Development of a Comprehensive Metric for Transportation, Environment, and Community Health

Center for Transportation, Environment, and Community Health
Final Report

by
Ruey Long Cheu, Esmaeil Balal

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16. Abstract This research develops a comprehensive metric that enables transportation planners and analysts to evaluate the impact of a transportation project on the environment and community health. The metric consists of transportation, environment, and community health as three different dimensions. Each dimension has a few identified criteria. Each criterion may further be described by several quantitative and qualitative indicators. A concept map has been used to visualize the relationships between the criteria, within and between the dimensions. The metric is a flexible template where criteria and indicators may be added to meet the needs of a transportation project. The applications of the metric have been demonstrated in 2 case studies.		
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Table of Contents

List of Figures

List of Tables

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1 INTRODUCTION

The Center for Transportation, Environment and Community Health (CTECH) aims to conduct research, educate professionals and the public on the relationships between transportation, environment, and community health. The effects of transportation on the environment have been studied by researchers since the 1970s. It is known that, in general, at the systems level, transportation has impact on environment, and transportation and environment both have impact on community health. For example, vehicles from the highway transportation system produce emissions. The pollutants have adverse impacts on the air quality. These polluted air, when inhaled, has adverse effects on human health. At the same time, excessive traffic congestion creates stress and fatigue for travelers, deteriorates the well-being of the community.

Transportation, environment, and community health are three large-scale systems. Each of them by itself is an industry or profession, a unique academic discipline, and governed by different laws and regulations. Therefore, each system has its own criteria to evaluate its states, and each criterion has its own measurable indicators. Since each system has several criteria, the relationship between two systems is driven by the underlying relationships between the criteria. Understanding the relationships between the criteria across the systems helps in better understanding of the complex interactions between any two systems. If there is any change in a physical component in one system (say, in transportation, increase in highway capacity at a critical bottleneck location in a city), there will be changes in the corresponding criterion and indicators (e.g., mobility criterion and mobility indicators) in the transportation system. The change in the criterion in the original system will trigger changes in one or more criteria in other systems. Knowledge about the linkages between transportation, environment, and community health help analysts and decision makers better prepared to evaluate the impact of a transportation project on environment, and community health.

The objective of this research is to develop a comprehensive metric, which can be served as a tool for engineers, planners, public health officers and other decision makers to evaluate the environment and community health impacts of a proposed surface transportation projects. To develop this metric, one needs to find the answers of the following questions:

1 What is transportation? What is environment? What is community health?
2 What are the criteria to evaluate the states of transportation, environment, and community health, respectively?
3 What criteria that have impacts on or are impacted by other criteria?
4 For each criterion, what are the qualitative and quantitative indicators?
5 How can the criteria between the systems, and the relationships between the criteria be visualized?

The structure of the metric to be developed in this research has transportation, environment, and community health as three separate ***dimensions*** (may be viewed as disciplines) at the highest level. The definitions of transportation, environment, and community health will be acquired through literature review and consultation with stakeholders. From the information gathered, several ***criteria*** will be identified, at the second level, to represent the states of each dimension. Each criterion is then evaluated, at the third level, by one or several qualitative and/or quantitative ***indicators***. Having identified each dimension's definition, criteria and indicators, a concept map will be developed to graphically layout the structure of the dimensions, criteria and indicators. The concept map will also consist of one-dirctional arrows that link pairs of criteria. Each arrow represents the relationship between two different criteria (which may be in two different dimensions).

Based on the dimension-criteria-indicator structure developed, a metric, in the form of tables with check lists, will be developed. As this research project progressed, it was soon realized that the comprehensive metric consisted of too many criteria and indicators, that it had to be split into three metrics, one for each dimension.

The transportation modes covered in this report are limited to surface transportation (private and public transportation modes). The transportation criteria and indicators, and therefore the proposed metric are applicable to transportation projects/systems at intersection, corridor and network levels. The indicators describe macroscopically the system's operational statistics, and quality of service at the aggregated level. Indicators that describe individual user's experience are not as indicative of the system's performance and therefore are not used. However, adverse environment and health conditions will impact significant number of users or residents. Such situations qualify certain criteria and indicators as system parameters.

The chapters of this report, which follow the sequence of tasks performed by the research team, are organized as follows:

- Chapter 2 reviewed the criteria of transportation, environment, and community health, respectively; the indicators of each of the criteria and the known relationships between transportation, environment, and community health via linkages between the criteria.
- Chapter 3 developed initial concept map which is a graphical presentation of the metrics and the relationships between the criteria.
- Chapter 4 proposed the initial metrics of transportation, environment, and community health.
- Chapter 5 conducted stakeholder interviews that gathered feedbacks on the initial metrics and concept map.
- Chapter 6 revised the initial metrics and concept map into the revised metrics and consummate based on the stakeholder feedbacks.
- Chapter 7 applied the revised metrics and concept map to two case studies.
- Chapter 8 summarized all the works performed, highlighted the contributions, and future research directions.

2 LITERATURE REVIEW

The purposes of this literature review were (i) to understand the criteria of transportation, environment, and community health, respectively; (ii) to understand the indicators (and units) of each of the criteria; (iii) to find the known relationships between transportation, environment, and community health via linkages between the criteria. Since transportation, environment, and community health are traditionally three different disciplines in science, engineering, and medicine, they were first reviewed as three dimensions.

This literature review was conducted in two parts. Section 2.1 reviewed transportation, environment, and community health, respectively. This section treated transportation, environment, and community health as different dimensions; each has its own sub-section. Each sub-section summarized the criteria and indicators (and units of measure, if available) that are used to assess the state of the dimension. The criteria may be defined as a particular aspect of the dimension, while indicators are specific qualitative or quantitative parameters (which may carry descriptive, binary, discrete or continuous values). A criterion may be measured collectively by different indicators. Because Section 2.1 reviewed the transportation, environment, and community health dimensions independently, some criteria or indicators that appear in one dimension may also appear in another dimension. This only reflects that the dimensions and criteria are inter-related, although they were treated as independent in Section 2.1 of this literature review.

Section 2.2 reviewed the relationships between transportation and environment, transportation and community health, and environment and community health. The linkages between the indicators in one dimension with indicators in other dimension were identified. Every pair of indicators that were found to be related were linked by a one-dimensional arrow with a vocabulary that described the relationship. The links between two pairs of indicators may then be chained to provide the indirect relationships between the first and the third indicator. For example, the links between a criterion in transportation and a criterion in environment may be chained with a link between the same criterion in environment and a criterion in community health, to realize an indirect connection between the criterion in transportation and the criterion in community health.

2.1 Criteria and Indicators

2.1.1 Transportation

Criteria

Transportation, in general, is defined as "everything involved in the moving either the person or goods from the origin to the destination" (Fricker et al. 2014). The American Society of Civil Engineers (ASCE) defines transportation engineering as "the utilization of technology and scientific rules to the planning, functional design, operation and management of facilities for any mode of transportation in order to provide safe, efficient, fast, comfortable, convenient, economical, and environmentally compatible movement of people and goods" (ASCE 2010). The U.S. Department of Transportation (USDOT) was established by Congress in 1956 with a mission to "serve the United States by ensuring a fast, safe, efficient, accessible and convenient transportation system that meets our vital national interests and enhances the quality of life of the American people, today and into the future" (Patt et al. 2012; USDOT 2016). Based on the definitions of ASCE and USDOT, the goals of transportation systems are to move people and goods in a safe, efficient, comfortable, cost effective, environmental friendly, and accessible manner. Therefore, the performance of transportation systems may be assessed via the following performance-based criteria:

- Mobility (includes efficiency)
- Safety
- Accessibility
- Comfort
- Environmental friendly
- Economy (include cost effectiveness)

ASCE has recently emphasized the incorporation of the concept of sustainability into civil infrastructure systems design and operations (ASCE 2010). Therefore, sustainability should be included as a criterion of a transportation system's (life cycle) performance.

<u>Indicators of Mobility</u>

Indicators of highway transportation systems mobility may be taken from the Highway Capacity Manual (HCM 2000) and the Texas A&M Transportation Institute Annual Mobility Scorecard (Schrank et al. 2015). For public transportation, mobility indicators may be taken from the Transit Capacity and Quality of Service Manual (TRB 2017). The HCM2010 has a list of "factors" that indicate the quality of service of highway facilities. These factors are derived from macroscopic parameters of traffic flow. Some of them that have relationships with environment or community health may be used as mobility indicators. The following are the frequently used mobility indicators for highway transportation facilities that are extracted from HCM2010 and the Annual Mobility Scorecard. The list is representative and is thus not exhaustive. The complete list of has indicators is too long to be listed here, and with the many modes and types of in infrastructure, it may be impossible to list all the indicators completely. In a transportation project, the actual mobility indicators, exact formulae, and unit of measures used depend on the transportation mode, the scale and need of a specific project. The typical mobility indicators are:

- Average travel time (in minutes);
- Average speed (in mph);
- Average delay (in sec/person, sec/vehicle);
- Level of service (letter grade from A to F);
- Vehicle-miles traveled or VMT (in vehicle-miles/day);
- Number of congested hour per day (hours/day); and
- Travel time reliability (index).

The performance indicators of transit systems may also be:

- Ridership (in person-trips/day);
- Number of transfers in the network or a specific origin-destination pair;
- Service hours (in hours/day);
- Average service headway (in minutes); and
- Service coverage area (in mi^2 or percent of area).

Indicators of Safety

There are many indicators for safety of highway transportation systems. The Bureau of Transportation Statistics (USDOT 2016), a Federal agency under the U.S. Department of Transportation uses many quantitative indicators. The American Association of State Highway & Transportation Officials (AASHTO) Highway Safety Manual (AASHTO 2010) and Institute of Transportation Engineers (ITE) Traffic Engineering Handbook (ITE 1999) also have their own lists of safety indicators. Essentially, these safety indicators are derived from

- number of crashes per year, also known as crash rate;
- number of injuries per year or injury rate; and
- number of fatalities per year, or fatality rate.

The number of injuries and number of fatalities are more reflective to the impact of a crash (i.e., to account for the number of persons affected) then just the number of injury crashes and number of fatal crashes, respectively.

In safety analysis, the above indicators (or statistics) may further be categorized into different types of crash (e.g., head-on, rear-end, side swipe), types of vehicles involved in crashes (e.g., trucks, passenger cars, motorcycles), outcomes of crashes (e.g., property damage, injury, fatal). Pedestrian count is included, if the subject of crash analysis concerns with pedestrian safety. At the systems level, the three indicators (crashes rate; injury rate; and fatality rate) listed above are sufficient, and are easily obtained from county, state and/or national database. The annual crash, injury and fatality rates may also be normalized by vehicle-miles traveled, number of licensed drivers, Annual Average Daily Traffic (AADT) or exposure, number of registered vehicles in the area, population in the area, etc.

In transportation engineering, the following safety indicators are most commonly used:

- number of crashes/year
- number of injuries/year
- number of fatalities/year
- number of crashes/100000-population/year
- number of injuries/100000-population/year
- number of fatalities/100000-population/year
- number of crashes/million-vehicles/year
- number of injuries/million-vehicles/year
- number of fatalities/million-vehicles/year
- number of crashes/million-VMT/year
- number of injuries/million-VMT/year
- number of fatalities/million-VMT/year

Instead of crash statistics, the safety of a highway transportation facility may also be replaced by a safety surrogate known as traffic conflicts. Crash rates are maintained and regularly updated by federal and state transportation or law enforcement agencies. These statistics, in standard formats, are public information. Traffic conflicts are near miss events that occur more frequently than crashes. Traffic conflicts need to be observed over a shorter period of a few days, but, because of the lack of systematic achieved record, it is not included as a safety indicator here.

Indicators of Accessibility

Accessibility is the potential to reach spatially dispersed opportunities (Paez et al. 2012). Accessibility may be defined as the ease to reach activities or to receive services. The accessibility to the economic, recreational, social, and service opportunities is an important component of the quality of life of a person. In the context of the scope of this research, the discussion is limited to the accessibility provided by surface transportation systems (from a person's origin to his/her desired destination). Accordingly, the accessibility indicators are what would be experienced by users of transportation systems to travel from one or multiple origins to one or multiple destinations, via a combination of surface transportation modes, aggregated at the systems (or community) level.

Accessibility in terms of passenger transportation (including transit) may be defined as "the extent to which land use and transport systems enable (groups of individuals) to reach activities by means of a combination of transport modes" (Geurs et al. 2004). This definition may be expanded to freight transportation, as "the extent to which land use and transportation systems enable freight to reach destinations by means of a combination of transportation modes". In simpler terms, accessibility is an indication of whether "a trip between an origin-destination pair can be made with reasonable effort and cost (Fricker et al. 2004). The "effort or cost" should also include "time". From the systems and network perspective, this definition should be expanded to cover multiple origins and multiple destinations. Another way of defining accessibility is "the desired destinations in the system that can be reached from all origins in the system with reasonable effort, cost and time."

Accessibility is affected by (1) land use or geographically how far opportunities are, (2) the availability of transportation connections of various modes; (3) the availability of activity opportunities or services at different times of a day; and (4) the individual's need (e.g., disability, car ownership) that limits the above options. Accessibility indicators can then be introduced to quantify the individual parts. Indicators that are based on spatial distribution, time period, headway and connectivity of transportation infrastructure are easier to quantify. Those that are related to temporal activity patterns are harder to compute. The following are suggested indicators of accessibility at the systems level (Geurs et al. 2004):

- Number of opportunities with a fixed travel time budget (number)
- Availability of opportunities (in numbers/day)
- No. of transportation modes (number)
- Service hours (availability of transportation service, in hours/day)
- Average service headway (in minutes)
- Average trip cost (in $)

Indicators of Comfort

Comfortable is stated by ASCE as one of the goals of transportation engineering. However, this criterion is subjective and difficult to quantify. Therefore, it is not considered further.

Indicators of Environmental

The environmental impacts of a transportation system, from construction, operations and maintenance, are of significant concerns. Because of its importance and variety of concerns, environment itself has many criteria (e.g., air quality, noise, vibration, light) and each has one or several indicators. Therefore, environment is designated in this research as a dimension, as the name of CTECH suggests. To avoid repetition, detail discussions of the environment dimension are made in the next sub-section.

Indicators of Economy

As economy is used as an indicator of mobility of transportation systems, its criteria should reflect the cost effectiveness at the system level, not individual user level. The economic criteria of transportation systems are indicated by different types of system costs. From the systems perspective, the economic indicators are project cost, operating and maintenance cost, energy cost and revenue (from fare collection, toll collection, tax, etc). The above indicators may be normalized into per user, trip, unit distance served, per year and so on, depending on the scope of analysis. The following indicators and units are recommended:

- Total project cost ($)
- Total operating and maintenance cost ($/year)
- Total energy cost ($/year)
- Total revenue ($/year)

Some researchers will argue that the indicators of Economy should also include the economic impacts of investment in a transportation project. Such economic impacts, such as job creation, consumption of goods and services are more difficult to estimate. Because the costs of concern are system level costs, individual user costs such as trip cost (which normally include transit fare, cost of gas consumed, toll, and etc.) is not considered.

The selected transportation criteria, and selected indicators for each criterion are listed in Table 1.

Table 1 Selected transportation criteria and indicators

Criterion	Indicator	Unit of measures
Mobility	Average travel time	minutes
	Average speed	mph
	Average delay	sec/person, sec/veh
	Level of service	A, B, C, D, E, F
	Vehicle-miles traveled	vehicle-miles/day
	No. of congested hours per day	hours/day
	Travel time reliability	
	Ridership	person-trips/day
	Number of transfers	person-trips/day
	Service hours	hours/day
	Average service headway	minutes
	Service coverage area	mi^2 or % of area
Safety	No. of crashes per year	See column on the left
	No. of injuries per year	
	No. of fatalities per year	
	No. of crashes/100000-population/year	
	No. of injuries/100000-population/year	
	No. of fatalities/100000-population/year	
	No. of crashes/million-vehicles/year	
	No. of injuries/million-vehicles/year	
	No. of fatalities/million-vehicles/year	
	No. of crashes/million-VMT/year	
	No. of injuries/million-VMT/year	
	No. of fatalities/million-VMT/year	
Accessibility	No. of opportunities with a fixed travel time budget	hours/day
	Availability of opportunities	hours/day
	No. of transportation modes	
	Service hours	hours/day
	Average service headway	minutes
	Average trip cost	$
Comfort	No indicator	-
Environmental friendliness	See Environment dimension	-
Economy	Total project cost	$
	Total operating and maintenance cost	$/year
	Total energy cost	$/year
	Total revenue	$/year

2.1.2 Environment

Definition

Environment is defined by Environmental Protection Agency (EPA) as the surroundings in which an organization operates including air, water, land, natural resources, flora, fauna, humans, and their interrelation (EPA 2016).

Criteria

The environmental concerns in transportation projects are primarily addressed by The National Environmental Policy Act (NEPA) of 1970 (EPA 2017). NEPA established EPA and requires Federal agencies to assess the environmental, social, and economic impacts of any planned transportation project (with public involvement) prior to making approval. The economic costs of transportation have been reviewed in Sub-Section 2.1.1 Transportation, under Indicators of Economy. The social impact of a transportation project will be addressed in Section 2.1.3 Community Health. This sub-section reviewed and proposed the environment criteria and indicators that are potentially related to transportation, and community health.

The following aspects of the environment are known to be related to or potentially related to transportation or community health: air quality, noise, ground vibration, and light. On the other hand, land use (or urban form) has influence on transportation demand, mode choice and social health. Kockelman (1996) suggested using the term "built environment" to describe land use. Therefore, the following five aspects of the environment were proposed as criteria for the environment:

- Air quality;
- Noise;
- Ground vibration;
- Light; and
- Build environment.

Indicators of Air Quality

The World Health Organization (WHO) defines air pollution as contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere (WHO 2015). Accordingly, air quality may be defined as the level of contamination of ambient air as measured by selected pollutants.

Vehicles are known as "mobile source" of pollutants while stationary facilities (such as gas stations, factories) are "point sources" of pollutants. The EPA, mandated by The Clean Air Act of 1990 (EPA 2017), has set National Ambient Air Quality Standards (NAAQS) (EPA 2016) for six "criteria" air pollutants:

- Carbon Monoxide (CO)
- Lead (Pb)
- Nitrogen Dioxide (NO_2)
- Ozone (O_3)

- Particulate Matters (PM), further divided into $PM_{2.5}$, PM_{10}
- Sulfur Dioxide (SO_2)

These six pollutions have the most significant impacts on human health. The effects of these pollutants on human health are covered in Section 2.2.3 Environment and Community Health.

The Clean Air Act also requires EPA to set two types air quality standards for these pollutants. The primary standards provide protection to human, while the secondary standards provide protection to animals and corps. The current primary standards for human are listed below:

- CO: 8-hour average and 1-hour average not to exceed 9 ppm and 35 ppm, respectively, more than once per year.
- Pb: rolling 3-month average not to exceed 0.15 mg/m$^{3.}$
- NO_2: 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years, not to exceed 100 ppb, and annual average not to exceed 53 ppm.
- O_3: annual 4th-highest daily maximum 8-hour concentration, averaged over 3 years not to exceed 0.070 ppm.
- $PM_{2.5}$: 3-year average not to exceed 12.0 mg/m^3 and 98th percentile averaged over 3 years not to exceed 35 mg/m$^{3.}$
- PM_{10}: 3-year average not to exceed 159 mg/m^3 more than once a year.
- SO_2: 99th percentile of 1-hour daily maximum concentrations, averaged over 3 years, not to exceed 75 ppb.

Therefore, it can be said that the air quality criteria may be measured by the six "criteria" air pollutants and method of sampling according to NAAQS.

EPA has also developed an Air Quality Index (AQI) that is used to report the overall air quality to the public. The AQI ranges from 0 to 500, and is divided into six levels of health concern: 0 to 50 for "good", 51 to 100 for "moderate", 101 to 150 for "unhealthy for sensitive groups", 151 to 200 for "unhealthy", 201 to 300 to "unhealthy", 301 to 500 for "hazardous" (EPA 2009). AQI is the sum of the indices of the six "criteria" pollutants. Each "criteria" pollutant's concentration is scaled linearly between its minimum and maximum values.

Indicators of Noise

Noise is unwanted or detrimental sound. Every area or neighborhood has its unique "noise signature" or consistent level of background noise (Forkenbrock et al. 1999; Litman 2003). The passing traffic (e.g., trucks or trains) temporarily increases the noise level. The magnitude of noise is measured by the pressure generated by its sound waves, in decibel (dB). The decibel follows logarithmic scale (base 10). That is, a noise twice as loud will only increase the numerical value by 10 dB. Noise comes in different frequencies. Human ears are more sensitive to sound at certain frequencies than others. The noise intensity calculated from audible frequencies by human is called A-scale or A-weighted noise level, with unit expressed in dB(A). Since the noise level varies with time, a single value in dB(A) called "equivalent sound level", denoted by $L_{eq}(h)$ is used to represent the sound level over a time period h.

Transportation induced noise is being managed by FHWA by three approaches (FHWA 2017):

- Land use planning and control;

- Source (vehicle noise, tire pavement noise) control; and
- Highway project noise mitigation.

These control methods provided insights on how noise, as a criterion of the environment, may be indicated.

In land use planning, national standard for noise in the urban environment has not been established. This is because the Federal government has no authority over the development and control of non-federal land. The authority to regulate noise in the neighborhood falls under the local (state, county, city, or tribal) government. However, only a few cities have guidelines for neighborhood noise control. The City of El Paso, Texas is used here as an example of standard of noise set by a local government. The City of El Paso classifies its land into three Noise Zones according to land use. For each Noise Zone, there are two allowable (maximum) exterior noise levels depending on day time (7:00 a.m. to 10:00 p.m.) or night time (10:00 p.m. to 7:00 a.m.). The allowable noise level ranges from 50 dB(A) to 70dB(A). Table 2 shows the Noise Zones and allowable noise levels. Residential properties have lower allowable noise level compared to commercial and industrial properties. For the same property, allowable noise level at night is 5 dB higher than the day time limit.

Table 2 Allowable noise levels in the City of El Paso

Noise zone	Land use	Allowable noise level (dB(A))
I	Single, double and multiple-family residential structures or property	Day: 50 Night: 55
II	Commercial properties	Day: 60 Night: 65
II	Manufacturing or industrial properties	Day: 65 Night: 70

Vehicles (engine) noise and tire-pavement noise are major sources of noise generated by highway transportation systems. The Noise Control Act of 1972 (EPA 2017) gives EPA the authority to regulate vehicle noise. Table 3 lists the motor vehicle maximum sound levels based on Gross Vehicle Weight Rating (GVWR). The noise levels are measured at 50 feet or 15 meters from the vehicles (FHWA 2017). The Noise Control Act of 1972 also authorized the Federal Motor Carrier Safety Administration (FMCSA) to enforce these noise standards for interstate commercial trucks. Noise caused by the friction between tire and pavement is audible and recognized as an important component. However, research in tire-pavement noise is still at its infancy (Cunniff, 1977).

Table 3 Motor vehicle maximum sound levels

	Maximum sound level (dB(A))		
	Speed limit of street ≤35 mph	Speed limit of street > 35 mph	Stationary run-up
Motor carrier vehicle engaged in interstate commerce of GVWR≥10,000 lbs	86	90	88
All other motor vehicles of GVWR≥10,000 lbs	70	79	-
Any motorcycle	78	82	-
Any motor vehicle or any combination or vehicles towed by any motor vehicle	70	79	-

NEPA provides Federal agencies the authority and responsibility for evaluating and mitigating adverse environmental effects of transportation projects including highway traffic noise. The Federal-Aid Highway Act of 1970 (Cunniff, 1977) further mandates FHWA to develop standards and regulations for mitigating highway traffic noise. The FHWA regulations (23 CFR 772) contain maximum acceptable highway traffic noise for different types of land uses and human activities. Compliance with the noise regulations is a requirement for state and local governments to receive Federal-Aid Highway Funds for a project through the state department of transportation. The standards and regulations states that the local government's project analysis procedure should include (1) identifying and quantifying traffic noise impacts of the project; (2) identifying and incorporating noise abatement indicators into the project; (3) identifying and implementing indicator to abate noise during construction. FHWA has developed Traffic Noise Model or TNM in short, to assist users to perform noise impact analysis (Rochat et al. 2012).

FHWA has set a goal that the abatement actions should reduce the noise level by 7 to 10 dB(A). The units of noise measurement are:

- $L_{eq}(h)$: hourly A-weighted equivalent sound level, in dB(A); or
- $L_{10}(h)$: hourly A-weighted sound level, in dB(A), that is exceeded 10% of the time.

FHWA has a table of Noise Abatement Criteria (NAC) for noise impact analysis. It specifies the desired $L_{eq}(h)$ or $L_{10}(h)$ that should be used. The ranges are $L_{eq}(h)$ from 52 to 72 dB(A) or $L_{10}(h)$ from 55 to 75 dB(A) depending on land use in the project vicinity.

From the above discussions, it was concluded that transportation related noise indicators, in dB(A), may be:

- Day time noise level
- Night time noise level
- Vehicle noise in roads with speed limit of 35 mph or less
- Vehicle noise in roads with speed limit of more than 35 mph
- Truck noise at stationary

The above noise levels may be measured in $L_{eq}(h)$ or $L_{10}(h)$.

Indicators of Ground Vibration

Ground vibrations are movements of the ground caused by human activities. Ground vibration resulting from surface transportation is caused by the passing of heavy vehicles or trains. Vibration often comes with noise, but other than negative health effect, vibration may also cause structural damage to pavement, bridges and buildings. Trains, especially freight trains, are the major sources of ground vibration caused by transportation, as inferred from the limited number of publications on the topic transportation-ground vibration (Ohrstrom et al. 1996; Waddington et al. 2015).

The level of ground vibration is measured by Peak Particle Velocity (PPV), which is the maximum ground particle movement speed, in inches per second (in/s) or millimeters per second (mm/s).

Ground vibration standards and guidance may be set by governmental agencies or professional groups. No national standard for vibration has been found in U.S. This is because the Federal government has no control over ground vibration on non-federal land. There should be different ground vibration standards for different vibration sources (excitation frequency) and different building types. India is one of the very few countries that have national ground vibration standards. Table 4 shows the ground vibration standard of India (Vibration Standard 2017) as an example to illustrate that the maximum PPV should depends on the type of building and the frequency.

Table 4 National vibration standard for India (Vibration Standard 2017)

Allowable vibration PPV (mm/sec)			
Type of structures	Dominant excitation frequency		
	<8 Hz	8-25 Hz	>25 Hz
Buildings/structures not belong to the owner			
1 Domestic house	5	10	15
2 Industrial buildings	10	20	25
3 Objects of historical importance	2	5	10
Buildings/structures belong to the owner			
1 Domestic house	10	15	20
2 Industrial buildings	15	25	50

Indicators of Light

Literature from the U.S. Federal government agencies concerning the definition, measurement and mitigation of light pollution was not found. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) Starlight Initiative Group developed a working definition of light pollution as “the introduction by humans, directly or indirectly, of artificial light into the environment.” In U.S., the majority (93%) of outdoor lighting is roadway and parking lot lighting. Light emitted from lamps at these transportation facilities is the major sources of light pollution (International Dark-Sky Association 2012).

Light is a kind of radiant energy. The range of the wavelength detectable by human eye is between 380 nm and 780 nm. The response of a human to light depends on many factors, including the sensitivity of the eye, and the radiant energy of light. The intensity of light is expressed in three different terms (AASHTO 2010):

- Lumen. Lumen is the short form of luminous flux, the total quantity of visible light emitted by a source. Lumen is a term which is also its unit, written as lm.
- Luminance. Luminance is the amount of emitted light per unit area of its source. The unit of luminance is candela per square meter (cd/m^2).
- Illuminance. Illuminance is the amount incident light per unit area of projected surface, i.e., lumens per unit area covered by the light. The unit of illuminance is lm/m^2 or lm/ft^2.

The unit lm/m^2 is also known as lux while lm/ft^2 is also known as foot candle. From the above discussions, it appears that even the industry has not set a common unit of measurement of light per unit area. The existing units are cd/m^2 for luminance and lm/m^2 or lm/ft^2 for illuminance. For the purpose quantifying light pollution in the environment, illuminance is the appropriate indicator because this is what a human receives in his/her surrounding environment.

Indicators of Built Environment

Built environment is proposed as the criterion for land use in this report. The built environment refers to the man-made space in which people live and conduct their socioeconomic activities (Roof 2008). There are several terms that are frequently used to describe the built environment: Transit Oriented Development (TOD), SmartCode, New Urbanism, mixed use, walkable street, Leadership in Energy and Environmental Design-Neighborhood Development (LEED-ND), and etc. They reduce the need for residents to make long trips, promote walking, bicycling and public transportation through high density housing that integrates mass transit. Kockelman (1997) proposed four indicators of a build environment: density, accessibility, entropy index, and dissimilarity index. Density is further divided into residential density and employment density. Entropy index reflects land use balance, i.e., jobs to household ratio. Dissimilarity index captures the extent of mixed use. The indicators were adopted for the built environment:

- Residential density
- Job density
- Entropy index
- Dissimilarity index

Some researchers may consider accessibility as an indicator for the built environment. Accessibility has been defined as one of the transportation criteria in Sub-Section 2.1.1. Accessibility depends on land use but it is more dependent on the transportation infrastructure network designs and the service provided. To avoid creating confusion between accessibility as a transportation criterion and accessibility as an environment indicator, it is recommended to leave accessibility as a criterion under the transportation dimension.

Table 5 lists the selected environment criteria and the indicators for each criterion, as discussed in this sub-section.

Table 5 Selected environment criteria and indicators

Criterion	Indicator	Unit of measure
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm mg/m^3 ppm mg/m^3 mg/m^3 ppb
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit ≤ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)
Vibration	Peak particle velocity, PPV	mm/sec or in/sec
Light	Illuminance	lm/m^2 or lm/ft^2
Built environment	Residential density Job density Entropy index Dissimilarity index	persons/mi^2 persons/mi^2

2.1.3 Community Health

Definition

Health is defined by World Health Organization (WHO) as a state of complete physical, mental and social well-being (WHO 1995). Traditionally, a community is marked by a geographical boundary that forms a neighborhood, city, county, or state. In the context of community health, a community is "a group of people who have common characteristics". Communities may be defined by geographical area, race, ethnicity, age, occupation, or a common interest (McKenzie et al. 2011). Community heath refers to the physical, mental, and social health status of a defined group of people and the actions taken to promote, protect, and preserve their health. The term community health is always used interchangeably, and often confused with public health. The Institute of Medicine defines public health as "what we as a society do collectively to assure the conditions in which people can be healthy" (Dishman 1988). To provide the conditions, the society (or community) needs an organized public healthcare infrastructure and services (normally provided by the government) and the associated efforts of private and voluntary organizations and individuals. The American Public Health Association (APHA) states that "Public health promotes and protects the health of people and the communities where they live, learn, work and play." (APHA 2018). The APHA explains that public health includes medical treatment, scientific research, disease prevention, public policy, emergency response, health education, and many other efforts that aim to improve the quality of life. From the above discussions, community health refers to the state of physical, mental, and social health (the outcomes) of a defined community while public health refers to the infrastructure, services and organized activities (the process) for the community to achieve healthy outcomes that improve quality of life.

Criteria

The U.S. Center for Disease Control and Prevention (CDC) does not provide a definition of community health. However, CDC has developed a Community Health Assessment Tool with Community Health Status Indicators (CHSI). CDC recognizes that there is no widely accepted definition of community health. Therefore, it provides a set of health metrics that cover a wide range of issues for users to conduct community health assessments. CDC (CDC 2015) has initially identified 42 "criteria" of community health. These "criteria" are placed into six categories. The six categories are then grouped under health outcomes or health determinants:

- Health outcomes (2 categories): mortality (6 "criteria"), morbidity (9 "criteria");
- Health determinants (4 categories): health care access and quality (3 "criteria"), health behaviors (7 "criteria"), demographics and social environment (14 "criteria"), physical environment (3 "criteria").

CDC has further identified, for each of the 42 "criteria", the statistics at the metropolitan statistical, county, or sub-county (census tract, census block groups) levels. The term "criteria" used by CDC corresponds to indicators in this report. The metropolitan statistical area, county, or sub-county merely reflect the size of the community. From 2015, the 42 "criteria" have been renamed and re-organized into 31 "factors" as listed in Table 6. County level data of these 31 "factors" have been used to compile county health statistics (County Health Statistics 2017). From Table 6, it may be inferred that CDC's definition of community health covers demographics, housing and healthcare accessibility and quality, life longevity, medical health and traffic safety. Not all of them are related or impacted by transportation or the environment. Those that have direct impacts with transportation and the environment are highlighted in bold in Table 6. It should be noted that although the remaining "factors" are not directly related to transportation and the environment, they may be impacted by the "direct factors" by indirect ways. When performing a community health assessment, an analyst may select a subset of the 31 "factors" (indicators) that meet his/her scope and objective.

Table 6 CDC's community health metric (County Health Statistics 2017)

	Health outcome		Health factors			
	Length of life	Quality of life	Health behaviors	Clinical care	Social & economic factors	Physical environment
Indicators	**Death before 75**	**Low birthweight**	Excessive drinking	Uninsured	Violent crime rate	**Air quality: $PM_{2.5}$**
		Poor or fair health	**Alcohol-impaired driving deaths**	Primary care physicians	**Injury deaths**	Drinking water violations
		Poor mental health days	**Adult obesity**	Dentists	High school graduation	
		Poor physical health days	**Physical inactivity**	Mental health providers	Some college	
			Access to exercise opportunity	Preventable hospital stays	Unemployment	
			STD rate	Diabetes monitoring	Children in poverty	
			Teen births	Mammography screening	Income inequality	
			Adult smoking		Children in single households	
					Social associations	

Since community health also include social health, Environmental Justice (EJ) may be part of community health. Environmental Justice is defined by the EPA (2017) as the "fair treatment for people of all races, cultures, and incomes, regarding the development of environmental laws, regulations, and policies". The concept of Environmental Equity: that all people should bear a proportionate share of environmental pollution and health risk and enjoy equal access to environmental amenities is what EJ policies seek to achieve. The objective of EJ policies is to overcome environmental racism caused by racial and economic advantages that have been built into enforcement, policy making, and the locating of waste disposal and polluting industries (Urban Environmental Justice Indices, 2013). USDOT and the FHWA issued Environmental Justice Orders (USDOT Order 5610.2 (FHWA 2012) and FHWA Order 6640.23 (FHWA 2012)) in 1997 and 1998 respectively. These Orders described how EJ elements can be incorporated into existing Federal programs. USDOT cited three core principles of EJ that can be used for analysis and decision-making. They are:

1. To avoid, minimize, or mitigate disproportionately high and adverse human health and environmental effects, including social and economic effects, on minority populations and low-income populations;
2. To ensure the full and fair participation by all potentially affected communities in the transportation decision-making process; and
3. To prevent the denial of, reduction in, or significant delay in the receipt of benefits by minority and low-income populations.

The above actions affect the planning process of a highway project. However, the outcome of EJ is hard to measure. The following indicators are based on what have been used in the case studies listed at FHWA's EJ website (FHWA 2017). All except one measure the process rather than the outcome, with yes/no answers:

- Involvement of the public (yes/no answer)
- Involvement of the minority groups (yes/no answer)
- Involvement of locally owned businesses (yes/no answer)
- Use demographic data in impact analysis (yes/no answer)
- Share of transportation funding to low income group (percent)

Many issues related to EJ are received and resolved by the project developer during the public involvement process (which obviously should include the minority groups and locally owned business). The process of analysis includes the use of demographic data to ensure that low income segment of the population will not be disadvantaged. Therefore, it may be said the public involvement process encompasses the five aforementioned indicators.

The selected indicators (highlighted in bold) in Table 6, plus public involvement are arranged under the three community health criteria in Table 7.

Table 7 Selected community health criteria and indicators

Criterion	Indicator	Unit of measure
Physical health	Death before 75 Low birthweight Poor or fair health Poor physical health days Adult obesity Physical inactivity Air quality: $PM_{2.5}$	no. of deaths % live birth % population days % population % population $\mu g/m^3$
Mental health	Poor mental health days	Days
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality due to alcohol impairment no. per 100,000 population yes/no (project specific)

2.1.4 Sustainability

Sustainability, according to ASCE, is "the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic and social resources" (ASCE 2010). ASCE further prescribes triple bottom lines of sustainability: economic sustainability, environmental sustainability and social sustainability.

The FHWA is promoting sustainable development through its Sustainable Highway Initiative. In FHWA's view, a sustainable highway should, throughout its lifecycle (from conception through construction, operations, maintenance and retirement), "address environmental, social and economic impacts, safety, affordability, and accessibility of transportation services" (FHWA 2017). Note that "environmental" is already a dimension in this report, "social" is a criterion in community health, while "economic impacts, safety, affordability, and accessibility" are mobility criteria. With these goals in mind, FHWA has developed a tool named Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) to assist in decision making on transportation programs and projects with sustainability consideration. INVEST is a web based tool. It has 81 "criteria" covering full life cycle analysis, organized into four modules:

- System Planning for States (SPS): sixteen (16) "criteria"
- System Planning for Regions (SPR): sixteen (16) "criteria"
- Project Development (PD): thirty-three (33) "criteria"
- Operations & Maintenance (OM) module: (14) "criteria"

Each "criterion" has a scoring system that earns 0 to 10 points. Because the sustainability goals have been included as dimensions or criteria in our proposed metric, it can be said that the INVEST analysis criteria have been integrated with the metric structure developed in this research.

ASCE, together with American Public Works Association, and American Council of Engineering Companies, have established the Institute for Sustainable Infrastructure (Institute for Sustainable Infrastructure 2017). The Institute's main activity is to use a software named ENVISION (Shivakumar et al. 2014) to promote sustainability of all kinds of civil infrastructures. ENVISION is a rating system consisting of 60 sustainability "criteria" that address the full range of environmental, social, and economic impacts (outcomes) to sustainability in project design, construction, and operation. These "criteria" are organized into five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. The five categories are further divided into 14 subcategories. Each "criterion" is graded by qualitative, quantitative, or binary (yes/no) score through which a project earns credits. Weights of the criteria may be adjusted to meet the local aspiration. At the end of the assessment, a project may receive a bronze, silver, gold or platinum award. Since the 60 "criteria" are developed for all kinds of civil infrastructure, not all of them are applicable to transportation, or relate transportation to environment or community health. In the context of this research, sustainability is a transportation criterion, and ENVISION's rating criteria are the indicators. The following ENVISION criteria that are direct indicators of transportation:

Quality of Life category:

QL2.1: Public health and safety
QL2.2: Noise and vibration
QL2.3: Light pollution
QL2.4: Community mobility and access
QL2.5: Alternative modes of transportation
QL2.6: Accessibility, safety and wayfinding

Climate &Risk category:

CR1.1: Greenhouse gas emissions
CR1.2: Air pollution emissions

If one regard sustainability as a metric, then economic sustainability, environmental sustainability and social sustainability are the three dimensions. The environmental sustainability dimension is equivalent to the environment dimension in the CTECH metric this report is trying to develop. Social sustainability, a dimension in sustainability, is similar to the social health criterion in the community health dimension of CTECH's metric. The dimension of economic sustainability is a criterion under CTECH's Transportation dimension. From the incompatibility in the dimensions and criteria, it appears that one should not put sustainability under the framework of transportation, environment and community health. Instead, one may view the sustainability metric as a collection of dimensions, criteria and indicators, with sustainability as the objective.

2.2 Relationships

In Section 2.1, transportation, environment and community health are treated as three independent dimensions, but may share similar criteria and indicators. After reviewing the definitions, criteria and indicators of transportation, environment and community health, respectively (with a focus on land or surface transportation), this section explores the direct relationships between any two dimensions.

2.2.1 Transportation and Environment

The performance of a transportation system is reflected by the mobility, safety, accessibility, comfort, environmental friendliness and economic criteria. Among the environment criteria, those affected by transportation are air quality, noise, ground vibration, and light.

The impacts of transportation on the environment is evident from the Federal law that requires that, during the planning and preliminary design stages of any transportation project, the project developer must conduct an Environmental Impact Assessment (EIA) and submit the EIA report to FHWA for approval if the project seeks Federal fund.

Transportation is the major source of mobile emissions. The longer the average travel time, slower average speed, longer average delay, worse level of service, more vehicles-mile traveled, more hours of congestion/day, cause more quantity of criteria pollutants be emitted by vehicles into the atmosphere. The six criteria pollutants have been reviewed in Sub-Section 2.1.2. Vehicle emission affects the growth of plants (at the vicinity of the highway) by altering the plant cells. Road dust blocks sunlight from reaching the plant and slow down photosynthesis (Glazier 2014).

Safety is also related to air quality. The more frequent and more severe the highway crashes, the more frequent and severe congestion these crashes create and thus causing more vehicle emissions.

Noise, ground vibration and light that are caused by transportation have been discussed in Sub-Section 2.1.2. Usually, noise and vibration are related to average speed. Noise are known to affect breeding of birds (Glazier 2014) (and perhaps other animals).

The environment, in reverse, influences human's transportation in different ways. Here, the environment refers to the built environment. Land use and transportation infrastructure design, influence travel decisions. Land use may encourage or discourage the use of certain modes of transportation. A neighborhood that is planned with the concept of TOD, SmartCode, walkable street, mixed use and/or LEED-ND encourages the use of public transportation (bus, tram, light rail, mass transit) and non-motorized modes (walking, bicycling). Mixed use, high density development also reduces the need to travel outside the neighborhood. Mixed use, combined with the availability of different modes of transportation also help to improve the accessibility.

The relationships between the transportation criteria and environment criteria are summarized in Table 8. These relationships are for illustrations and they are by no mean exhaustive.

Table 8 Relationships between transportation and environment

Dimension: Transportation		Dimension: Environment
Criterion: Mobility	*generates*	Criterion: Air quality
Criterion: Mobility	*generates*	Criterion: Noise
Criterion: Mobility	*generates*	Criterion: Vibration
Criterion: Mobility	*generates*	Criterion: Light
Dimension: Environment		Dimension: Transportation
Criterion: Built environment	*influence*	Criterion: Mobility
Criterion: Built environment	*influence*	Criterion: Accessibility

2.2.2 Transportation and Community Health

The transportation criteria are mobility, safety, accessibility, comfort, environmental friendliness and economy. The indicators of these criteria have been summarized in Table 1. The review in Sub-Section 2.1.3 has found that community health refers to the state of physical, mental, and social health of a defined community. Accordingly, the proposed criteria for community health are physical health, mental health, and social health. Their indicators have been listed in Table 7.

Transportation directly affects community health in three ways: (1) mobility; (2) safety; and (3) accessibility.

Transportation mode (mobility) has direct impact on physical health. The attractiveness of public transportation has been listed in the last several indicators under the mobility criterion in Table 1. The use of public transportation, combined with walking and bicycling as the modes to access public transportation involves physical activities. In contrast, users of private vehicles always drive from one garage to another garage. The frequent use of active transportation (walking, bicycling) improves the physical health of the travelers, e.g., reduce obesity, improve cardiovascular health (Glazier 2014).

Long commute is reflected in the values of the following mobility indicators: average travel time, average speed, average delay, LOS, number of congested hour, travel time reliability. Long commute has negative effects on mental health and social health because it leads to higher stress, exhaustion and takes time away from family and social activity.

The stress of commute describes the direct impact transportation has on mental health. According to Novaco et al. (1979), long commute to work can affect an individual's mental health in physiology, task performance, and mood of commuters. This study found that higher levels of congestion had various negative mental effects on commuters. (Novaco et al. 1979)

The lack of accessible transportation made people less satisfied and this had affected their work performance, mood, and their physiological arousal. The increase in accessibility is usually due to the availability of a variety of transportation modes, longer service hours, shorter headway, and etc. Better accessibility helps to reduce the stress in commuting and improve mental health.

It has been discussed in Sub-Section 2.1.1 that safety is a performance criterion of transportation systems. The safety of streets in a neighborhood's is always indicated by the accident frequency and/or accident rate (see the indicators of safety in Sub-Section 2.1.1). Traffic accidents results in delays, property damages, injuries, death and caused emotional and financial stress on the travelers involved. Safety not only impacts social health, it also affects the victim's physical and mental health.

The accessibility from one place to another opens up economic, social and recreational opportunities for the travelers. Accessibility affects mental and social health.

Economy of transportation systems refers to the initial cost, and maintenance and operating cost. The costs will eventually pass down to the users. Higher system cost will induce more mental stress to the community.

Community health also has effect on transportation. Senior citizens, residents with disability and illness (physical health) needs special transportation to cater to the mobility needs of this group of users. Persons with mental health (especially depression) are likely to make few trips outside their residence. A community that has a strong social bond is likely to have higher participation in social activities and therefore generates transportation demand that alter the service hours, service frequency, area of coverage, and etc.

The relationships between the transportation criteria and community health criteria are summarized in Table 9.

Table 9 Relationships between transportation and community health

Dimension: Transportation		Dimension: Community Health
Criterion: Mobility	*affects*	Criterion: Physical health
Criterion: Mobility	*affects*	Criterion: Mental health
Criterion: Safety	*affects*	Criterion: Physical health
Criterion: Safety	*affects*	Criterion: Mental health
Criterion: Safety	*affects*	Criterion: Social health
Criterion: Accessibility	*affects*	Criterion: Mental health
Criterion: Accessibility	*affects*	Criterion: Social health
Criterion: Economy	*affects*	Criterion: Mental health
Dimension: Community health		Dimension: Transportation
Criterion: Physical health	*affects*	Criterion: Mobility
Criterion: Mental health	*affects*	Criterion: Mobility
Criterion: Social health	*affects*	Criterion: Mobility

2.2.3 Environment and Community Health

The air quality, noise, ground vibration, light and built environment are criteria of the environment (see Table 5). The criteria of community health are physical, mental and social health (see Table 7).

Air pollution has adverse effect on physical health. The pollutants produced by vehicle emissions is a major cause of diseases such as cancer, respiratory diseases and heart failure. The six criteria pollutants included in NAAQS (CO, Pb, CO_2, O_3, PM and SO_2) are regarded as most harmful to a person's physical health. Carbon monoxide reacts with hemoglobin in the blood and limits oxygen consumption which may lead to dizziness, loss of vision, and even heart failure. Ozone causes respiratory problems, reduce lung function, aggravates asthma, emphysema and bronchitis. Particulate matters have been associated with cardiac arrhythmias and heart attacks. Those with existing respiratory diseases, such as asthma and chronic bronchitis may have aggravated symptoms. Sulfur dioxide forms sulfuric acid that aggravates respiratory problems to asthmatic people, cause wheezing, chest tightness, and shortness of breath. It has an unpleasant smell or taste which can cause acid rain. The pollutants emitted by vehicles are also known to cause asthma among schoolchildren (EPA 2009).

It is very difficult to calculate the total health impacts of vehicle emission because motor vehicles are not the only source of pollutants (Litman 2003). Nevertheless, other than physical health, air pollution also negatively affects a patient's mental health.

Traffic noise causes sleep disorder, stress, and cardiovascular problems (blood pressure, heart rate). Residents who live nearer to highways experienced greater annoyance to noise than those who live further (Welch et al. 2013). It is estimated that in Europe, 3% of the ischaemic heart diseases are caused by traffic noise (Babisch 2005). Another study (Sullivan 2011) concluded that long exposure to traffic noise is a cause of depression. Overall, traffic noise has negative impacts on physical health and mental health.

Excessive light disrupts a person's sleep pattern by decreasing melatonin production in human body. Factors that influence melatonin secretion are (i) time of day; (ii) duration of exposure to light; (iii) light intensity; and (iv) wavelength (Falchi et al. 2011). The higher intensity and shorter wavelength of environmental friendly bulbs are suspected to disrupt melatonin production, disrupt sleeping cycle and lead to the weakening of mental and physical health.

The SmartCode, New Urbanism, mixed use, walkable street, and LEED-ND design concepts encourage urban planners to designate pockets of space such as parks, playgrounds, dog parks, sports fields for people to gather to interact. Such public facilities in the built environment are important infrastructure for community health.

Table 10 Relationships between environment and community health

Dimension: Environment		Dimension: Community Health
Criterion: Air quality	*affects*	Criterion: Physical health
Criterion: Air quality	*affects*	Criterion: Mental health
Criterion: Noise	*affects*	Criterion: Physical health
Criterion: Noise	*affects*	Criterion: Mental health
Criterion: Vibration	*affects*	Criterion: Mental health
Criterion: Light	*affects*	Criterion: Physical health
Criterion: Light	*affects*	Criterion: Mental health
Criterion: Built environment	*affects*	Criterion: Social health

2.2.4 Indirect Relationships

This sub-section illustrated how criteria of three dimensions are related. More specifically, this sub-section explores how a criterion of the first dimension affects a criterion of the second dimension, through another criterion in the third dimension; hence the term indirect relationship.

The following indirect relationship concerns with how transportation affects environment which then affects community health:

- Mobility deteriorates air quality; and poor air quality leads to poor physical health.
- Mobility generate noise and vibration; and higher noise and vibration levels lead to poor physical health.
- Mobility generate noise, ground vibration and light; and higher noise and vibration and light levels lead to poor mental health.
- A safer transportation system has fewer crashes which contributes to better air quality, lower noise and vibration levels; and better air quality, lower noise and vibration levels lead to better physical health.

The environment has impacts in transportation and transportation has impacts on community health:

- The built environment that follows the concept of TOD, SmartCode, New Urbanism, mixed use, walkable street, and LEED-ND reduces the need to make long trips by cars, promote walking, bicycling and public transportation. The kind of neighborhood design is conducive for physical activity and therefore creates an indirect impact on physical health.
- Similarly, built environment improves the accessibility of public transportation, reduces the stress of travel thereby improve mental health.

These are just a few examples that can be observed by chaining two pairs of relationships in Tables 8, 9 and 10 in a series, as displayed in Table 11. The numerous possibilities can be visualized in a concept map which will be developed in Section 3.

Table 11 Examples of relationships between transportation, environment and community health

Dimension: Transportation		Dimension: Environment		Dimension: Community Health
Criterion: Mobility	*affects*	Criterion: Air quality	*affects*	Criterion: Physical health
Criterion: Mobility	*generates*	Criterion: Noise	*affects*	Criterion: Physical health
Criterion: Mobility	*generates*	Criterion: Vibration	*affects*	Criterion: Physical health
Criterion: Safety	*affects*	Criterion: Air quality	*affects*	Criterion: Physical health
Criterion: Safety	*affects*	Criterion: Noise	*affects*	Criterion: Physical health
Criterion: Safety	*affects*	Criterion: Vibration	*affects*	Criterion: Physical health
Criterion: Mobility	*affects*	Criterion: Air quality	*affects*	Criterion: Mental health
Criterion: Mobility	*generates*	Criterion: Noise	*affects*	Criterion: Mental health
Criterion: Mobility	*generates*	Criterion: Vibration	*affects*	Criterion: Mental health
Dimension: Environment		Dimension: Transportation		Dimension: Community Health
Criterion: Built environment	*affects*	Criterion: Mobility	*affects*	Criterion: Physical health
Criterion: Built environment	*affects*	Criterion: Accessibility	*affects*	Criterion: Mental health

2.3 Transportation, Environment and Community Health Wheel

The dimensions, criteria and indicators for transportation, environment and community health, as discussed earlier in this chapter, may be graphically represented in a wheel as shown in Figure 1. This figure is inspired by Boyd Cohen's smart city wheel (ref: http://www.smart-circle.org/smartcity/blog/boyd-cohen-the-smart-city-wheel) which is well known among the smart cities advocates. The wheel consists of three rings, each divided into three parts. The inner ring represents the three dimensions, i.e., transportation, environment and community health, respectively. The intermediate ring lists the criteria for each dimension. The criteria shown in Figure 1, under the dimensions of transportation, environment and community health are the same as the criteria in Tables 1, 5 and 7 respectively. The outer ring is supposed to show all the indicators under each criteria. Because there are too many indicators than the space permitted, readers are directed to refer to the indicators already appeared in Tables 1, 5 and 7.

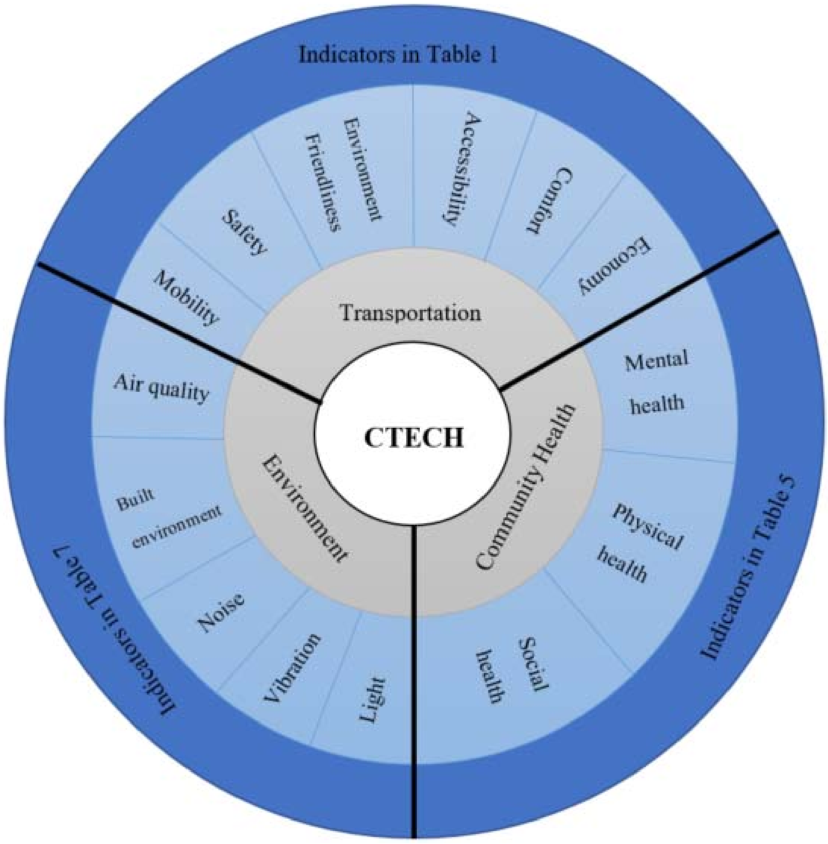

Figure 1 Transportation, environment and community health Wheel

3 CONCEPT MAP

A concept map is a graphical presentation that helps to organize and represent knowledge of a subject. It is used to organize ideas, show relationships, generate questions about the subject, and more. Given a subject, the key concepts (and vocabulary) that relate to the subject are identified, ranked in order from general concepts to specific concepts. Any two concepts are then connected by creating one or several directional links with phrases and words that describe the relationships. In the end, a concept map looks like a directed graph with nodes and one-directional links that represent the knowledge, concept and vocabulary and their relationship about a particular subject.

Figure 2 shows the concept map that was developed to illustrate the findings in Chapter 2. This concept map was developed by means of Visual Understanding Environment or VUE (ref: http://vue.tufts.edu/). The concept map has three boxes in the center that represents the three dimensions. Each dimension is surrounded by its criteria (as listed in Tables 1, 5 and 7). Figure 2 does not include the indicators as doing so will make the concept map too complicated to be visually appealing. In addition, the concept map also uses one-directional arrows to shows the influence of one criterion to another criterion. The arrows are drawn based on the relationships as discussed in Tables 8 to 11. Obviously, there are relationships between the indicators of the same criterion (in reverse), indicators between two criteria of the same dimension or between two dimensions. These are at a lower level and have too many relationships to be analyzed.

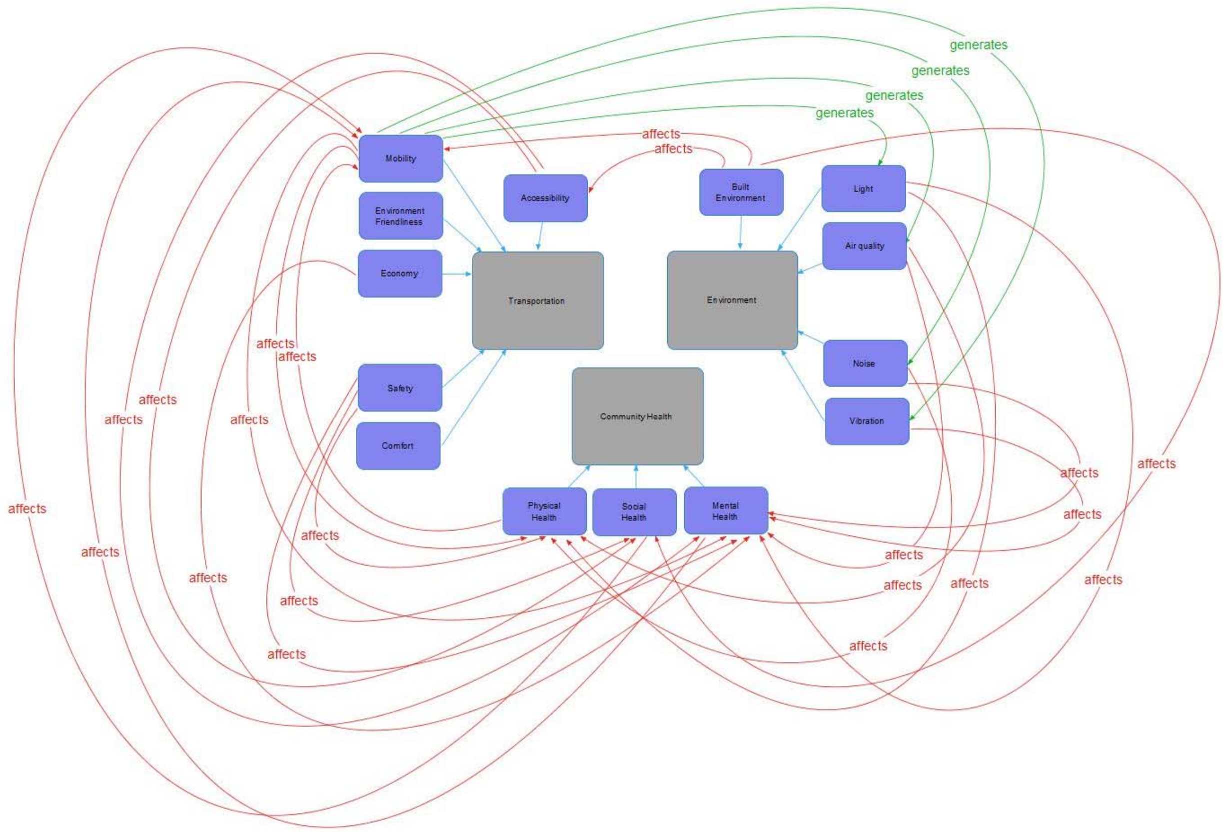

Figure 2 Initial concept map

4 PROPOSED METRICS

The metrics of transportation, environment and community health have been constructed based on the findings of the literature review in Chapter 2. The proposed metrics of transportation, environment and community health are shown in Tables 12, 13 and 14 respectively. In each table, the criteria, indicators as well as unit of measures are shown.

Table 12, the proposed metric of transportation, was taken from the criteria, indicators and unit of measures in Table 1, and then by removing the two following indicators:

- The Comfort indicator was removed because it has no practical way of measurement other than user surveys.
- The Environment friendliness indicator was deleted because it was already used as one dimension.

Table 13, the proposed metric of environment, is the same as Table 5.

Table 14, the proposed metric of community health, was modified from Table 7. The following criterion and indicators were dropped from the list with the reasons given:

- The mental health criterion was removed because its only indicator (poor mental health days) was impractical to measure unless one asks the participants to do self-reports.
- Two physical health indicators, namely poor physical health days and physical inactivity were impractical to measure, like the mental health indicator.
- Another physical health indicator, $PM_{2.5}$ was deleted because it was already included in the metric of environment.

In the end, Table 14 has only two criteria, both consists of indicators which may be found in medical, labor or transportation statistics maintained by federal or state agencies.

Table 12 Proposed metric for transportation

Proposed metric of transportation		
Criterion	**Indicator**	**Unit of measure**
Mobility	Average travel time	minutes
	Average speed	mph
	Average delay	sec/person, sec/veh
	Level of service	A, B, C, D, E, F
	Vehicle-miles traveled	vehicle-miles/day
	No. of congested hours per day	hours/day
	Travel time reliability	
	Ridership	person-trips/day
	Number of transfers	person-trips/day
	Service hours	hours/day
	Average service headway	minutes
	Service coverage area	mi^2 or % of area
Safety	No. of crashes per year	See column on the left
	No. of injuries per year	
	No. of fatalities per year	
	No. of crashes/100000-population/year	
	No. of injuries/100000-population/year	
	No. of fatalities/100000-population/year	
	No. of crashes/million-vehicles/year	
	No. of injuries/million-vehicles/year	
	No. of fatalities/million-vehicles/year	
	No. of crashes/million-VMT/year	
	No. of injuries/million-VMT/year	
	No. of fatalities/million-VMT/year	
Accessibility	No. of opportunities with a fixed travel time budget	hours/day
	Availability of opportunities	number/day
	No. of transportation modes	
	Service hours	hours/day
	Average service headway	minutes
	Average trip cost	$
Economy	Total project cost	$
	Total operating and maintenance cost	$/year
	Total energy cost	$/year
	Total revenue	$/year

Table 13 Proposed metric of environment

	Proposed metric of environment	
Criterion	Indicator	Unit of measure
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm mg/m^3 ppm mg/m^3 mg/m^3 ppb
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit $\leq$ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)
Vibration	Peak particle velocity, PPV	mm/sec or in/sec
Light	Illuminance	lm/m^2 or lm/ft^2
Built environment	Residential density Job density Entropy index Dissimilarity index	$persons/mi^2$ $persons/mi^2$

Table 14 Proposed metric of community health

Proposed metric of community health		
Criterion	Indicator	Unit of measure
Physical health	Death before 75 Low birthweight Poor or fair health Adult obesity	no. of deaths % live birth % population % population
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality no. per 100,000 population yes/no (project specific)

With the proposed metrics for transportation, environment and community health in Tables 12, 13 and 14 respectively, the concept map was updated and it is shown in Figure 3.

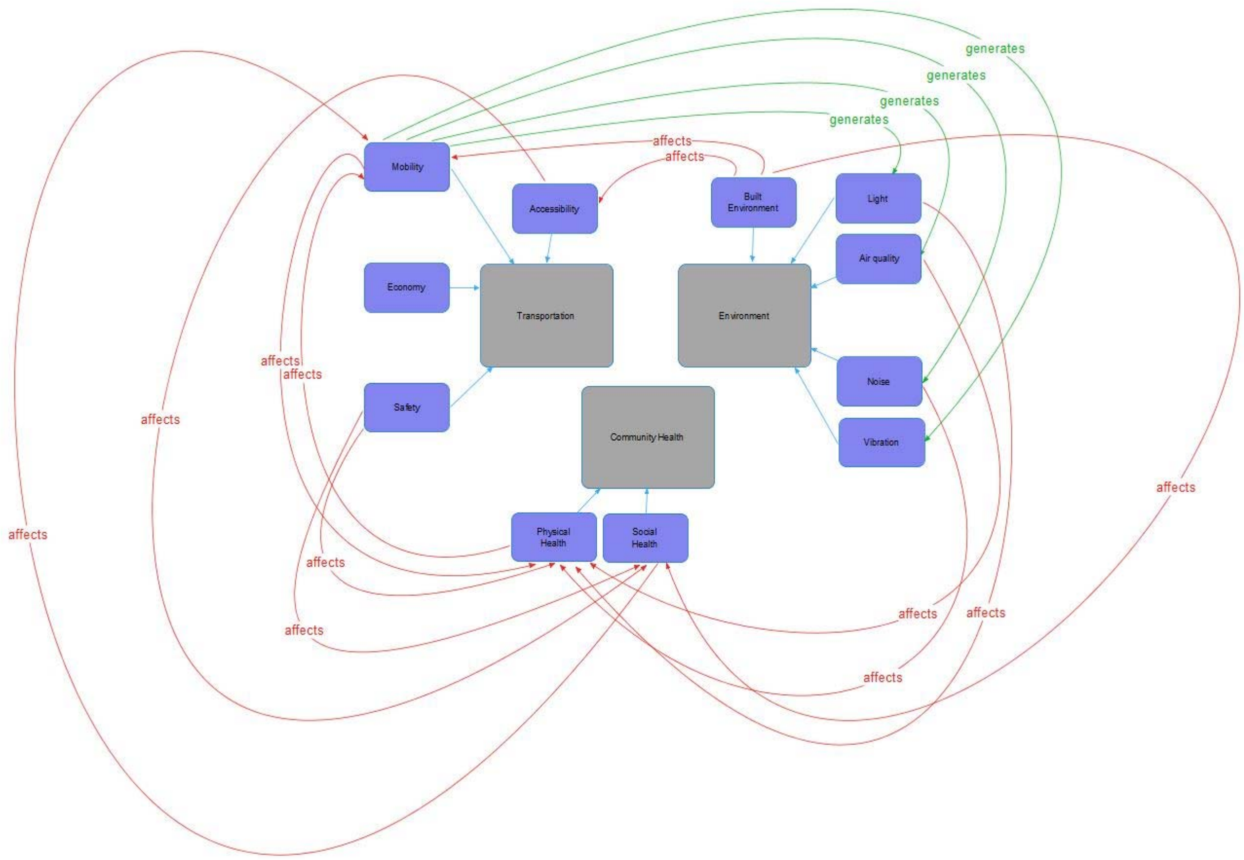

Figure 3 Revised concept map

5 STAKEHOLDER INTERVIEWS

5.1 Interview Implementation

After the initial metrics and concept map had been proposed in Chapter 4, feedbacks from stakeholders were gathered to improve the metrics and the concept map. The feedbacks were obtained by a series of interviews conducted between October 17, 2017 and October 27, 2017, in the participants' offices. The participants of the interviews were:

- A senior planner at El Paso Metropolitan Planning Organization (El Paso MPO)
- A planner at El Paso MPO
- A sustainability program specialist in the City of El Paso
- A project manager at Texas Department of Transportation (TxDOT) El Paso District
- A planner-project engineer at TxDOT El Paso District
- An environmental coordinator at TxDOT El Paso District
- A researcher with expertise in air quality monitoring in UTEP
- A researcher with expertise in health-environment interactions in UTEP
- A researcher with expertise in health inequality and environmental justice in UTEP

A follow-up interview was made with a senior officer of Paso del Norte Health Foundation on January 17, 2018. The information learned from this interview have been incorporated in this chapter.

During each interview, the stakeholder participant was presented with the metrics and concept map, after a description on the background of the project. An interview form with a list of questions was asked so the comments were solicited in a structured way. The survey form can be found in the Appendix. The participants either filled up the forms themselves, or the interviewers (authors) recorded their comments on the survey form based on the answer given verbally. The feedbacks obtained from the participants were organized by questions and the origin responses are transcribed below without personal identifier. Not all the participants answer every questions. All of them answered the questions which their expertise existed.

5.2 Questions Asked and Feedbacks Received

<u>Question 1</u>

Question: *Table A-1* (in the interview form, which is Table 12 in Chapter 4 of this report) *shows the selected criteria, and selected indicators for transportation. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

Answers:

- El Paso MPO has a list of measures used to evaluate projects that involve four types of trips by all modes: (1) trips within a community; (2) between two communities; (3) from a community to the region; and (4) between regions. For example, in a new highway construction project, a community may be defined as the areas divided by the new highway. The trips between communities may be trips across the highway. The trips from the community to the region refer to trips from the local area to anywhere within the metropolitan area. The trips between two regions are inter-metropolitan trips. The measures are:

National goal	Measure
Safety	5-year rolling crash rates Total fatality, serious injury
Congestion reduction	Peak hour excessive delay per capita % Non-SOV (Single Occupancy Vehicle) travel
System reliability	% Person-miles traveled on network that are reliable
Freight movement & economic vitality	Truck travel time reliability index
Environmental sustainability	% Change in CO_2 Emissions on NHS (National Highway System)

- The only mobility measures that we are obtaining from the Travel Demand Model and will be reported in the Metropolitan Transportation Plan are: speed index, annual hours of delay and commute times from environmental Justice.

Question 2

Question: *Table A-2* (in the interview form, which is Table 13 in Chapter 4 of this report) *shows the selected criteria, and selected indicators for environment. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

Answers:

- The six NAAQS criteria pollutants are listed correctly. Instead of measuring O_3, you may use its pre-cursors, i.e., VOC (Volatile Organic Compound) and NO_2 which react in photo-chemical process to produce O_3. The unit for Pb and PM are $\mu g/m^3$.
- El Paso MPO only reports to TxDOT CO_2, O_3 and PM_{10}. These three compounds are non-attainment or marginal in the El Paso area.
- For lighting standard, check the New Mexico Department of Transportation website. It may have some guidelines already posted. In two-hour drive east of El Paso there is the McDonald Observatory. The staff can give an idea of the threshold of light pollution. The freeway rest area has lighting restriction because of that.

Question 3

Question: *Table A-3* (in the interview form, which is Table 14 in Chapter 4 of this report) *shows the selected criteria, and selected indicators for community health. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

Answers:

- Obtaining statistics of mental health is not an issue. Mental health statistics are available at
  - Texas Health and Human Services' Behavioral Risk Factor Surveillance System at http://dshs.texas.gov/chs/brfss/query/brfss_form.shtm, and
  - Texas Healthcare Information Collection at http://dshs.texas.gov/thcic. There is a subset of "research data file", which lists data by zip code.

- Public involvement may use the number of public meetings, and number of public hearings as well.
- We recommended you to contact TxDOT El Paso District.
- You may contact Paso del Norte Health Foundation and other internet resources below:
  International
    - http://www.cedar.iph.cam.ac.uk/research/modelling/ithim/
    - http://content.tfl.gov.uk/healthy-streets-for-london.pdf
    - https://tfl.gov.uk/corporate/about-tfl/corporate-and-social-responsibility/transport-and-healthcare
    - http://www.heatwalkingcycling.org/

  National
    - https://www.cdc.gov/nccdphp/dch/pdf/HealthEquityGuide.pdf
    - https://www.surgeongeneral.gov/library/calls/walking-and-walkable-communities/index.html
    - https://www.nap.edu/catalog/24624/communities-in-action-pathways-to-health-equity
    - https://health.gov/paguidelines/
    - http://www.humankinetics.com/products/all-products/implementing-physical-activity-strategies
    - https://chronicdata.cdc.gov/
    - http://www.chronicdisease.org/
    - https://livabilityindex.aarp.org/
    - https://www.cdc.gov/healthyplaces/transportation/hia_toolkit.htm
    - https://www.planning.dot.gov/documents/Volpe_FHWA_MPOHealth_12122012.pdf
    - https://www.fhwa.dot.gov/publications/publicroads/13mayjun/05.cfm
    - https://www.planning.dot.gov/Documents/Health/IntHealthTA.htm
    - https://www.transportation.gov/mission/health/Integrate-Health-and-Transportation-Planning
    - http://www.saferoutespartnership.org/sites/default/files/pdf/The_Final_Active_Primer.pdf

  MPO resources
    - https://metroplanorlando.org/programs-resources/health-transportation/
    - https://www.psrc.org/sites/default/files/t2040update2014appendixo_0.pdf
    - https://www.psrc.org/sites/default/files/acg.pdf
    - https://www.psrc.org/sites/default/files/compilations_final_final.pdf
    - http://www.ctps.org/data/html/studies/bikeped/pedestrian_level_of_service.html
    - http://www.nashvillempo.org/regional_plan/health/
    - http://t4america.org/healthy-mpos/
    - http://t4america.org/maps-tools/healthy-metros/
    - http://t4america.org/maps-tools/mpo-case-studies/
    - http://t4america.org/2016/06/22/introducing-planning-for-a-healthier-future/

  Local
    - https://www.elpasotexas.gov/~/media/files/coep/public%20health/community%20health%20assessment%20final%20report.ashx?la=en
    - https://www.umcelpaso.org/get-file.php?class=Document&id=300
    - http://www.pdnhf.org/who_we_are/initiatives/pdn-county-to-county-trail

Question 4

Question: *Figure A-1* (in the interview form, which is Figure 3 in Chapter 4 of this report) *is a concept map which shows the relationship between the criteria and indicators. Do you think any other relationships should be added? If so, please explain your reason.*

Answers:
- There should be many arrows to and from [Economy], [Environment friendliness], and [Build environment].
- [Accessibility] has influence on the [Built environment], because a neighborhood may be deigned to be accessible by public transportation, or to achieve a level of accessibility measure.

Question 5

Question: *Please share with us any comment you have concerning the linkages between transportation, environment, and community health.*

Answers:
- The El Paso MPO is training a planner to use EPA's MOVES to estimate emissions due to transportation projects. Right now emission estimation is done by giving TransCAD data and outputs (such as Vehicle-Miles Traveled or VMT) to TxDOT Austin Office. TxDOT Austin Office then contracts Texas A&M Transportation Institute (TTI) in College Station, Texas, to run MOVES. TxDOT only requires air quality indicators from MOVES outputs. TxDOT does not requires MPO to estimate noise, light, and vibration.
- For the case study, one candidate is the Montana corridor improvement. The segment of Montana between Global Reach to the Tierra Este is to be widen. MPO has the EIA report with data that can be used.
- One possible road project for the case study is the Farm to Market Road FM1281 in the town of Horizon City. This project is in the planning stage, and FHWA wants community health to be part of environmental impact assessment. However, this is a specific case. TxDOT is able to let the UTEP researchers know about the FHWA's specific requirement.
- The indicators should be aggregated statistics. Furthermore, it should be already collected and made available by public agencies in the city, county, state or national levels, upon request for research purposes.
- There is a trend that "public health" refers to infrastructure that promote healthy living. This include facilities to promote active transportation, medical care, law enforcement, emergency response, restaurant inspection, parks & recreation systems. Some of the data is not easy to obtained.

5.3 Follow-Up Actions

Based on the feedbacks obtained from the stakeholder interviews, the following responses were noted and if possible, actions were taken to modified the metrics and the concept map:

Question 1

- Five-year rolling crash rate, in crashes/year, is already an indicator in Table 12.
- Total fatality and serious injury is not a good measure compared to the rate per 100000-population per year, per million vehicles per year and per million-VMT per year.
- Peak hour excessive delay per capita is not as good as the average delay per vehicle. The latter is easier to compute or measure.
- Percent non-SOV is related to vehicle reduction and has impact on the environment criteria. This is added as a mobility indicator but is expressed as % HOV (High Occupancy Vehicles).
- System reliability is measured by % person-miles traveled on network that are reliable. FHWA's guidelines to estimate travel time reliability is available at https://www.fhwa.dot.gov/tpm/rule/pm3/reliability.pdf. It uses recorded travel times not estimated or projected travel time that can be obtained from a regional planning (e.g., TransCAD) model. This is the reason why MPO did not selected this measure as one of the measures for the development of the metropolitan transportation plan. However, given that travel time reliability is a mobility indicator heavily promoted by FHWA, it is still included in the list.
- Again, truck travel time reliability index is a mode specific part of travel time reliability Table 12.
- Environmental sustainability was not added to Table 12 because environmental friendliness has been removed and designated as a dimension.
- Speed index is the ratio of speed during congested hour to free-flow speed. This indicator was added to mobility criteria. Annual hours of delay is equivalent to average delay. Commute times are equivalent to travel times.

Question 2

- The unit for Pb and PM were changed to $\mu g/m^3$.
- Since O_3 is officially one of NAAQS criteria pollutants, it was kept in the list and not changed to VOC and NO_2.
- The authors searched the New Mexico Department of Transportation website and could not find any stand or specification on roadway or parking lot lighting.
- In two-hour drive east of El Paso there is the McDonald Observatory. The staff can give an idea of the threshold of light pollution. The freeway rest area has lighting restriction because of that.

Question 3

- Since statistics of mental health (% population with equal to or greater than 5 days of poor mental health) is available at the state agency's website, this criterion is restored with a new indicator stated here.
- For public involvement criteria, instead of using yes/no public meeting, the indicator was changed to number of public meetings and hearings.
- The authors visited Paso del Norte Foundation and was informed that it focused on sponsored activities like nutrition education, tobacco and alcohol use education. There is insufficient data, in terms of spatial coverage and frequency, for computation of indicators. The websites in the

list have been visited but no new information was found that can be added to the existing criteria and indicators.
- The McDonald Observatory, being an observatory, has strict restriction on the surrounding ambient light level. The lighting standard cannot be applied to public highways.

Question 4

- The arrows have been updated in the concept map.

Question 5

- The authors followed up with TxDOT on the FM1282 project and was informed that specific detail of community health requirement has not been provided by FHWA. However, public meetings will be held in early 2018. At that time, more information will be available.
- The distinction between "public health" and "community health" was consistent with the discussion in Sub-Section 2.3.1.

All the changes described above, based on the outcomes of the stakeholder interviews, were implemented. The revised metrics and concept map are presented in Chapter 6.

6 REVISED METRICS AND CONCEPT MAP

This chapter presents the revised metrics of transportation, environment and community health in Tables 15, 16 and 17 respectively. It also presents the revised concept map in Figure 4. The revisions were based on the findings of the stakeholder interviews conducted in Chapter 5.

Table 15 Revised metric for transportation

Revised metric of transportation		
Criterion	**Indicator**	**Unit of measure**
Mobility	Average travel time	minutes
	Average speed	mph
	Average delay	sec/person, sec/veh
	Level of service	A, B, C, D, E, F
	Vehicle-miles traveled	vehicle-miles/day
	Percent HOV	percent
	Speed index	
	No. of congested hours per day	hours/day
	Travel time reliability	
	Ridership	person-trips/day
	Number of transfers	person-trips/day
	Service hours	hours/day
	Average service headway	minutes
	Service coverage area	mi^2 or % of area
Safety	No. of crashes per year	See column on the left
	No. of injuries per year	
	No. of fatalities per year	
	No. of crashes/100000-population/year	
	No. of injuries/100000-population/year	
	No. of fatalities/100000-population/year	
	No. of crashes/million-vehicles/year	
	No. of injuries/million-vehicles/year	
	No. of fatalities/million-vehicles/year	
	No. of crashes/million-VMT/year	
	No. of injuries/million-VMT/year	
	No. of fatalities/million-VMT/year	
Accessibility	No. of opportunities with a fixed travel time budget	hours/day
	Availability of opportunities	hours/day
	No. of transportation modes	
	Service hours	hours/day
	Average service headway	minutes
	Average trip cost	$
Economy	Total project cost	$
	Total operating and maintenance cost	$/year
	Total energy cost	$/year
	Total revenue	$/year

Table 16 Revised metric of environment

Revised metric of environment		
Criterion	Indicator	Unit of measure
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm μg/m^3 ppm mg/m^3 μg/m^3 ppb
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit ≤ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)
Vibration	Peak particle velocity, PPV	mm/sec or in/sec
Light	Illuminance	lm/m^2 or lm/ft^2
Built environment	Residential density Job density Entropy index Dissimilarity index	persons/mi^2 persons/mi^2

Table 17 Revised metric of community health

Revised metric of community health		
Criterion	Indicator	Unit of measure
Physical health	Death before 75 Low birthweight Poor or fair health Adult obesity	no. of deaths % live birth % population % population
Mental health	Percent population with ≥5 days of poor mental health	% population
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality no. per 100,000 population yes/no (project specific)

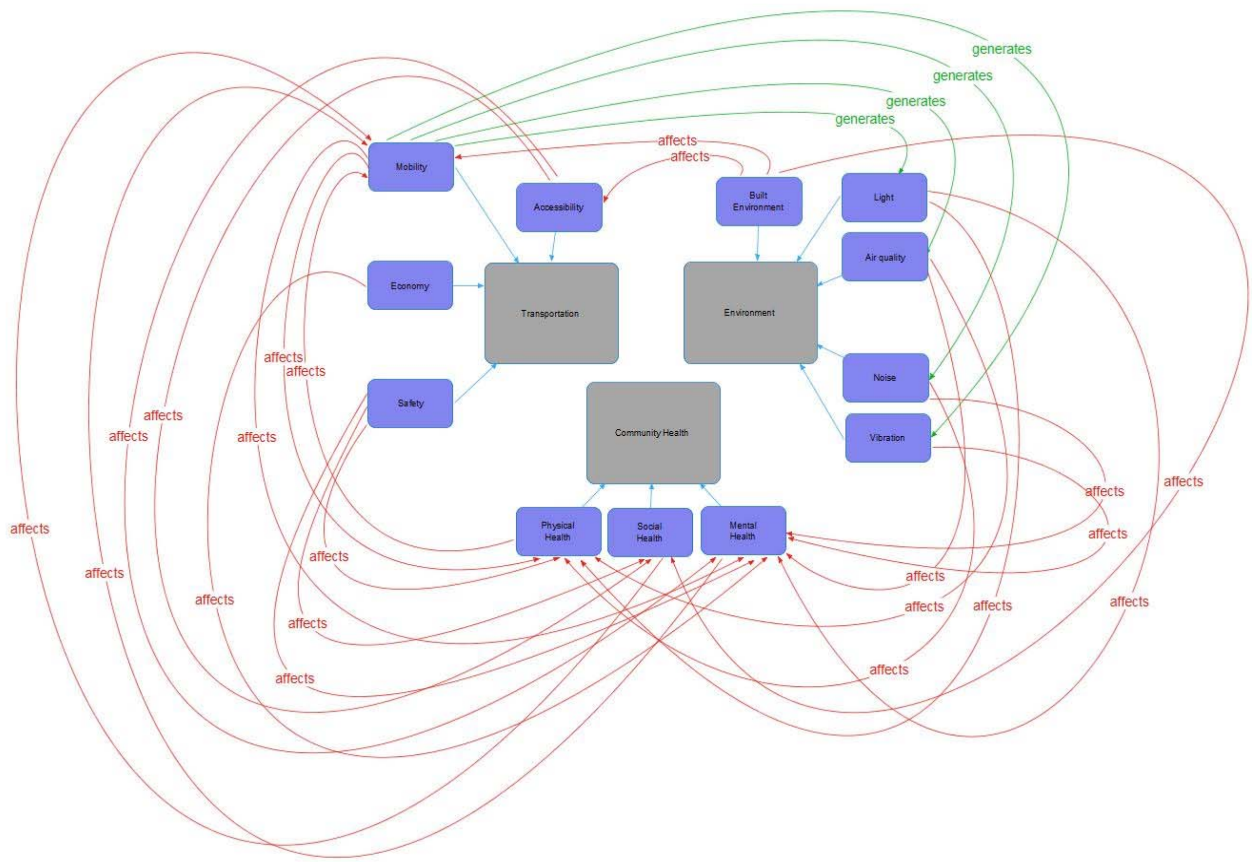

Figure 4 Revised concept map

7 CASE STUDIES

7.1 Purpose

The purpose of this chapter is to illustrate how to the proposed metrics and concept map may be applied to transportation projects. Two projects of different characteristics were recommended by the Texas Department of Transportation (TxDOT) El Paso District, and Sun Metro (the transit operator which is part of the City of El Paso). They are:

- Case Study 1: Loop 375 Transmountain West
- Case Study 2: Alameda Corridor Bus Rapid Transit (BRT)

Case Study 1 is a typical TxDOT highway project that expands the capacity of Transmountain Road. Case Study 2 is a project initiated by the city that adds a transit service along a major corridor in the city. At the time of writing, the project in Case Study 1 is near completion, and the new lanes and interchanges have been opened to traffic. For Case Study 2, most of the street improvements have been completed or are in progress, and bus service is yet to commence. These projects were recommended by the respective agencies to avoid the possibility of these case studies in influencing the project implementations. It is important to note that the metrics and concept map proposed in this research may be applied at any phase in a project. However, the research team recommends that these tools be applied as early into a project as possible, and the metrics and concept map revised periodically (e.g., when an indicator is added or removed, or when new data become available).

In each of the following case study, the background of the proposed project is first introduced. The available project data are then presented. The metrics and concept map with the organized data are then showed. For each project, examples of what engineers or planners may learn from the applied metrics and concept map are suggested.

7.2 Case Study 1

7.2.1 Background

The TxDOT EI Paso District has proposed improvements to Loop 375, a state highway, from the Interstate Highway 10 (I-10) interchange to 0.479 mile east of the Tom Mays Unit of the Franklin Mountains State Park. The project is known as Loop 375 – Transportation West (TxDOT, Loop_375, 2017). The proposed improvements include the following components:

- Converting the two-lane undivided highway into a four-lane divided highway with frontage roads;
- Converting two at-grade priority intersections into interchanges;
- Add a direct connector from westbound of Loop 375 to eastbound of I-10;
- Add a direct connector from westbound of I-10 to eastbound of Loop 375;
- Add a bicycle-and-hiking trail along Loop 375.

The project location is shown in Figure 5. The project boundary is shown in Figure 6. This project is 100% funded by the State of Texas at an estimated cost of $98.5 million.

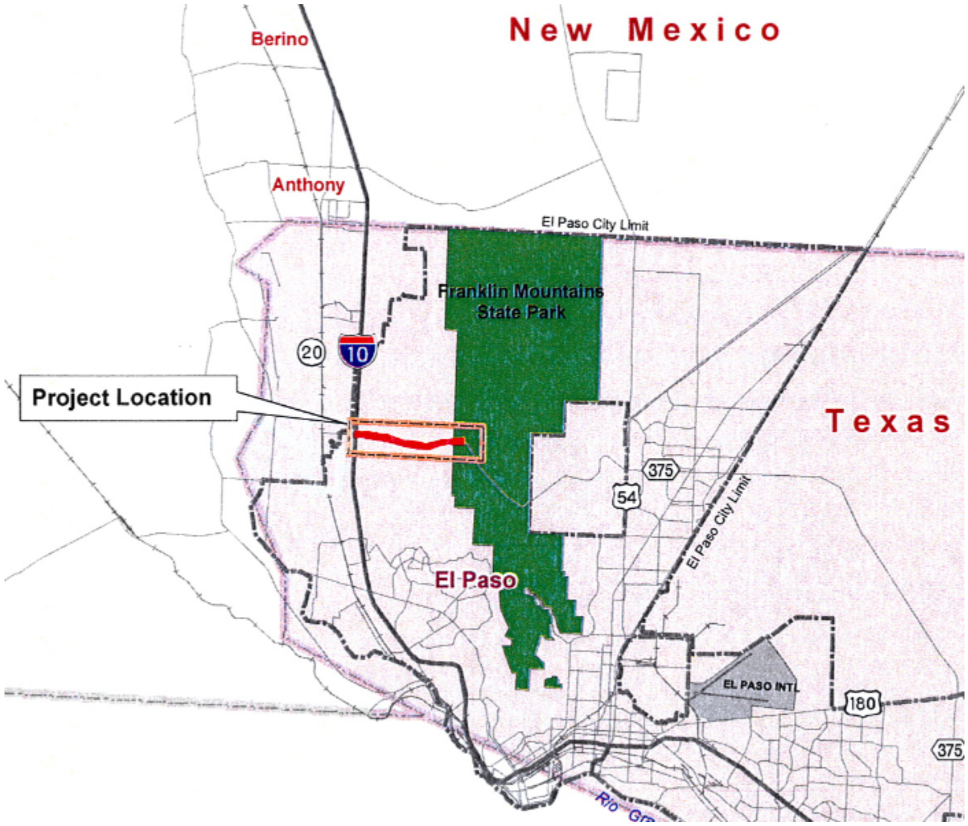

Figure 5 Project location of Case Study 1 (from TxDOT (2017))

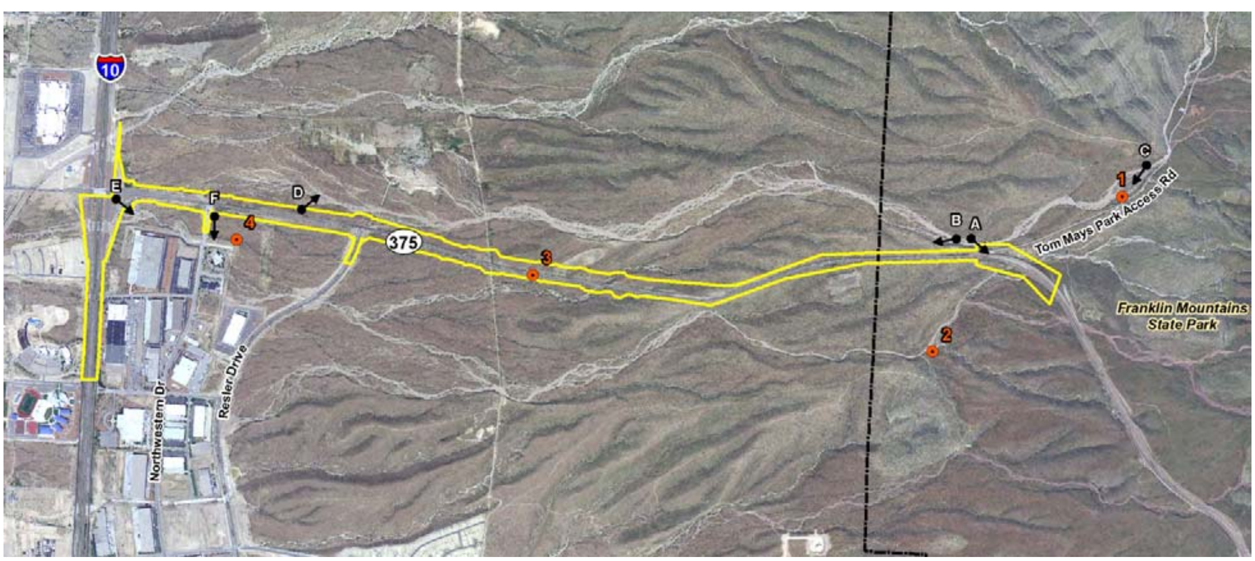

Figure 6 Project boundary of Case Study 1 (from TxDOT (2017))

The environmental impact assessment was documented in TxDOT (2011). The Federal Highway Administration (FHWA) determined that this project would not have a significant impact on the human or natural environment (FHWA, 2011). These two reports were used as the main sources of data for the case study.

7.2.2 Project Data

The data extracted from the Environmental Assessment report (TxDOT, 2011) and the Finding of No Significant Impact report (FHWA, 2011) were summarized below. Both reports used year 2015 as the base year, and 2035 as the horizon year.

Traffic projection:

- Average annual daily traffic (AADT) in 2015 = 40,000 veh/day on Transmountain Rd
- Average annual daily traffic (AADT) in 2035 = 71,000 veh/day on Transmountain Rd
- City wide mode share: auto=93.5%, transit= 2.5%, bicycle=0.8%, walking=3.2%
- Revised AADT in 2015 = 22,100 veh/day, with 4.2% trucks
- Revised AADT in 2035 = 33,200 veh/day, with 4.2% trucks

Traffic operations:

The estimated performance measures for the year 2035 with no build and build alternatives are listed in Table 18. These statistics were based on the original AADT estimate. The travel time and speed estimates were calculated along the Transmountain Road, from one end of the project boundary to another end of the project boundary.

Table 18 Transportation performance measures for Case Study 1 in 2035

Performance measures in 2035	No build	Build	Improvement
Average travel time, minutes	30.2	7.5	22.7
Average speed, mph	13	34	21
Intersection level of service (LOS)	F	A to E	1 to 5 levels
Corridor level of service (LOS)	F	Eastbound C Westbound F	0 to 2 levels
Average maximum queue length at intersection, ft	1,429	425	1004
No. of conflict points per intersection	16	5 to 9	7 to 11

Air quality:

- Traffic Air Quality Analysis (TAQA) for CO was not conducted because the projected AADT in year 2035 was less than the threshold of 140,000 vehicles/day required by the State of Texas.
- Mobile Source Air Toxic (MSAT) Analysis was not conducted because the projected AADT in year 2035 was less than the threshold of 140,000 vehicles/day required by the State of Texas.

- PM_{10} Hot Spot Analysis was not performed because the Consultative Partners (MPO, EPA, TCEQ, FHWA) jointly determined that the project is not of local air quality concern, based on the fact that the projected AADT was less than 125,000 vehicles/day, and less than 8% of the vehicles were trucks.

Traffic noise:

Traffic noise levels in 2035 were estimated at two spots within the project boundary:

- At Receiver 1: L_{eq} will be reduced from 61 dBA in from no build to 55 dBA with build;
- At Receiver 2: L_{eq} will be reduced from 50 dBA in from no build to 48 dBA with build;
- The project will not increase the traffic noise level;
- However, there will be an increase of 3 dBA caused by new housing development that will be associated with the highway capacity expansion. A 3 dBA increase is barely perceptible to the human ear.

Public involvement:

- The project team maintained a website that provided frequently updated information to the public;
- Many stakeholder meetings have been held during the project planning phase;
- One public meeting and one public hearing were held during which many feedbacks were received, documented, and responded.

Cost:

The total project cost was $98,473,449 (2011 dollars).

7.2.3 Metrics

The above data were organized into Tables 19, 20 and 21, the metrics of transportation, environment and community health, respectively. It was assumed that the analyst was interested in the traffic, environmental and health condition arising from this project in 2035, therefore, only the 2035 data were transferred into the metrics.

Table 19 Revised metric of transportation for Case Study 1

Metric of transportation			
Criterion	Indicator	Unit of measure	Value
Mobility	Average travel time	minutes	7.5
	Average speed	mph	34
	Average delay	sec/person, sec/veh	--
	Level of service	A, B, C, D, E, F	A to F
	Vehicle-miles traveled	vehicle-miles/day	--
	Percent HOV	percent	--
	Speed index		--
	No. of congested hours per day	hours/day	--
	Travel time reliability		--
	Ridership	person-trips/day	--
	Number of transfers	person-trips/day	--
	Service hours	hours/day	--
	Average service headway	minutes	--
	Service coverage area	mi^2 or % of area	--
Safety	No. of crashes per year		--
	No. of injuries per year		--
	No. of fatalities per year		--
	No. of crashes/100000-population/year		--
	No. of injuries/100000-population/year		--
	No. of fatalities/100000-population/year		--
	No. of crashes/million-vehicles/year		--
	No. of injuries/million-vehicles/year		--
	No. of fatalities/million-vehicles/year		--
	No. of crashes/million-VMT/year		--
	No. of injuries/million-VMT/year		--
	No. of fatalities/million-VMT/year		--
Accessibility	No. of opportunities with a fixed travel		--
	time budget	hours/day	--
	Availability of opportunities		--
	No. of transportation modes		--
	Service hours	hours/day	--
	Average service headway	minutes	--
	Average trip cost	$	--
Economy	Total project cost	$	98.5 mil
	Total operating and maintenance cost	$/year	--
	Total energy cost	$/year	--
	Total revenue	$/year	--

Table 20 Revised metric of environment for Case Study 1

Metric of environment			
Criterion	Indicator	Unit of measure	Value
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm $\mu g/m^3$ ppm mg/m^3 $\mu g/m^3$ ppb	-- -- -- -- -- -- --
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit $\leq$ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)	-- -- -- 48, 55 --
Vibration	Peak particle velocity, PPV	mm/sec or in/sec	--
Light	Illuminance	lm/m^2 or lm/ft^2	--
Built environment	Residential density Job density Entropy index Dissimilarity index	$persons/mi^2$ $persons/mi^2$	-- -- -- --

Table 21 Revised metric of community health for Case Study 1

Metric of community health			
Criterion	Indicator	Unit of measure	Value
Physical health	Death before 75 Low birthweight Poor or fair health Adult obesity	no. of deaths % live birth % population % population	-- -- -- --
Mental health	Percent population with ≥5 days of poor mental health	% population	--
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality no. per 100,000 population yes/no (project specific)	-- -- yes

7.2.4 Concept Map

The criteria in the metrics (Tables 19, 20, and 21) that have indicator measures had been identified in the concept map. From the identified criteria, the outgoing arrows were highlighted in bold and they are shown in Figure 7. For example, in the mobility criterion, three indicators (average speed, average travel time, level of service) already had the other values estimated in the project report. Using this values, we may be able to estimate the impacts of the transportation project on light, air quality noise, and vibration criteria under the environment dimension. In addition, data on the noise indicator under the environment criterion have been found. These need to the possibility of using noise level to estimate is impacts on physical health criterion and the mental health criterion under the community health dimension. On the other hand, the total project cost is reported as an indicator under the economic criterion as part of the transportation dimension. Based on this we can highlight the arrow that collects the economy criterion under the transportation dimension to the mental health criterion under the community health dimension. Another criterion in the transportation dimension that can impact community health dimensions is accessibility. Figure 7 highlights the arrows that illustrate the impact of accessibility criterion may have on social and physical health of a community.

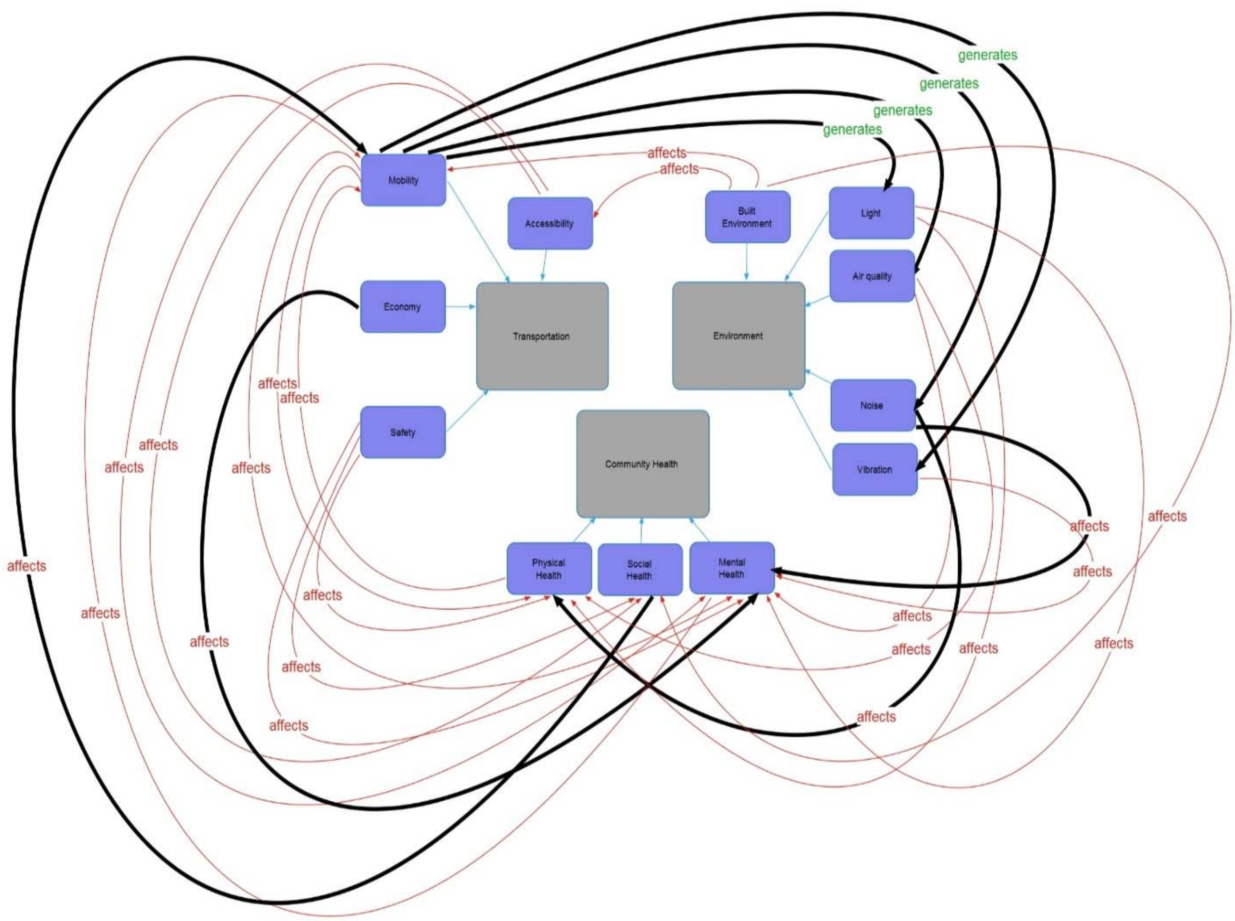

Figure 7 Concept map of Cases Study 1

7.2.5 Discussions

This sub-section discusses the potential applications of the metrics and concept based on what have been developed in Case Study 1.

Missing indicators

The first obvious thing to observe is not every indicator has a value. For this case study, the missing indicator values in the metrics were not found in the project documents. One of the reasons was that the analysis, such as air quality analysis, was not mandated by laws. Another reason may be these are not parts of the project specification, and these considerations were not important factors for the project.

When an analyst observes the metrics, he/she can immediately visualize what indicator values are missing, or which criterion has few values or no value at all. The metric can be used as check list against the project requirements. The project team can also compare what are important for the project, with the available criteria and indicator values, and then determine what analysis should be made.

New Indicator

Users may also add one or more dimensions, criteria or indicators to the metrics, if these new dimensions, criteria or indicators are important to the project. Here, Case Study 1 is used to illustrate this application. In Table 19, it is obvious that there is no indicator measure value for the Safety criterion. In this Transmountain West project, one of the most commented safety concerns received by the project team from the public is bicycle and pedestrian access to the Franklin Mountain State Park. Number of conflict points per intersection, as reported in the environmental assessment report (TxDOT 2011), has been used to indicate the safety of the facilities, with and without this project, to the bicyclists and pedestrians. This safety indicator has been added to the metric of transportation in Table 22. Accordingly, the concept map has been updated to the one in Figure 8. The metrics of the environment and community health remain the same.

Incremental Analysis

The metrics presented in Tables 19 to 21 and the concept map in Figure 8 help an analyst to visualize and analyze the transportation, environmental and community health impacts of the project. To perform incremental analysis, i.e., the improvements or negative effects, from no build to build alternatives, the metrics may contain numerical data on changes in indicator values. For example, the incremental metric of transportation is shown in Table 22. Note that, negative values in the table indicate improvements in performance. The metrics of environment and community health have also been updated and they become Tables 23 and 24. The incremental concept map may then be drawn based on the available incremental indicator values in Tables 22, 23 and 24. In this example, the incremental concept map is the same as in Figure 8.

Table 22 Incremental metric of transportation for Case Study 1

Incremental metric of transportation			
Criterion	Indicator	Unit of measure	Incremental value
Mobility	Average travel time	minutes	-22.7
	Average speed	mph	-21
	Average delay	sec/person, sec/veh	--
	Level of service	A, B, C, D, E, F	From F to (A to F)
	Vehicle-miles traveled	vehicle-miles/day	--
	Percent HOV	percent	--
	Speed index		--
	No. of congested hours per day	hours/day	--
	Travel time reliability		--
	Ridership	person-trips/day	--
	Number of transfers	person-trips/day	--
	Service hours	hours/day	--
	Average service headway	minutes	--
	Service coverage area	mi^2 or % of area	--
Safety	No. of conflict points per intersection		-7 to -11
	No. of crashes per year		--
	No. of injuries per year		--
	No. of fatalities per year		--
	No. of crashes/100000-population/year		--
	No. of injuries/100000-population/year		--
	No. of fatalities/100000-population/year		--
	No. of crashes/million-vehicles/year		--
	No. of injuries/million-vehicles/year		--
	No. of fatalities/million-vehicles/year		--
	No. of crashes/million-VMT/year		--
	No. of injuries/million-VMT/year		--
	No. of fatalities/million-VMT/year		
Accessibility	No. of opportunities with a fixed travel		--
	time budget	hours/day	--
	Availability of opportunities		--
	No. of transportation modes		--
	Service hours	hours/day	--
	Average service headway	minutes	--
	Average trip cost	$	
Economy	Total project cost	$	98.5 mil
	Total operating and maintenance cost	$/year	--
	Total energy cost	$/year	--
	Total revenue	$/year	--

Table 23 Incremental metric of environment for Case Study 1

Incremental metric of environment			
Criterion	Indicator	Unit of measure	Incremental value
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm μg/m^3 ppm mg/m^3 μg/m^3 ppb	-- -- -- -- -- -- --
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit ≤ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)	-- -- -- -2, -6 --
Vibration	Peak particle velocity, PPV	mm/sec or in/sec	--
Light	Illuminance	lm/m^2 or lm/ft^2	--
Built environment	Residential density Job density Entropy index Dissimilarity index	persons/mi^2 persons/mi^2	-- -- -- --

Table 24 Incremental metric of community health for Case Study 1

Incremental metric of community health			
Criterion	Indicator	Unit of measure	Incremental value
Physical health	Death before 75 Low birthweight Poor or fair health Adult obesity	no. of deaths % live birth % population % population	-- -- -- --
Mental health	Percent population with ≥5 days of poor mental health	% population	--
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality no. per 100,000 population yes/no (project specific)	-- -- yes

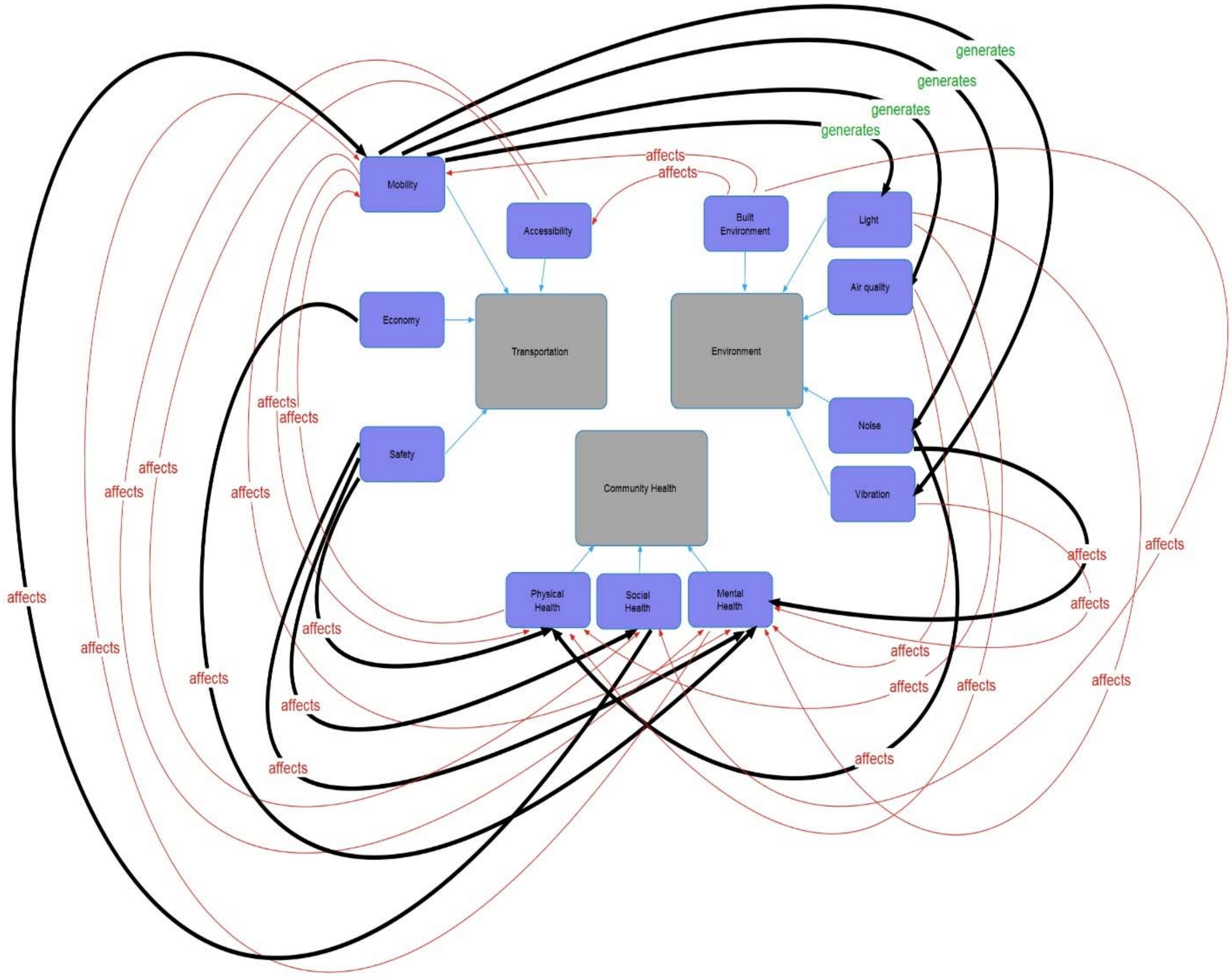

Figure 8 Concept map of Cases Study 1

7.3 Case Study 2

7.3.1 Background

In 2008, the City of El Paso started to plan for a Rapid Transit System (RTS) to complement the regular bus service in the city. The RTS is essentially a basic form of Bus Rapid Transit (BRT) system, where part of the routes runs like regular bus service in mixed traffic. Only portions of the routes have dedicated bus lanes. However, the RTS has a distinct image given by its unique vehicles, bus shelters, fare collection system, and etc. The first RTS route, branded as BRIO, started operating on the first route along Mesa Street in October 2014. The construction and implementation of the second RTS route is in progress. The BRT service on this new route will run mostly along Alameda Avenue, from the downtown towards the east, which is the project of Case Study 2. This project is known officially by the City of El Paso, and its transit department Sun Metro, as the Alameda Corridor RTS project.

The Alameda Corridor refers to the roadway and the surrounding area served by new RTS route of interest, or more specifically the service coverage area. The planned RTS will run along Alameda Avenue between the Downtown Transfer Center (DTC) and Mission Valley Transfer Center (MVTC). Figure 9 shows the two transfer centers with the Alameda Corridor highlighted in light green (currently served by Sun Metro regular bus route 61). This figure also highlights Sun Metro regular bus routes 3, 7, 21, 22, 62, 66 and 204, which have at least one stop along the Alameda Corridor. These regular bus routes have headways that range from 16 to 65 minutes. Riders on 12 other bus routes (routes 4, 23, 24, 25, 42, 55, 60, 63, 65, 67, 69 and 84) may also be affected as these routes cross the Alameda Corridor, providing/attracting potential transfer passengers. The transit network formed by the above 21 routes (proposed BRT plus 20 bus routes) is the study area.

The Alameda Corridor RTS will run between along a 14.5-mile route (in each direction) between DTC and MVTC. There will be 19 stops in each direction (see Figure 10). The vehicles will be 60-feet low-floor articulated buses each with a capacity of 58 sitting and 25 standing passengers. Each vehicle has space for three bicycles and two wheelchairs. Arrival time information will be provided to passengers through in-vehicle screens and digital display panels at the stops. Passengers on board will be able to use free wireless internet. The headway is 10 minutes during the peak period and 15 minutes during the off-peak period. Ticketing machines will be installed at all the stops for off-board fare collection.

The City of El Paso awarded Lockwood, Andrews & Newman Inc. (LAN) which prepared the conceptual engineering, preliminary engineering, final design, and construction phase of this RTS project. The construction work was awarded to Martinez Bros. Contractors, LLC. The infrastructure works included street widening, intersection improvements, landscaping, construction of sidewalk, stations and shelter, illumination, bus priority signals, real-time schedule information; on-platform automated ticket vending and fare collection and purchase of new vehicles that run on CNG. The total project cost is $38.5 million, which is 100% funded by the City. All the constructions are expected to complete in spring 2018 and RTS service will commence in summer 2018.

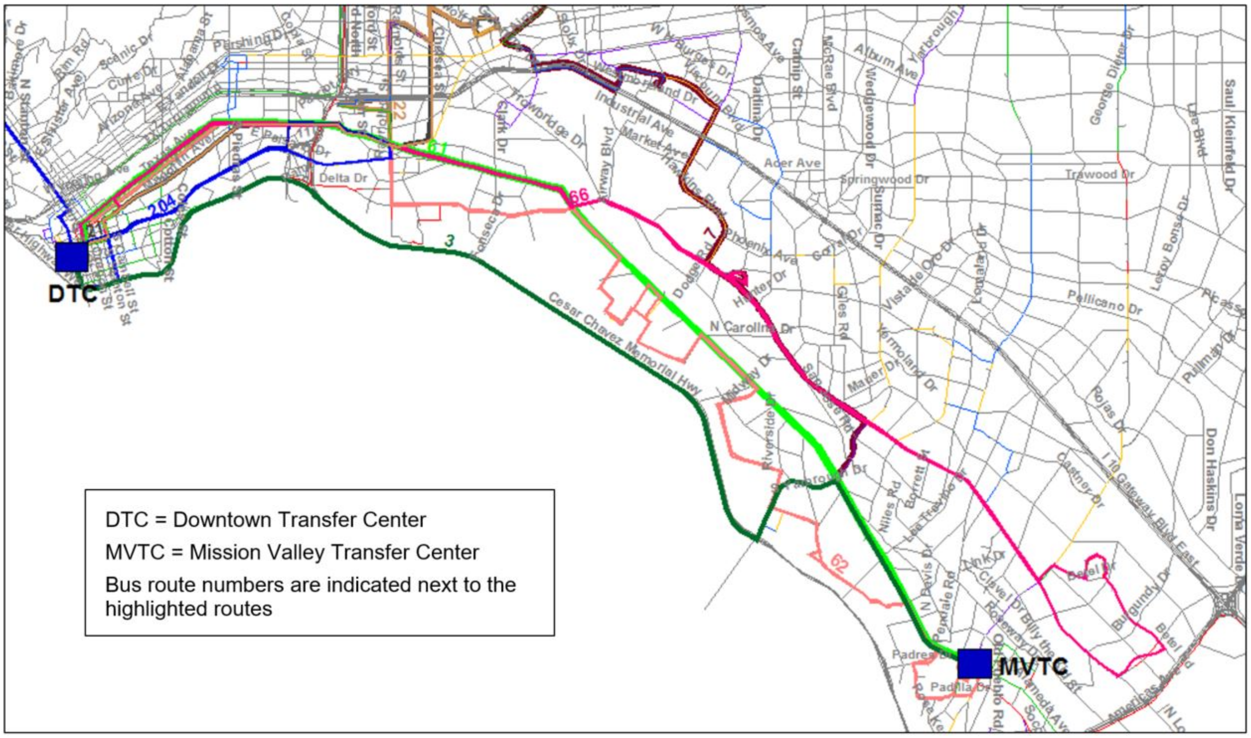

Figure 9 Project area with existing transit routes in Case Study 2

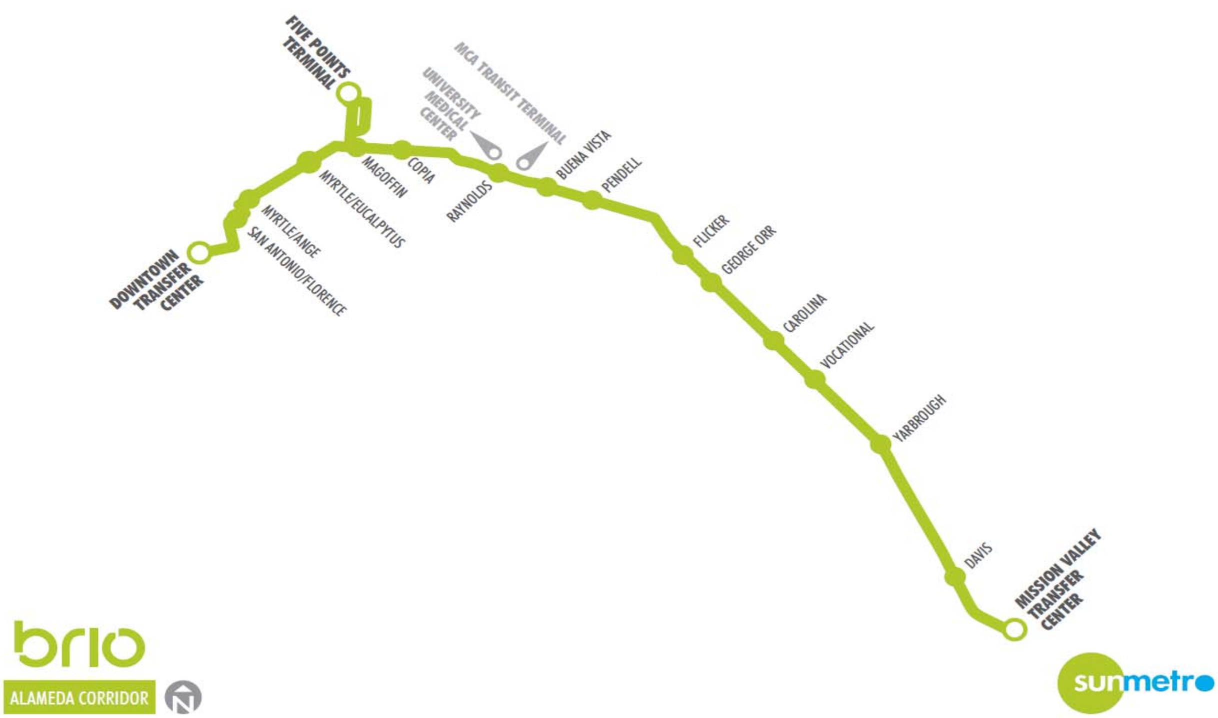

Figure 10 Alameda Corridor BRT stations in Case Study 2

7.3.2 Project Data

Texas Transportation Institute (TTI) was contracted by the City of El Paso to perform alternative RTS design analysis, traffic impacts and ridership estimation (TTI 2010). The alternative analysis was to compare the travel time of buses with no RTS, plus three levels of RTS implementations. Traffic impacts studied the effects of the different levels of RTS implementations on passenger cars travel time, speed, and delay. Ridership estimation predicted the number of trips the RTS will carry in a day. All the forecasts were for the target year of 2015. Umlauf et al. (2016) estimated the daily ridership of this RTS route by after considering (i) new riders who will switch from other modes to RTS; (ii) cancellations and re-routing of existing regular bus service. Their estimates were for year 2016. These two reports were the main sources of data for the metrics and concept map. Other data were taken from the official Sun Metro BRIO website (City of El Paso 2017).

This case study is to compare the no RTS (i.e., do nothing) and the RTS alternative. Therefore, incremental analysis is of interest. Since both reports have the target year differ by one year, and both made ridership estimations that produced different numbers, it is better to use the relative percentage difference than absolute difference, when comparing the alternatives.

In TTI (2010), there were three RTS alternatives or levels of implementation:

1. Transportation system management. This was with minimum improvement from the existing bus services and with minimum investment. An example was simply to convert a regular bus service to express service without changing the infrastructure.
2. Downtown BRT Core with Transportation System Management. This option included building new stations, buying new vehicles, improved fare collection system and intelligent transportation systems to improve on-time reliability, etc. Part of the route in or near downtown ran on exclusive bus lanes.
3. Fully Dedicated Bus Rapid Transit. This is the most expensive alternative which had better facilities of everything in the second alternative, plus exclusive bus lanes all the way.

Alternative two was among the three which design was the closest to the RTS system adopted by the City of El Paso. Therefore, the data, if taken from TTI (2010) were from this alternative. The data listed below were taken from TTI (2010) unless otherwise specified.

<u>RTS:</u>

- Service coverage area
    - 22404 persons, 3454 households, 19130 employed
- Service hours
    - 6:00 a.m. to 8:00 p.m. or 14 hours/day
- Average service headway
    - 10 minutes during peak (6:00 a.m. to 9:00 a.m., 3:00 p.m. to 6:00 p.m.)
    - 15 minutes during off-peak (9:00 a.m. to 3:00 p.m., 6:00 p.m. to 8:00 p.m.)
- Bus travel time (RTS compared to regular bus)
    - Improved by 10.4% during the morning peak
    - Improved by 9.5% during the afternoon peak
    - Improved by 10.0% overall

- Ridership
    - 3452 pax-trips/day, increased by 11.1% (TTI, 2010)
    - 4180 pax-trips/day (Umlauf et al., 2016)

<u>Other Traffic:</u>

- Average delay
    - Increased by <1.0 second/vehicle or <0.75% during the morning peak
- Average travel time
    - Increased by <0.3% during the morning peak

<u>Cost:</u>

- Total project cost
    - $38.5 million
- Revenue (estimated by the authors)
    - $1.88 million/year, based on daily ridership estimate of $4,180/day, 300 days of operations/year and $1.50/trip

7.3.3 Metric

The above project data were mapped into the metric of transportation. In this transit project, there was no environmental assessment report because the project is 100% supported by local funds. Therefore, the metrics of the environment and community health are not shown here.

The metric of transportation, has been modified with new features that are unique to this project and as shown in Table 25:

1. A new indicator "average bus travel time" has been added to the Mobility criterion;
2. A new column named "relative increase" has been added to the table. This column displays the data of the relative improvement in the indicator values before and after the implementation of the RTS, expressed in percent.

Indicators such as service hours, headway and service coverage area, appear in the mobility as well as accessibility criteria.

Table 25 Metric of transportation for Case Study 2

Metric of transportation				
Criterion	Indicator	Unit of measure	Value	Relative increase
Mobility	Average travel time	minutes	--	<0.3%
	Average speed	mph	--	--
	Average delay	sec/veh	--	<0.75%
	Level of service	A, B, C, D, E, F	--	--
	Vehicle-miles traveled	veh-miles/day	--	--
	Percent HOV	percent	--	--
	Speed index		--	--
	No. of congested hours per day	hours/day	--	--
	Travel time reliability		--	--
	Ridership	person-trips/day	4,180	--
	Number of transfers	person-trips	--	--
	Service hours	person-trips/day	14	--
	Average service headway	minutes	10, 15	--
	Service coverage area	persons	22,404	--
	Average bus travel time	minutes	--	-10.0%
Safety	No. of crashes per year		--	--
	No. of injuries per year		--	--
	No. of fatalities per year		--	--
	No. of crashes/100000-pop/year		--	--
	No. of injuries/100000-pop/year		--	--
	No. of fatalities/100000-pop/year		--	--
	No. of crashes/mil-veh/year		--	--
	No. of injuries/mil-veh/year		--	--
	No. of fatalities/mil-veh/year		--	--
	No. of crashes/mil-VMT/year		--	--
	No. of injuries/mil-VMT/year		--	--
	No. of fatalities/mil-VMT/year		--	--
Accessibility	No. of opportunities with a fixed		--	--
	travel time budget	hours/day	--	--
	Availability of opportunities		--	--
	No. of transportation modes		--	--
	Service hours	hours/day	14	--
	Average service headway	minutes	10, 15	--
	Average trip cost	$	1.50	--
Economy	Total project cost	$	38.5 mil	--
	Total O&M cost	$/year	--	--
	Total energy cost	$/year	--	--
	Total revenue	$/year	1.88 mil	--

7.3.4 Concept Maps

The concept maps for this case study are shown in Figures 11 and 12. In this case study, in addition to the new features in the metric, we illustrate the possibility of drawing two concept maps for one project. The concept map in Figure 11 is based on the absolute values of the available project data. This concept map helps to analyze the relationships between the criteria. It answers the question: "what criteria among the environment and community dimensions will be impacted by the transportation dimension's mobility, accessibility, and economy criteria?". In Table 25, under the transportation dimension, the following criteria have the indicators value provided in the project reports:

- mobility criterion: ridership, service hours, average service headway, service coverage area;
- accessibility criterion: service hours, average service headway, average trip cost
- economy criterion: total project cost, total revenue.

Therefore, in the concept map in Figure 11, the five arrows that originated from the mobility, economy and accessibility criteria in the transportation dimension are highlighted. This arrows lead to the following criteria under the community health dimension: physical health, social health, mental health. In the original metric, there were arrows that also point to the air quality, light, noise and vibration criteria under the environment dimension. However, upon closer examination on the mobility criterion, the available indicator values in Table 25 are all related to transit service. It is known that, the air quality, noise, light and vibration depend on the total traffic flow. Since there is no indicator value for the total traffic flow, it is impossible to estimate the impact of mobility criterion on the air quality, noise, light and vibration criteria. Therefore, the related arrows are not highlighted in bold. Using this concept map, the analyst can see that, they are numerical data in the mobility accessibility and economy criteria that can be used to estimate the magnitude of the impact of this project on physical, social, mental health. Typically, each highlighted arrow requires a model. If the model does not exist, research may be proposed to develop the model to fill the gap.

The second concept map is based on the relative changes in the indicator values in the project data. The highlighted arrows in Figure 12 indicate the positive or negative effects by changing the regular bus service to the RTS. Available numerical data for the relative changes had only been found in three indicators under the mobility criterion in the transportation metric. Therefore, in Figure 12, only two arrows that originated from the mobility criterion were highlighted. One of these arrows pointing to the physical health criterion while the other arrow points to the mental health criterion. Of course, they are many criteria that will be impacted. However, the data was not found in the available reports. Again, users of this metric and concept maps are able to identify the missing criteria and indicators and may perform additional studies to estimate them.

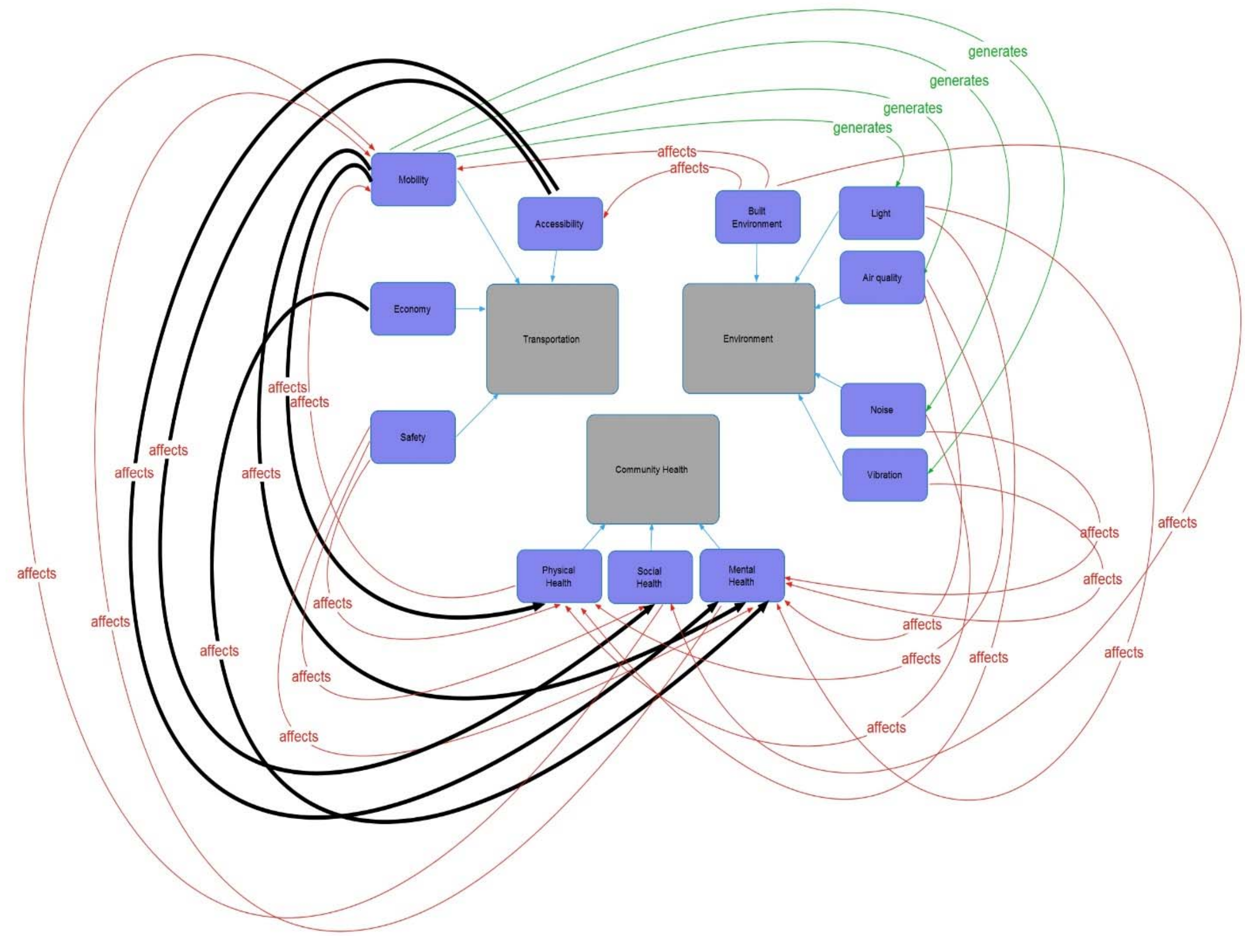

Figure 11 Concept map of Case Study 2 based on absolute attribute values

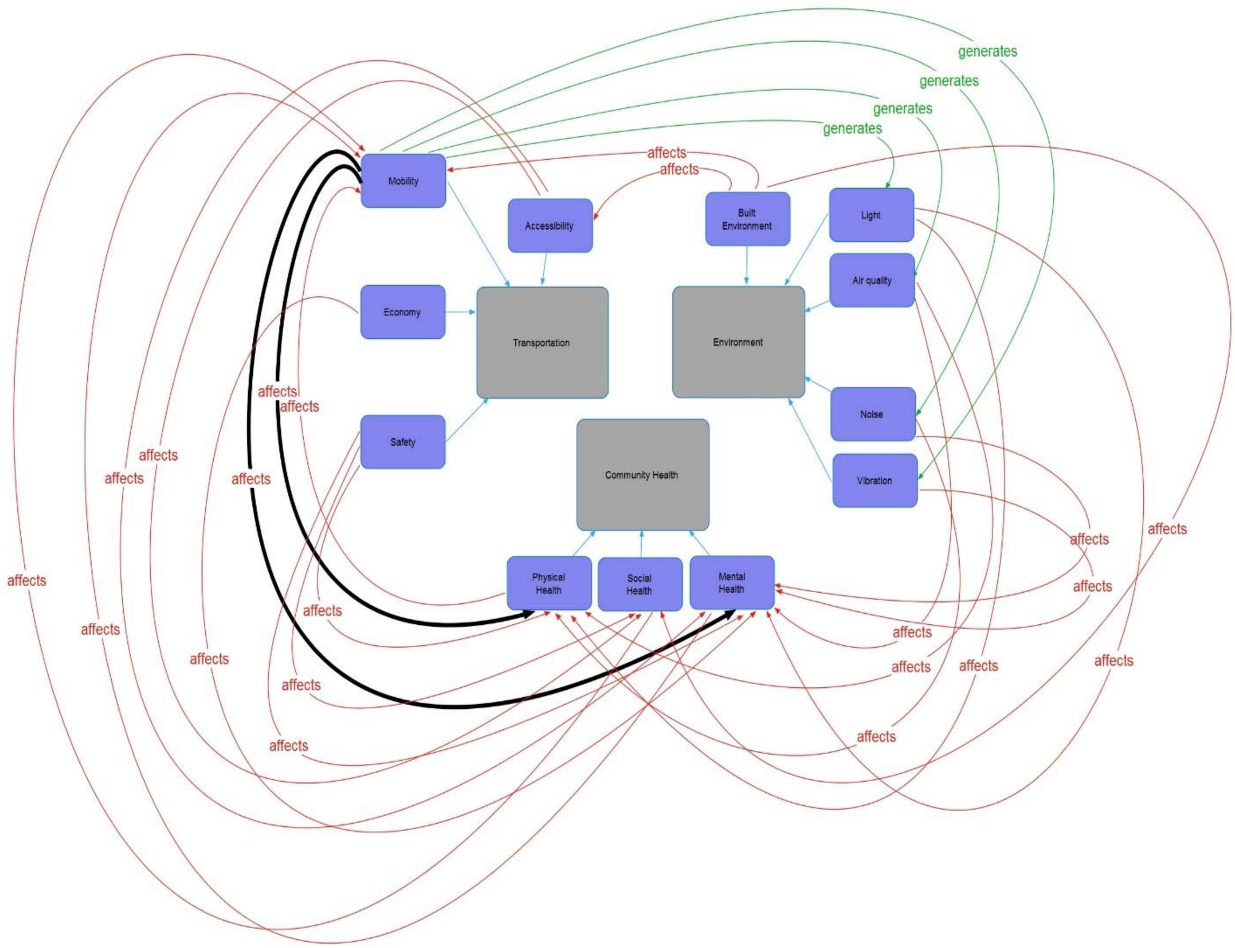

Figure 12 Concept map of Case Study 2 based on relative attribute values

8 CONCLUSION

8.1 Summary of Work Done

In this research, the criteria and indicators of transportation, environment, and community health have been reviewed. The selected indicators will organize into three metrics, one for each dimension;

- metric of transportation;
- metric of environment;
- metric of community health.

Each metric consists of several criteria, and each criterion consists of peace indicators. The unit of measure for each indicator has also been specified.

The concept map has been developed to visualize the relationships between the criteria of the three dimensions. The concept map illustrates the three dimensions (transportation, environment, and community health), their criteria and directional arrows. Each arrow represents the positive or negative relationship of one criterion with another.

The proposed metrics then concept map templates have been applied to two case studies. These 2 case studies not only have illustrated the potential applications of these tools, but has also demonstrate the flexibility of adopting them to meet specific project requirements.

The proposed metrics and concept map templates, when visualized with the available project data, may be used to understand how an indicator will impact others, and from there identifying missing criteria or indicators that are important. These will provide justification for further studies to assess the project impacts especially on the environment and community health.

Possible ways of customizing the metrics and concept map are:

- Editing or adding an indicator, all changing the unit of measure;
- Adding a new criterion (with at least an indicator).

The metrics and concept map have been developed to analyze the data for a single project scenario all alternative. To compared two alternatives, analysts may use the metrics and concept map to perform incremental analysis. In this case, the metrics may be called incremental metrics, and the "Value" column be changed to "Incremental value" on "relative increase".

8.2 Research Contributions

The criteria and indicators of transportation have been well documented and studied. Researchers and practitioners also have good ideas of what criteria and indicators of environment are. Scientific methods have been developed to collect, analyze, and predict the values of indicators of transportation and community health. However, the criteria and indicators of community health are not well understood, at least to the transportation practitioners and researchers. This is, perhaps, an initial effort to review, identify, and organize the dimensions, criteria, and indicators of transportation, environment, and community health into 3 metrics. The relationships between the criteria, and the relationships between the indicators were examined and graphically represented in the concept map.

The metrics and concept map develop have the potential to be used as basic tools for transportation planners and engineers to understand the impacts of all transportation project on the environment and community health. The improved understanding of these impacts may lead to additional specifications or studies than what is required currently by the agencies. The metrics and concept map also expose the gaps (our lack of understanding or models) that predict the impact of one criteria on another. It helps to ship to the future research directions.

8.3 Future Research Directions

The metrics and concept map develop in this research are living tools, which may be called version 1. As new criteria and indicators are being discovered, they may be added to the metrics and concept map. This report includes the templates of the metrics and concept map. An electronic version may be developed that will link the three metrics together and automatically display the concept map. Being restricted by page size, concept map only the dimensions and criteria. The electronic version may include all the indicators. No scientific equations or models may be embedded in the arrows that automatically calculate the effect of one indicators on others.

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APPENDIX - STAKEHOLDER INTERVIEW FORM

Background

The Center for Transportation, Environment, and Community Health (CTECH) will pursue research and innovation to support sustainable mobility of people and goods while preserving the environment and improving community health. CTECH will leverage the existing strength of partner universities to create an innovative, multidisciplinary education program capable of training a workforce that will meet the complex challenges at the intersection of transportation, environment, and community health. CTECH is conducting a survey on the criteria of transportation, environment, and community health and the relationships between them. It is generally known that, transportation has impact on the environment, and transportation and environment both have impact on community health. Transportation, environment, and community health are three large-scale systems. Each of these systems has its own criteria to evaluate its state or condition, and each criterion has its own measurable indicators or variables.

1- *Table A-1 shows the selected criteria, and selected indicators for transportation. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

2- *Table A-2 shows the selected criteria, and selected indicators for environment. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

3- *Table A-3 shows the selected criteria, and selected indicators for community health. Do you think any other criteria or indicators should be added? If so, please explain your reason.*

4- *Figure A-1 is a concept map which shows the relationship between the criteria and indicators. Do you think any other relationships should be added? If so, please explain your reason.*

5- *Please share with us any comment you have concerning the linkages between transportation, environment, and community health.*

Table A-1 Selected transportation criteria and indicators

Proposed metric of transportation		
Criteria	Indicator	Unit of measures
Mobility	Average travel time	minutes
	Average speed	mph
	Average delay	sec/person, sec/veh
	Level of service	A, B, C, D, E, F
	Vehicle-miles traveled	vehicle-miles/day
	No. of congested hours per day	hours/day
	Travel time reliability	
	Ridership	person-trips
	Number of transfers	person-trips/day
	Service hours	hours/day
	Average service headway	minutes
	Service coverage area	mi^2 or % of area
Safety	No. of crashes per year	See column on the left
	No. of injuries per year	
	No. of fatalities per year	
	No. of crashes/100000-population/year	
	No. of injuries/100000-population/year	
	No. of fatalities/100000-population/year	
	No. of crashes/million-vehicles/year	
	No. of injuries/million-vehicles/year	
	No. of fatalities/million-vehicles/year	
	No. of crashes/million-VMT/year	
	No. of injuries/million-VMT/year	
	No. of fatalities/million-VMT/year	
Accessibility	No. of opportunities with a fixed travel time budget	hours/day
	Availability of opportunities	number/day
	No. of transportation modes	hours/day
	Service hours	hours
	Average service headway	minutes
	Average trip cost	$
Economy	Total project cost	$
	Total operating and maintenance cost	$/year
	Total energy cost	$/year
	Total revenue	$/year

Table A-2 Selected environment criteria and indicators

Proposed metric of environment		
Criteria	Indicator	Unit of measures
Air quality	Carbon Monoxide (CO) Lead (Pb) Nitrogen Dioxide (NO_2) Ozone (O_3) Particulate Matters ($PM_{2.5}$, PM_{10}) Sulfur Dioxide (SO_2) Air Quality Index (AQI)	ppm mg/m^3 ppm mg/m^3 mg/m^3 ppb
Noise	Day time $L_{eq}(h)$ or $L_{10}(h)$ Night time $L_{eq}(h)$ or $L_{10}(h)$ Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit ≤ 35 mph Vehicle noise $L_{eq}(h)$ or $L_{10}(h)$ in roads with speed limit > 35 mph Truck noise at stationary	dB(A) dB(A) dB(A) dB(A) dB(A)
Vibration	Peak particle velocity, PPV	mm/sec or in/sec
Light	Illuminance	lm/m^2 or lm/ft^2
Built environment	Residential density Job density Entropy index Dissimilarity index	persons/mi^2 persons/mi^2

Table A-3 Selected community health criteria and indicators

Proposed metric of community health		
Criteria	Indicator	Unit of measures
Physical health	Death before 75 Low birthweight Poor or fair health Adult obesity	no. of deaths % live birth % population % population
Social health	Alcohol-impaired driving deaths Injury deaths Public involvement	% road fatality no. per 100,000 population yes/no (project specific)

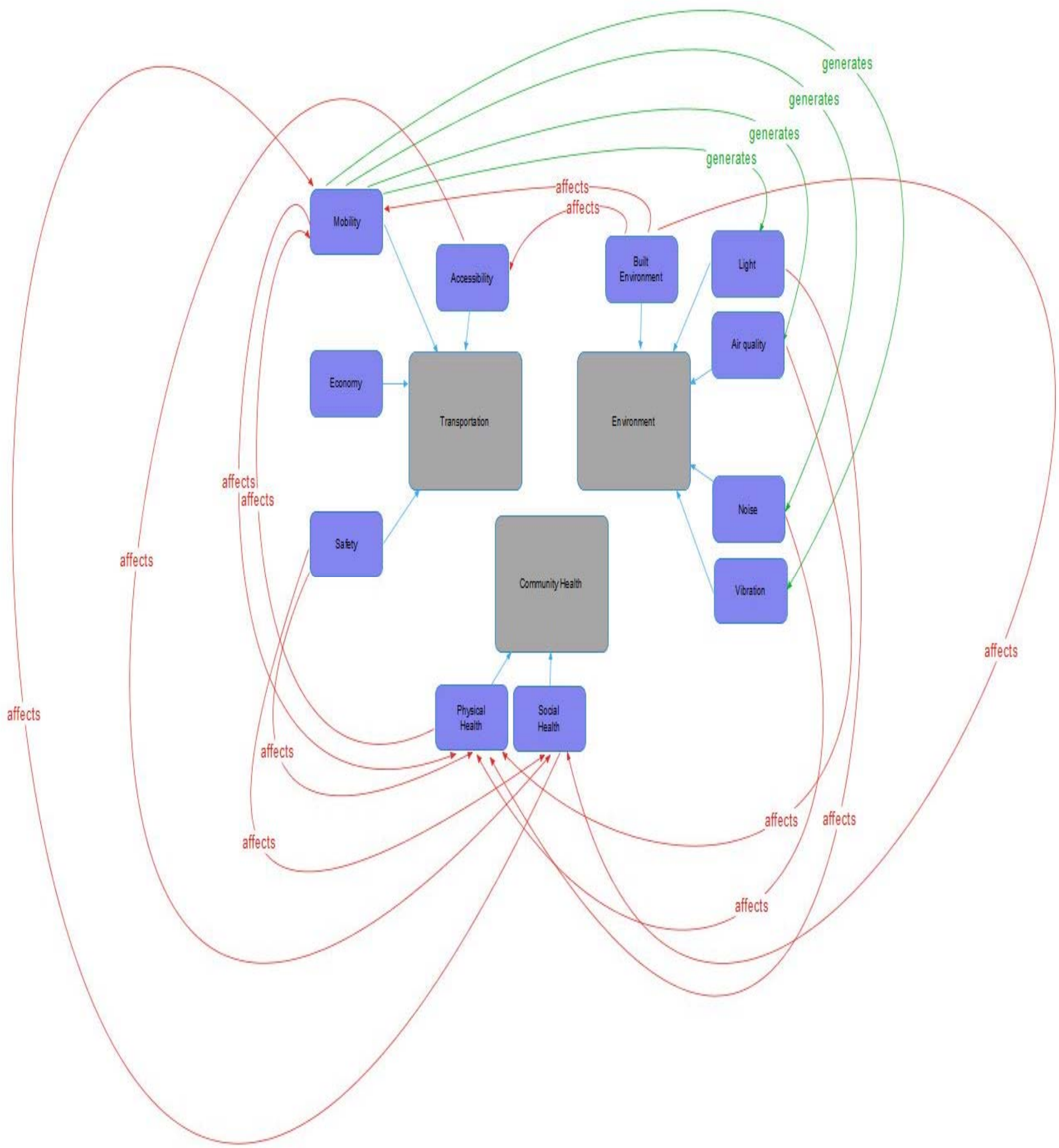

Figure A-1 Concept map