally associated with emissions from diesel vehicles. The indicator is defined as TAZ-level emissions of NOx and PM_{10} emissions, expressed as NOx-equivalent emissions weighted by pollutant damage costs (in lbs per day). NOx-equivalent PM_{10} emissions are obtained based on the ratio of pollutant damage costs ($/ton of emissions) defined by the FHWA's Highway Economics Requirements System, based on the work of McCubbin and Deluchi (*164; 165*). In this work, NOx is listed as having a damage cost of $3,625 per ton, while the damage cost for PM is $4,825. The ratio of damage costs is applied to the PM_{10} emissions to obtain NOx-equivalent emissions, which are added to NOx emissions to compute the indicator. The emissions estimation process used to compute the NOx and PM_{10} emissions is the same as for the previous GHG measure. Further details of the estimation process are provided in Appendix A. As with the previous measure, lower NOx-equivalent emissions are desirable for this indicator.

6.4.2.4. Land Use Mix

In general, mixed land use, or land use with greater densities of population and activity are desirable from a sustainability perspective. This indicator makes use of the “area type” data attribute in the El Paso TDM data. Each link in the transportation network is associated with an area type, based on land use, population, and employment characteristics in the surrounding areas. The area types are numbered from 1 through 5, representing dense urban environments through low-density rural areas. The classification of area types are based on a calculated “density factor” that takes into account population density, employment density and regional employment-population ratios (*155*). GIS is used to aggregate the link-level area type assignments to a representative TAZ-level area type, which represented the land use mix indicator. A lower number (close to area type 1) is considered desirable for this indicator.

6.4.2.5. Employment to Population Ratio

The employment to population ratio is an indicator used to represent livability considerations from the perspective of access to jobs and economic opportunities.

Employment and population data from the travel demand model at the TAZ level is used to compute this ratio. The indicator is specifically defined as the ratio of the lower number to the higher number (between population and employment) in a TAZ. The indicator therefore will always have a value of between 0 and 1, where a value closer to 1 is more desirable.

6.4.2.6. Proximity to Bicycle Routes

GIS layers of state- and city-maintained bicycle lanes/routes were obtained, and used for the calculation of this indicator. It was calculated using GIS software, and is defined as the distance of the TAZ centroid to the nearest bicycle route, in feet. Lower values of this measure are desirable, indicating easier access to bicycle facilities for the TAZ.

6.4.2.7. Proximity to Parks and Recreation

This indicator is calculated in a similar manner to the previous indicator, using the location of public parks and public recreational facilities in the region. Lower values are again desirable for this indicator, indicating easier access to park and recreation facilities.

6.4.2.8. Proximity to Transit Facilities

This indicator is calculated in a similar manner to the previous indicator, using the location of transit facilities (existing, and planned, for future analysis years). Lower values are again desirable for this indicator, indicating easier access to transit facilities.

6.4.2.9. Proximity to Clinics and Hospitals

This indicator is calculated in a similar manner to the previous indicator, using the location of clinics and hospitals in the region. Lower values are again desirable for this indicator, indicating easier access to healthcare facilities.

6.4.2.10. Safety

While traffic safety estimates (in terms of crashes per year) are generally modeled at the facility level using crash count models or other methods, there is a growing body of literature focused on estimation of crashes based on transportation planning data at the level of TAZs (*166-168*). This indicator makes use of the PLANSAFE model, developed for use with TAZ-level data as part of a National Cooperative Highway Research Program project (*169*). This indicator is quantified for each TAZ as the uncalibrated total annual crashes using the PLANSAFE model, and lower values of this indicator are desirable. Appendix B contains further information on the computation of crashes based on the model used.

6.4.2.11. Traffic Density

Traffic density, also sometimes termed as traffic intensity, is used in literature to represent traffic and emissions exposure levels. It is expressed as VMT per square mile for each TAZ, and lower values are desirable for this indicator. The VMT computations are obtained from the travel demand model data during the computation of emissions. The TAZ area in square miles is included in the attributes of the TAZs.

6.5. Quantification of Indicators

6.5.1. Data Assembly

The first step in the analysis was to assemble the required data from the travel demand model files, which included a TAZ master file containing demographic attributes for each TAZ for each of the analysis years (2010,2020,2030 and 2040), and individual network files containing network-level attributes at the link level for each year's model output. Data from the various files were exported from TransCAD into the required formats, which included ESRI ArcGIS files for spatial linkages and for computation of proximity indicators, and MS-Excel spreadsheets/comma separated variable (CSV) format for computations.

6.5.2. Data Review and Computation of Indicators

A majority of the computations of the indicators and indices were done in MS-Excel, and linked spatially for visualization in ArcGIS. The statistical analysis package R was also used for reviewing data trends and performing specific statistical analyses.

The travel demand model area comprises of 815 TAZs, which includes El Paso County as well as a portions of Dona Ana and Otero counties in New Mexico. For purposes of this analysis, only TAZs in El Paso County were considered. Further, TAZs that did not have base year VMT (i.e. no traffic activity on network links for 2010), or those that did not have any base year residents or employment (i.e. where total population and employment in 2010 was zero) were also eliminated from the analysis. After elimination of TAZs based on these criteria, a total of 723 TAZs in El Paso County remained, as shown in Figure 7. Appendix C provides a summary of some key data elements for the analysis TAZs. Appendix D includes maps of locations of transit stations, bike facilities, and other elements used for the quantification of proximity indicators. The indicators were calculated for each of these 723 TAZs based on methods defined in Section 6.4.

6.5.3. Development of Sustainability, Livability, and Health Indices

The eleven indicators quantified for each TAZ in this study are expressed in different units, and have different desired directions, as shown in Table 8. Further, individual subsets of these indicators are applicable to the sustainability, livability, and health discourse. In order to assess the overall differences between the indicator sets, there is a need to express relative performance of individual measures and aggregate them at the TAZ level. Figure 8 shows the process of developing TAZ-level sustainability, livability, and health index values to allow for comparison of results and to examine trends and commonalities in the data. The process is a simplified MCDA approach, similar to other examples in the literature (*120; 124; 170*), and is described briefly below:

- Quantified indicators for each TAZ are scaled (expressed on a 0-1 scale) to allow for easy comparison of low-performing and high-performing TAZs. TAZs are ranked into quintiles, based on their indicator values and desired direction of the indicator. For example, in the case of the GHG emissions measure, TAZs with highest emissions will rank in the lowest quintile, and vice-versa. The bottom- to top-performing quintiles are then assigned scores of 0, 0.25, 0.5, 0.75, and 1. This approach to scaling allowed for an even distribution of scaled indicator values among the TAZs It also ensured that TAZs with extreme indicator values did not disproportionately affect scores of other TAZs, which is possible with other scaling approaches that were based on normalization of values to highest and lowest observed values in the dataset.

- The scaled indicator values corresponding to the sustainability, livability, and health datasets were then aggregated as a simple averages to obtain composite sustainability index, livability index, and health index values for each TAZ. The use of average values is equivalent to assigning equal weights to all measures comprising the respective index – which was determined to be appropriate for purposes of this analysis.

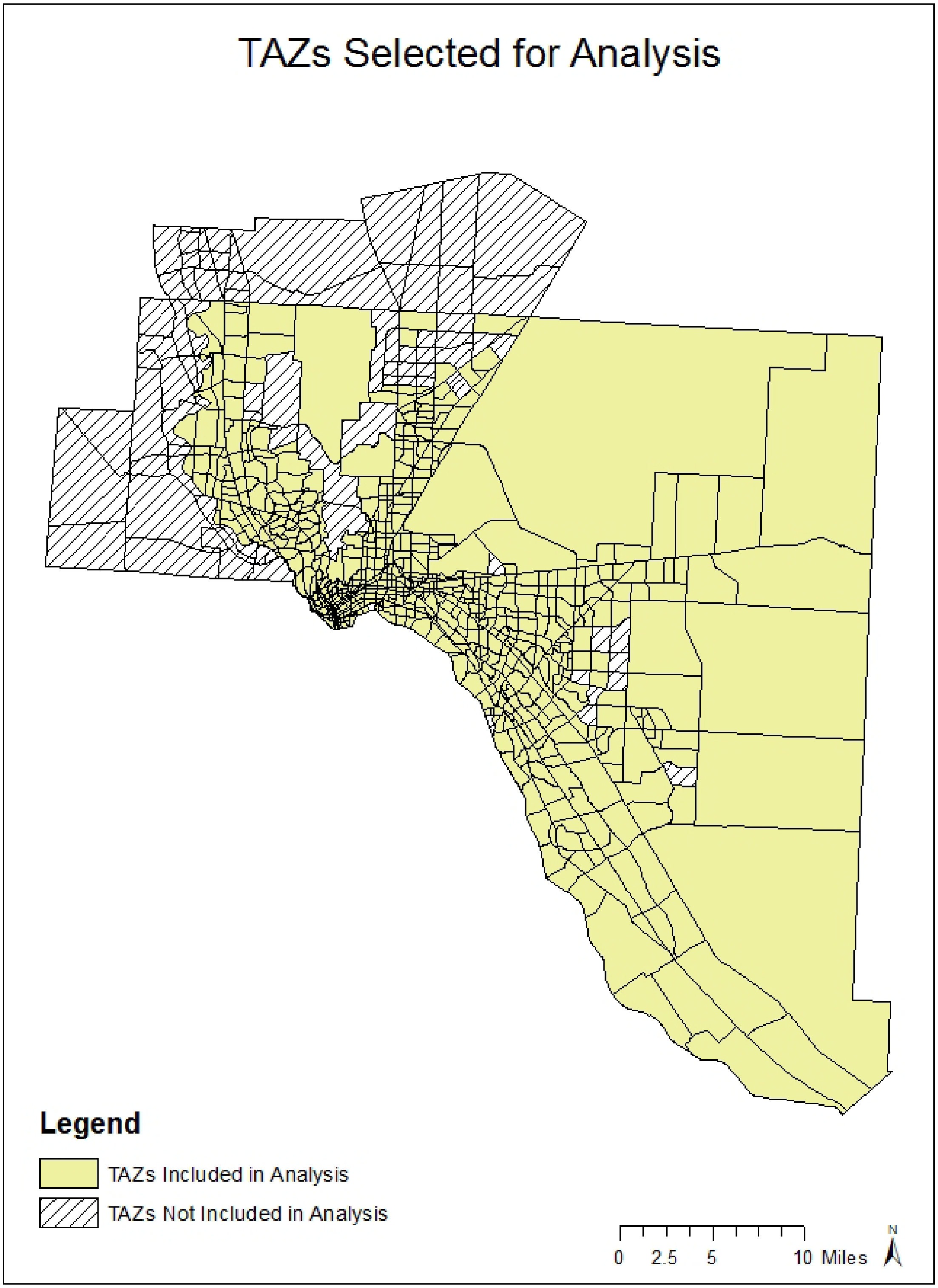

Figure 7. Subset of TAZs Selected for Analysis

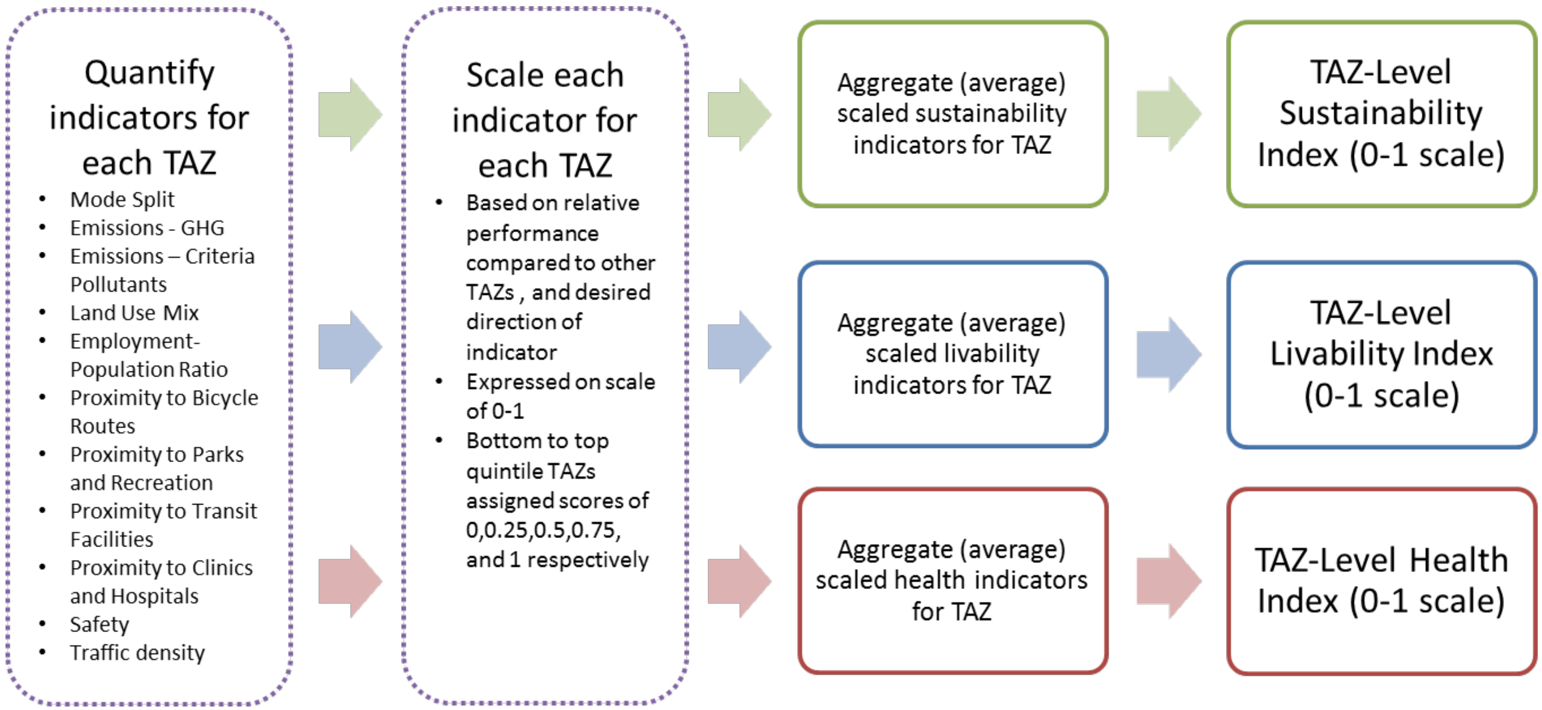

Figure 8. Process of Developing TAZ-Level Sustainability, Livability, and Health Indices

6.6. Quantitative Analysis Results

Using the methods described in previous sections, TAZ-level indicators, scaled indicators, and sustainability, livability and health indices were computed for four analysis years (2010, 2020, 2030, and 2040) based on the El Paso travel demand model data. The results were also linked to spatial data to allow for visualization of results for better interpretation. This section provides a summary of results obtained for the sustainability, livability and health indices. Appendix E contains results for individual indicator values for all 11 indicators.

Figure 9 , Figure 10, and Figure 11 show maps of the calculated sustainability, livability, and health index values, respectively, for each analysis year, between the different TAZs. Two main observations can be drawn from looking at these figures:

- First, there is very little change between the relative distribution of scores for the sustainability, livability, and health indices over time (i.e. TAZs scoring well on one particular analysis year, tend to perform well other analysis years)
- Second, there do not appear to be high correlations or clear trends between the livability, health, and sustainability indices for any given year.

These findings are confirmed by the correlation matrix shown in Figure 12. The part of the correlation matrix below the diagonal displays the correlation coefficients between each pair of values, i.e. the sustainability index values for each analysis year, the livability index values for each analysis year, and the health index values for each analysis year. The part above the diagonal presents the same information visually, with dots representing the direction and strength of the correlation. The findings show that there are high correlations between the same index for different analysis years. For example, the 2010 sustainability index values are seen to have correlation coefficients of 0. 93, 0.89, and 0.87, with the 2020, 2030 and 2040 sustainability index values respectively. There are similarly high correlations for the livability and health indices as well. However, for a given analysis year, the correlations between the sustainability, livability, and health indices are found to be very low. For example, in 2010, the correlation between the sustainability and livability index pairs, the livability and health index pairs, and the health and sustainability index pairs, are 0.11,0.33, and 0.48 respectively.

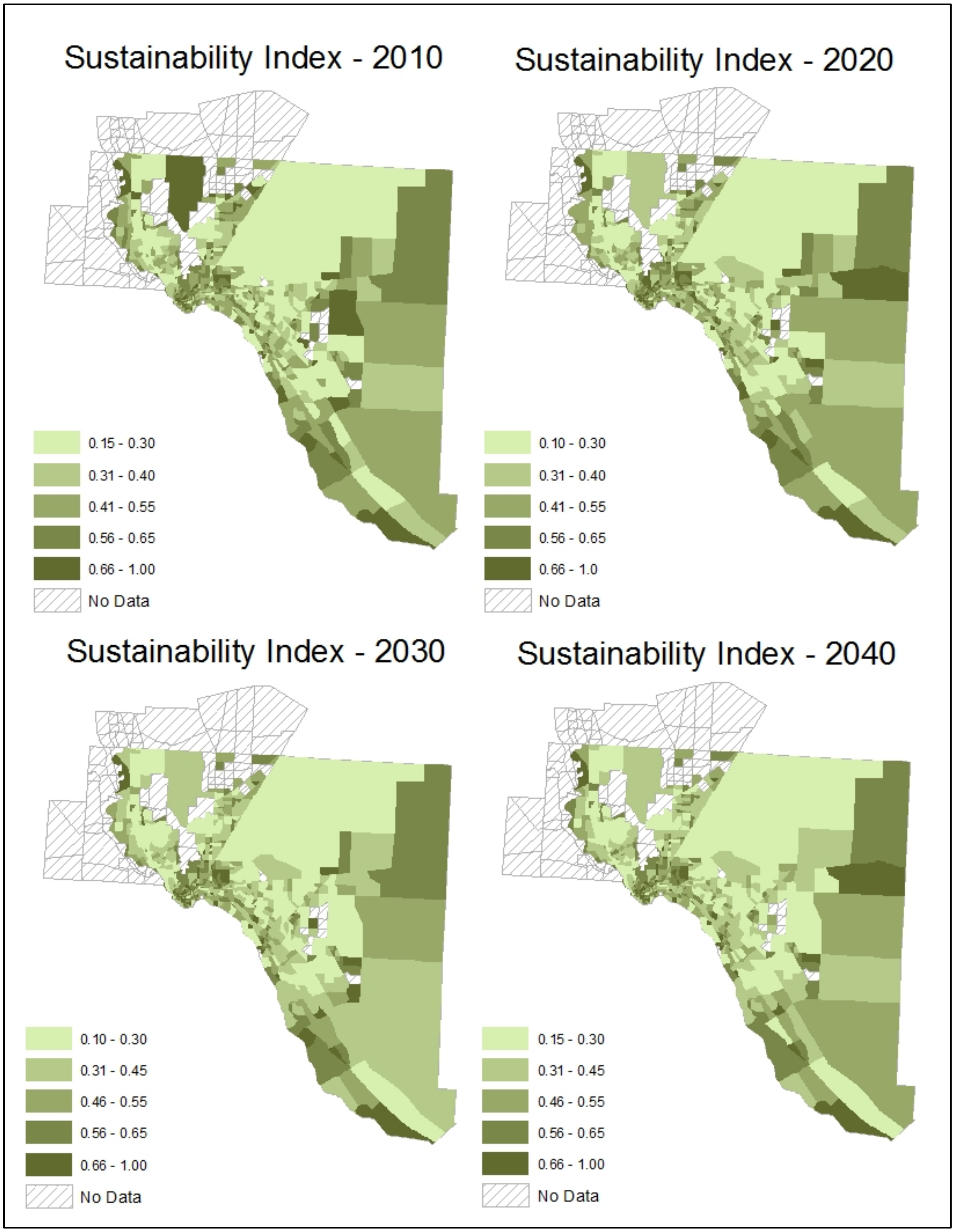

Figure 9. Sustainability Index Values by TAZ – All Analysis Years

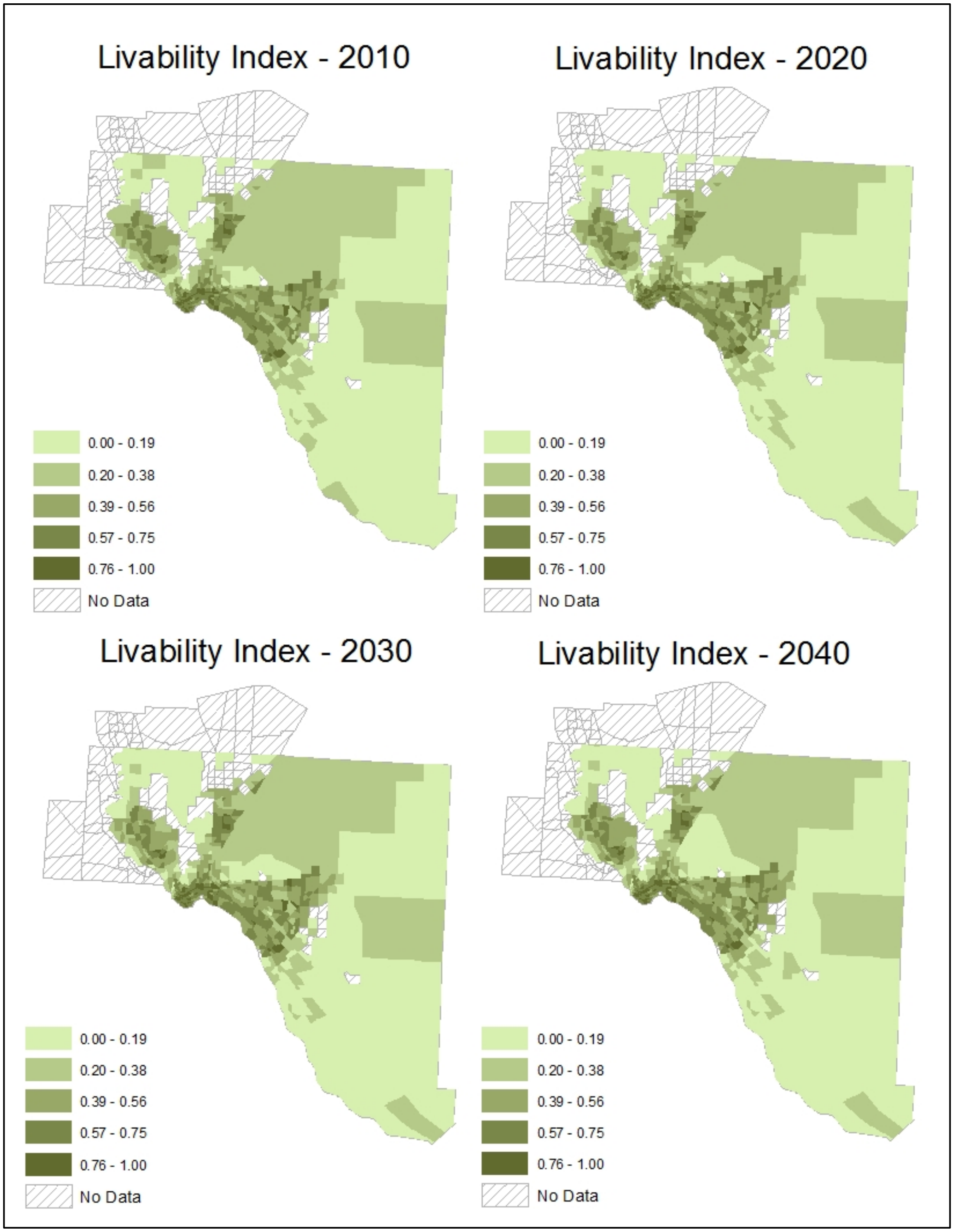

Figure 10. Livability Index Values by TAZ – All Analysis Years

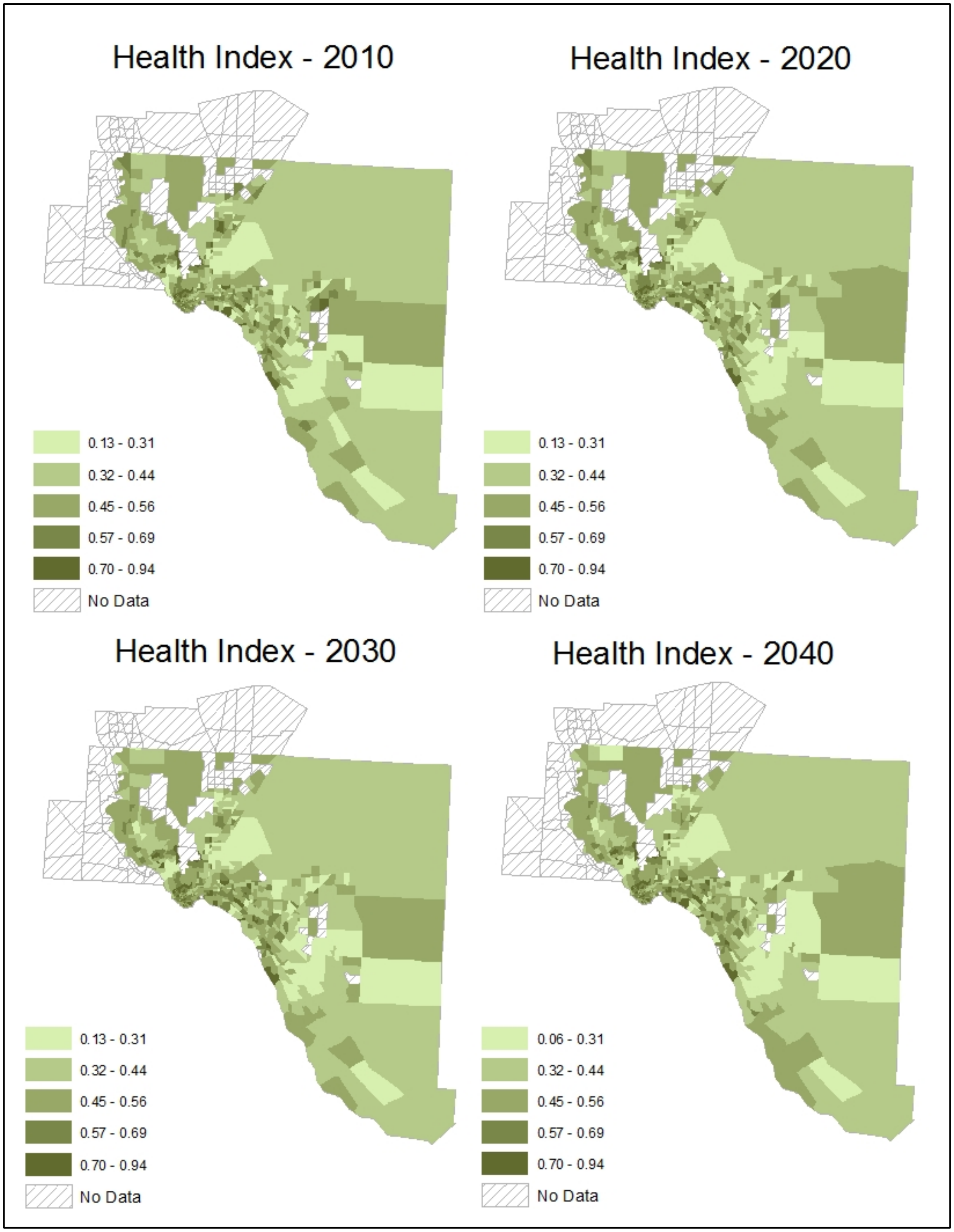

Figure 11. Health Index Values by TAZ – All Analysis Years

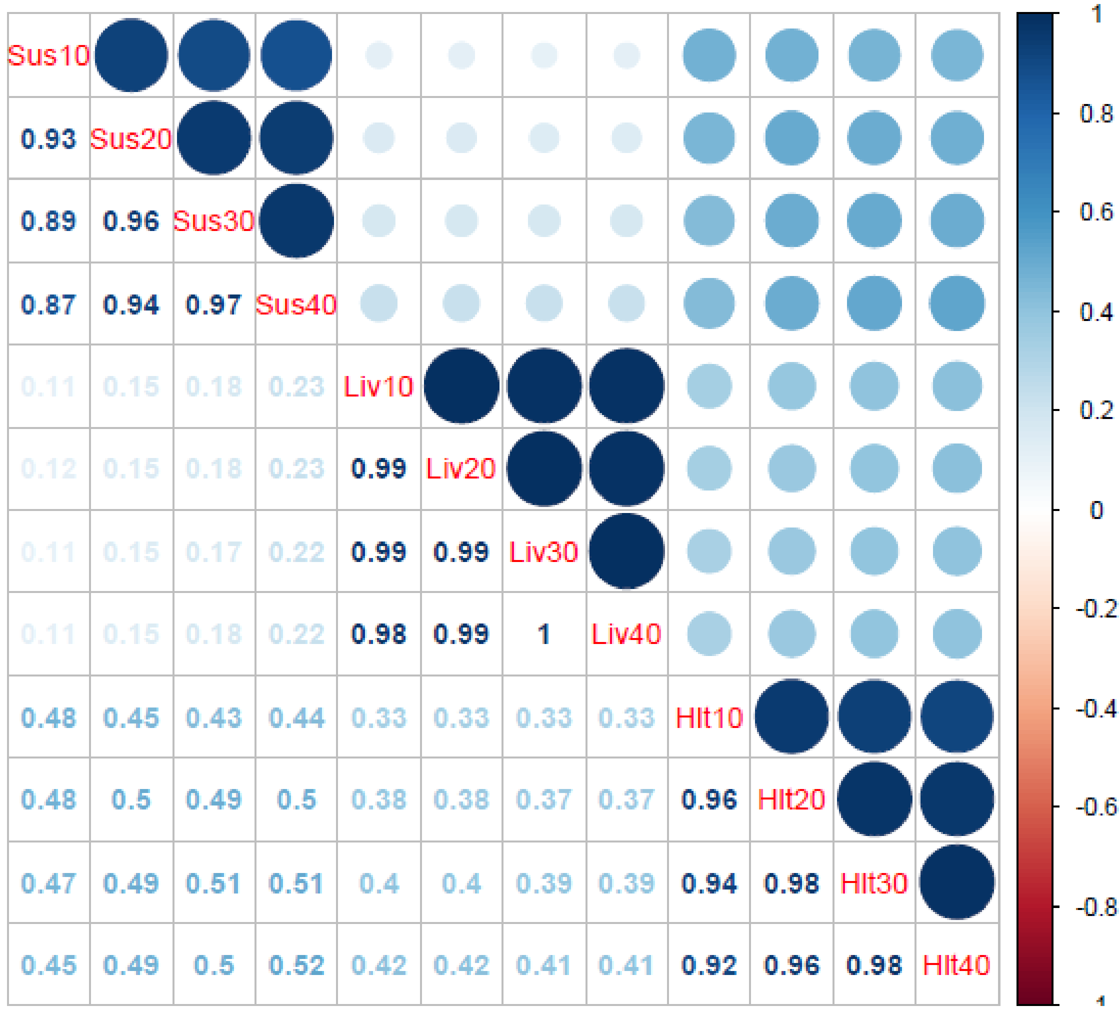

Figure 12. Correlation Matrix for Three Index Values over Four Analysis Years

It is also interesting to note that the livability and health index pairs, and sustainability and health index pairs, both have relatively higher correlations than the sustainability-livability index pair for all the analysis years. The former two pairs each share an overlapping indicator, while there are no overlaps between the livability and sustainability indicator sets, as seen in . Additional findings and observations from this data include that areas scoring well from a livability and health perspective tend to be located closer to downtown and urbanized areas, compared to performance from a sustainability perspective, which seems to be more widely dispersed.

6.6.1. CO_2 Emissions as a Proxy for Sustainability Index

Often, CO_2 emissions from transportation are discussed as being a proxy for sustainable transportation, especially in an eco-centric view of the subject. An additional analysis was conducted to assess whether the sustainability index value was related to the CO_2 emissions measure. It was seen that the sustainability index values and the scaled CO_2 emissions measure were highly correlated (correlation coefficients in the range of 0.9 for all analysis years), despite the CO_2 measure being one of five measures comprising the sustainability index. This is shown visually in Figure 13 for the 2010 and 2040 analysis years. This result is partially explained by interrelationships between the CO_2 emissions indicator and other indicators in the sustainability set. The CO_2 emissions indicator is highly correlated to vehicle miles of travel, as is the criteria pollutant indicator, while the safety indicator computation takes into account factors such as roadway length and population density, which are likely related to overall travel. However, from the perspective of reduced automobile travel being viewed as sustainable, a case can still be made for CO_2 emissions as a proxy for sustainability.

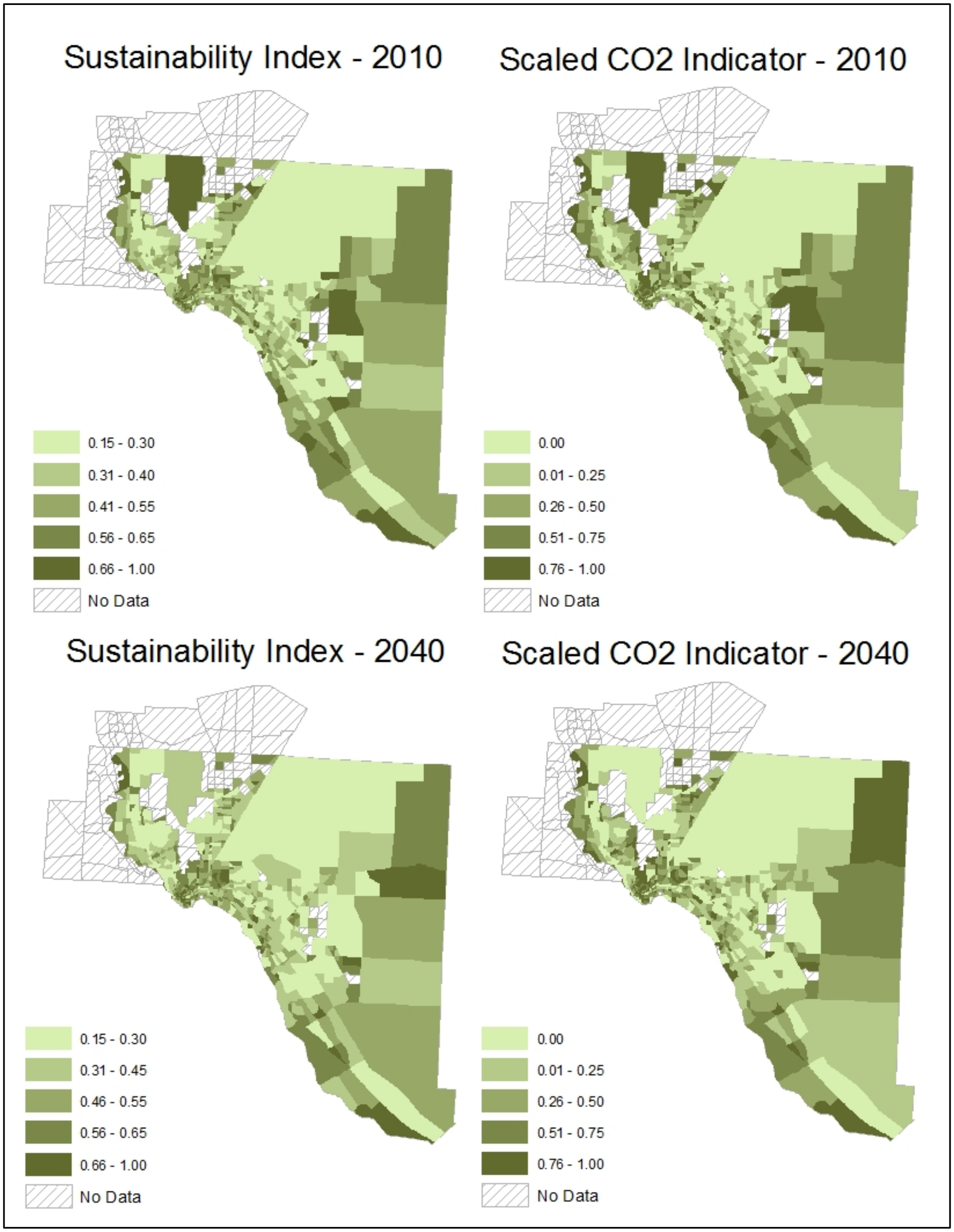

Figure 13. Scaled CO_2 Indicator vs Sustainability Index for 2010 and 2040

6.6.2. Assessment of Equity Implications – Index Values for Low-Income and High-Income Areas

An additional analysis was conducted to see if areas associated with lower or higher incomes showed different trends in sustainability, livability, and health index values compared to all areas. For this analysis, only TAZs associated with a residential population for the base year (2010) were selected. Of these 627 zones, 39 were identified as low-income TAZs, having a median household income below that of the lowest income group in the travel demand model demographics, i.e. a median income of $14,220 in 2007. Similarly, 27 high-income TAZs were identified, with incomes greater than the highest income group in the travel demand model demographics, i.e. a median income of $71,101 in 2007.

As seen in Table 9, the average index values for the low-income zones were actually higher than the average for all zones in the analysis – which is an interesting finding with regards to potential equity considerations. This could be explained due to the location of the low-income TAZs being close to the densely populated urbanized areas, leading to better overall performance on some indicators such as proximity to various services. For the higher-income TAZs, it is seen that livability and sustainability index values tend to be lower than average, while the health index values remain close to average values.

Table 9. Index Values for Low Income TAZs vs Overall Averages*

Analysis Year	Dataset	Average Sustainability Index Value	Average Livability Index Value	Average Health Index Value
2010	All TAZs	0.48	0.51	0.49
	Low-Income TAZs	0.58	0.66	0.55
	High-Income TAZs	0.42	0.40	0.50
2020	All TAZs	0.48	0.51	0.49
	Low-Income TAZs	0.56	0.67	0.56
	High-Income TAZs	0.41	0.40	0.49
2030	All TAZs	0.48	0.51	0.49
	Low-Income TAZs	0.56	0.67	0.56
	High-Income TAZs	0.42	0.40	0.50
2040	All TAZs	0.48	0.51	0.49
	Low-Income TAZs	0.55	0.67	0.55
	High-Income TAZs	0.42	0.40	0.50

** Overall averages for subset of 627 TAZs with residential population*

6.7. Summary

This section describes a case study for El Paso, Texas, that was conducted to investigate how alternative discourse related to sustainable transportation can affect outcomes measured using indicators. Data from the regional travel demand model and other sources were used to quantify a sustainability index, livability index, and health index for zones in the region, for four analysis years. Each index comprised of representative indicators, which were normalized and aggregated in accordance with common multi-criteria decision-making methods.

The analysis results demonstrated little correlation between the quantified livability, sustainability, and health indices across the El Paso region. It was also seen that the indices showed relatively low levels of change over time, i.e, the relative performance of a zone according to the various metrics tended to stay the same, despite the modeled changes to the transportation system, demographics, and land use.

Additional analyses of CO_2 emissions compared to the sustainability index as a whole indicated the potential for an eco-centric perspective on sustainability to match fairly well with a broader triple-bottom-line perspective. An analysis of trends in index values for lower-income and higher-income TAZs produced counter-intuitive findings that showed better performance in low-income zones, and relatively worse performance in high-income zones with regards to the sustainability and livability indicator values.

Overall, the findings from this section provide a means of validating sustainable transportation-related concepts by demonstrating the practical impact of results obtained from measuring theoretical constructs.

7. CONCLUSIONS

The findings from this study serve to advance knowledge in the area of sustainability as it relates to transportation planning, by investigating how discourse can affect measured outcomes. The main contributions of this study include:

- *Advancing the understanding of issues, challenges and complexities* – the literature review and critical analysis shed light on the complexities and challenges for sustainable transportation and made the case for a two-part research approach to address theoretical concepts and their practical implications.
- *Analysis of Discourse* – there is limited research systematically discussing nuances of discourse related to sustainability in the transportation sector. This study provided a means of mapping the different spaces occupied by different types of sustainability discourse, and demonstrating the differences among frameworks that address sustainability in an implicit as well as explicit manner.
- *Transportation Planning Implications* – the study demonstrated that despite theoretical overlaps between discourse such as sustainability, livability, and health, these concepts do not necessarily address the same issues from a practical perspective.

The study hypothesis was that "*alternative conceptualizations of sustainable transportation promote complementary goals and values and can serve as proxies for each other*". The study findings lead to the conclusion that this hypothesis is not supported, especially at the quantitative level, when the concepts are translated to metrics and quantified.

7.1. Study Findings

At the outset, the study explored the concept of sustainability and how it relates to transportation. Definitions and frameworks for sustainable transportation, and discourse in this area were then explored. This was followed by a review of alternative discourse that has emerged paralleling sustainability considerations in theory and in practice in transportation. Finally, the area of sustainability indicators, as a means of evaluating sustainability and related concepts was discussed.

A critical analysis of the literature review findings demonstrated the complexities and interrelationships in sustainable transportation. There is no "one-size-fits-all" approach to sustainable transportation, and research in this area must address both theoretical and practical elements. The study design therefore aimed to validate alternative conceptualizations of sustainable transportation through a qualitative analysis of discourse, followed by an indicator-based quantitative analysis that is applied to a test case.

The qualitative analysis explored six alternative conceptualizations of sustainable transportation, discussing their scope, coverage of sustainability dimensions, and treatment of equity. A holistic transportation sustainability perspective, representing an idealized vision for sustainability was contrasted against anthropocentric and eco-centric views of sustainability, and against alternative discourse of livability, health and resilience. The findings indicated the presence of overlaps and well as gaps in coverages between the concepts. This indicated the potential for these concepts to work toward complementary goals, but also highlighted the danger associated with certain aspects of holistic sustainability being neglected.

A quantitative analysis using sustainability indicators was then conducted to investigate how alternative discourse related to sustainable transportation can affect outcomes measured using indicators. This was done for a test case in the El Paso metropolitan region. Local data were used to quantify indicators that were aggregated to a sustainability index, livability index, and health index for traffic analysis zones in the region, for four analysis years.

The analysis results demonstrated little correlation between the quantified livability, sustainability, and health indices for a specific analysis year. It was also seen that the indices tended to stay the same over time, indicating that the relative performance of a zone remained unchanged despite the modeled changes to the transportation system, demographics, and land use. Additional analyses of CO_2 emissions compared to the sustainability index as a whole indicated the possibility that an eco-centric perspective could serve as a reasonable proxy for a triple-bottom-line sustainability perspective. An equity analysis showed lower-income zones having higher index values compared to overall averages, with high-income zones faring worse than average in terms of the sustainability and livability indices. These findings are somewhat counterintuitive, and indicate that areas that may be considered sustainable or livable from a transportation and land use perspective do not necessarily correlate to having a better quality of life, from a perspective of overall income or poverty levels.

While the El Paso region is unique in terms of its geography and location, its transportation system is similar to that of many large cities in the U.S., and the study findings could be expected to be generalizable to other regions. However, further application of this research to other areas is required to conclusively determine the generalizability of the findings.

7.2. Implications

The main implication of this study is that the concept of sustainability should not be replaced by alternative discourse such as livability, health, or resilience in the transportation sector, despite theoretical overlaps that exist between the concepts. At a practical level, this is a mixed outcome for sustainability advocates. On one hand, it demonstrates the value of sustainability as a concept which cannot be replaced by other discourse or organizing principles. On the other hand, it can be viewed as a negative outcome, since it indicates that alternative approaches such as livability and health cannot necessarily serve as proxies for sustainability, which may be useful in advancing sustainability programs in politically challenging climates.

The study also reiterates the inherent complexity of sustainability issues, and brings to light the importance of indicators used for measuring concepts. In this study, the approach to indicator selection was to rely on examples from the literature and the stated goals of the relevant discourse. It therefore is representative of a good-faith attempt by a transportation practitioner to quantify a concept (such as sustainability, livability, or health) that has been deemed as important, and to presumably make planning decisions accordingly. However, the results also show the influence that indicator selection can have on overall results, and raises the possibility of indicators being "cherry-picked" to produce desired outcomes.

Further, the study also confirms what has been addressed at length in literature and research – that transportation cannot be made sustainable in isolation. The results also indicate very small changes in relative performance of TAZs over time, for the sustainability, livability, as well as health indices – pointing to the relative inelasticity of sustainability indicators, and the importance of a strategic, long-term view on sustainability issues.

7.3. Limitations and Scope for Future Research

Travel demand model data was identified as the most suitable for this study, due to the availability of comparable data for over time, covering a range of transportation, land use, and demographic factors. However, using travel demand model data constrained the analysis to the level of a TAZ – disaggregating the data further (to the census block level) could have allowed for a more nuanced analysis, and inclusion of finer-scale metrics looking at access and proximity at the household level, or using facility level design information is assessing aspects such as livability, walkability or access. Further, several of the proximity analysis datasets (such as hospitals, clinics, etc) did not include projections over time, due to lack of reliable data sources.

Further, the travel demand model data used in this study only covered a single transportation and land use scenarios. Using data from multiple alternative scenarios could have provided further insight into differences and trends in indicators. Further, application of a similar analysis to other regions can help identify whether the findings are broadly generalizable, or unique to the El Paso case study region.

The MCDA methodology used provided a simplified aggregation system that scaled indicators into ranges based on the overall distribution of values. While allowing for intuitive comparisons and visualizations, this approach also had the effect of masking the impact of extreme values in the dataset – which could be seen as either a benefit or a detriment. Also, this study did not investigate the issue of weighting of indicators, but assumed equal weights for the analysis, with very limited overlapping indicators.

An alternative analysis approach could consider greater overlap of indicators, by using varying weights to represent the sustainability, livability, and health frameworks on a common indicator set. Delphi methods or other approaches can be used for identification of weights in such an analysis.

This study sets the stage for further research into the validation of sustainability concepts through the use of indicators. Areas for future research include:

- Similar studies with expanded indicator sets or for the comparison of multiple transportation and land use scenarios.
- Implementing the study approach in other areas to determine if the findings are generalizable.
- Use of further disaggregated data with applicable measures to test the concepts at a finer scale.
- Research into the impact of indicator selection, indicator weighting, and examination of influential indicators that can serve as proxies for sustainability.

- Use of Delphi methods or other approaches to identify and prioritize indicators to reflect the different frameworks of interest.

REFERENCES

[1] Hall, R. P., and N. A. Ashford. Primer on the Emergence and Evolution of Sustainable Development (1951-2012) Virginia Tech, VA 2012.

[2] Gudmundsson, H., R. P. Hall, G. Marsden, and J. Zietsman. *Sustainable Transportation: Indicators, Frameworks, and Performance Management*. Springer-Verlag Berlin Heidelberg, 2015.

[3] Beatley, T. The Many Meanings of Sustainability: Introduction to a Special Issue of JPL. *Journal of Planning Literature,* Vol. 9, No. 4, 1995, pp. 339-342.

[4] WCED. *Our Common Future*. Oxford ; New York : Oxford University Press, 1987., 1987.

[5] Zietsman, J., T. Ramani, V. Reeder, J. Potter, and J. DeFlorio. *A Guidebook for Sustainability Performance Measurement for Transportation Agencies*. Transportation Research Board of the National Academies, Washington, D.C., 2011.

[6] Hardin, G. The Tragedy of the Commons. *Science,* Vol. 162, No. 3859, 1968, pp. 1243-1248.

[7] Kidd, C. V. The Evolution of Sustainability. *Journal of Agricultural and Environmental Ethics,* Vol. 5, No. 1, 1992, pp. 1-26.

[8] Solow, R. M. Sustainability: An Economist's Perspective. The Eighteenth J. Seward Johnson Lecture. Woods Hole, MA: Woods Hole Oceanographic Institution, 1991.

[9] Centre for Sustainable Transportation, *Definition and Vision of Sustainable Transportation*. 2002 http://cst.uwinnipeg.ca/documents/Definition_Vision_E.pdf . Accessed December 8, 2016.

[10] Campbell, S. Green Cities, Growing Cities, Just Cities?: Urban planning and the Contradictions of Sustainable Development. *Journal of the American Planning Association,* Vol. 62, No. 3, 1996, pp. 296-312.

[11] Holden, E., K. Linnerud, and D. Banister. Sustainable Passenger Transport: Back to Brundtland. *Transportation Research Part A: Policy and Practice*, Vol. 54, 2013, pp. 67-77.

[12] Hjorth, P., and A. Bagheri. Navigating towards Sustainable Development: A System Dynamics Approach. *Futures,* Vol. 38, No. 1, 2006, pp. 74-92.

[13] Becker, J. How Frameworks Can Help Operationalize Sustainable Development Indicators. *World Futures*, Vol. 63, No. 2, 2007, pp. 137-150.

[14] Waheed, B., F. Khan, and B. Veitch. Linkage-Based Frameworks for Sustainability Assessment: Making a Case for Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) Frameworks. *Sustainability,* Vol. 1, No. 3, 2009, pp. 441-463.

[15] Gasparatos, A., M. El-Haram, and M. Horner. A Critical Review of Reductionist Approaches for Assessing the Progress towards Sustainability. *Environmental Impact Assessment Review,* Vol. 28, No. 4–5, 2008, pp. 286-311.

[16] Turner, K. R. *Speculations on Weak and Strong Sustainability* Centre for Social and Economic Research on the Global Environment University of East Anglia and University College London. Working Paper GEC 92-26, 1992.

[17] Hediger, W. Reconciling “Weak” and “Strong” Sustainability *International Journal of Social Economics,* Vol. 26, No. 7/8/9, 1999, pp. 1120-1144.

[18] Kopnina, H. Evaluating Education for Sustainable Development (ESD): Using Ecocentric and Anthropocentric Attitudes toward the Sustainable Development (EAATSD) scale. *Environment, Development and Sustainability,* Vol. 15, No. 3, 2013, pp. 607-623.

[19] Rijsberman, M. A., and F. H. M. van de Ven. Different Approaches to Assessment of Design and Management of Sustainable Urban Water Systems. *Environmental Impact Assessment Review,* Vol. 20, No. 3, 2000, pp. 333-345.

[20] Gladwin, T. N., J. J. Kennelly, and T.-S. Krause. Shifting Paradigms for Sustainable Development: Implications for Management Theory and Research. *Academy of Management Review,* Vol. 20, No. 4, 1995, pp. 874-907.

[21] Hawken, P., A. B. Lovins, and L. H. Lovins. *Natural Capitalism: The Next Industrial Revolution*. Routledge, 2013.

[22] Wackernagel, M., and W. E. Rees. Perceptual and Structural Barriers to Investing in Natural Capital: Economics from an Ecological Footprint Perspective. *Ecological Economics,* Vol. 20, No. 1, 1997, pp. 3-24.

[23] Rockstrom, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. Planetary

Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society,* Vol. 14, No. 2, 2009.

[24] Fiala, N. Measuring sustainability: Why the Ecological Footprint is Bad Economics and Bad Environmental Science. *Ecological Economics,* Vol. 67, No. 4, 2008, pp. 519-525.

[25] Wildavsky, A. If Planning is Everything, Maybe it's Nothing. *Policy Sciences,* Vol. 4, No. 2, 1973, pp. 127-153.

[26] Marcuse, P. Sustainability is not Enough. *Environment and Urbanization,* Vol. 10, No. 2, 1998, pp. 103-112.

[27] Low, N., and B. Gleeson. If Sustainability Is Everything, Maybe It's Nothing?In *State of Australian Cities Conference, Griffith University, Brisbane, No. 30,* Citeseer, 2005. pp. 01-01.

[28] Swyngedouw, E. Trouble with Nature:'Ecology as the New Opium for the Masses'. *The Ashgate Research Companion to Planning Theory*, 2010, pp. 299-318.

[29] Gunder, M. Sustainability: Planning's Saving Grace or Road to Perdition? *Journal of Planning Education and Research,* Vol. 26, No. 2, 2006, pp. 208-221.

[30] Black, W. R. Sustainable Transportation: a US perspective. *Journal of Transport Geography,* Vol. 4, No. 3, 1996, pp. 151-159.

[31] Rittel, H. W. J., and M. M. Webber. Dilemmas in a General Theory of Planning. *Policy Sciences,* Vol. 4, No. 2, 1973, pp. 155-169.

[32] Head, B. W. Wicked Problems in Public Policy. *Public Policy,* Vol. 3, No. 2, 2008, pp. 101-118.

[33] Batie, S. S. Wicked Problems and Applied Economics. *American Journal of Agricultural Economics,* Vol. 90, No. 5, 2008, pp. 1176-1191.

[34] Frame, B. Wicked',Messy', and Clumsy': Long-Term Frameworks for Sustainability. *Environment and Planning C,* Vol. 26, 2008, pp. 1113-1128.

[35] Jamieson, D. Sustainability and Beyond. *Ecological Economics,* Vol. 24, No. 2–3, 1998, pp. 183-192.

[36] Baumgartner, R. J., and J. Korhonen. Strategic Thinking for Sustainable Development. *Sustainable Development,* Vol. 18, No. 2, 2010, pp. 71-75.

[37] Broman, G. I., and K.-H. Robèrt. A Framework for Strategic Sustainable Development. *Journal of Cleaner Production,* Vol. 140, Part 1, 2017, pp. 17-31.

[38] Kates, R. W., W. C. Clark, R. Corell, J. M. Hall, C. C. Jaeger, I. Lowe, J. J. McCarthy, H. J. Schellnhuber, B. Bolin, N. M. Dickson, S. Faucheux, G. C. Gallopin, A. Grübler, B. Huntley, J. Jäger, N. S. Jodha, R. E. Kasperson, A. Mabogunje, P. Matson, H. Mooney, B. Moore, T. Riordan, and U. Svedin. Sustainability Science. *Science,* Vol. 292, No. 5517, 2001, p. 641.

[39] Christen, M., and S. Schmidt. A Formal Framework for Conceptions of Sustainability–a Theoretical Contribution to the Discourse in Sustainable Development. *Sustainable Development,* Vol. 20, No. 6, 2012, pp. 400-410.

[40] Zietsman, J., and L. R. Rilett. *Sustainable Transportation: Conceptualization and Performance Measures*.Report SWUTC/02/167403-1, Southwest Region University Transportation Center, College Station, Texas, 2002.

[41] Booz Allen Hamilton, *Strategic Issues Facing Transportation – Volume 4*: *Sustainability as an Organizing Principle for Transportation Agencies*, National Cooperative Highway Research Program Report 750, Transportation Research Board of the National Academies, Washington, D.C., 2014.

[42] Amekudzi, A., M. Meyer, and C. Ross. *Transportation Planning and Sustainability Guidebook.* Prepared for the Federal Highway Administration, 2011.

[43] Hall, R. P. *Understanding and Applying the Concept of Sustainable Development to Transportation Planning and Decision-Making in the US.* Ph.D. Dissertation, Massachusetts Institute of Technology, 2006.

[44] Ramani, T., J. Zietsman, H. Gudmundsson, R. Hall, and G. Marsden. Framework for Sustainability Assessment by Transportation Agencies. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2242, 2011, pp. 9-18.

[45] Litman, T. *Sustainability and Livability: Summary of Definitions, Goals, Objectives and Performance Indicators.* Victoria Transport Policy Institute, 1250 Rudlin Street Victoria, British Columbia V8V 3R7 Canada, 2010.

[46] Jeon, C. M., and A. Amekudzi. Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics. *Journal of infrastructure systems,* Vol. 11, No. 1, 2005, pp. 31-50.

[47] Pei, Y., A. Amekudzi, M. Meyer, E. Barrella, and C. Ross. Performance Measurement Frameworks and Development of Effective Sustainable Transport

Strategies and Indicators. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2163, 2010, pp. 73-80.

[48] Goldman, T., and R. Gorham. Sustainable Urban Transport: Four Innovative Directions. *Technology in Society,* Vol. 28, No. 1–2, 2006, pp. 261-273.

[49] Black, J. A., A. Paez, and P. A. Suthanaya. Sustainable Urban Transportation: Performance Indicators and Some Analytical Approaches. *Journal of Urban Planning and Development*, Vol. 128, No. 4, 2002, pp. 184-209.

[50] van den Bergh, J. C. J. M., and H. Verbruggen. Spatial Sustainability, Trade and Indicators: an Evaluation of the 'Ecological Footprint'. *Ecological Economics*, Vol. 29, No. 1, 1999, pp. 61-72.

[51] Amekudzi, A. A., C. Jotin Khisty, and M. Khayesi. Using the Sustainability Footprint Model to Assess Development Impacts of Transportation Systems. *Transportation Research Part A: Policy and Practice*, Vol. 43, No. 4, 2009, pp. 339-348.

[52] La Gennusa, M., P. Ferrante, B. L. Casto, and G. Rizzo. An Integrated Environmental Indicator for Urban Transportation Systems: Description and Application. *Energies,* Vol. 8, No. 10, 2015, pp. 11076-11094.

[53] Richardson, B. C. Sustainable Transport: Analysis Frameworks. *Journal of Transport Geography,* Vol. 13, No. 1, 2005, pp. 29-39.

[54] Low, N., B. Gleeson, and E. Rush. Making Believe: Institutional and Discursive Barriers to Sustainable Transport in Two Australian Cities. *International Planning Studies,* Vol. 8, No. 2, 2003, pp. 93-114.

[55] Gudmundsson, H., and M. Höjer. Sustainable Development Principles and their Implications for Transport. *Ecological Economics,* Vol. 19, No. 3, 1996, pp. 269-282.

[56] Martinez, L., and P. Crist. Urban Mobility System Upgrade: How Shared self-Driving Cars Could Change City Traffic. Presented at Transportation for Sustainability, An International Conference, Washington D.C., 2015.

[57] Banister, D., and D. Stead. Impact of Information and Communications Technology on Transport. *Transport Reviews,* Vol. 24, No. 5, 2004, pp. 611-632.

[58] Binswanger, M. Technological Progress and Sustainable Development: What About the Rebound Effect? *Ecological Economics,* Vol. 36, No. 1, 2001, pp. 119-132.

[59] Bruun, E., and M. Givoni. Sustainable Mobility: Six Research Routes to Steer Transport Policy. *Nature*, Vol. 523, No. 7558, 2015, pp. 29-31.

[60] Bond, A. J., and A. Morrison-Saunders. Sustainability Appraisal: Jack of All Trades, Master of None? *Impact Assessment and Project Appraisal,* Vol. 27, No. 4, 2009, pp. 321-329.

[61] Chazal, J. d. A Systems Approach to Livability and Sustainability: Defining Terms and Mapping Relationships to link Desires with Ecological Opportunities and Constraints. *Systems Research and Behavioral Science,* Vol. 27, No. 5, 2010, pp. 585-597.

[62] Godschalk, D. R. Land Use Planning Challenges - Coping with Conflicts in Visions of Sustainable Development and Livable Communities. *Journal of the American Planning Association,* Vol. 70, No. 1, 2004, pp. 5-13.

[63] Gough, M. Z. Reconciling Livability and Sustainability: Conceptual and Practical Implications for Planning. *Journal of Planning Education and Research,* 2015.

[64] Appleyard, B., C. Ferrell, M. Carroll, and M. Taecker. Toward Livability Ethics. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2403, 2014, pp. 62-71.

[65] Bocchini, P., D. Frangopol, T. Ummenhofer, and T. Zinke. Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. *Journal of Infrastructure Systems,* Vol. 20, No. 2, 2013, p. 04014004.

[66] Coaffee, J. Risk, Resilience, and Environmentally Sustainable Cities. *Energy Policy,* Vol. 36, No. 12, 2008, pp. 4633-4638.

[67] Adger, W. N. Social and Ecological Resilience: are they Related? *Progress in Human Geography,* Vol. 24, No. 3, 2000, pp. 347-364.

[68] Common, M. *Sustainability and Policy: Limits to Economics*. Cambridge University Press, 1995.

[69] Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C. S. Holling, and B. Walker. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. *AMBIO: A Journal of the Human Environment,* Vol. 31, No. 5, 2002, pp. 437-440.

[70] Holling, C. S. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems,* Vol. 4, No. 5, 2001, pp. 390-405.

[71] Wang, J. Y. ‘Resilience thinking’in Transport Planning. *Civil Engineering and Environmental Systems,* Vol. 32, No. 1-2, 2015, pp. 180-191.

[72] Winkelman, S., A. Bishins, and C. Kooshian. Planning for Economic and Environmental Resilience. *Transportation Research Part A: Policy and Practice,* Vol. 44, No. 8, 2010, pp. 575-586.

[73] Cox, A., F. Prager, and A. Rose. Transportation Security and the Role of Resilience: A Foundation for Operational Metrics. *Transport Policy,* Vol. 18, No. 2, 2011, pp. 307-317.

[74] Litman, T. *Evaluating Transportation Resilience: Evaluating the Transportation System's Ability to Accommodate Diverse, Variable and Unexpected Demands with Minimal Risk.* Online TDM Encycolpedia, Victoria Transport Policy Institute http://www.vtpi.org/tdm/tdm88.htm . Accessed December 8, 2016.

[75] Litman, T. Lessons From Katrina and Rita: What Major Disasters Can Teach Transportation Planners. *Journal of Transportation Engineering,* Vol. 132, No. 1, 2006, pp. 11-18.

[76] McMichael, A. J., C. D. Butler, and C. Folke. New Visions for Addressing Sustainability. *Science,* Vol. 302, No. 5652, 2003, pp. 1919-1920.

[77] McMichael, A. J. Population Health as the ‘Bottom Line’ of Sustainability: a Contemporary Challenge for Public Health Researchers. *The European Journal of Public Health,* Vol. 16, No. 6, 2006, pp. 579-581.

[78] King, M. Health is a Sustainable State. *The Lancet,* Vol. 336, No. 8716, 1990, pp. 664-667.

[79] McMichael, A. J., R. E. Woodruff, and S. Hales. Climate Change and Human Health: Present and Future Risks. *The Lancet,* Vol. 367, No. 9513, 2006, pp. 859-869.

[80] Patz, J. A., D. Campbell-Lendrum, T. Holloway, and J. A. Foley. Impact of Regional Climate Change on Human Health. *Nature,* Vol. 438, No. 7066, 2005, pp. 310-317.

[81] Haines, A., R. S. Kovats, D. Campbell-Lendrum, and C. Corvalan. Climate Change and Human Health: Impacts, Vulnerability and Public Health. *Public Health,* Vol. 120, No. 7, 2006, pp. 585-596.

[82] Killingsworth, R. E., A. De Nazelle, and R. H. Bell. Building a New Paradigm: Improving Public Health through Transportation. *ITE Journal*, Vol. 73, No. 6, 2003, pp. 28-32.

[83] Lee, C., and A. V. Moudon. Physical Activity and Environment Research in the Health Field: Implications for Urban and Transportation Planning Practice and Research. *Journal of Planning Literature,* Vol. 19, No. 2, 2004, pp. 147-181.

[84] Frank, L. D. Land Use and Transportation Interaction: Implications on Public Health and Quality of Life. *Journal of Planning Education and Research,* Vol. 20, No. 1, 2000, pp. 6-22.

[85] Litman, T. Integrating Public Health Objectives in Transportation Decision-Making. *American Journal of Health Promotion,* Vol. 18, No. 1, 2003, pp. 103-108.

[86] Frank, L. D., J. F. Sallis, T. L. Conway, J. E. Chapman, B. E. Saelens, and W. Bachman. Many Pathways from Land Use to Health: Associations between Neighborhood Walkability and Active Transportation, Body Mass Index, and Air Quality. *Journal of the American Planning Association,* Vol. 72, No. 1, 2006, pp. 75-87.

[87] Sallis, J. F., L. D. Frank, B. E. Saelens, and M. K. Kraft. Active Transportation and Physical Activity: Opportunities for Collaboration on Transportation and Public Health Research. *Transportation Research Part A: Policy and Practice,* Vol. 38, No. 4, 2004, pp. 249-268.

[88] Burbidge, S. K. Merging Long Range Transportation Planning with Public Health: A Case Study from Utah's Wasatch Front. *Preventive Medicine,* Vol. 50, Supplement, 2010, pp. S6-S8.

[89] Lyons, W., H. Peckett, L. Morse, M. Khurana, and L. Nash. *Metropolitan Area Transportation Planning for Healthy Communities*. Publication FHWA-HEP-13-006. U.S. Department of Transportation, Research and Innovative Technology Administration, John A.Volpe National Transportation Systems Center, 2012.

[90] Lyons, W., L. Morse, L. Nash, and R. Strauss. *Statewide Transportation Planning for Healthy Communities*. Publication FHWA-HEP-14-028. U.S. Department of Transportation, Research and Innovative Technology Administration, John A. Volpe National Transportation Systems Center, 2014.

[91] TransFrom and California Department of Public Health. *Creating Healthy Regional Transportation Plans - A Primer for California's Public Health Community on Regional Transportation Plans and Sustainable Communities Strategies*, 2012.

http://www.transformca.org/resource/creating-healthy-regional-transportation-plans Accessed December 8, 2016.

[92] USDOT. *Transportation and Health Tool.* United States Department of Transportation. http://www.transportation.gov/transportation-health-tool Accessed November 5 2015.

[93] Dannenberg, A. L., and A. M. Wendel. Measuring, Assessing, and Certifying Healthy Places.*Making Healthy Places*, Springer, 2011. pp. 303-318.

[94] Brownson, R., C. Hoehner, K. Day, A. Forsyth, and J. Sallis. Measuring the Built Environment for Physical Activity. *American Journal of Preventive Medicine*, Vol. 36, No. 4, 2009, pp. S99-S123.e112.

[95] Davis, A. Transport and Health—What is the Connection? An Exploration of Concepts of Health Held by Highways Committee Chairs in England. *Transport Policy,* Vol. 12, No. 4, 2005, pp. 324-333.

[96] Amekudzi-Kennedy, A., M. Akofio-Sowah, R. Boadi, R. Brodie, S. Amoaning-Yankson, J. Smith-Colin, J. Fischer, and T. Wall. Transportation System Health: Meeting Deficiency Needs and Growth Aspirations Systemically- Concepts, Applications Presented at Transportation Research Board Annual Meeting, Washington D.C. , 2016.

[97] Federal Highway Administration and Federal Transit Administration,*The Transportation Planning Process Briefing Book* . Transportation Planning Capacity Building Program, 2015.

[98] Zietsman, J., T. Ramani, and M. R. Pryn. *Towards Sustainable Transport Planning in the United States* Working paper prepared for SUSTAIN Research Network, Danish Research Council, Copenhagen, Denmark, 2015.

[99] Banister, D., J. Pucher, and M. Lee-Gosselin. Making SustainableTransport Politically and Publicly Acceptable.In *Institutions and Sustainable Transport: Regulatory Reform in Advanced Economies*, Edward Elgar Publishing, Cheltenham, England, 2007. pp. 17-50.

[100] Barrella, E., A. Amekudzi, and M. Meyer. Evaluating Sustainability Approaches of Transportation Agencies Through a Strengths, Weaknesses, Opportunities, and Threats Framework. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2357, 2013, pp. 41-49.

[101] Barrella, E., A. Amekudzi, M. Meyer, C. Ross, and D. Turchetta. Best Practices and Common Approaches for Considering Sustainability at US State Transportation

Agencies. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2174, 2010, pp. 10-18.

[102] Amekudzi, A. A. Evaluating Sustainable Development: A Quality-of-Life Focus for Transportation Decision Making. *TR News*, No. 288, 2013.

[103] Federal Highway Administration *Advancing a Sustainable Highway System: Highlights of FHWA Sustainability Activities*, 2014. https://www.sustainablehighways.dot.gov/FHWA_Sustainability_Activities_June2014.aspx Accessed December 8, 2016.

[104] United States Department of Transportation. *Beyond Traffic 2045: Trends and Choices*, 2015.

[105] United States Department of Transportation. *Ladders of Opportunity: Transportation Empowerment Pilot* https://www.transportation.gov/ladders/tep Accessed November 5 2015.

[106] Federal Highway Administration. *Climate Change and Transportation* http://www.fhwa.dot.gov/environment/climate_change/ Accessed November 5, 2015.

[107] Partnership for Sustainable Communities. *Partnership for Sustainable Communities: Livability Principles* https://www.sustainablecommunities.gov/mission/livability-principles. Accessed November 5, 2015.

[108] Environmental Protection Agency. *Smart Growth*. http://www2.epa.gov/smartgrowth. Accessed November 5, 2015.

[109] Federal Highway Administration. *Context Sensitive Solutions* http://contextsensitivesolutions.org/ Accessed November 5, 2015.

[110] Federal Highway Administration. *INVEST Version 1.2* Federal Highway Administration. https://www.sustainablehighways.org/. Accessed November 5, 2015.

[111] United States Department of Transportation. *Livability in Transportation Guidebook: Planning Approaches that Promote Livability*, 2010.

[112] Ramsey, K., and A. Bell. *Smart Location Database Version 2.0 User Guide*, USEPA Smart Growth Program, 2014

[113] Sørensen, C. H., H. Gudmundsson, and S. Leleur. *National Transport Planning – Sustainability, Institutions, Tools.*Working Paper, Technical University of Denmark, Institute for Transport, 2013

[114] Gallopín, G. C. Environmental and Sustainability Indicators and the Concept of Situational Indicators. A Systems Approach. *Environmental Modeling & Assessment,* Vol. 1, No. 3, 1996, pp. 101-117.

[115] Maclaren, V. Urban Sustainability Reporting. *American Planning Association. Journal of the American Planning Association,* Vol. 62, No. 2, 1996, pp. 184-202.

[116] Marsden, G., C. Kelly, C. Snell, and J. Forrester. *Improved indicators for Sustainable Transport and Planning: Delvierable C1: Sustainable Transprtation Indicators: Selection and Use.* DISTILLATE Research Program, 2005. http://www.distillate.ac.uk/outputs/reports.php#reportsC.Accessed November 5, 2015.

[117] Litman, T. Developing Indicators for Comprehensive and Sustainable Transport Planning. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2017, 2007, pp. 10-15.

[118] Castillo, H., and D. E. Pitfield. ELASTIC – A Methodological Framework for Identifying and Selecting Sustainable Transport Indicators. *Transportation Research Part D: Transport and Environment,* Vol. 15, No. 4, 2010, pp. 179-188.

[119] Lautso, K., and S. Toivanen. SPARTACUS System for Analyzing Urban Sustainability. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 1670, 1999, pp. 35-46.

[120] Haghshenas, H., and M. Vaziri. Urban Sustainable Transportation Indicators for Global Comparison. *Ecological Indicators,* Vol. 15, No. 1, 2012, pp. 115-121.

[121] World Business Council on Sustainable Development. *Sustainable Urban Mobility - Methodology and Indicator Calculation Method,* 2015. http://www.eltis.org/resources/tools/methodology-and-indicator-calculation-method-sustainable-urban-mobility. Accessed November 5, 2015.

[122] Accorsi, R., E. Zio, and G. E. Apostolakis. Developing Utility Functions for Environmental Decision Making. *Progress in Nuclear Energy,* Vol. 34, No. 4, 1999, pp. 387-411.

[123] Ramani, T., J. Zietsman, W. L. Eisele, D. Rosa, D. Spillane, and B. Bochner. *Developing Sustainable Transportation Performance Measures for TXDOT's*

Strategic Plan : Technical Report. Texas A&M Transportation Institute, 2009 http://tti.tamu.edu/documents/0-5541-1.pdf. Accessed November 5, 2015.

[124] Jeon, C. M., A. A. Amekudzi, and R. L. Guensler. Evaluating Plan Alternatives for Transportation System Sustainability: Atlanta Metropolitan Region. *International Journal of Sustainable Transportation,* Vol. 4, No. 4, 2010, pp. 227-247.

[125] Muench, S. T., J. Anderson, and T. Bevan. Greenroads: A Sustainability Rating System for Roadways. *International Journal of Pavement Research and Technology,* Vol. 3, No. 5, 2010, pp. 270-279.

[126] Oswald, M., and S. McNeil. Rating Sustainability: Transportation Investments in Urban Corridors as a Case Study. *Journal of Urban Planning and Development,* Vol. 136, No. 3, 2009, pp. 177-185.

[127] McVoy, G., K. Gunasekera, L. R. Sousa, and P. Schaffner. An Analytical Framework for Sustainability Analysis of Transportation Investments Across the Triple Bottom Line Using a Common Metric.Presented at the International Conference on Ecology and Transportation, Scottsdale, Arizona, 2013.

[128] Berke, P. R., and M. M. Conroy. Are we Planning for Sustainable Development? An Evaluation of 30 Comprehensive Plans. *Journal of the American Planning Association,* Vol. 66, No. 1, 2000, pp. 21-33.

[129] Gudmundsson, H., and C. H. Sørensen. Some use—Little influence? On the Roles of Indicators in European Sustainable Transport Policy. *Ecological Indicators,* Vol. 35, 2013, pp. 43-51.

[130] Clevenger, C. M., M. E. Ozbek, and S. Simpson. Review of Sustainability Rating Systems used for Infrastructure Projects.In *49th ASC Annual International Conference Proceedings*, 2013. pp. 10-13.

[131] Marsden, G., M. Kimble, J. Nellthorp, and C. Kelly. Sustainability Assessment: The Definition Deficit. *International Journal of Sustainable Transportation,* Vol. 4, No. 4, 2010, pp. 189-211.

[132] Innes De Neufville, J. Validating Policy Indicators. *Policy Sciences,* Vol. 10, No. 2-3, 1978, pp. 171-188.

[133] Miller, H. J., F. Witlox, and C. P. Tribby. Developing Context-Sensitive Livability Indicators for Transportation Planning: a Measurement Framework. *Journal of Transport Geography,* Vol. 26, 2013, pp. 51-64.

[134] Geurs, K. T., and B. Van Wee. Accessibility Evaluation of Land-Use and Transport Strategies: Review and Research Directions. *Journal of Transport Geography,* Vol. 12, No. 2, 2004, pp. 127-140.

[135] R. Joumard, H. Gudmundsson (Eds.), Indicators of Environmental Sustainability in Transport, Les collections de l'INRETS, 2010.

[136] Benenson, I., K. Martens, Y. Rofé, and A. Kwartler. Public Transport versus Private Car GIS-Based Estimation of Accessibility Applied to the Tel Aviv Metropolitan Area. *The Annals of Regional Science,* Vol. 47, No. 3, 2011, pp. 499-515.

[137] Yigitcanlar, T., N. Sipe, R. Evans, and M. Pitot. A GIS-Based Land Use and Public Transport Accessibility Indexing Model. *Australian Planner,* Vol. 44, No. 3, 2007, pp. 30-37.

[138] Randall, T. A., and B. W. Baetz. Evaluating Pedestrian Connectivity for Suburban Sustainability. *Journal of Urban Planning and Development,* Vol. 127, No. 1, 2001, pp. 1-15.

[139] Golub, A., and K. Martens. Using Principles of Justice to Assess the Modal Equity of Regional Transportation Plans. *Journal of Transport Geography,* Vol. 41, 2014, pp. 10-20.

[140] Rowangould, G. M. A Census of the US Near-Roadway Population: Public Health and Environmental Justice Considerations. *Transportation Research Part D: Transport and Environment,* Vol. 25, 2013, pp. 59-67.

[141] Brown, A. L., and J. K. Affum. A GIS-Based Environmental Modelling System for Transportation Planners. *Computers, Environment and Urban Systems,* Vol. 26, No. 6, 2002, pp. 577-590.

[142] Malczewski, J. GIS-Based Multicriteria Decision Analysis: A Survey of the Literature. *International Journal of Geographical Information Science,* Vol. 20, No. 7, 2006, pp. 703-726.

[143] Jeon, C. M., A. A. Amekudzi, and R. L. Guensler. Sustainability Assessment at the Transportation Planning Level: Performance Measures and Indexes. *Transport Policy,* Vol. 25, 2013, pp. 10-21.

[144] Jakimavičius, M., and M. Burinskiene. A GIS and Multi-Criteria-Based Analysisand Rankingof Transportation Zonesof Vilnius City. *Technological and Economic Development of Economy,* Vol. 15, No. 1, 2009, pp. 39-48.

[145] Marsden, G., and A. D. May. Do Institutional Arrangements Make a Difference to Transport Policy and Implementation? Lessons for Britain. *Environment and Planning C: Government and Policy,* Vol. 24, No. 5, 2006, pp. 771-789.

[146] Whittemore, A. Finding Sustainability in Conservative Contexts: Topics for Conversation between American Conservative Élites, Planners and the Conservative Base. *Urban Studies*, Vol. 50, No. 12, 2013, pp. 2460-2477.

[147] Leedy, P. D., and J. E. Ormrod. *Practical Research : Planning and Design*. Pearson, Boston, 2005.

[148] Gilbert, R., N. Irwin, B. Hollingworth, and P. Blais. Sustainable Transportation Performance Indicators (STPI). Presented at Transportation Research Board Annual Meeting, Washington D.C. , 2003.

[149] US Census Bureau. *Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2015 - United States -- Combined Statistical Area* http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk. Accessed October 10, 2016.

[150] National Cooperative Highway Research Program, *Travel Demand Forecasting: Parameters and Techniques*. Transportation Research Board of the National Academies, Washington, D.C., 2012.

[151] Spielberg, F., and P. Shapiro. *Determination of the State of the Practice in Metropolitan Area Travel Forecasting: Findings of the Surveys of Metropolitan Planning Organizations.* Report prepared for Committee B0090. Transportation Research Board of the National Academies, 2007.

[152] Federal Highway Administration. *Defining Traffic Analysis Zones*. https://www.fhwa.dot.gov/planning/tmip/publications/other_reports/technical_synthesis_report/page01.cfm Accessed October 10, 2016.

[153] You, J., Z. Nedović-Budić, and T. J. Kim. A GIS-Based Traffic Analysis Zone Design: Technique. *Transportation Planning and Technology,* Vol. 21, No. 1-2, 1998, pp. 45-68.

[154] El Paso Metropolitan Planning Organization *Horizon 2040 Metropolitan Transportation Plan*. http://www.elpasompo.org/MTPDocs/HorizonMTP_020514.pdf Accessed October 10, 2016.

[155] El Paso Metropolitan Planning Organization *2040 Horizon Model - Model Development Report.* 2013.

[156] Paso Del Norte Mapa. *Paso Del Norte Map for Public Access*. http://www.pdnmapa.org/. Accessed October 10, 2016.

[157] Karner, A. Planning for Transportation Equity in Small Regions: Towards Meaningful Performance Assessment. *Transport Policy,* Vol. 52, 2016, pp. 46-54.

[158] California Planning Roundtable *Deconstructing Jobs-Housing Balance*, 2008. http://www.cproundtable.org/media/uploads/pub_files/CPR-Jobs-Housing.pdf Accessed October 10, 2016.

[159] Horner, M., and A. Murray. A Multi-objective Approach to Improving Regional Jobs-Housing Balance. *Regional Studies,* Vol. 37, No. 2, 2003, pp. 135-146.

[160] Giuliano, G. Is Jobs-Housing Balance a Transportation Issue*? Transportation Research Record: Journal of the Transportation Research Board*, No. 1305, 1991, pp. 305-312.

[161] Cervero, R. Jobs-Housing Balance Revisited: Trends and Impacts in the San Francisco Bay Area. *Journal of the American Planning Association,* Vol. 62, No. 4, 1996, pp. 492-511.

[162] Rioux, C. L., D. M. Gute, D. Brugge, S. Peterson, and B. Parmenter. Characterizing Urban Traffic Exposures Using Transportation Planning Tools: An Illustrated Methodology for Health Researchers. *Journal of Urban Health,* Vol. 87, No. 2, 2010, pp. 167-188.

[163] Texas A&M Transportation Institute, *Development of a Transportation Air Quality Sketch Planning Tool for the El Paso Region*. Report prepared for the El Paso Metropolitan Planning Organization and the Texas Commission on Environmental Quality, 2016.

[164] McCubbin, D. R., and M. A. Delucchi. The Health Costs of Motor-Vehicle-Related Air Pollution. *Journal of Transport Economics and Policy*, 1999, pp. 253-286.

[165] Federal Highway Administration *Highway Economic Requirements System - State Version: Technical Report*. 2005.

[166] Lovegrove, G. R., and T. Sayed. Macro-Level Collision Prediction Models for Evaluating Neighbourhood Traffic Safety. *Canadian Journal of Civil Engineering,* Vol. 33, No. 5, 2006, pp. 609-621.

[167] Ladron de Guevara, F., S. Washington, and J. Oh. Forecasting Crashes at the Planning Level: Simultaneous Negative Binomial Crash Model Applied in Tucson,

Arizona. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1897, 2004, pp. 191-199.

[168] Pulugurtha, S. S., V. R. Duddu, and Y. Kotagiri. Traffic Analysis Zone Level Crash Estimation Models Based on Land Use Chacteristics. *Accident Analysis & Prevention,* Vol. 50, 2013, pp. 678-687.

[169] Washington, S. *Incorporating Safety into Long-Range Transportation Planning*. Transportation Research Board of the National Academies, Washington, D.C., 2006.

[170] Ramani, T., J. Zietsman, W. Knowles, and L. Quadrifoglio. Sustainability Enhancement Tool for State Departments of Transportation Using Performance Measurement. *Journal of Transportation Engineering*, Vol. 137, No. 6, 2011, pp. 404-415.

APPENDIX A

EMISSIONS ESTIMATION METHODOLOGY

The estimation of TAZ-level CO_2, NOx, and PM emissions was performed using an emissions analysis tool developed for the El Paso MPO. The analysis tool contains built-in emissions factors from EPA's MOVES model, aggregated into composite rate-per-distance emissions factors by time period, taking into account VMT mix, roadway functional classification, and other factors.

The emissions estimation methodology is as shown in Figure A- 1. The analysis tool calculates link-level daily emissions for each pollutant based on the network file from the travel demand model. The link-level emissions are computed by multiplying the flow over the link length (VMT) with the appropriate emission factor (based on pollutant, time of day, and roadway type). The link-level emissions were then aggregated to the TAZs based on link location, and used for the analysis in this study.

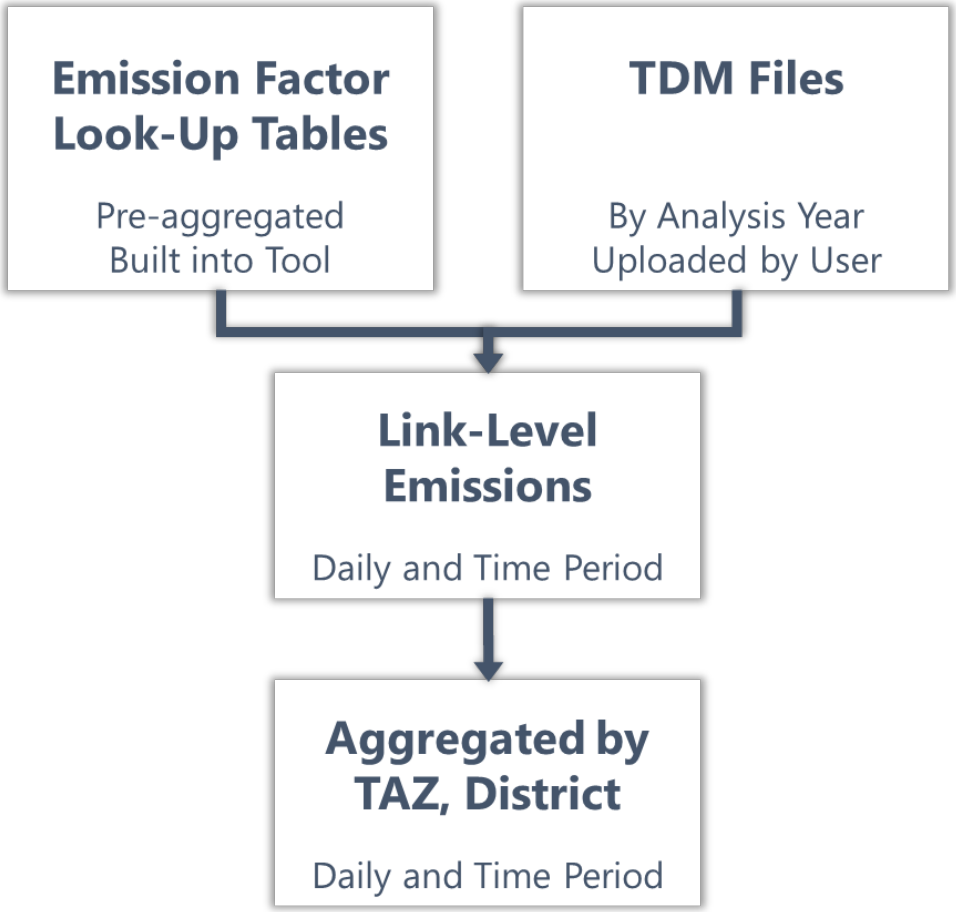

Figure A- 1. Emissions Estimation Process

APPENDIX B

TAZ-LEVEL CRASH ESTIMATION METHODOLOGY

The PLANSAFE model was developed as part of a National Cooperative Highway Research Program Project titled *Incorporating Safety into Long-Range Transportation Planning*[1]. It is a planning-level model used to predict motor vehicle accidents per traffic analysis zone or larger sub-areas. It consists of eight models in log linear regression form, with different sets of data inputs, used to predict different types of accidents (for example, fatalities, or injuries, or accidents involving pedestrians) at the TAZ level.

As noted by the authors, the models are appropriate for prediction of crashes and aggregate safety differences, but the input variables are not to be taken as predictors (i.e. as explanatory variables) of crashes. For planning applications, authors recommend calculating expected crash counts using the model, and calibrating the estimates using baseline correction factors based on historical accident data.

For purposes of this study (where TAZs are ranked based on relative performance with respect to another), the uncalibrated model is used directly to provide a TAZ-level crash estimate.

[1] Washington, S. van Schalkwyk, I., Mitra, S., Meyer, M. D., Dumbaugh, E., & Zoll, M. (2006). Incorporating safety into long-range transportation planning, National Cooperative Highway Research Program Report 492, Transportation Research Board, Washginton, D.C.

The model used is the total accident frequency model, which is shown in the equation below:

$$Log(AccidentFrequency + 1) = 5.020 + 0.474 \times 10^{-1}(POP\_PAC) + 0.196 \times 10^{-3}(POP16\_64) + 0.151 \times 10^{-2}(TOT\_MILE)$$

Where
POP_PAC is population density (persons per acre)
POP16_64 is total population aged 16 to 64
TOT_MILE is mileage of all functional classification of roads

The above equation was applied to estimate total annual crashes for each TAZ. The population density and mileage of roadways in each TAZ were obtained directly from TDM data. The population aged 16-64 was estimated based on total population and the age distribution for the general population in El Paso county based on U.S. Census Bureau data[2], which estimates population aged 16 to 64 to be approximately 65% of the total population.

[2] El Paso County Population by Age Groups, 2015 http://www.txcip.org/tac/census/agegroups.php?FIPS=48141

APPENDIX C

SUMMARY OF KEY TAZ ATTRIBUTES AND DATA

Table C- 1. Descriptive Summary of Key TAZ Attributes

Attribute		Analysis Year			
		2010	2020	2030	2040
Area (square miles)*	Total for all TAZs	953.51			
	Average per TAZ	1.32			
	Minimum	0.0022			
	Maximum	159.45			
Roadway Length (miles)	Total for all TAZs	1,989.52			
	Average per TAZ	2.75			
	Minimum	0.0593			
	Maximum	47.63			
VMT (miles per day)	Total for all TAZs	16,271,348	18,804,867	21,850,822	25,196,793
	Average per TAZ	22,505	26,009	30,222	34,850
	Minimum	11	20	21	21
	Maximum	395,166	445,529	546,169	622,416
Population	Total for all TAZs	802,956	893,508	969,222	1,036,758
	Average per TAZ	1,111	1,236	1,341	1,434
	Minimum	-	-	-	-
	Maximum	8,816	9,264	9,437	17,202
Employment	Total for all TAZs	300,617	332,562	369,722	412,312
	Average per TAZ	416	460	511	570
	Minimum	-	-	-	-
	Maximum	16,847	20,048	20,048	20,048

APPENDIX D

LOCATIONS FOR PROXIMITY INDICATORS

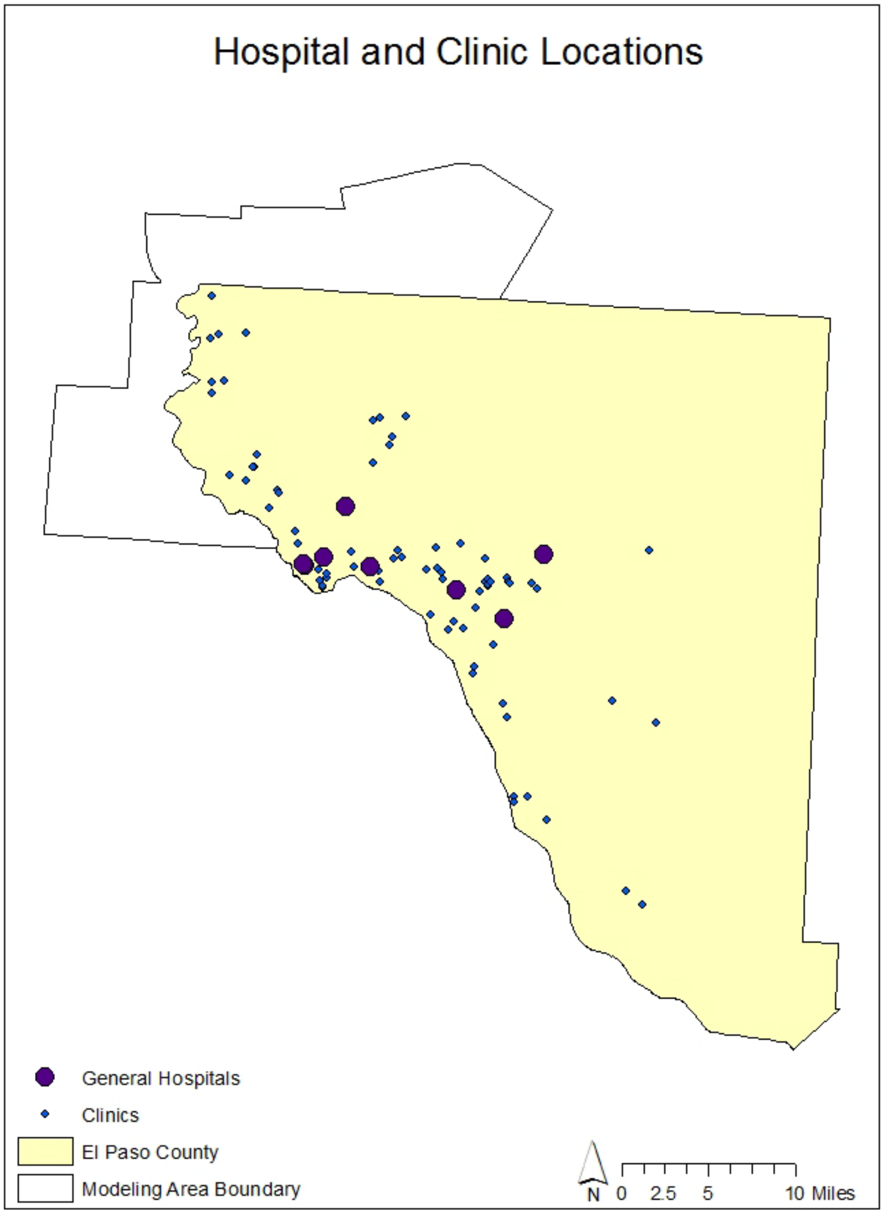

Figure D- 1. Hospital and Clinic Locations

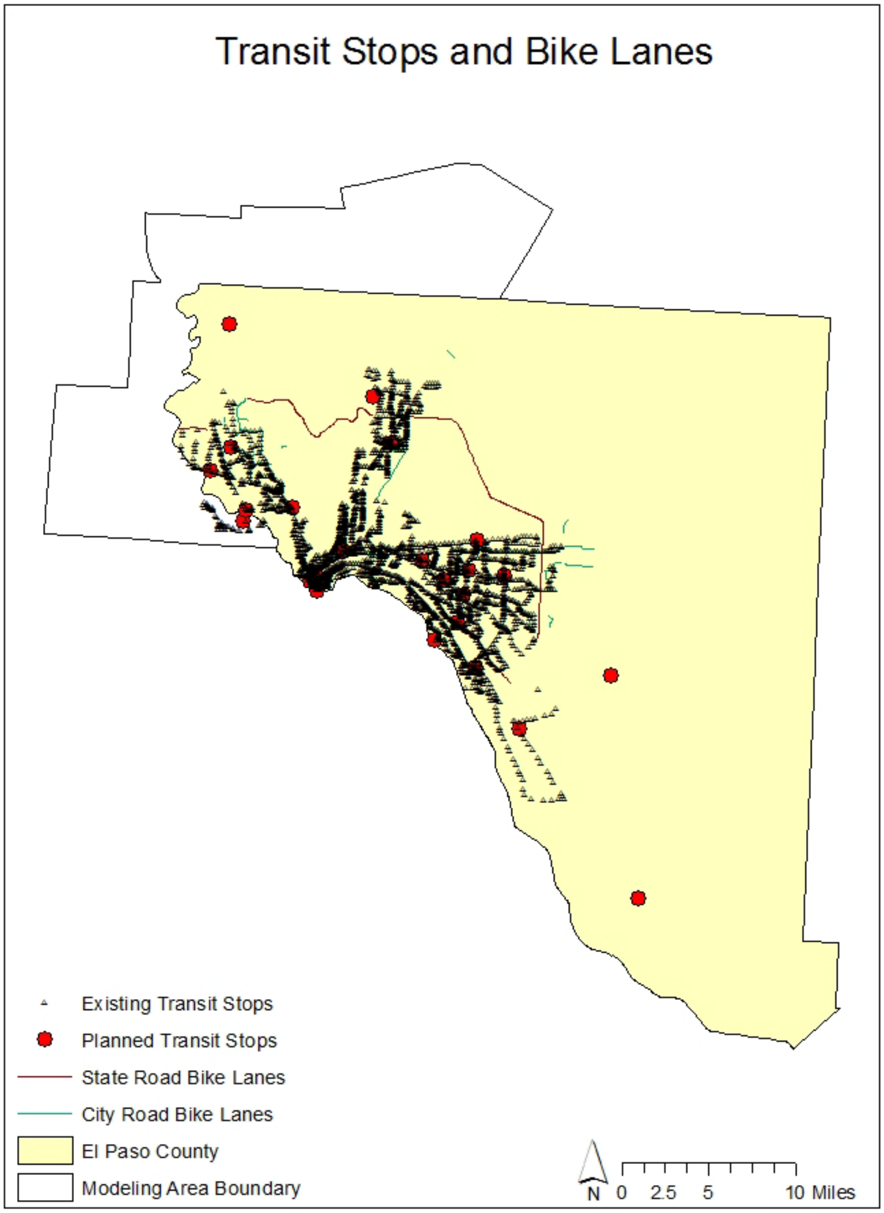

Figure D- 2. Transit Stops and Bike Lanes

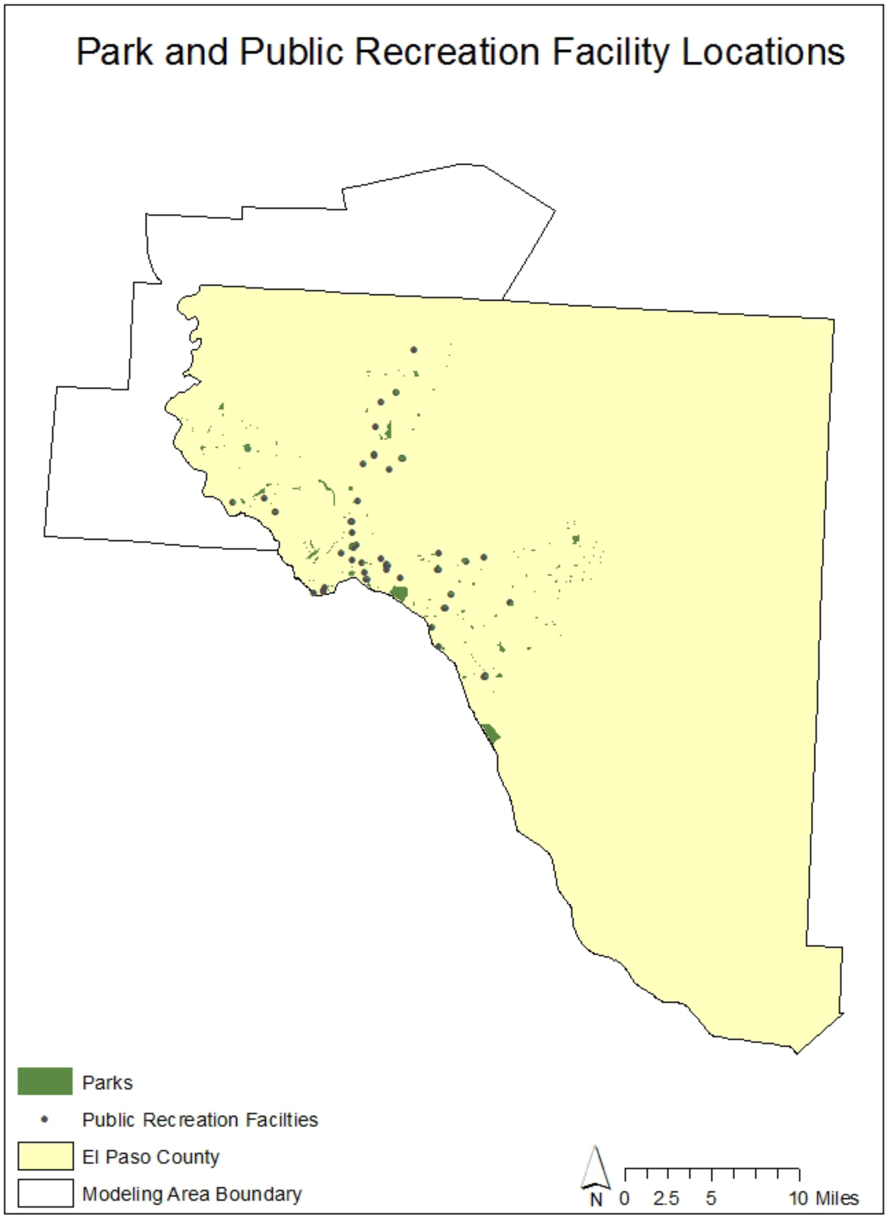

Figure D- 3. Parks and Public Recreational Facilities

APPENDIX E

RESULTS FOR INDIVIDUAL MEASURES

This appendix provides maps[3] showing the raw indicator value ranges for each TAZ, for each analysis year. In the case of indicators of proximity, where certain attributes remained unchanged over time, a single map is provided for multiple analysis years. The following figures are included in this appendix:

- Figure E- 1 – Mode split indicator values for 2010, 2020, 2030 and 2040
- Figure E- 2 – GHG emissions indicator values for 2010, 2020, 2030 and 2040
- Figure E- 3– Criteria pollutant emissions indicator values for 2010, 2020, 2030 and 2040
- Figure E- 4– Employment-population ratio indicator values for 2010, 2020, 2030 and 2040
- Figure E- 5– Land use indicator values for 2010, 2020, 2030 and 2040
- Figure E- 6 – Proximity to bicycle routes (same for all analysis years), proximity to parks and recreation facilities (same for all analysis years), proximity to transit for 2010 (based on existing transit stops) and 2020,2030,and 2040 (including existing and new planned stops)
- Figure E- 7 – Proximity to clinics and hospitals (same for all analysis years)
- Figure E- 8– Safety indicator values for 2010, 2020, 2030 and 2040

[3] The raw (not scaled) indicator values are shown, with the units indicated in the legend. All maps categorize the data using natural breaks, with the exception of the traffic density measure map, which uses quantiles to allow for a better spread of measure values.

- Figure E- 9– Traffic density indicator values for 2010, 2020, 2030 and 2040

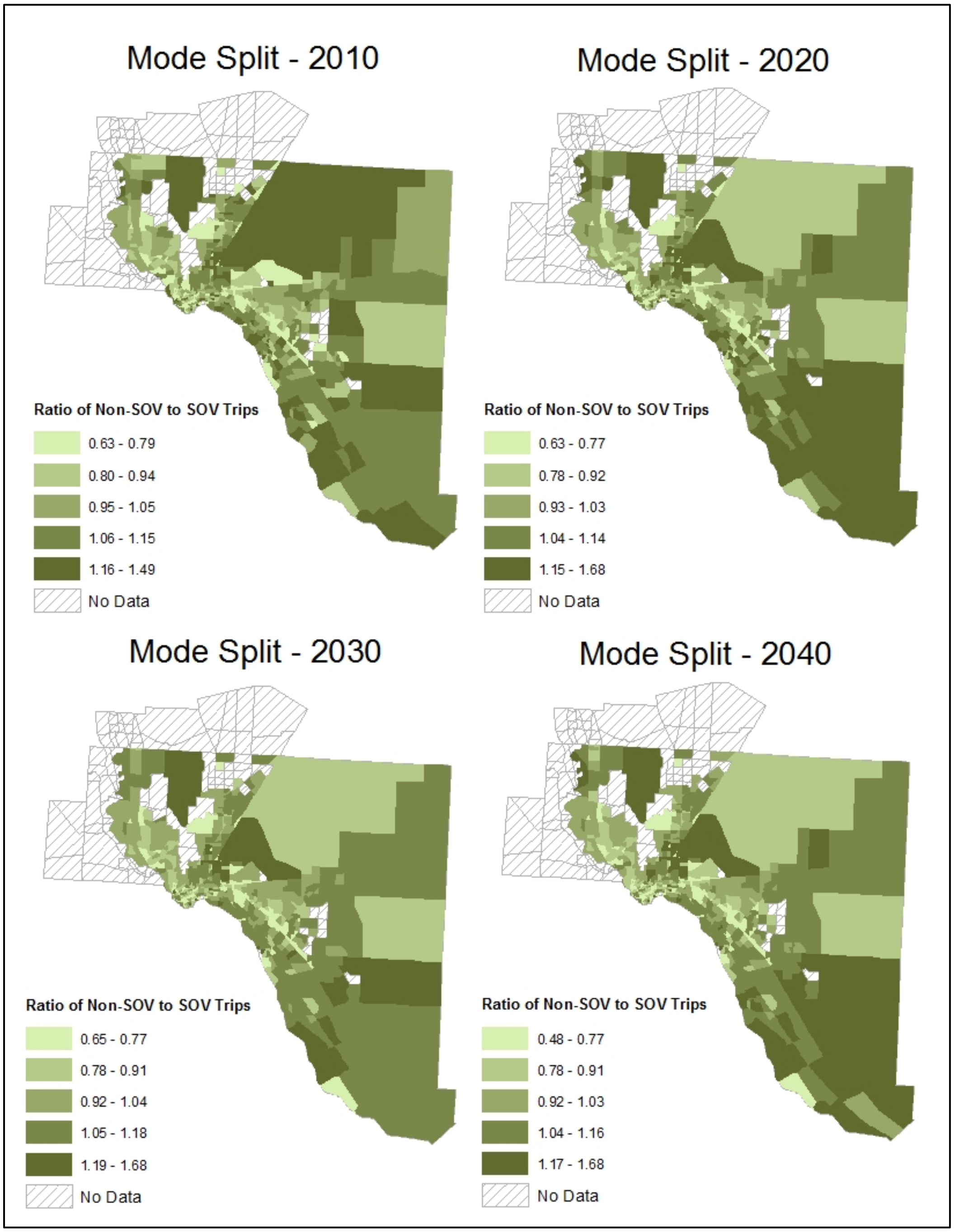

Figure E- 1. Mode Split Indicator Values

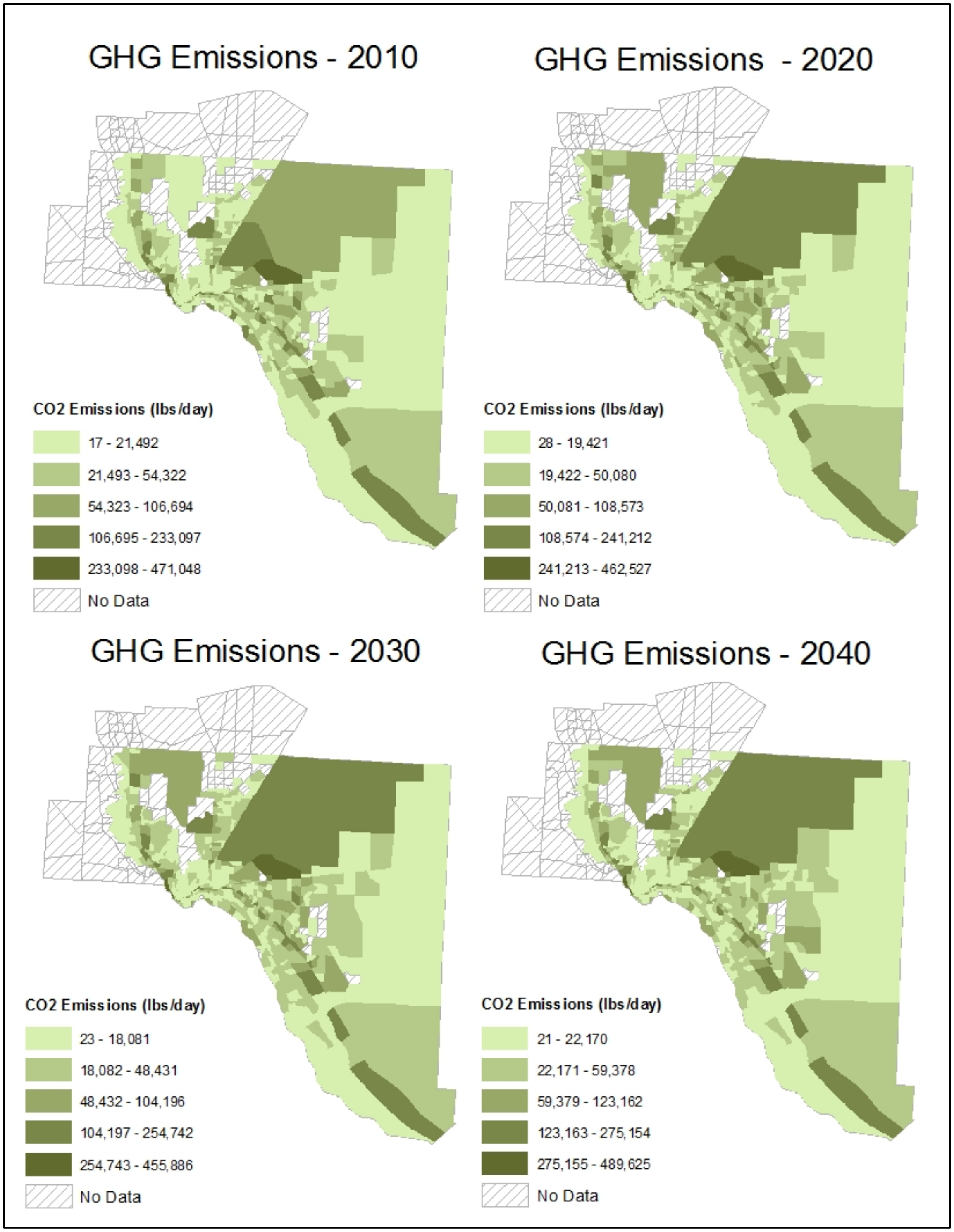

Figure E- 2. GHG Emissions Indicator Values

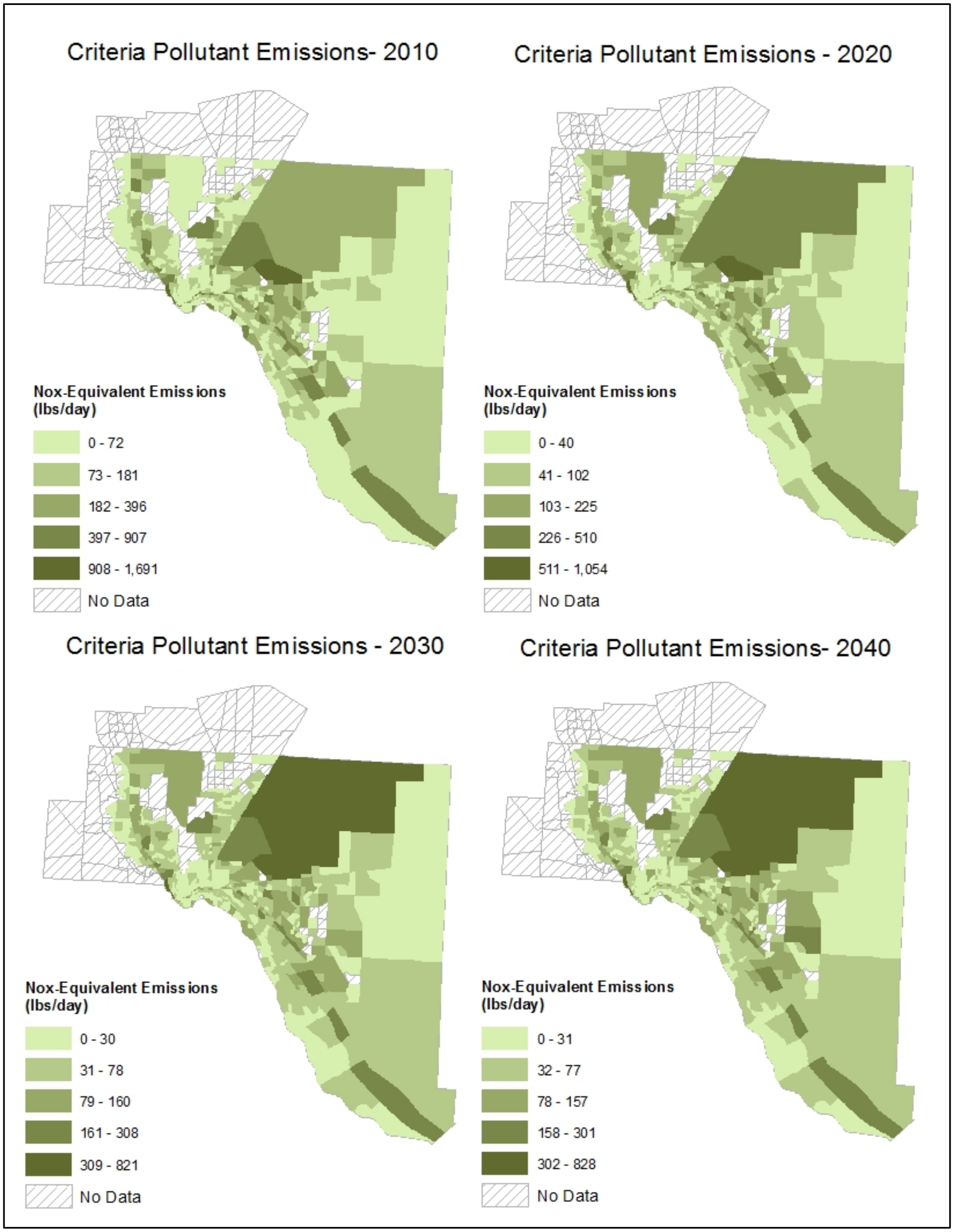

Figure E- 3. Criteria Pollutant Emissions Indicator Values

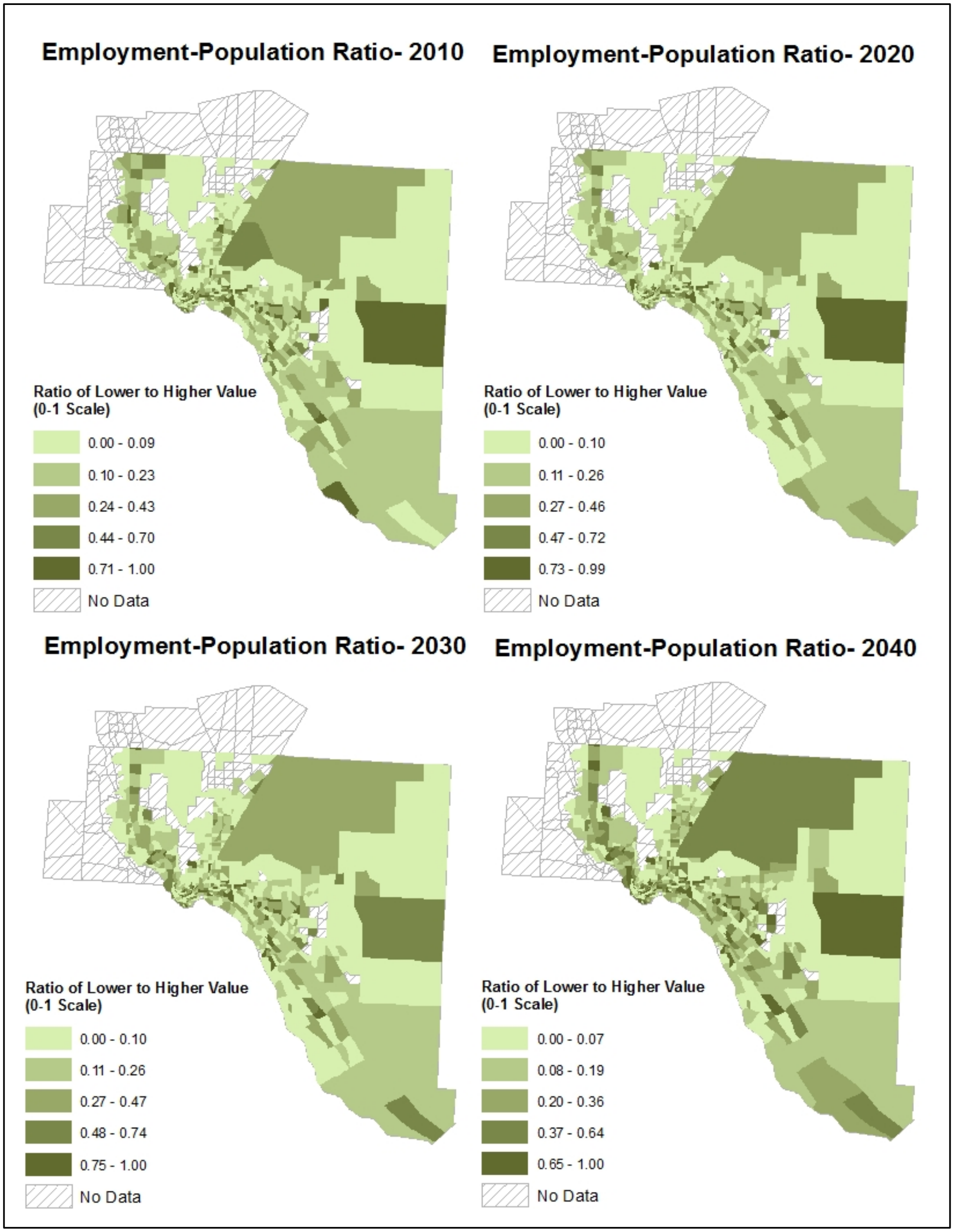

Figure E- 4. Employment-Population Ratio Indicator Values

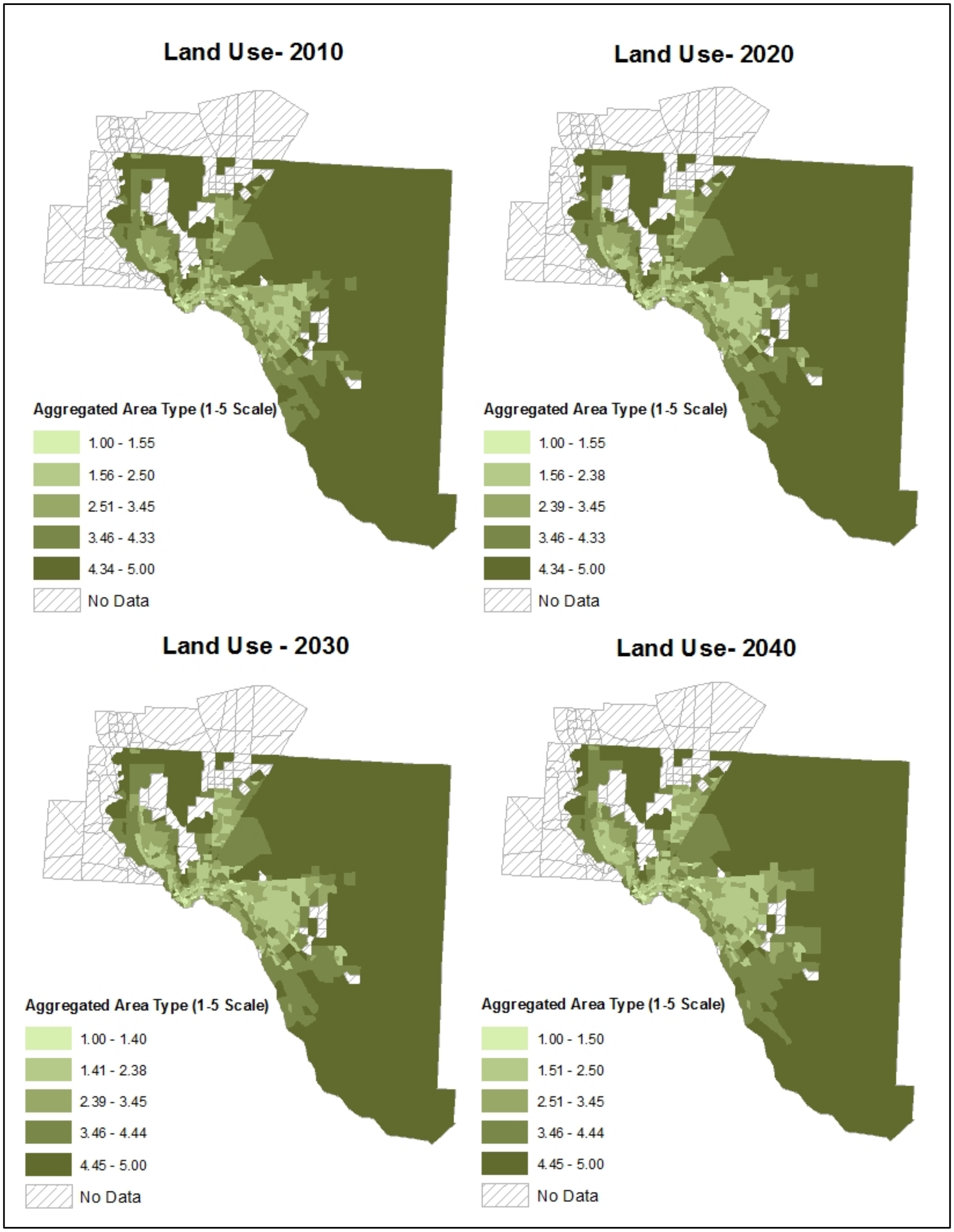

Figure E- 5. Land Use Indicator Values

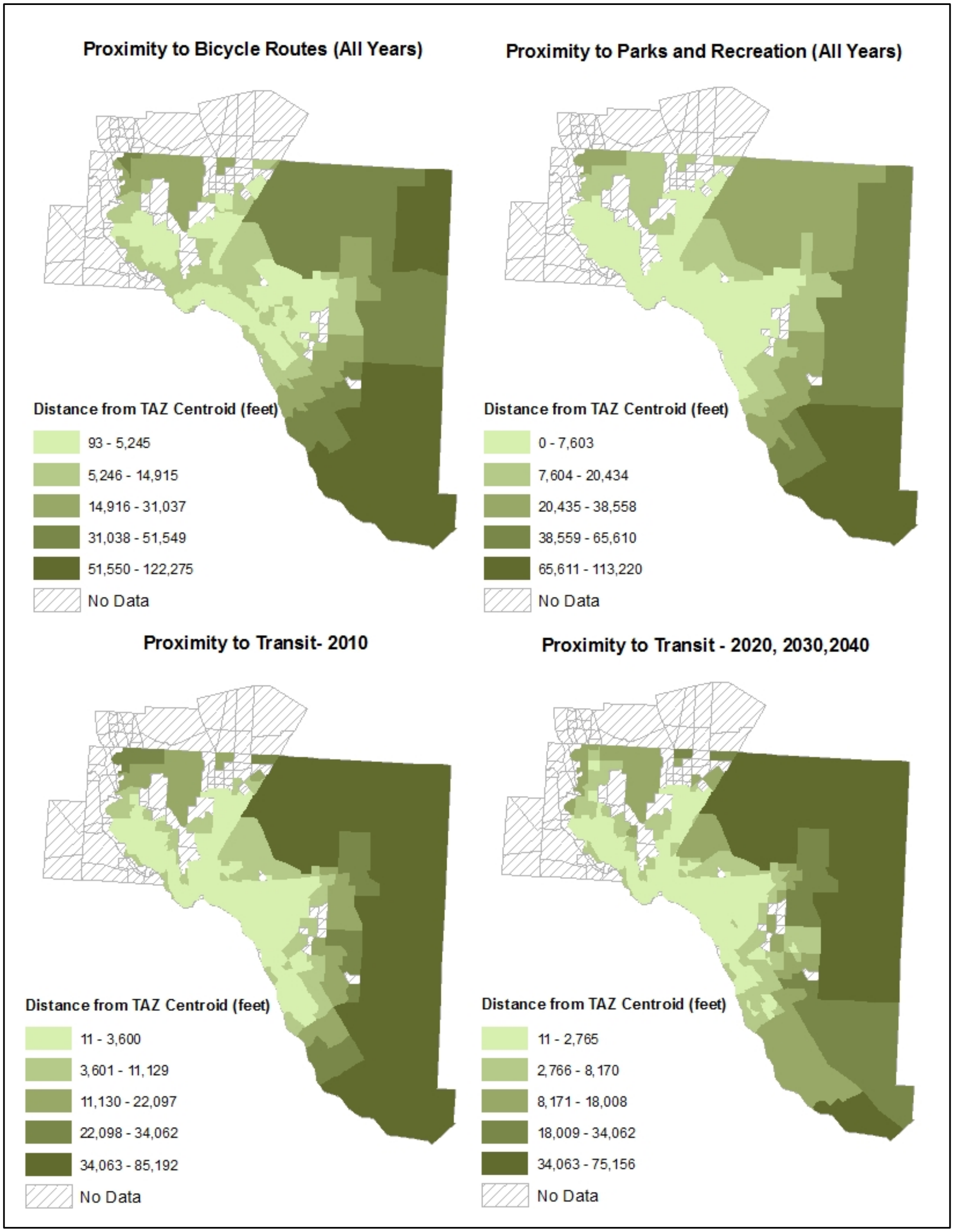

Figure E- 6. Proximity to Bicycle Routes, Parks and Recreation, and Transit

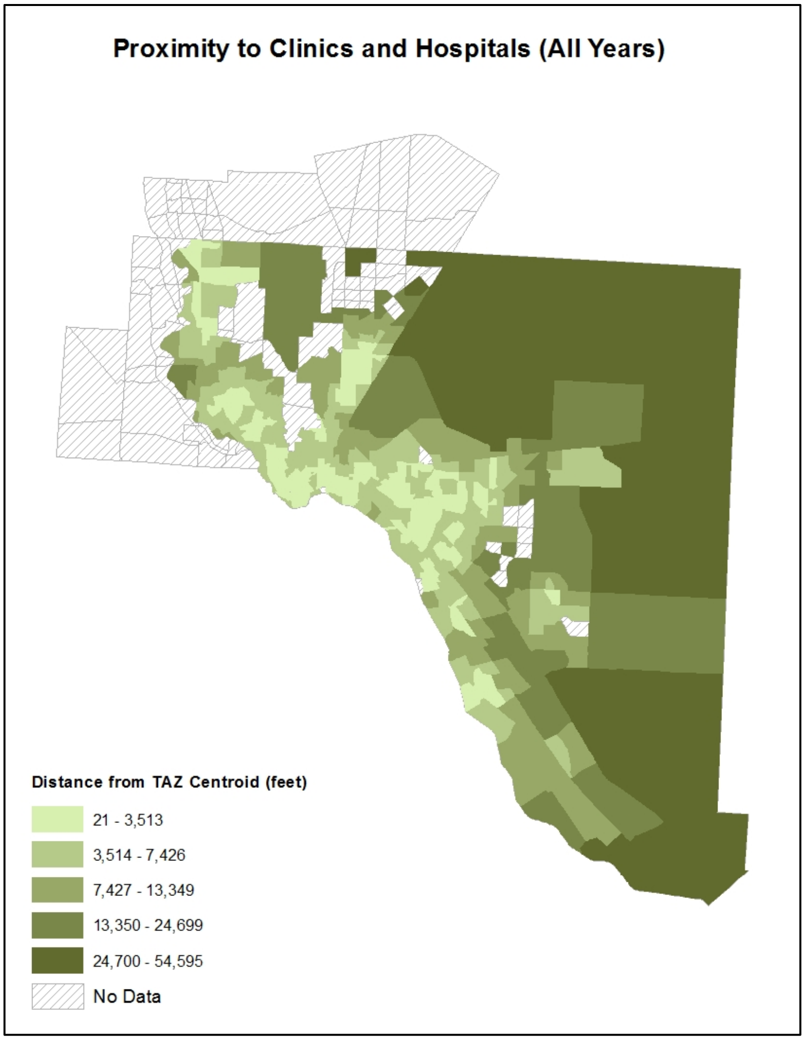

Figure E- 7. Proximity to Clinics and Hospitals

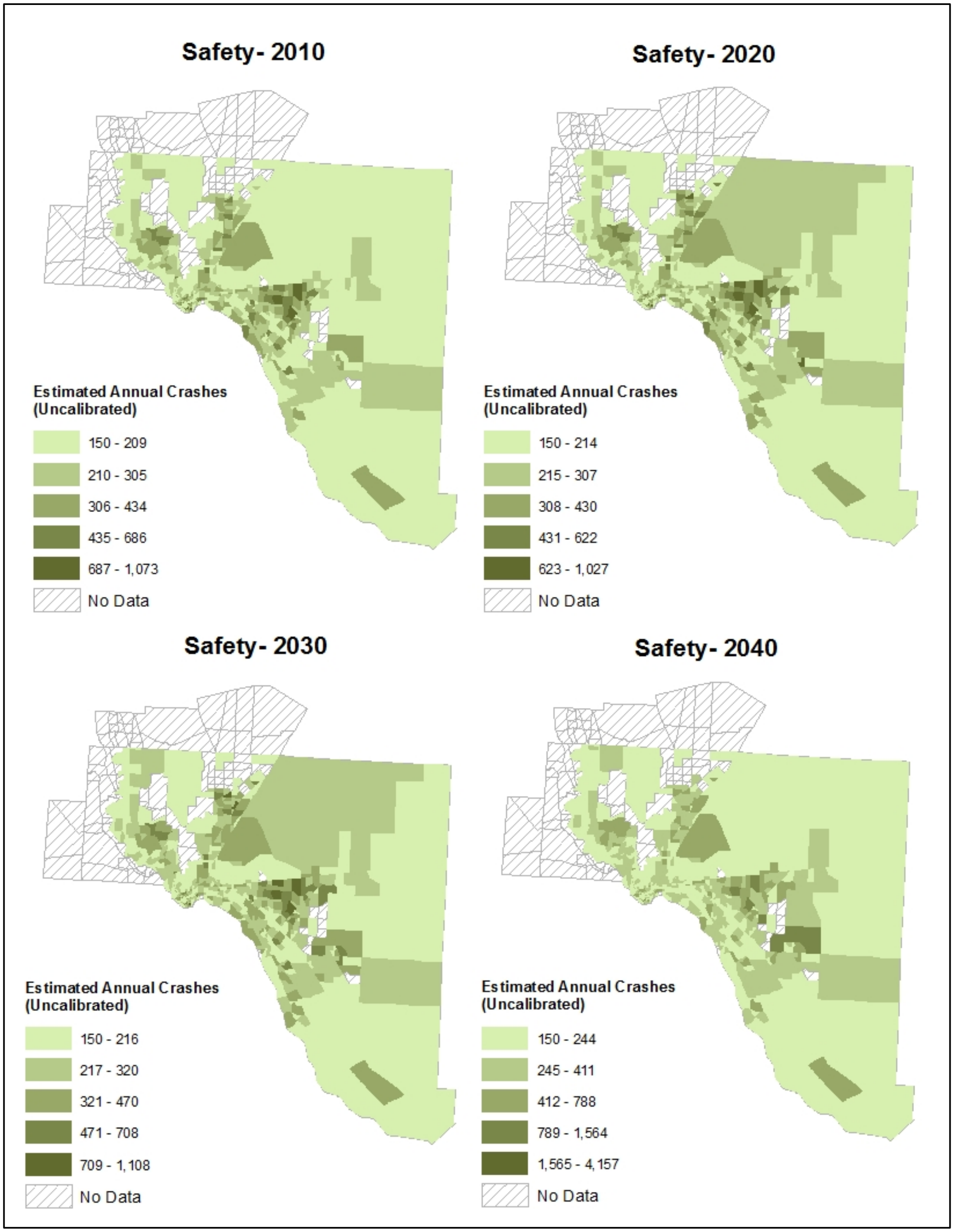

Figure E- 8. Safety Indicator Values

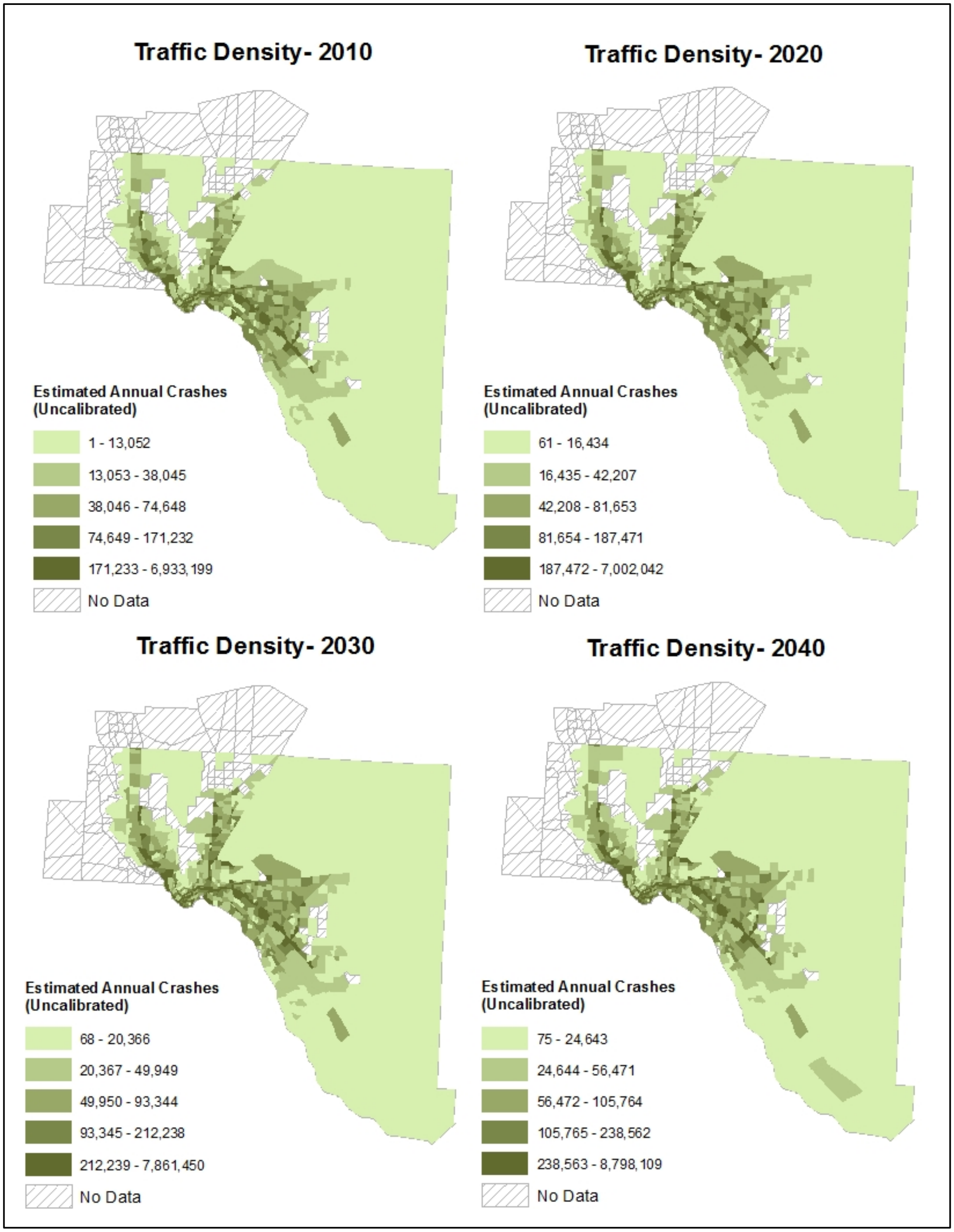

Figure E- 9. Traffic Density Indicator Values