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A Multi-Objective Sustainable Model for Transportation Asset Management Practices

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16. Abstract

Transportation Asset Management (TAM) practices has gained popularity in the United States and worldwide with the aim to provide the required level of service for the transportation infrastructure network in the most cost-effective manner. However, TAM is a complex decision-making process since many objectives and different perspectives, often producing conflicting goals, must be considered.

The report presents a Multi-Objective Sustainable (MOS) model to integrate economic, social, and environmental sustainable objectives into TAM decision-making. A comprehensive literature review of sustainable performance measures for TAM are described to address concerns on-road vehicle emissions, safety, and livability. The Quality Deployment Matrix (QFD) is proposed for selection of the performance measures. MOS can be used by transportation agencies to evaluate different scenarios in the context of Target-Driven or Budget-Driven decisions. An application of the MOS model is demonstrated in a case study for the Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area, CA.

The implementation of the MOS-TAM can help agencies to prioritize projects for funding in a sustainable manner addressing the needs of motorized users and pedestrians. MOS enhances the traditional TAM methods and improves the communication to stakeholders by providing helpful insights of the environmental and social consequences of TAM decisions.

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Chapter 1: Introduction

Transportation Asset Management (TAM) has gained popularity in the United States (U.S.) and worldwide with the aim to provide the required level of service for the transportation infrastructure network in the most cost-effective manner. A question arises: what is sustainability in the context of asset management? In general, terms, sustainability is defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). Sustainability can be also perceived as the balance of a triple bottom line of economic, social, and environmental dimensions (Elkington 1997). However, sustainability principles are often not explicitly considered in the transportation asset management decision-making process.

In modern TAM, environmental and social sustainability factors should be integrated with traditional performance-based analysis and cost-effectiveness concepts. The decision context for TAM becomes even more complex with sustainability as many perspectives are taken into account. Furthermore, due to a growing transportation funding gap, climate change, and increasing numbers of road fatalities, it is vital not only to maintain the infrastructure at a certain level of service, but also include incentives to promote environmental and social sustainability.

1.1 Background

Transportation Asset Management (TAM) evolved from Pavement Management fundamental principles and practices. The AASHTO Road Test marked the beginning of pavement management in 1950s. President Eisenhower's Federal-Aid Highway Act of 1956 gave the impulse for building thousands of miles of paved roads that resulted in a need to maintain them in an acceptable condition in the most cost-effective manner. During the 1970s, pavement management systems (PMS) received increasing attention of academia and State Departments of Transportation (DOTs) as a tool to support funding allocation decisions.

First, PMS started as a pavement inventory and condition assessment methods to identify sections in need of maintenance and prioritize funding allocation using ranking methods as the “worst-first” approach. (Finn 1998). With the advancement of computers, pavement management was able to assist agencies in solving problems that are more complicated. PMS were extended to include comprehensive larger inventory of assets, condition prediction models, methods to identify pavement needs over the planning period, and impact analysis tools to evaluate alternative maintenance strategies. It was demonstrated that it is more cost-effective to maintain pavements in good condition than allow them to deteriorate (Witczak 1987), since the cost of rehabilitation or reconstruction can be 6 to 10 times more expensive than timely preventive maintenance (Galehouse et al. 2006).

Nowadays, the majority of transportation agencies and state Departments of Transportation (DOTs) manage their pavement networks with a PMS tool. The most popular tools for pavement management in local agencies include StreetSaver® (also referred to as MTC-PMS) developed by Metropolitan Transportation Commission (MTC) in Oakland, California (CA), MicroPAVER developed by US Army Corps of Engineers, and Cartegraph. Other pavement management tools popular among state DOTs include the Highway Performance Monitoring System (HPMS) and the Highway Economic Requirements System State Version (HERS-ST) both developed by Federal Highway Administration; the Highway Development and Management System (HDM-4) developed by the World Bank, AgileAssets Enterprise Asset Management Software, and in-house customized systems. TAM tools have evolved from PMS by including inventory and condition assessment not only for pavements, but also for other assets such as culverts, signs, lighting, guardrails, and curb ramps.

Transportation Asset Management Process

Transportation asset management is defined as “a strategic and systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision-making based upon quality information and well-defined objectives” (AASHTO 2011). TAM process is shown in Figure 1.1.

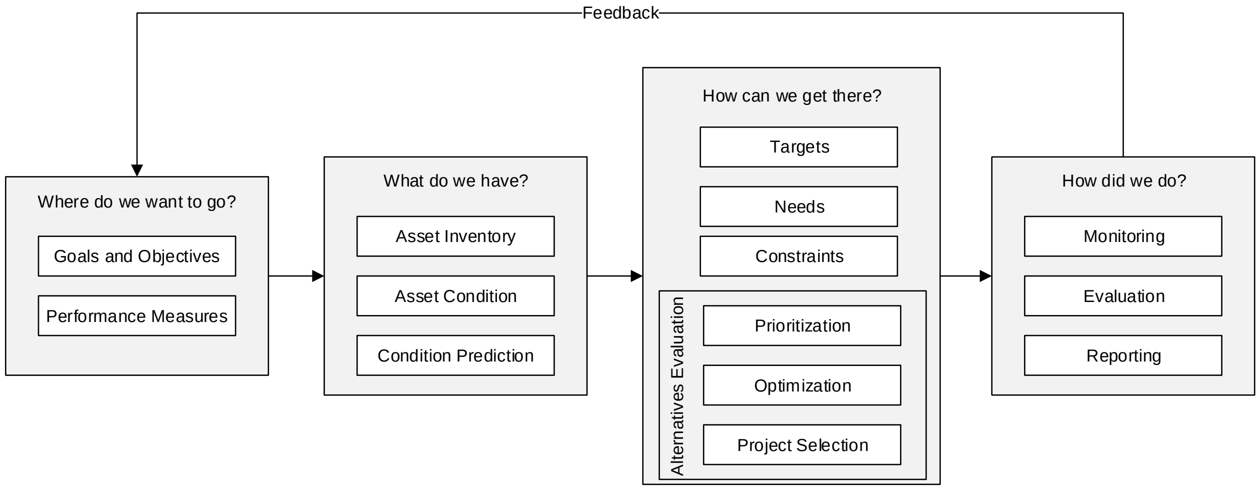


Figure 1.1. Transportation Asset Management (TAM) Process. (based on FHWA 2012 and 2013)

Where do we want to go?

Goals and objectives set the direction that an agency wants to aspire to in the future. Performance measures are selected to set target objectives and monitor whether the actions undertaken lead to the desired results. It is challenging to balance the right set of performance measures while keeping in mind the data collection effort. In addition, as an agency matures, the desired performance measures can change, so it is important to evaluate the project impact through the performance measures but also the suitability of performance measures towards the goals and objectives.

Goals capture the overall desired end state in broad terms (FHWA 2013), for example a transportation system in good repair. Strategic goals are usually set in a Long Range Transportation Plan (also called Metropolitan Transportation Plan or Regional Transportation Plan) based on those priorities a Metropolitan Planning Organization identifies transportation projects for the next four years in the Transportation Improvement Program (FHWA 2013).

What do we have?

Once the goals and objectives are known, the attention focuses on what assets are in the transportation network in order to build an inventory, what their current condition is, and predicting the performance over the planning period.

How can we get there?

Specific target objectives are set using performance measures. Needed work is identified based on the gap between the current and the ideal state set as a target. Often there are not sufficient resources to pursue all the needed work. Alternative Budget-Driven scenarios are evaluated based on priorities. Priorities can differ, for example new construction usually have had the priority, however some agencies may choose to focus "on maintaining and repairing the existing transportation infrastructure before considering expansion" (Caltrans 2014). Caltrans conducted state-wide focus groups in 2014 to learn what the citizen priorities are and reported that "participants from urban and rural areas felt the highest priority was to maintain and restore the current transportation infrastructure". In the same survey, some participants felt that as long as the transportation infrastructure caters primarily to cars, it is difficult to persuade people to switch to other modes. Caltrans also found that opinions differ by region on whether adequate biking infrastructure means: "providing adequate width and maintenance of shoulders" or "constructing new bikeways" (Caltrans 2014). The trade-offs across different types of assets for the alternative Target-Driven and Budget-Driven scenarios are analyzed to finally prioritize funding and select projects over the planning period.

How did we do?

The implementation of TAM practices based on performance measures increases accountability and transparency fostering the effective allocation of funding. Performance measures are useful for communicating the value of projects to the public and decision makers, and for measuring and tracking the state before and after project implementation. According to

Ramani et al. (2013), “good performance measures should be context specific and measurable, have specific target values or directions, and have an appropriate level of detail.” Performance measures are used to setup a specific level of service that is desirable and measurable over time. For example, International Roughness Index (IRI) can be a performance measure, with a target of a minimum network IRI.

NCHRP Report 708 A Guidebook for Sustainability Performance Management for Transportation Agencies (Zietsman and Ramani 2011) includes an extensive discussion of the objectives and performance measures that can be used to reach sustainability goals including safety, accessibility, equal mobility, efficiency, security, prosperity, economic viability, ecosystems, waste generation, resource consumption, and air quality.

Lately, we observe an apparent trend to foster sustainability principles, both in road construction practices and in pollution from on-road vehicles. For example, there is an ongoing effort to improve fuel efficiency of vehicles due to issues with limited non-renewable resources and air pollution. One of the many ways to achieve that is to maintain roads in good condition. Several studies (Watanatada et al. 1987, FHWA 2000, Chatti and Zaabar 2010, Lidicker at el. 2013, Greene at al. 2013) suggest a relationship between pavement roughness and fuel consumption. Consequently, fuel consumption is used to estimate vehicle gas emissions to assess environmental impacts (Chatti and Zaabar 2010). Traditional TAM, oriented towards motorized vehicles often lack to accommodate all roadway users. Hence, social sustainability looks to increase livability and walkability in the neighborhoods, and to improve safety for all roadway users. As a result, there is a significant shift towards alternative modes of transportation through accommodating pedestrians, cyclists, and mass transit users in the urban roadways.

1.2 Research Objectives

The primary objective of this research is to propose a multi-objective model with performance measures based upon sustainability principles in order to enhance the current TAM process. The specific main objectives of this study are to:

- Identify performance measures for TAM to mitigate the environmental impact caused by pollutant emissions.
- Use of the Quality Function Deployment Matrix for the selection of performance measures that better suit the asset management goals and objectives established by transportation agencies.
- Develop a multi-objective performance-based sustainable (MOS) model for TAM.
- Apply the multi-objective sustainable model in a case study for Metropolitan Transportation Commission (MTC) in San Francisco Bay Area, CA.

1.3 Organization of the Report

This report is organized into five chapters:

Chapter 1 introduces the topic of sustainability in the TAM decision-making process. Background and research objectives are also described in this Chapter.

Chapter 2 includes a comprehensive literature view of sustainable performance measures for TAM, including definitions, goals, objectives, and performance measures for economic, environmental, and social sustainability.

Chapter 3 introduces the Quality Function Deployment matrix and explains how to select performance measures using the matrix in the context of a multi-objective sustainable model.

Chapter 4 describes the multi-objective sustainable (MOS) model for transportation asset management. The MOS model includes performance measures to address economic, environmental, and social sustainability aspects in the context of target-oriented decisions or budget limitations.

Chapter 5 shows an application of the MOS model in a case study for the Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area, CA.

Chapter 6 summarizes the conclusions of the research project, emphasizes the contribution of the study, and provides recommendations for future research.

Chapter 2: Synthesis of Goals, Objectives, and Performance Measures for Transportation Asset Management

2.1 Definition of Sustainability in Transportation

A sustainable system is a system that meets present and future needs while it:

• "Preserves and restores environmental and ecological systems,

• Fosters community health and vitality,

• Promotes economic development and prosperity, and

• Ensures equity between and among population groups and over generations." (Ramani et al. 2013)

"Transportation has significant economic, social and environmental impacts" (ADD40 2008) and therefore it is crucial to manage transportation assets with sustainability in mind. Table 2.1 shows examples of sustainability challenges in the transportation sector.

Table 2.1. Sustainability challenges in transportation. (ADD40 2008)

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

Economic challenges refer to the accessibility of points of interest, travel times between places, costs of the transportation infrastructure including construction, maintenance, and transportation users' costs ranging from vehicle, insurance, vehicle operating, fuel, tolls, and mass transit user costs. Mobility barriers caused by inadequately engineered transportation infrastructure is challenge when the needs of people with disabilities and seniors are not taken into account; as well as low-income population transportation needs that rely on active transportation or mass transit. Accident damages should also be considered, whether they occur from inadequate infrastructure design or from insufficient transportation choices such as impaired driving accidents in urban areas with no night mass transit service. Another challenge is the depletion of non-renewable resources caused by the materials used to build and maintain the infrastructure transportation network and vehicles; as well as the energy consumption in the life cycle phase.

Social challenges tied to transportation refers to the equity and affordability to travel from home to work and leisure activities including the mobility of people with disabilities and seniors; as well as impacts of the air quality and transportation options on human health. Transportation infrastructure also influences aesthetics, community cohesion, and livability.

Environmental challenges related to transportation include the mitigation of local and global air pollution caused by combustion and energy production, leading to climate change. There is also noise pollution, water pollution, and hydrologic impacts due to rainwater runoff that may cause degradation of the ecological system, and animals living in it.

Economic, social, and environmental sustainability challenges are often interconnected. For example, a collision causes economical loss due to property damage, healthcare costs, and reduced productivity. Road closures after a collision also cause traffic congestions, increasing fuel consumption and vehicle gas emissions, resulting in environmental and "social costs from pain and reduced quality of life" (ADD40 2008).

2.2 Economic Sustainability

2.2.1. Economic Sustainability Goals

Table 2.2 shows examples of goals for economic sustainability. Although, there are some goals related to all three areas of sustainability including social and environmental. For example, the preservation of the multimodal transportation system (Caltrans 2015) and the reduction of car dependence by improving people’s ability to meet most of their daily needs without driving (Dondero et al. 2013) reduces air pollution (environmental effect) and promotes social equity and livability (social effect). Mitigation of traffic congestion (Ramani et al. 2013) influences fuel savings (economic) and air quality (environmental). The improvements on multimodal mobility and accessibility for all users (Caltrans 2015) have also social and economic impacts. The possibility to walk, bike, or use mass transit for daily activities (social) generates savings on transportation user costs (economic).

Table 2.2 Examples of economic sustainability goals.

Goal	Sustainability Area	Source
Improve people’s ability to meet most of their daily needs without having to drive	Economic / Social / Environmental	Dondero et al. 2013
Preserve multimodal transportation system	Economic / Social / Environmental	Caltrans 2015
Reduce project delays	Economic	Briseno 2015
Improve international mobility	Economic	Ramani et al. 2013
Promote economic development	Economic	Ramani et al. 2013
Ensure system effectiveness and efficiency	Economic	Ramani et al. 2013, Zietsman and Ramani 2011
Mitigate traffic congestion	Economic / Environmental	Ramani et al. 2013
Improve multimodal mobility and accessibility for all users	Economic / Social	Caltrans 2015
Improve the convenience and quality of trips, especially for walk, bike, transit, car/vanpool, and freight	Economic / Social	Dondero et al. 2013
Ensure the transportation system is secure from, ready for, and resilient to threats from all hazards.	Economic / Social	Zietsman and Ramani 2011

Economic sustainability goals include reduction in project delays (Briseno 2015), and transportation system effectiveness and efficiency (Ramani et al. 2013, Zietsman and Ramani 2011). Furthermore, taking precautions so that the transportation system is secure from, ready for, and resilient to threats from all hazards as extreme weather events, gradual climate change and terrorist attacks foster both economic and social sustainability (Zietsman and Ramani 2011).

2.2.2 Economic Sustainability Objectives

Objectives describe specific and measurable statements that are more general than performance measures (FHWA 2013). Table 2.3 shows examples of economic sustainability objectives.

Table 2.3 Examples of economic sustainability objectives.

Objective	**Source**
Re-invest in the local economy through reducing expenditures on fuel and related vehicle use	Dondero et al. 2013
Use transportation investment to support economic development, job creation, and commerce	Maurer et al. 2013
Improve travel time reliability and speed consistency for freight between representative origins and destinations	Dondero et al. 2013
Ensure affordable transportation for all communities	Zietsman and Ramani 2011
Minimize travel time delay (by mode) for affected population due to maintenance activities	Zietsman and Ramani 2011
Use value management tools (life cycle costing, risk management, return on investment) for transportation decision making	Maurer et al. 2013
Maintain pavement on roadways in good condition	Dondero et al. 2013
Maintain average asset age no more than 50% of the useful life	Dondero et al. 2013
Reduce fuel consumption	Dondero et al. 2013
Program projects that improve the capacity of the transportation system to recover swiftly from incidents	Zietsman and Ramani 2011

Economic sustainability objectives include re-investing in the local economy through reducing expenditures on fuel and related vehicle use (Dondero et al. 2013). Transportation investments are used to support economic development, job creation, and commerce (Maurer et al. 2013). Improvement on travel time reliability and speed consistency for freight between representative origins and destinations (Dondero et al. 2013) are desired, as well as ensuring affordable transportation options for communities of all ages and incomes. Travel delay by mode due to maintenance activities are minimized (Zietsman and Ramani 2011) and value management tools such as life-cycle costing, risk management, and return on investment are used in the decision-making process (Maurer et al. 2013). Maintaining pavements in good condition and assets (Dondero et al. 2013) create savings both for the agency and the users

(Watanatada et al. 1987, FHWA 2000, Chatti and Zaabar 2010, Lidicker at el. 2013, Greene at al. 2013). Promoting projects that improve capacity of the transportation system in such way that the system can recover swiftly from incidents (Zietsman and Ramani 2011), such as extreme weather events, also improve economic and social sustainability.

2.2.3 Economic Sustainability Performance Measures

Table 2.4 shows examples of performance measures for economic sustainability.

Table 2.4 Economic sustainability performance measures.

Performance measure	**Source**
Total and congested vehicle miles travelled (VMT) per capita	Briseno 2015
Congested arterial VMT per capita	Briseno 2015
Annual daily traffic (ADT)	
Highway buffer index	Briseno 2015
Agency expenditures on transportation infrastructure	ADD40 2008
Agency routine maintenance costs	Dondero et al. 2013
Agency delayed maintenance costs	Dondero et al. 2013
Asset current condition (condition index, remaining service life)	AAMCOG 2008
Asset required condition	AAMCOG 2008
Pavement roughness	OECD 2001
User expenditures on transport	ADD40 2008
User savings from smooth pavement	World Bank undated
Social cost of CO_2	
Fuel consumption based on pavement condition	Dondero et al. 2013
Gallons of gasoline saved/displaced, using gasoline gallon equivalents based on lower heating value ratio	NREL 2013
Proportion of household income spent on transportation	ADD40 2008
Housing/transportation affordability index	Briseno 2015
Job commute costs including time and money (per location)	ADD40 2008, Briseno 2015
Point to point travel cost	Ramani et al. 2013
Property values	SHRP 2 2012
% of spending on projects in areas of key origins and destinations for transportation-disadvantaged populations	Dondero et al. 2013
Jobs created	

In transportation asset management, a major economic performance measure in the agency expenditures on construction and maintenance of the transportation infrastructure.

Routine and delayed maintenance costs (ADD40 2008) are related to the asset condition (AAMCOG 2008) expressed through a number of pavement condition indices. The International Roughness Index (IRI) (OECD 2001) is used among departments of transportation; and the Pavement Condition Index (PCI) is typically used by local agencies for condition assessment. Another indicator is the remaining service life. Transportation costs can also include road user costs estimated from roughness (ADD40 2008), fuel consumption, and tire-wear. The damage to society caused by CO_2 emissions can be estimated from fuel consumption (Dondero et al. 2013) or gallons of gasoline; therefore, cost savings due to improved pavement condition can be used to setup performance-based sustainability targets (NREL 2013).

Other examples of economic sustainability performance measures include, annual average daily traffic, congested miles, housing affordability, highway buffer index, funds spent on transportation projects, and job creation. Housing affordability index that includes transportation costs, as one of the two major expenses of households, (Briseno 2015) is also valuable to show whether neighborhoods have affordable transportation options. Proportion of household income spent on transportation (ADD40 2008) indicates the affordability of transportation and identify any groups in disadvantage. Housing expenditures and transportation costs from home to work or school should be less than 30% of household income to qualify as affordable. The buffer index is used to measure the time add by road users to the expected travel time to arrive on-time (Briseno 2015). Percentage of funds spent on projects improving mobility of transportation-disadvantaged population can indicate the level of fairness and accessibility to transportation (Dondero et al. 2013). Alternatively, job commute costs including time (ADD40 2008, Briseno 2015) or point to point travel costs (Ramani et al. 2013) together with property values (SHRP 2 2012) are also used to assess transportation accessibility. Jobs created by construction or maintenance of transportation assets is considered as an economic and social performance measure.

2.3 Environmental Sustainability

2.3.1 Environmental Sustainability Goals

Table 2.5 shows examples of goals for environmental sustainability.

Table 2.5 Examples of environmental sustainability goals.

Goal	Source
Improve the environment living conditions	Ramani et al. 2013
Improve air quality	Dondero et al. 2013
Reduce transportation-related emissions of air pollutants and greenhouse gases.	Zietsman and Ramani 2011
Practice environmental stewardship	Briseno 2015
Protect and enhance environmental and ecological systems while developing and operating transportation systems.	Zietsman and Ramani 2011
Reduce waste generated by transportation-related activities.	Zietsman and Ramani 2011
Reduce the use of non-renewable resources and promote the use of renewable replacements.	Zietsman and Ramani 2011

Environmental sustainability goals include improvements on the environmental living conditions (Ramani et al. 2013), air quality (Dondero et al. 2013) by the reduction of transportation-related emissions of air pollutants, and greenhouse gases (Zietsman and Ramani 2011). Environmental sustainability goals should be fostered during the construction and maintenance phase through an environmental stewardship of environmental and ecological systems (Briseno 2015) by reducing the waste from transportation-related activities and by promoting the use of renewable resources (Zietsman and Ramani 2011).

2.3.2 Environmental Sustainability Objectives

Table 2.6 shows examples of objectives for environmental sustainability.

Table 2.6 Examples of environmental sustainability objectives.

Objective	Source
Reduce criterion pollutant emissions from transportation	Ramani et al. 2013
Reduce GHG emissions from transportation	Ramani et al. 2013
Reduce growth rate of single occupant vehicle travel	Maurer et al. 2013
Enhance 3R (reduce, reuse, and recycle) efforts	Maurer et al. 2013
Improve habitat in or adjacent to the right-of-way	Dondero et al. 2013
Manage and treat storm water volumes and flow	Dondero et al. 2013

Environmental sustainability objectives include the reduction of pollutant and greenhouse gas emissions from transportation activities (Ramani et al. 2013), and the reduction of single occupant vehicle trips. A transportation agency can setup objectives to mitigate the negative impacts from construction, use, and end of life phases (Maurer et al. 2013). For example, the usage of materials that are permeable or reflect heat can mitigate urban heat island effect. Improving habitat in the right-of-way as well as managing storm water flow positively affect the flora and fauna around the roadways and have an aesthetic purpose (Dondero et al. 2013).

2.3.3 Environmental Sustainability Performance Measures

Table 2.7 shows examples of performance measures for environmental sustainability.

Table 2.7 Examples of environmental sustainability performance measures.

Performance measure	**Source**
Total vehicle emissions	ADD40 2008
Total vehicle gas consumption	World Bank undated
Climate change emissions (CO2, CH4) per capita	ADD40 2008, Briseno 2015
Tons of CO2e prevented from being emitted to the atmosphere	NREL 2013
Particulate matter (PM) emissions	Ramani et al. 2013
Ozone related emissions (NOx and VOCs)	Ramani et al. 2013
Days exceeding national/state standards by region/air basin and statewide	FHWA 2012
Travel noise levels	Ramani et al. 2013
People exposed to traffic noise above 55 LAeq.T	ADD40 2008
Water pollution	Lane and Sherman 2012
Land use (pollution/runoff/disruption/new utilities demand/TOD)	Lane and Sherman 2012
Tree canopy	Dondero et al. 2013
Average environmental compliance score for construction and maintenance projects	Maurer et al. 2013
Percentage of management plans implemented for endangered species sites	Maurer et al. 2013
Tons of reused materials on construction and maintenance projects	Maurer et al. 2013

Examples of environmental sustainability performance measures are total vehicle gas consumption, total vehicle emissions (ADD40 2008), individual emissions of particulate matter (Ramani et al. 2013), emissions related to climate change, such as CO_2 and CH_4 (ADD40 2008, Briseno 2015, NREL 2013), and ozone emissions (NO_X and VOCs) (Ramani et al. 2013). The air pollution outcomes are observed by the number of days that exceeds the air quality standards (FHWA 2012). Other aspects of environmental pollution from transportation include increased noise levels (Ramani et al. 2013), where a threshold is set for unacceptable levels, for example above 55 LAeq.T (ADD40 2008).

The impact on the ecosystem is assessed by reporting water pollution (Lane and Sherman 2012) and environmental compliance violations (Maurer et al. 2013) during construction or maintenance activities; percentage of plans implementing considerations for endangered species (Maurer et al. 2013); assessing tree coverage (Dondero et al. 2013) of pavement surfaces as the shade slow down deterioration (McPherson and Muchnick 2005). Share of reused and recycled materials in construction and maintenance projects is also enforced in order to reduce resource depletion (Maurer et al. 2013).

2.4 Social Sustainability

2.4.1 Social Sustainability Goals

Table 2.8 shows examples of goals for social sustainability.

Table 2.8 Examples of social sustainability goals.

Goal	Source
Increase livability	Ramani et al. 2013
Promote equity	Caltrans 2015, Ramani et al. 2013, Zietsman and Ramani 2011
Improve public safety	Caltrans 2015, Zietsman and Ramani 2011
Improve multimodal safety especially for the most vulnerable users	Dondero et al. 2013, Zietsman and Ramani 2011
Demonstrate that planned investments do not disproportionally impact transportation-disadvantaged populations	Dondero et al. 2013

Social sustainability goals are intended to increase livability standards of neighborhoods (Ramani et al. 2013) and equity (Caltrans 2015, Ramani et al. 2013, Zietsman and Ramani 2011) in order to ensure that planned investments do not disproportionally affect transportation-disadvantaged populations (Dondero et al. 2013). Improving public safety (Caltrans 2015), in particular safety for vulnerable road users, also promotes social sustainability (Dondero et al. 2013, Zietsman and Ramani 2011).

2.4.2 Social Sustainability Objectives

Table 2.9 shows examples of goals for social sustainability.

Table 2.9 Examples of social sustainability objectives.

Objective	**Source**
Improve intermodal connectivity	Maurer et al. 2013
Support pedestrian and bicycle modes	Ramani et al. 2013
Improve pedestrian and bicycle linkages to activity centers	Maurer et al. 2013
Reduce average trip length	Maurer et al. 2013
Improve safety for neighborhoods and for all road users	Maurer et al. 2013
Reduce the number and severity of crashes	Zietsman and Ramani 2011
Ensure safety is considered early in project planning	Zietsman and Ramani 2011
Develop programs that maximize return on safety investment	Zietsman and Ramani 2011
Improve safe, attractive, and affordable access to work, school, goods, and other key destinations by walking, bicycling and transit	Dondero et al. 2013
Improve the quality of walk, bicycle, car/vanpool, and transit trips	Dondero et al. 2013

Social sustainability objectives are related to improvements of intermodal connectivity (Maurer et al. 2013), such as improving pedestrian, bicycle, and transit modes (Ramani et al. 2013), and creating links to activity centers (Maurer et al. 2013) to reduce the average trip length for daily activities (Maurer et al. 2013). Safety improvements is another factor affecting social sustainability. Safety improvements in the neighborhoods benefits all road users (Maurer et al. 2013), resulting in less number and severity of collisions. Transportation agencies can promote projects that maximize the return of investment on safety improvements (Zietsman and Ramani 2011) by taking into account the social benefits of reducing fatalities, property damage, and travel delays (Cambridge Systematics 2008). Safe, attractive and affordable access to daily activities by walking, bicycling, and mass transit trips (Dondero et al. 2013) have also positive impacts on public fitness and health.

2.4.3 Social Sustainability Performance Measures

Table 2.10 shows examples of performance measures for social sustainability.

Table 2.10 Examples of social sustainability performance measures.

Performance measure	Source
Population density	SHRP 2 2012
Residential and employment densities for new growth (environmental justice (EJ)/non EJ communities)	Briseno 2015
Number of areas with a bicycle or pedestrian plan	Maurer et al. 2013
Quality of walking/bicycle/transit infrastructure	ADD40 2008
Livability characteristics	FHWA 2010
Length of sidewalks per corridor mile	Ramani et al. 2013
Average density of sidewalk mileage within municipalities that have pedestrian plans	Maurer et al. 2013
Length of bicycle lanes per corridor mile	Ramani et al. 2013
Walk miles travelled and bicycle miles travelled	Briseno 2015
% of population within 30-minute walk, bike, or transit trip of key destinations	Dondero et al. 2013
Transit accessibility – housing and jobs within 0.5 mile of transit stops with frequent service	Briseno 2015
Transit travel time reliability	Briseno 2015
Police-reported traffic incidents	ADD40 2008
Fatalities/serious injuries per capita and per VMT	Briseno 2015
Number of crashes involving a driver with blood concentration of 0.08 g/dL of higher	NHTSA 2009
Number of speeding-related fatalities	NHTSA 2009
Number of pedestrian fatalities/incidents	NHTSA 2009
Road fatality risk as fatalities / population or registered vehicles	OECD 2001
Fatalities or injuries per mile	Derrible 2013
Improvements to areas that have reported fatalities and injuries	Dondero et al. 2013
Traffic incident economic costs	ADD40 2008

Population density (SHRP 2 2012) is a social sustainability performance measure, especially residential and employment densities for new developments in order to prevent sprawl (Briseno 2015). Also, the quality of active transportation infrastructure is measured by the quantity of areas with bicycle or pedestrian plans (Maurer et al. 2013), overall quality of transit, walking and bicycle infrastructure (ADD40 2008) such as length or density of sidewalks in urban areas (Ramani et al. 2013, Maurer et al. 2013), and other livability characteristics. The accessibility to transportation infrastructure is assessed by the percentage of population living within a 30 minute transit, walk, or bicycle trip from key destinations and jobs (Dondero et al. 2013), or jobs and housing within 0.5 mile of transit stops (Briseno 2015).

Form another perspective, the actual usage of the active transportation infrastructure is measured by transit miles travelled (TMT), walk miles travelled (WMT), and bicycle miles travelled (BMT). Travel time reliability of transit is also an important indicator that affects the willingness of users to opt for that type of transportation, especially in competition with cars (Briseno 2015).

Finally, safety of a transportation network is assessed by several measures, including traffic incidents reported to police (ADD40 2008), and fatalities or serious injuries to motorists, pedestrians, and bicyclists (NHTSA 2009). Those incidents are measured per mile, per VMT, per capita or per number of registered vehicles (Derrible and Cottryl 2013, Briseno 2015, OECD 2001). In order to tight safety to infrastructure expenses, improvements in areas with safety problems are reported along with the prevented economic costs of injuries and fatalities.

2.5 Summary

Goals, objectives, and performance measures help transportation agencies to manage their assets in the most effective way. Modern TAM requires an integrated approach that connects these three key elements though the adoption of sustainability principles to balance economic, environmental, and social aspects. In this context, the selection of the right performance measures to assess the current and desired state is an important decision, especially since data collection is costly. The next chapter focuses on selecting the right set of performance measures to reach agency’s goals taking into account sustainability challenges.

Chapter 3: Quality Function Deployment Matrix for Selection of Performance Measures

Transportation agencies spend a significant amount of money on transportation infrastructure projects, but at the end, do they get what they wanted? The aim of establishing performance measures is to quantify the effectiveness and efficiency of the decisions, while increasing accountability. The selection of a set of performance measures becomes vital in the asset management process. However, with the complexity of the decision-making process, practitioners are easily overwhelmed by the selection and application of adequate performance measures.

Data collection and management is expensive and time consuming, therefore it becomes an optimization problem as agencies want to focus only on the minimum amount of performance measures that will satisfactorily indicate the effectiveness and efficiency of the decisions. As the Pareto 80/20 principle suggests, 20% of the performance measures should have an impact on 80% of the objectives. Customer needs and desires, engineering requirements, and monetary limitations are considered in performance-based management (Cambridge Systematics 2010).

This study shows how a Quality Function Deployment (QFD) matrix can be used for selecting the most relevant performance measures by transferring customer needs (objectives, priority) to engineering requirements (performance measures that need attention) and fiscal limitations (difficulty). The QFD matrix method has been successfully used for translating customer requirements to technical parameters for over 50 years. In this study, the QFD matrix focuses on environmental and social performance measures to incorporate sustainability principles in the decision-making process.

3.1 Quality Function Deployment Matrix

The Quality Function Deployment matrix was developed in Japan in 1960s and since then it has been successfully applied extensively in manufacturing, especially in the automotive industry, where it helps to relate customer expectations to technical requirements. This chapter describes the possible use of a QFD matrix in transportation asset management, showing an example for the selection of performance measures for economic, environmental, and social sustainability.

As Figure 3.1 shows, the QFD matrix consists of two main sections: agency objectives (left column) and candidate performance measures (top row). Priority and difficulty are considered in the QFD matrix. Priority shows the importance of each objective for the agency. Difficulty incorporates the demand of resources (time, money, personnel) required for collection of the data for each performance measure.

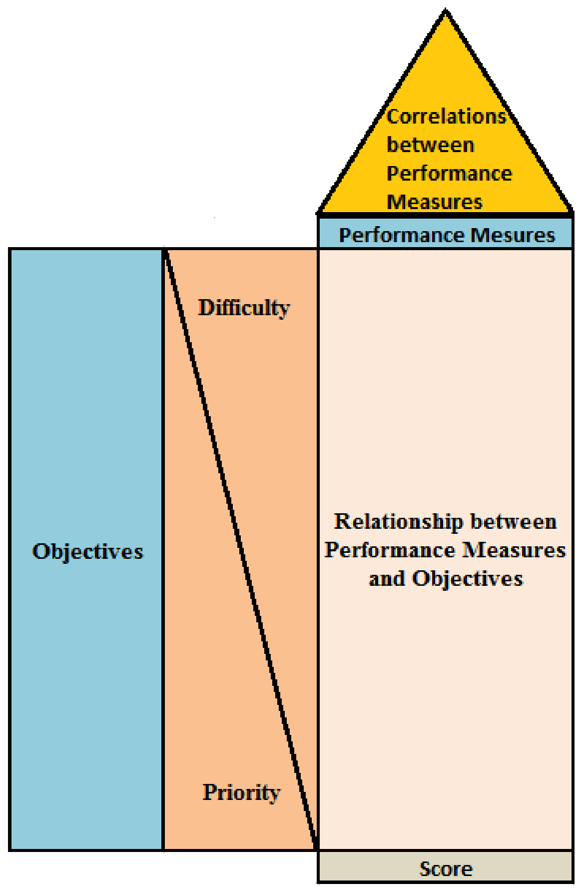


Figure 3.1 Quality Function Deployment Matrix Scheme

Filling out the matrix forces the decision makers to identify the objectives and relevant performance measures. The performance measures are grouped into categories. Once the matrix is filled out, the categories with most relevant performance measures affecting the objective are identified. A triangle with correlations between performance measures indicating a strong, weak, or no relationship with the objectives is included at the top of the matrix

At the bottom of the QFD table, scores are calculated for each performance measure, considering the priority, difficulty, and relationship between performance measures and objectives. Performance measures with high scores are further investigated. For example, if similar performance measures receive a high score, the correlation triangle on top of the matrix can help decide which performance measure to keep, by analyzing its relationship with the others.

A QFD matrix is a powerful tool, but needs to be used wisely. The outcomes depend on the quality of data. To get the most benefit, it is recommended that this matrix be filled out in a brainstorming meeting of experts, and preferably with different backgrounds to complement their expertise. Therefore, it is highly recommended to carefully select the group of experts that will set up the matrix.

As a result, the framework for performance measures assessment is developed to relate what the agency wants to how it can be measured. Once the matrix is completed, it shows a well-arranged description of the decision context:

- objectives and their priority
- candidate performance measures and their difficulty
- correlations among the performance measures
- performance measure score considering the relationship to objective, priority, and difficulty

The following steps are described to develop the QFD matrix to select performance measures for environmental and social objectives for TAM. In this example, the researchers' expertise was used to fill out the matrix.

1. Agency Objectives: The first step is to set up the customer expectations. In the case of transportation asset management, this step lists the objectives that the agency wants to achieve for the environment and the society. Environmental objectives considered air, economic objectives maintenance cost and asset condition, and social objectives included livability, jobs creation, and safety.

2. Priority: Assign priority to each objective. The selection of scale depends on preferences of the agency and its goals depend on its maturity. In the example presented here, 5 represents the highest priority and 1 the lowest.

3. Performance Measures: While many conventional performance measures used to monitor and track progress are useful to monitor sustainability, some have stronger links to sustainability than others (Zietsman et al. 2011). Therefore, the matrix contains a list of candidate performance measures that are related to the sustainability social and environmental objectives. The strongest performance measures, as related to the objectives, are selected at the end of the process.

Candidate performance measures are chosen in six categories: vehicle, physical infrastructure, safety, agency, pollutants, and user costs. Performance measures that contribute to safety and accessibility of urban roads to all users, including motorists, pedestrians and bicyclists are: selected based on the literature review summarize in Chapter 2:

- Vehicle: Section Average Daily Traffic, Total Vehicle Gas Consumption.
- Physical infrastructure: Pavement Condition Index (PCI), pavement Remaining Service Life (RSL), fuel consumption based on pavement condition, section livability characteristics.
- Safety: accidents due to speeding on a section, accidents due to alcohol impaired driving on a section, crashes involving a pedestrian or bicyclist on a section, improvements in areas that have reported fatalities and injuries.
- Agency: agency expenditures percentage of spending on projects for transportation-disadvantaged population, jobs created.

- Emissions: total vehicle emissions, ozone, carbon dioxide (CO_2) emissions, particulate matter (PM) emissions.
- User cost: social cost of CO_2, user cost savings when compared to a Do Nothing scenario.

4. Difficulty: Difficulty is assigned to each candidate performance measure to reflect the time, cost, and personnel constraints. This gives the opportunity to tailor the matrix to an agency of any maturity level in their data management stage of development. This example uses a scale for each measure to provide a better comparison among the measures: 1 for data that already exists, 1.5 for data that could be collected, and 2 for data collection that requires a considerable amount of resources. It is observed that level of difficulty in data collection has a significant role in the resulting score. Even performance measures that have an influence on several objectives are sometimes not chosen because of the difficulty factor that decreased the final rating. Therefore, it is recommended to carefully set the difficulty scale. On the other hand, the consideration of data collection difficulty makes the QFD matrix a great tool for an agency of any maturity level.

5. Correlations: Performance measures influence one another. For example, traffic volume affects emissions. To describe this effect in the matrix, correlations such as strong positive (++), slight positive (+), strong negative (--), slight negative (-) are used. Even though these correlations do not affect the numerical calculations, it gives the opportunity to consider various sets of performance measures to evaluate the tradeoffs if desired.

6. Relationship between Objectives and Performance Measures: Each performance measure is evaluated based on its influence towards achieving the objective. The question that helps in filling out the matrix is "How much can this performance measure indicate if the objective is being met?" The scale used is 9 for a significant relationship/effect, 3 for a considerable relationship/effect, and 1 for a weak relationship/effect. For example, traffic volume has a strong relationship with changes in vehicle emissions, considerable effect on asset condition, livability, safety, and weak relationship with agency costs.

7. Score: Multiply the relationship by priority to obtain a total of points for each performance measure, and divide by the level of difficulty.

The score is calculated as $\frac{\sum_i^n relationship_j^i * priority_j^i}{difficulty_j^i}$, where i and j indicate row and column. A strong relationship between an objective and a performance measure, as well as high priority of the objective, increases the score while a performance measure with a high level of difficulty decreases the score. As these coefficients have a major influence on the score, it is recommended to customize them to reflect the agency specific needs. On the bottom of the table, the percentage of each performance measure is indicated for each group of performance measures, and values above average are highlighted. An overall ranking is also included and selected performance measures are highlighted. Figure 3.2 shows the developed QFD matrix following the process previously described.

	Objectives	Difficulty / Priority	Section Average Daily Traffic	Total Vehicle Gas Consumption	Pavement Condition Index	Pavement Remaining Service Life	Fuel Consumption Based on Pavement Condition	Section Livability Characteristics	Accidents due to Speeding on a Section	Accidents due to Alcohol Impaired Driving on a Section	Crashes Involving a Pedestrian or Bicyclist on a Section	Improvements in Areas that Have Reported Fatalities and Injuries	Agency Expenditures	% of Spending on Projects for Transportation-Disadvantaged Pop.	Jobs Created	Total Vehicle Emissions	Ozone	Carbon Dioxide (CO_2) Emissions	Particulate Matter (PM) Emissions	Social Cost of CO_2	User Savings from Smooth Pavement
		Candidate Performance Measures related to:	**Vehicle**		**Physical Infrastructure**				**Safety**				**Agency**			**Pollutants**				**User Cost**	
			1.0	1.5	1.0	1.0	1.5	1.0	2.0	2.0	1.5	3.0	1.0	2.0	1.0	2.0	2.0	1.0	2.0	1.0	1.0
Environmental	Reduce Vehicle Emissions	4	9	9	9	3	9	1					3			9	9	9	9	9	9
Economic	Affordable Agency Maintenance Cost	5	1	1	3	9	1						9								
	Acceptable Asset Condition	5	3	1	9		9						3								
Social	Foster Livability	3	3					9	3	1	9	3	3	9							
	Jobs Creation	3											3	1	9						
	Improve Safety	5	3		1			3	9	9	9	9	3	3							
		% in Group	72%	28%	39%	22%	22%	18%	23%	21%	41%	15%	68%	15%	17%	20%	20%	40%	20%	50%	50%
		Overall Rank	3	11	2	5	4	7	12	14	6	16	1	15	12	16	16	8	16	8	8

Figure 3.2 QFD Matrix for Multi-Objective Sustainability Model

3.2 Performance Measures Selected from the QFD Matrix

Vehicle

In the vehicle category, "Section Average Daily Traffic" and "Distribution of Vehicle Classes" are selected as the input variables for the Multi-Objective Sustainability (MOS) model and will be used in the environmental module to estimate CO_2 emissions based on the pavement condition.

Physical infrastructure

"Pavement Condition Index" and "Pavement Remaining Service Life" are current output variables in the StreetSaver® software, and "Fuel Consumption Based on Pavement Condition" and Section Livability Characteristics" are added as sustainability performance measures.

Safety

Safety related performance measures include crashes due to speeding, impaired driving, physical infrastructure characteristics such as distance between pedestrian crosswalks, existence of protected bikeways, fatality risk for pedestrians and bicyclists, and improvements in areas that have reported crashes. After evaluating the measures versus the desired objectives, the selected performance measures to represent safety are "Crashes Involving a Pedestrian or Bicyclist on a Section" and "Distance between Pedestrian Crosswalks".

Agency

"Agency Expenditures" and "Jobs Created" are selected as the performance measures in this category.

Pollutants

All pollutants had a significant relationship with the objective of reducing vehicle emissions. "Carbon Dioxide" (CO_2) is selected because it accounts for 95% of mobile-source emissions (SHRP 2013). To estimate CO_2 emissions, the fuel consumed by vehicles is multiplied by emission factors that have been established by the Intergovernmental Panel on Climate Change (IPCC 2006).

User Costs

User costs from using the transportation infrastructure network are assessed through the "Social cost of CO_2" which estimates the "changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (Interagency Working Group on Social Cost of Carbon, United States Government 2013).

3.3 Summary

As a result of the QFD matrix selection process, a summary of the performance measures selected for the MOS model are shown in Figure 3.3.

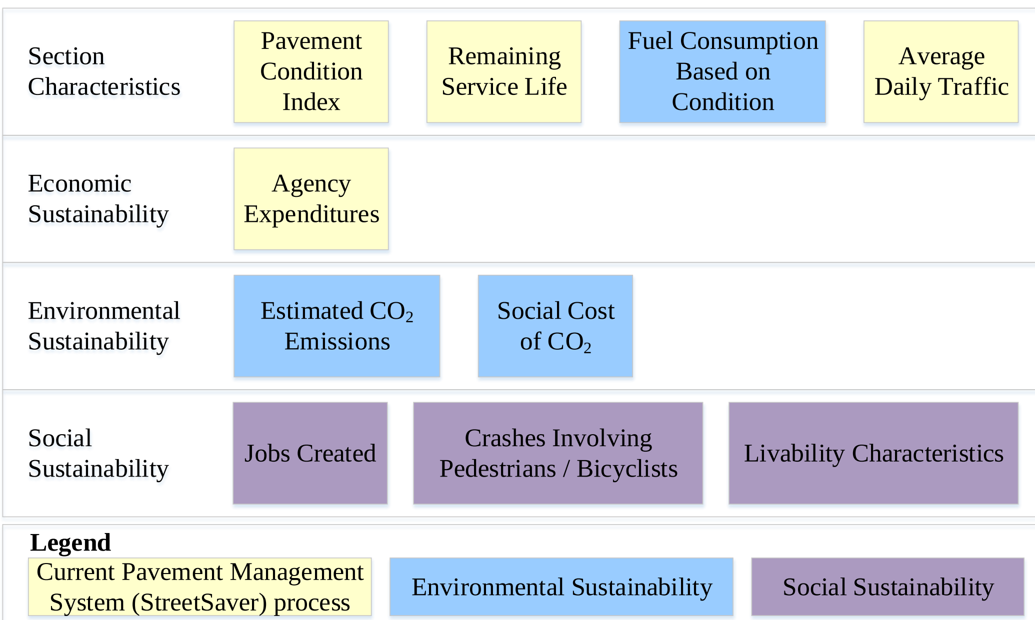


Figure 3.3 Selected Performance Measures from the QFD matrix

Existing pavement performance measures such as Pavement Condition Index (PCI), remaining service life (RSL), average daily traffic (ADT) and agency expenditures are considered in the model used by StreetSaver®. Fuel consumption based on pavement condition, CO_2 emissions and their corresponding social costs are added into the model. Social sustainability is also described by: new jobs created by infrastructure improvement projects, crashes involving pedestrian and bicyclists, and livability characteristics.

Chapter 4: Development of the Multi-Objective Sustainable (MOS) Model

Transportation Asset Management (TAM) considers various asset classes. For the multi-objective sustainable (MOS) model, the following assets are included:

- Pavements
- Sidewalks
- Buffers
- Crosswalks

The multi-objective sustainable (MOS) model builds upon an existing pavement management system, and expands to other roadway assets (sidewalks, buffers, crosswalk). Sidewalks provide a paved designated place for pedestrians to walk and therefore are important for overall walkability and livability. Buffers divide sidewalks from travel lanes and increase pedestrian's comfort and perceived safety, therefore a buffer width is included in the model. Since crosswalks are crucial to pedestrian safety and walkability, the spacing between crosswalks is also considered in the model. Desired livability characteristics are defined by minimum sidewalk width, minimum buffer width, and maximum crosswalk spacing. Assets that do not satisfy the desired livability characteristics are below the livability threshold and become candidates for improvement.

4.1 Integration of the Multi-Objective Sustainable Model into StreetSaver

The MOS model aims to complement an existing Pavement Management System, StreetSaver®, developed by the Metropolitan Transportation Commission in Oakland, CA.

"The MTC StreetSaver™ Pavement Management Program Software was developed to provide decision support tools related to pavement assets for local agencies. It includes the following major elements:

a. Inventory of basic data related to existing pavements

b. Condition assessment and calculation of the PCI for pavement surfaces

c. *Determination of work needed (programmed maintenance, rehabilitation, and reconstruction) and funds required to complete that work*

d. *Identification of candidate projects that would provide the best return on funds allocated to work on existing pavements*

e. *Analysis of several measures of impacts from various alternative funding scenarios*

f. *Determination of current value of pavements using the GASB straight-line approach*

g. *Database management needed to enter, store, retrieve, and generate reports related to the above"* (Smith 2014).

The StreetSaver® process with the proposed enhancements to incorporate sustainability is shown in Figure 4.1.

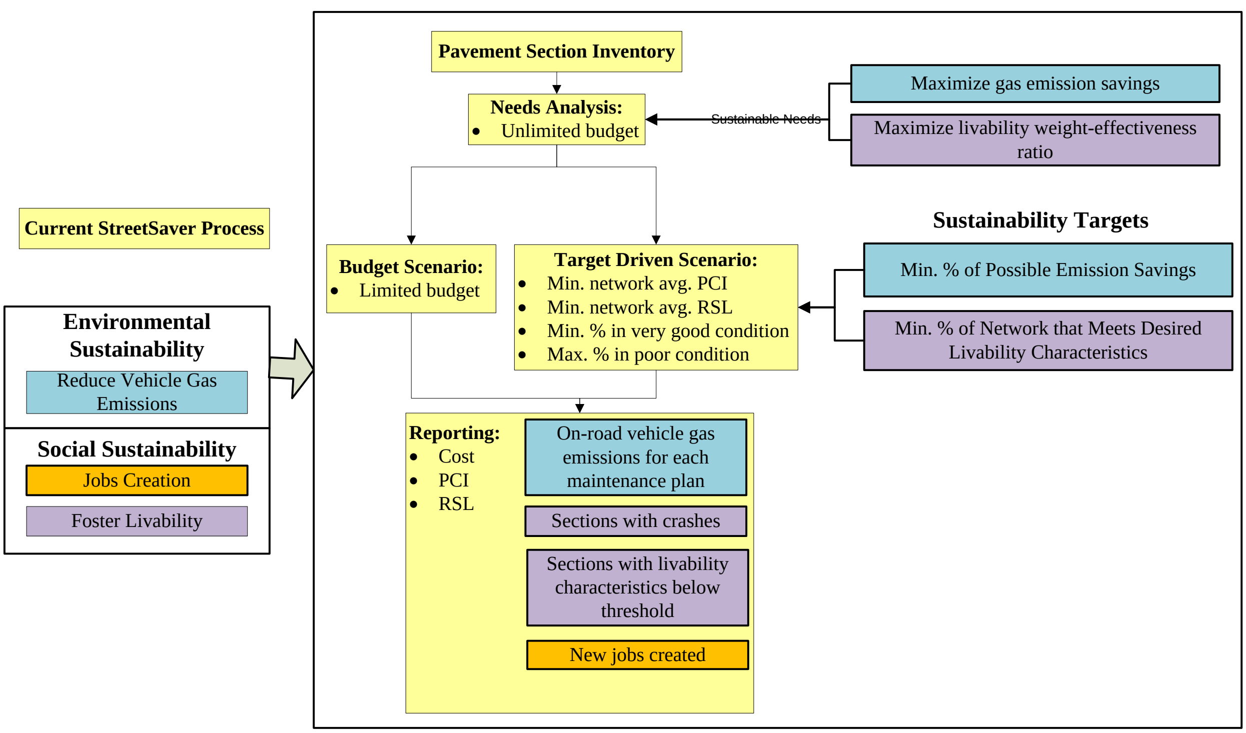


Figure 4.1 Multi-Objective Sustainable Model Overall Framework

The individual modules are discussed in the following section.

Inventory and Condition Assessment

The inventory includes information about individual assets, such as their location, material, construction date, inspection history, and condition. Current condition is assessed and projected to the future to identify the maintenance treatments over the planning period. The MOS model assumes that inventories and condition assessment methodologies already exist for pavements, sidewalks, buffers, and crosswalks.

Needs Analysis

The first step is to identify the network treatment and budget needs to preserve the infrastructure transportation network in an optimal level of service over the period of analysis. No funding constraints are included in the analysis process. At present, StreetSaver® only considers the pavement condition in the criteria for the needs analysis. In the MOS model, the current needs estimation is extended to quantify *Sustainable Needs* based on environmental and social sustainability goals. After running the needs analysis, alternative Target-Driven, and Budget-Driven scenarios analyses are conducted to quantify the impact on performance of different maintenance and rehabilitation strategies and funding constraints.

Target-Driven Scenario

Target-Driven Scenario currently addresses four targets: minimum PCI, minimum remaining service life, minimum percentage of network in very good condition, maximum percentage of network in poor condition. Two sustainability target objectives are added to address environmental and social sustainability goals:

- % of maximum possible emission savings (compared to Do Nothing Scenario)
- % of network that meets desired livability characteristics or requirements

Budget Scenario

Budget Scenario considers a limited budget for maintenance treatments and predicts pavement condition index (PCI) and remaining service life under the available budget. All maintenance projects are ranked based on weight-effectiveness ratio (WER) that takes into account the functional class, treatment annualized cost (EUAC), and treatment effectiveness (condition improvement and service life extension after treatment) (Smith 1996).

The *Sustainable Budget Scenario* prioritizes available funding considering environmental and/or social sustainable goals. In the MOS model, WER calculation for pavements stays unchanged, however there is a new concept introduced to rank the other assets (sidewalks, buffers, crosswalks) based on livability. WER_{LIV} depends on asset importance due to location, EUAC, and remaining service life after improvement.

The MOS model can be applied considering two budgets: one budget for pavements and another for sidewalks, buffers and crosswalks, since roadway maintenance and rehabilitation funding is often separate from pedestrian improvements due to different local, state, and federal funding sources. However, project prioritization can be based on independent rankings when considered projects for funding allocation, or a combined ranking method could be used to identify network sections in need of both pavement treatments and non-pavement improvements.

Project network level coordination

Pavement sections that are selected for a treatment and in need of improvement in sidewalk/buffer/crosswalk can be assigned a higher priority in the overall ranking. A combined Weight Effectiveness Ratio (WER_{COMB}), which includes WER (pavements) with WER_{LIV} (sidewalks, buffers, crosswalks), is calculated using the following formula:

$$WER_{COMB} = x\, WER + y\, WER_{PAV}$$

In this formula, *x* and *y* are weighting coefficients defined by the decision maker, and as default values x=1 and y=1 are used.

Reporting

Currently, results of the scenario analysis are shown in various reports including maintenance costs, predicted pavement condition index (PCI), and remaining service life. In order to address the sustainability objectives, reports will also include:

- Estimation of on-road vehicle gas emissions
- Sections with crashes since the last treatment
- Sections with livability characteristics below threshold values
- Estimation of new jobs created

Figure 4.2 shows a flowchart with the sustainable objectives and their connection to the current StreetSaver® process.

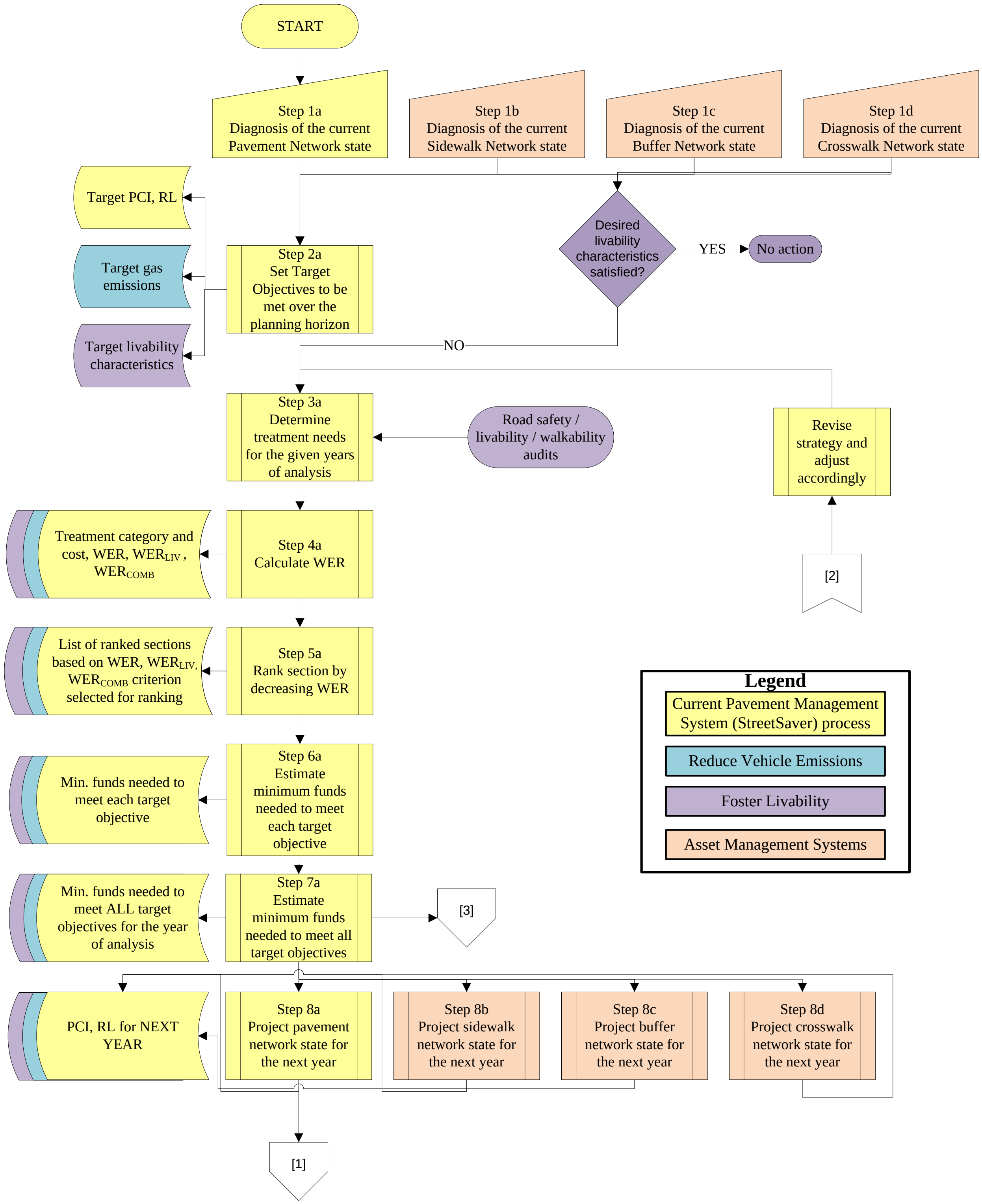


Figure 4.2 Flowchart with Current StreetSaver Processes Integrated with Enhanced Sustainability Target Performance Objectives

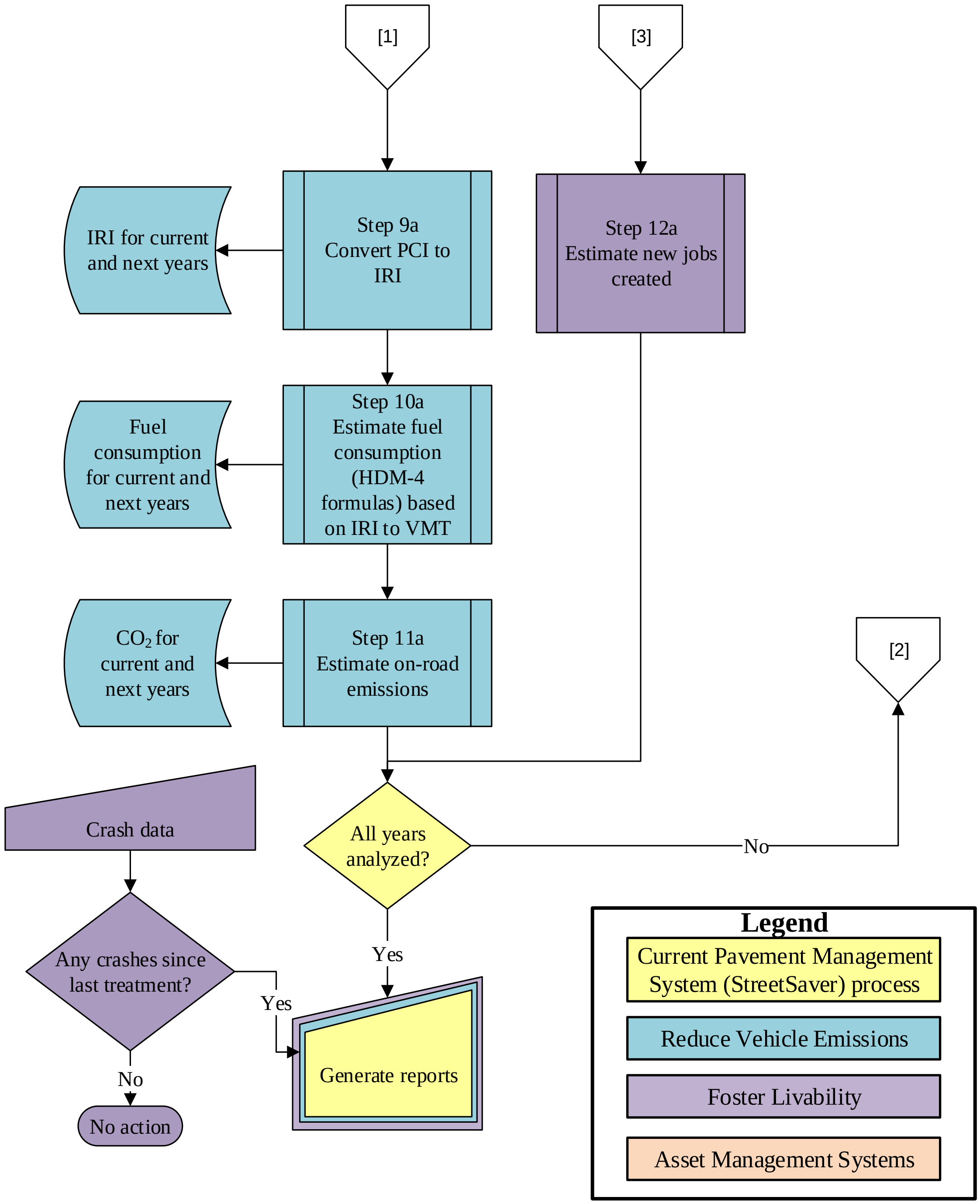


Figure 4.2 Flowchart with Current StreetSaver Processes Integrated with Enhanced Sustainability Target Performance Objectives (continued)

4.2 Target Objectives of the Multi-Objective Sustainable Model (MOS)

The MOS model aims to maintain the pavement network, sidewalks, buffers, and crosswalks at the desired network state at the minimum cost, while taking into account environmental and social target objectives expressed in terms of savings on gas emissions and livability characteristics. Parameters in Table 4.1 are used to characterize the transportation network state and to set targets over the planning horizon. For the purpose of this study, the enhanced sustainability targets are defined at the network level, however they could be also expanded as targets for individual functional classes (e.g. arterial, collector, residential/local, other).

Table 4.1 StreetSaver current targets with enhanced sustainability targets

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life	Minimum Percentage of the Pavement Network Group in Very Good Condition	Maximum Percentage of the Pavement Network Group in Poor Condition	% of Maximum Possible Emission Savigns (compared to Do Nothing Scenario)	% of Sidewalks that Meet Desired Livability Characteristics	% of Buffers that Meet Desired Livability Characteristics	% of Crosswalks that Meet Desired Livability Characteristics
Entire Network	b_1	b_2	b_3	b_4	b_{30}	b_{40}	b_{50}	b_{60}
Arterial	b_5	b_6	b_7	b_8	-	-	-	-
Collector	b_9	b_{10}	b_{11}	b_{12}	-	-	-	-
Residential/Local	b_{13}	b_{14}	b_{15}	b_{16}	-	-	-	-
Other	b_{17}	b_{18}	b_{19}	b_{20}	-	-	-	-

Note: Yellow: current StreetSaver targets, blue: environmental sustainability targets, purple: social sustainability targets.

4.3 Mathematical Formulation of the Multi-Objective Sustainable Model

The sustainability considerations added to the current StreetSaver process, as shown in Figure 4.1 include:

Sustainability Goal I: Maximize gas emissions savings S:

Maximize S: $\sum_{i=1}^{N} \Delta E_i * X_i$

subject to:

Sustainability Target I: % of Maximum possible potential emission savings

$$\frac{E_D - \sum_{i=1}^{N}(E_{Di} - E_{Ti}\, X_i)}{\sum_{i=1}^{N} E_{Di}} \geq \; b_{30}$$

where:

S ……… objective function for maximizing CO_2 emission savings

X_i ……… 0 if section *i* is not selected for a treatment, 1 otherwise

E_{Di} ……… CO_2 emissions estimated based on a section condition when no treatment is applied

E_{Pi} ……… potential CO_2 emission savings estimated as a difference between Do Nothing (E_D) and Needs Scenario (E_N)

E_N ……… CO_2 emissions total estimated for a Needs scenario (ideal situation)

b_{30} ……… maximum percentage of emissions target produced above Needs

Sustainability Goal II: Maximize weight-effectiveness livability ratio (WER_{LIV})

Maximize L: $\sum_{j=1}^{m} WER_{LIVj}\, X_j + \sum_{k=1}^{q} WER_{LIVk}\, X_k + \sum_{l=1}^{r} WER_{LIVl}\, X_l$

subject to:

Sustainability Target II-a: Percentage of sidewalks that meet the desired livability characteristics:

$$\sum_{j=1}^{m} l_{j42} + p_{j41} X_j \geq \; b_{40}$$

Sustainability Target II-b: Percentage of buffers that meet desired livability characteristics

$$\sum_{k=1}^{q} l_{k52} + p_{k51}X_k \geq b_{50}$$

Sustainability Target II-c: Percentage of crosswalks that meet desired livability characteristics

$$\sum_{l=1}^{r} c_{l62} + p_{l61}X_l \geq b_{60}$$

where:

L	………	objective function for maximizing livability characteristics
WER_{LIVj} WER_{LIVk} WER_{LIVl}	………	weighted effectiveness livability ratio of asset *j, k, l*
X_j,X_k,X_l	………	0 if asset *j, k, l* is not selected for a treatment, 1 otherwise
l_{j42}	………	sidewalk *j* length with unsatisfactory width
p_{j41}	………	sidewalk *j* length moved to satisfactory width due to improvement
b_{40}	………	% of sidewalks meeting desired livability characteristics
l_{k52}	………	buffer *k* length with unsatisfactory width
p_{k51}	………	buffer *k* length moved to satisfactory width due to improvement
b_{50}	………	% of buffers meeting desired livability characteristics
c_{l62}	………	crosswalk *l* with unsatisfactory spacing
p_{l61}	………	crosswalk *l* length moved to satisfactory width due to improvement
b_{60}	………	% of crosswalks meeting desired livability characteristics

4.4 Framework for Environmental Sustainability

The framework for environmental sustainability focuses on pavement assets that carry motorized vehicles. Transportation produces 27% of all emissions, electricity 31%, industry 21%, commercial and residential 12%, and agriculture accounts for 9% of all CO_2 emissions emitted in the U.S. in 2013 (EPA 2015a). Vehicle fuel consumption and related gas emissions depends on several variable including but not limited to fuel, engine, vehicle weight, tire pressure, speed, and driving style. Several studies (Watanatada et al. 1987, FHWA 2000, Chatti and Zaabar 2010, Lidicker at el. 2013, Greene at al. 2013) suggest a tangible relationship between pavement roughness and fuel consumption. Therefore, fuel consumption and gas emissions are estimated from pavement roughness condition.

Input Data

Data used to estimate gas emissions are shown in Table 4.2.

Table 4.2 Overview of input data for environmental sustainability framework

Description	**Source**
Pavement condition (PCI)	Inspection
International Roughness Index [in/mi,m/km]	Relationship between PCI and IRI (Dewan 2002, Park et el. 2007)
VMT for analyzed sections	StreetSaver
Speed [mph, kph]	Generalized, assumed constant 70 mph and medium size vehicle
Fuel consumption [mL/km]	HDM-4 estimates based on IRI (Chatti and Zaabar 2010)
Lower heating value [gigajoule per liter]	American Petroleum Institute
Carbon emission factor [kg CO_2 per gigajoule]	Intergovernmental Panel on Climate Change (IPCC 2006)
Social cost of CO_2 [$ per metric ton of CO_2]	Interagency Working Group on Social Cost of Carbon (United States Government 2013)

Methodology

Fuel consumption of a vehicle is correlated with pavement condition (Watanatada et al. 1987, FHWA 2000, Chatti and Zaabar 2010, Lidicker at el. 2013, Greene at al. 2013). Rolling resistance is one of several forces that affect the vehicle fuel consumption. However, in urban areas where the speed limits are 30 mph (48km/h) for residential streets, and 35-45 mph (56-72 km/h) for arterials (City of El Paso 2005); the effect of rolling resistance is larger than internal friction or air drag as shown in Figure 4.3.

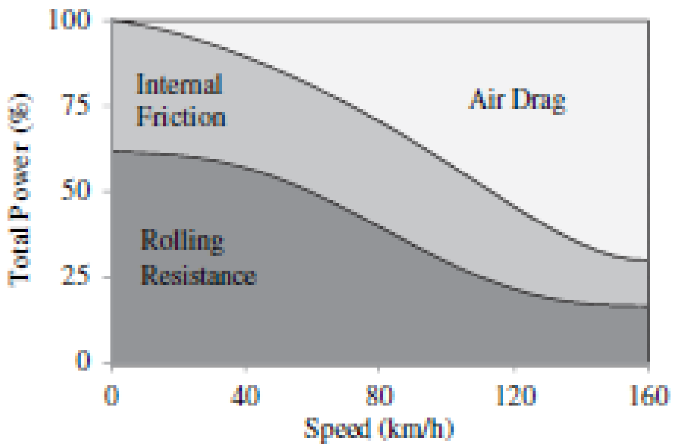


Figure 4.3 Energy Distribution in a Passenger Car versus Speed. (Chatti and Zaabar 2010)

Residential streets are expected to carry less than 1,000 vehicles per day, collectors 1,000-8,000 vehicles per day, and arterials 4,000-45,000 vehicles per day (Fort Worth 2009). Residential streets carry on 68.6% of the total mileage on the U.S. roads, collectors 20.5%, arterials 9.5%, and the remaining mileage is carried by interstates and freeways (FHWA 1996).

It is a considered that the better the pavement condition is (lower roughness), the lower the vehicle gas consumption will be; therefore emissions are reduced when maintaining pavements in good condition. Although, there are several other factors influencing the vehicle gas consumption such as fuel, engine, vehicle weight, tire pressure, speed, driving style; generalizations are made to estimate the vehicle gas emissions for network level management decisions.

The Pavement Condition Index (PCI) and International Roughness Index (IRI) are the most popular indices to define the pavement condition. PCI is defined as “a measure of the present condition of the pavement based on the distress observed on the surface of the pavement, which also indicates the structural integrity and surface operational condition (localized roughness and safety)” (ASTM D6433−11). PCI ranges from 0 (worst condition) to 100 (best possible condition). IRI is “an index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h)” (ASTM E867−06). These two measures are not directly related since they are intended to evaluate two different aspects of pavement performance (condition, serviceability), however there are studies developed in attempt to find a relationship between PCI and IRI (Dewan 2002, Park et el. 2007). Some of the equations over predict the IRI value for PCIs below 50, and the results of the PCI-IRI equation are not reliable throughout the entire interval of PCI 0 to 100.

For the MOS model a simplification is made using as a reference IRI condition levels defined in the NCHRP Report 713 Estimating Life Expectancies of Highway Assets (Thompson et al. 2012) and the Mechanistic-Empirical Pavement Design Guide (AASHTO 2008). IRI condition levels in NCHRP 713 (Thompson et al. 2012) consider IRI ≤ 60 in/mi as very good, $60<IRI\leq94$ as good, $94<IRI\leq170$ as fair, $170<IRI\leq220$ mediocre, and $IRI > 220$ as poor. Mechanistic-Empirical Pavement Design Guide (AASHTO 2008) classifies pavement condition into five categories (excellent, good, fair, poor, very poor), while only the last three categories have IRI thresholds: $IRI>120$ in/mi for fair condition, $IRI > 170$ for poor condition, and $IRI > 220$ for very poor condition.

Table 4.3 shows the adjusted conversion between PCI and IRI for the MOS model using expert judgement since the NCHRP and AASHTO values seem to be too strict for urban streets.

Table 4.3 PCI to IRI adjusted conversion.

<table>
<tr><th rowspan="2">Pavement condition levels</th><th>StreetSaver PCI condition levels</th><th>IRI condition levels (NCHRP 713)</th><th>IRI condition levels (AASHTO 2008)</th><th colspan="3">MOS model Adjusted Conversion</th></tr>
<tr><th>PCI</th><th>IRI [in/mi]</th><th>IRI [in/mi]</th><th>PCI</th><th>IRI [in/mi]</th><th>IRI [m/km]</th></tr>
<tr><td rowspan="4">Good</td><td rowspan="4">70 < PCI</td><td rowspan="4">IRI < 94
(IRI < 1.49 m/km)</td><td rowspan="4">undefined</td><td>100</td><td>30</td><td>0.5</td></tr>
<tr><td>90</td><td>61</td><td>1.0</td></tr>
<tr><td>80</td><td>93</td><td>1.5</td></tr>
<tr><td>71</td><td>121</td><td>1.9</td></tr>
<tr><td rowspan="3">Fair</td><td rowspan="3">70 > PCI < 50</td><td rowspan="3">94< IRI <170
(1.49 <IRI< 2.7 m/km)</td><td rowspan="3">undefined</td><td>70</td><td>124</td><td>2</td></tr>
<tr><td>60</td><td>156</td><td>2.5</td></tr>
<tr><td>51</td><td>185</td><td>2.9</td></tr>
<tr><td rowspan="4">Poor</td><td rowspan="4">50 < PCI < 25</td><td rowspan="4" colspan="2">170 < IRI < 220
(2.7 < IRI < 3.5 m/km)</td><td>50</td><td>188</td><td>3.0</td></tr>
<tr><td>40</td><td>215</td><td>3.4</td></tr>
<tr><td>30</td><td>242</td><td>3.8</td></tr>
<tr><td>26</td><td>249</td><td>3.9</td></tr>
<tr><td rowspan="2">Very Poor</td><td rowspan="2">25 < PCI < 0</td><td rowspan="2" colspan="2">IRI > 220 *(IRI > 3.5 m/km)*</td><td>25</td><td>255</td><td>4.0</td></tr>
<tr><td>0</td><td>380</td><td>6.0</td></tr>
</table>

In practice, transportation agencies using PCI as the primary index in their TAM should develop their own relationship between PCI and IRI, or add IRI as one of the primarily collected measures. Alternatively, agencies could estimate IRI from the asset value. The HDM-4 study developed formulas to estimate asset value (AV) as a function of terminal IRI (TIRI), current IRI (CIRI), and initial IRI (IRI0) (Bennett 2000):

$$AV = \max(0,(TIRI - CIRI)) / (TIRI - IRI0) * \text{initial cost of pavement}$$

However, more research is needed to demonstrate if that relationship can be used for urban streets. In the next step, IRI is associated with fuel consumption using HDM-4 estimates calibrated for U.S. conditions (Chatti and Zaabar 2010), as Table 4.4 shows.

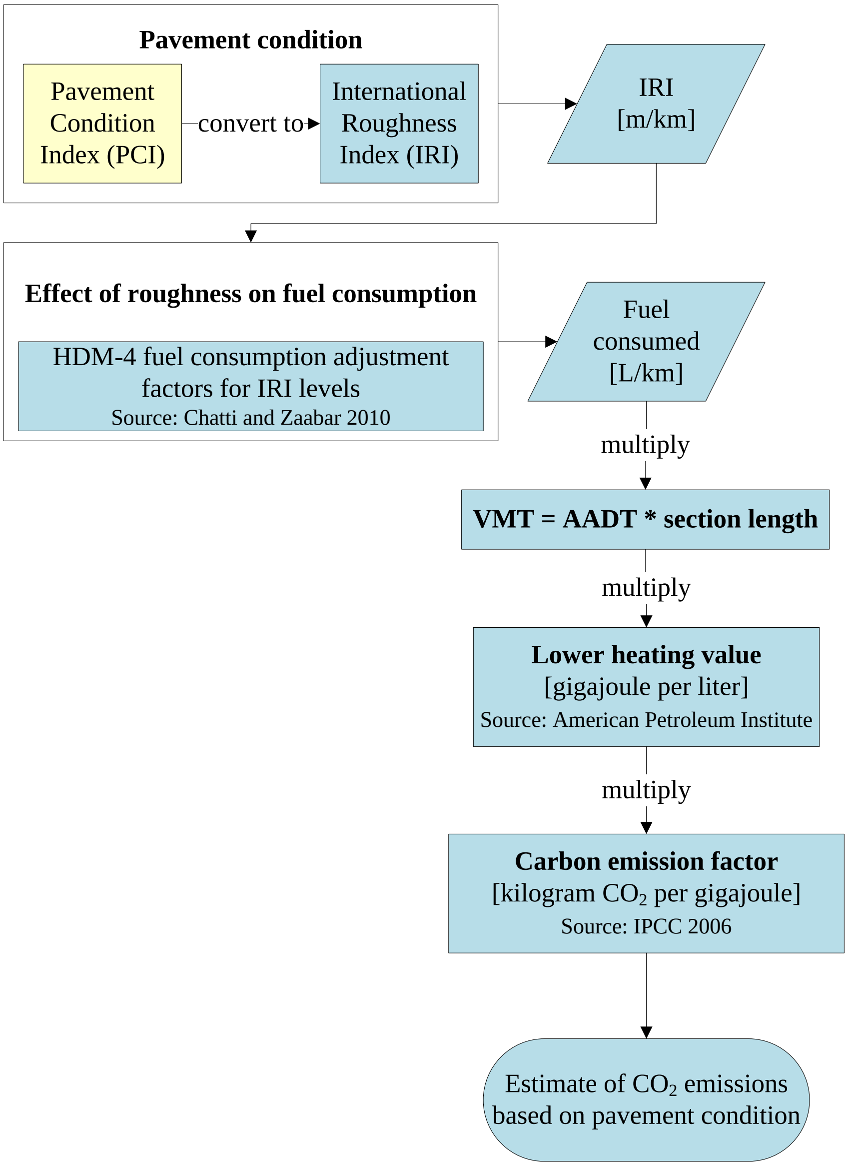
Table 4.4 Effect of roughness on fuel consumption. (Chatti and Zaabar 2010)

Speed	Vehicle Class	Calibrated HDM 4 model					
		Base (mL/km)	Adjustment factors from the base value				
		IRI (m/km)					
		1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13
	Van	76.99	1.01	1.02	1.03	1.04	1.05
	SUV	78.69	1.02	1.05	1.07	1.09	1.12
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11
88 km/h (55 mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13
	Van	96.98	1.01	1.02	1.03	1.04	1.05
	SUV	101.29	1.02	1.04	1.07	1.09	1.11
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08
112 km/h (70 mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12
	Van	128.96	1.01	1.02	1.03	1.03	1.04
	SUV	140.49	1.02	1.04	1.06	1.08	1.10
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06

$$\text{mpg} = \frac{2352}{\text{mL/km}}$$

CO_2 is chosen to represent the overall emissions since it accounts for 95% of mobile-source emissions (SHRP 2013). CO_2 emissions for gasoline, diesel, biogasoline, biodiesel, natural gas, and propane by multiplying the fuel consumed by gas emission factors established by Intergovernmental Panel on Climate Change (IPCC 2006).

Figure 4.4 summarizes the process of estimating CO_2 emissions from motorized vehicles on a pavement section of a certain condition.



Note: Yellow: current StreetSaver targets, blue: environmental sustainability targets

Figure 4.4 Process to Calculate CO_2 Estimation using IPCC Emissions Factors.

The formula to estimate the CO_2 emissions based on pavement condition is:

$$CO_2\ emissions = \sum_{i=1}^{N} PCI_i * length * \ fuel_{factor} \ * AADT_i * LHV * CEF$$

where:

PCI_i	....	pavement condition of section *i*
$length_i$	....	section *i* length
$fuel_{factor}$	....	fuel consumption factor based on pavement condition, estimated based on HDM-4 fuel consumption factors (Chatti and Zaabar 2010)
$AADT_i$	....	annual average daily traffic at section i
LHV	....	lower heating value (American Petroleum Institute)
CEF	....	carbon emission factor (IPCC 2006)

An alternative way is to use the Environmental Protection Agency models EMFAC2014 (for CA, Emission Factors) or MOVES2014a (rest of U.S., Motor Vehicle Emission Simulator), to estimate CO_2, hydrocarbons, oxides of nitrogen, and particulate matter. MOVES 2014a includes thirteen vehicle types, six fuel types, urban and rural roads; and it can model various geographic bounds (national, state, or county), and vehicle activities (driving, idling and parking) (EPA 2015b).

Finally, CO_2 emissions are converted to dollars using estimates for 2010-2050. Federal agencies such as EPA use the "Social Cost of Carbon" (SCC) to estimate the benefits (value of damages avoided) of CO_2 reductions. The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. There are several integrated assessment models (DICE FUND, PAGE) that estimate the SCC based on various factors, including predicted space heating, sea level rise, land loss, gross domestic product, and population. United States Government Interagency Working Group on Social Cost of Carbon developed original U.S. government's SCC estimates based on simulations of five scenarios at three discount rates, using three different models (DICE, FUND, PAGE), and finally decided to use for regulatory analysis the values shown in Table 4.5 (Interagency Working Group on Social Cost of Carbon, United States Government 2013).

Table 4.5 Social Cost of CO_2, 2010-2050, in 2007 Dollars per Metric Ton of CO_2
(Interagency Working Group on Social Cost of Carbon, United States Government 2013)

Discount rate / **Year**	**5.0%**	**3.0%**	**2.5%**
2010	$ 11	$ 33	$ 52
2015	$ 12	$ 38	$ 58
2020	$ 12	$ 43	$ 65
2025	$ 14	$ 48	$ 70
2030	$ 16	$ 52	$ 76
2035	$ 19	$ 57	$ 81
2040	$ 21	$ 62	$ 87
2045	$ 24	$ 66	$ 92
2050	$ 27	$ 71	$ 98

Table 4.6 shows that different fuel types produce different amount of CO_2 emissions. The most CO_2 is produced by burning a gallon of diesel fuels (EIA 2015).

Table 4.6 CO_2 produced by fuel burning (U.S. Energy Information Administration 2015)

Fuel type	**CO_2 emissions** (1 metric ton = 2000 lb)
Gasoline (without ethanol)	19.64 lb/gal
E10 (gasoline with 10% ethanol)	17.68 lb/gal
Diesel	22.38 lb/gal
Pure ethanol	12.72 lb/gal
B20 (20% biodiesel, 80% petroleum diesel fuel)	20.22 lb/gal
B100 (100% biodiesel)	20.13 lb/gal

Output

CO_2 emissions are calculated for a Do-Nothing scenario and the alternative Target-Driven or Budget-Driven scenarios under consideration. It is expected that the Needs Analysis (unlimited budget) will yield the highest reduction in CO_2 emissions when compared to a Do-Nothing scenario. This reduction is considered the optimal situation with the highest savings on gas emissions. Reduction in CO_2 is then calculated for each pavement maintenance scenario.

Hence, the agency costs spent on maintenance as well as the social costs of CO_2 are reported for the scenarios under consideration.

4.5 Framework for Social Sustainability

The social sustainability framework brings a more holistic approach to transportation asset management decisions. When developing a pavement maintenance plan, not only the pavement condition and resulting gas emissions should be considered, but also:

- Job creation: based on the cost of maintenance treatments, new jobs created are estimated and included in the reports for the scenarios under consideration.
- Livability: improvements on sidewalks, buffers, and crosswalks as identified by road safety audits and livability assessments are prioritized for funding allocation. Pavement sections with crashes that involved a motorized vehicle, a bicyclist, or a pedestrian since the last maintenance treatment are reported.

4.5.1 Sub-model for Job Creation Estimates

Maintenance jobs create significant amount of blue-collar jobs that helps to reduce unemployment rates of vulnerable populations. In this module, jobs creation is estimated from the funding allocated to maintenance each year of the analysis period.

Input Data

Data used for the estimates are shown in Table 4.7.

Table 4.7 Overview of input data for job creation estimates

Description	Source
Median jobs per $1M of maintenance project	SHRP Report S2-C03-RR-1 (construction only, 5 to 90 jobs per $1M), San Jose Memorandum 2013 (construction only, 18 jobs per $1M), NYSDOT website (construction only, 24 jobs per $1M)

As Figure 4.6 shows, funds allocated each year of the analysis are multiplied by the job creation factor determined by the agency. The Transportation California estimates that one billion dollars invested in road construction and maintenance creates 18,000 jobs. (City of San Jose 2013). The estimation of jobs created is shown in reports for each of the maintenance strategies or budget scenarios, as shown in Figure 4.5.

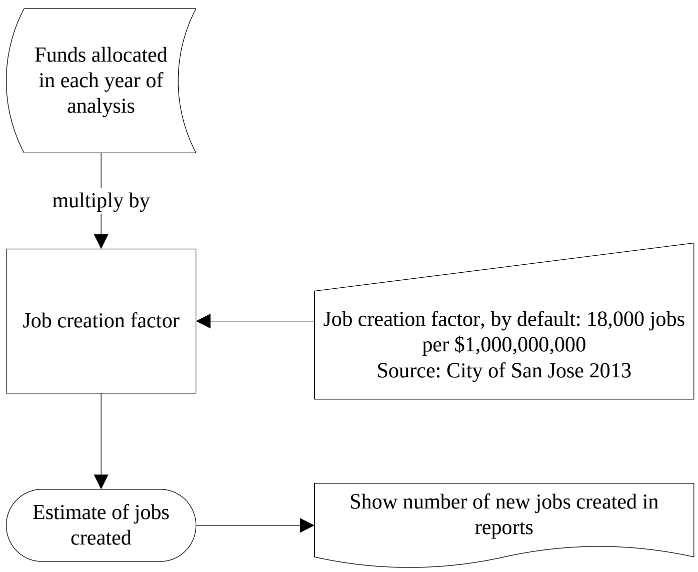


Figure 4.5 Process of Job Creation Estimation.

City of Los Altos - Asset

Needs - Projected PCI/Cost Summary

Inflation Rate = 0.00 % Printed: 11/20/2015

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost	Jobs Created
2015	83	77	$3,195,341	$3,553,996	$6,749,337	121
2016	83	75	$1,030,587	$1,071,679	$2,102,266	37
2017	83	74	$186,422	$1,186,806	$1,373,228	24
2018	83	73	$425,872	$1,036,436	$1,462,308	26
2019	83	71	$183,016	$526,833	$709,849	12

% PM	PM Total Cost	Rehab Total Cost	Total Cost	Total Jobs Created
40.50%	**$5,021,238**	**$7,375,750**	**$12,396,988**	220

Figure 4.6 Reporting of Job Creation Estimation.

Mathematical Formulation

$$jobs = cost_{total} * factor_{jobcreation}$$

4.5.2 Sub-model for Livability

Several cities have adopted complete street guidelines to accommodate motorized vehicles as well as pedestrians, and bicyclists. San Francisco adopted a Better Streets Plan in 2010 to foster streets that will be “memorable, support diverse public life, vibrant places for commerce, promote human use and comfort, promote healthy lifestyles, safe, create convenient connections, ecologically sustainable, accessible, as well as attractive, inviting and well-cared for”. The livability sub-model is inspired in the Better Streets Plan but focusing entirely on active transportation as a preliminary network level evaluation conducted to identify any possible gaps between the desired livability characteristics and the current state. Livability indicators (Schlossberg 2006) are described by four aspects:

- Connectivity
- Quality
- Proximity
- Safety

Connectivity

Connectivity is characterized by block length and intersection density, indicating the opportunities for a pedestrian to cross the street. Connectivity is described by graph theory where different types of links are used to model the traffic volume and infrastructure characteristics (Dill 2004, Zhang and Kukadia 2005, Gori 2014). Unlike roads that are constructed by a city, sidewalks are often fully or partially financed by property owners, which does not promote continuity, connectivity, or a use of adequate buffers, width, and edges. Burden (2001) considers that streets are more than just a place for moving and storing vehicles. To do so, street blocks shorter than 600 ft. are recommended to improve network transportation connectivity and to discourage speeding. In addition, distances can be shortened in existing neighborhoods by converting back alleys, utility corridors and waterways into pedestrian zones (Burden 2001) in order to make walking to schools, parks and shopping centers possible and practical. In addition, alleys and other access ways for non-motorized traffic can improve connectivity in neighborhoods with large blocks (Los Angeles County 2011).

Quality

Quality of the infrastructure is captured by the width and physical condition of sidewalk, crossings, and visibility of pavement markings. Pedestrians also appreciate visual interests along their route (Park et al. 2014), such as art installations, rest areas with benches, and proximity to shopping opportunities. Several cities build shopping centers and supermarkets right next to transit centers to reduce the perceived waiting time as well as shorten walking distances and offer users the opportunity to congregate their trips, where shopping can be done on their way from work without the need to make a separate trip. The quality of walking experience is also influenced by the buildings surrounding the sidewalk, their height compared to street width, transparency of first floors, existence of parking lots between a sidewalk and a building and other urban planning factors (Park et al. 2014) not directly related to transportation asset management.

Proximity

Proximity represents the pedestrian catchment area, indicating if the locations where pedestrians need to go are within their maximum acceptable walking distance, e.g. ¼ mile (Gori 2014).

Safety

Safety is another important factor for pedestrians in the decision whether to walk or drive. Not only traffic safety related to crashes, ease of crossing and traffic speed, but also fear of crime is included in their decisions (Park et al. 2014). Users value features such as perceived safety and separation from high speed traffic, and bicycle parking in front of activity centers and transit stops (Nuworsoo 2013).

Input Data

This study will focus on quality and safety in its livability sub-model. For illustration purposes, four assets that address needs of pedestrians, such as sidewalks, crosswalks, buffers, and lightings are included. In future research, it is desirable to include also assets for bicyclists. Figure 4.7 shows an example of the input data categories needed in the livability sub-model. Data categories include quality, safety, and additional two categories to account for roadway sections characteristics and other features (construction cost, maintenance cost, and remaining service life).

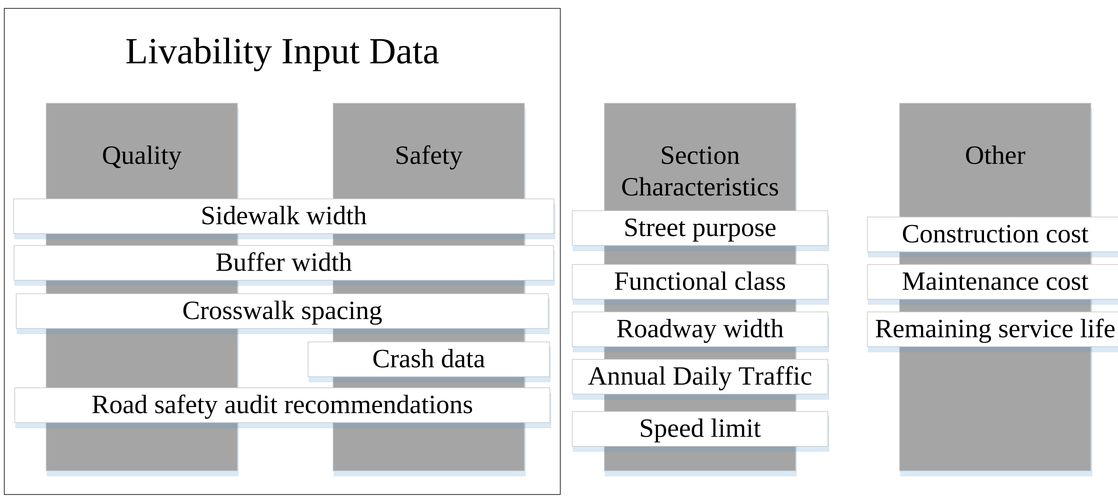


Figure 4.7 Livability Input Data with Roadway Section Characteristics and Other Data

Table 4.8 shows an overview of the data format for the livability sub-model. Most of the data already exist in asset inventories for sidewalks, buffers, and crosswalks (pavement markings). The livability sub model process to prioritize projects is shown in Figure 4.8.

Table 4.8 Overview of data format for livability sub-model

Quality	
Description	**Format**
Existing sidewalk characteristics:	Width [ft]
Existing buffer characteristics:	Width [ft]
Existing crosswalk characteristics:	Spacing [ft]
Desired sidewalk characteristics:	For purpose types and functional classes – desired width
Desired buffer characteristics:	For purpose types and functional classes – desired width
Desired crosswalk characteristics:	For purpose types and functional classes – desired spacing
Safety	
Description	**Format**
Crash data	Transportation Injury Mapping System (TIMS), TransBase
Road safety audit recommendations	Audit recommendations by local agencies
Livability/walkability audit recommendations	Audit recommendations by local agencies
Roadway Characteristics	
Description	**Format**
Section type	Purpose: access (safe routes to school, proximity of hospital / transit / shopping), general Functional class: arterial, collector, residential Roadway width [ft], traffic volume [ADT], speed limit
Cost and Service Life Data	
Construction cost	Agency records
Maintenance cost	Agency records
Remaining service life	Agency records

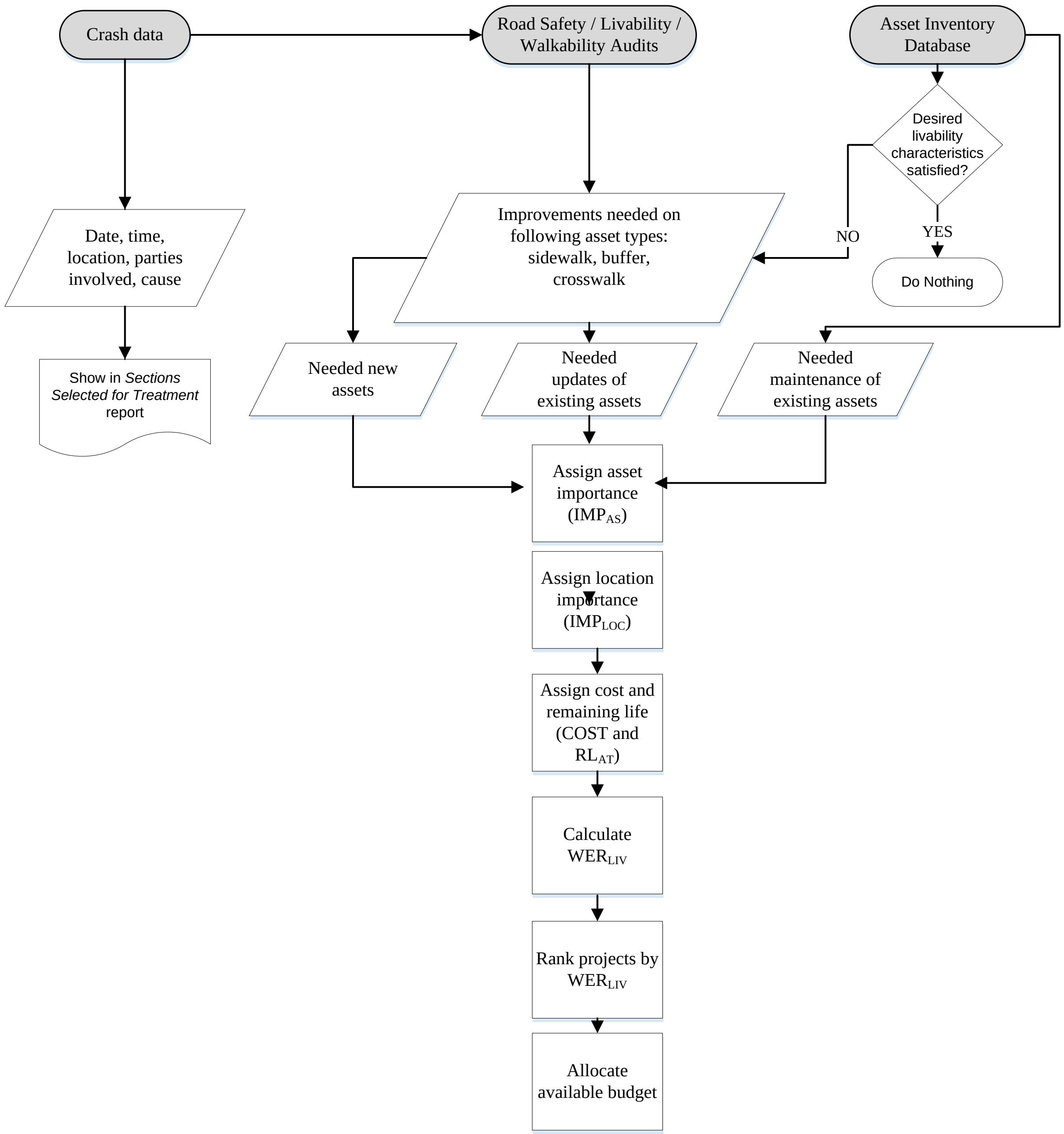


Figure 4.8 Livability Sub-model Processes to Prioritize Projects.

Quality and roadway characteristics data include inspections, condition predictions, life expectancy, and construction/maintenance costs. Safety data have two major sources: crash statistics, and audit recommendations. Crash data are found on enforcement reports, crashes involving motorists, pedestrians and bicyclists. Road safety, livability, walkability audits identify network deficiencies and improvements needed for the construction of new assets, and upgrade or maintenance of the existing assets.

Condition data of the assets (sidewalks, buffers, crosswalks) is not included in the livability sub-model, because it is assumed that these assets have their own inventories and condition inspections records. For that reason, the livability sub-model focuses on non-condition related features, such as asset width and spacing. Improvement projects for sidewalks, buffers, and crosswalks are prioritized based on its location, importance, cost of improvement, and the remaining service life after treatment (RL_{AT}).

Sidewalk width

According to livability principles, urban roadways (except roads where pedestrian access is prohibited) should have a sidewalk on both sides or at least a paved shoulder to enable pedestrian movement without forcing them to step into the travel lanes. Unlike street roads that are constructed by a city, sidewalks are often fully or partially financed by property owners resulting sometimes in lack of continuity, connectivity, or use of adequate buffers, width, and edges.

The desired sidewalk width can vary depending upon the section purpose, to account for proximity to schools, hospitals, transit stations, or retail that attracts higher pedestrian traffic activity. For example, streets in a one-mile radius around schools have specific requirements reflecting the “Safe Routes to School” principles to enhance the safety of children while promoting an active life-style. Safe routes to school reduce school-aged pedestrian fatalities by 44% (Dimaggio and Li 2013) and lead to an increase in active transportation to schools by 13% with a 15% reduction in gas emissions (Ewing and Greene 2003). Minimum width of a sidewalk that enables walking side by side is 5ft, but sidewalks in proximity of activity centers with higher pedestrian volumes demand 8 to 12 ft (Burden 2001). Downtown sidewalks are typically 20 to 30 ft wide (Burden 2001). In the MOS model, the desired sidewalk width depends on the functional class or street purpose, ranging from 5 ft. to 8 ft. Redundant utility poles or signs should be reduced and kept out of the sidewalk where possible, so the horizontal clearance of a sidewalk is not affected, and there are no obstacles in the walkway.

Buffer width

For higher speed and volume roads, 4 to 6 ft. landscaping strips dividing the sidewalk from the travel lanes, or on street parking can create an "important physical and psychological buffers between people and moving traffic" (Burden 2001). On-street parking can provide a buffer zone for pedestrians. From the point of view of a pedestrian, who benefits from compact and high-density developments, on-street parking is preferred as large parking lots decrease the density and lead to larger walking distances. In the MOS model, the desired buffer width depends on the functional class and street purpose, as well as on the speed limit of adjacent travel lanes.

Crosswalk spacing

Crosswalks present an opportunity for pedestrians to cross a street and by law, crosswalks exist at all right angle intersections (at the end of a block), whether marked or unmarked (City of San Francisco 2010). Marked crosswalks can be painted or created by using a special paving material to distinguish it from the rest of the roadway. Pedestrian safety on marked crosswalks can be enhanced by placing pedestrian warning signs, advance stop and yield signs, adding flashing beacons, or pedestrian signals (City of San Francisco 2010). Since sidewalks are usually above the roadway level, curb ramps provide a continuous transition between the two levels "for people using wheelchairs, strollers, walkers, crutches, handcarts, bicycles, and pedestrians who have trouble stepping up and down high curbs" (City of San Francisco 2010). City of San

Francisco has implemented an American with Disabilities Act (ADA) transition plan for converting ADA non-compliant existing curb ramps to required slopes and dimensions.

Marked crosswalks can be also located mid-block. Blocks larger than 600 ft. create a perception of isolation and need adequate pedestrian crossing opportunities (Ewing and Cervero 2010). Adequate midblock crossing points every 300 ft. allow easy and safe crossing for pedestrians, who are usually not willing to go more than 150 ft. out of their way to cross a street (Burden 2001). Therefore, the desired crosswalk spacing is setup to 300 ft. in the MOs model for all functional classes.

Section characteristics

Functional classes typically include arterial, collector, residential, and local streets. In order to address livability requirements, streets are divided according to their purpose into several additional categories. For example, in a Lower Manhattan, New York City study, streets are divided into four categories (Lethco et al. 2009):

- Access streets: mainly for through and local traffic, bus routes, with sidewalks and crosswalks to promote pedestrian safety.
- Activity streets: no through traffic, pedestrian movement prioritized, at certain times pedestrian-only zones.
- Support streets: no through traffic, link access streets and parking areas, sightlines, and pedestrian visibility around parking areas addressed.
- Residential streets: no through traffic, pedestrian movement prioritized, resident parking only.

Due to high vehicle volume on arterials, pedestrians may feel uneasy about the medium or high speed traffic and if possible, the pedestrian traffic should be directed through a calmer street. However, if the accommodation of pedestrians in an arterial is inevitable, buffers, medians, and well-visible crosswalks may be necessary in order to build a safe and comfortable pedestrian infrastructure. On streets that accommodate pedestrians and bicyclists, the vehicle throughput should be maintained with minimal changes as shown in a case study from Eugene, Oregon. In this study, a one-way street nearby a university was fitted with a widened sidewalk, contraflow bike lane and back-in angle parking, as a result the pedestrian volume increased by 25%; while mid-block pedestrian crossings increased by 17%, bicycle volume increased by 68%, and vehicular traffic decreased by 4% (Barnes and Schlossberg 2013).

Traffic speed is also an important factor that influences pedestrian's safety, ability to cross a street, and overall comfort. A pedestrian's chance to survive in a collision with a motorized vehicle steeply decreases with speed since for 20 mph the chance of survival is 95%, for 30 mph the likelihood of survival is 45% and for speed 40 mph the chance of survival is 15% (FHWA 2002). Los Angeles County's Model Design Manual for Living Streets recommends maximum speeds 20 to 35 mph and 20 to 25 mph for local streets. The maximum speed limit should be considered in the initial road design, so that the design itself limits speeding (Los Angeles County 2011).

Methodology

In MOS, two street section purpose categories are defined:

- Access section: pedestrian movement prioritized, includes Safe Routes to School zones, proximity of parks, hospitals, transit, shopping.
- General section: all other sections.

The livability sub-model process for the needs analysis requires three data sources:

- Crash data
- Road safety, livability, and walkability audits
- Asset inventory database

Crash data, such as date, time, location, parties involved and cause are extracted from enforcement reports and sections. Streets with crashes in the last three years are reported to raise awareness of the safety issues. Figure 4.9 shows an example of reporting a high crash street section in the *Sections Selected for Treatment* report.

City of Los Altos - Asset

Needs - Sections Selected for Treatment

Interest: .00% **Inflation: .00%** Printed: 11/23/2015

Street Name	Begin Location	End Location	Street ID	Section ID	FC	Surface	PCI	Cost	Treatment	High Crash Section?
Year: 2015										
EVAMARIE AV	FALLEN LEAF LN	CHRISTINA DR	EVEMAR	FALCHR	R	AC/AC	100	$50,260	MILL & MEDIUM OVERLAY(2 IN.)	
GALLI DR	CIELITO DR	GORDON WY N	GALLDR	CIEGOR	R	AC/AC	100	$85,536	MILL & MEDIUM OVERLAY(2 IN.)	
GORDON WY S	HAWTHORNE AV	HILLVIEW AV	GORDOS	HAWHIL	R	AC/AC	100	$66,300	MILL & MEDIUM OVERLAY(2 IN.)	HIGH CRASH SECTION
MIRAVALLE AV	GRANT RD	END (Baricated)	MIRAVA	GRAEND	R	AC	100	$87,204	MILL & MEDIUM OVERLAY(2 IN.)	
SANTA RITA AV	PORTOLA AV W	LOS ALTOS AV	SANTAV	PORLOS	R	AC/AC	100	$66,500	MILL & MEDIUM OVERLAY(2 IN.)	
TRAVERSO CT	END	TRAVERSO AV	TRAVCT	ENDTRA	R	AC/AC	100	$18,924	MILL & MEDIUM OVERLAY(2 IN.)	
					Treatment Total			$374,724		

Figure 4.9 Example of Crash Data added in the Needs-Sections Selected for Treatment Report.

Improvements needed on sidewalks, buffers and crosswalks are identified through road safety, livability, and walkability audits. The improvements are divided into three categories:

- New assets (e.g. adding a buffer where there is none).
- Updates of existing assets (e.g. sidewalk widening).
- Maintenance of existing assets (identified by maintenance plans in the asset inventory database).

The asset inventory database holds data for all sidewalks, buffers, and crosswalks. The desired livability characteristics are shown in Table 4.9 and include:

- Desired sidewalk width
- Desired buffer width
- Desired crosswalk spacing

Table 4.9 Desired livability characteristics by functional class and street purpose category

Functional class	Street purpose	Sidewalk	Buffer (incl. edge & furnishings)	Crosswalk
		Desired sidewalk width	Desired buffer width	Desired crosswalk spacing
Arterial	General	10 ft.	-	-
	Access	12 ft.	4 ft. (+ 1' for every 5 mph increment over 25 mph)	300 ft.
Collector	General	10 ft.	-	-
	Access	12 ft.	4 ft. (+ 1' for every 5 mph increment over 25 mph)	300 ft.
Residential	General	6 ft.	-	-
	Access	10 ft.	4 ft.	300 ft.

The desired livability characteristics are aimed towards addressing the needs of pedestrians. More factors could be included such as tree coverage, intersections, as well as assets affecting bicyclists. Based on the Better Streets Plan, the pedestrian-oriented criteria that the City of San Francisco uses for prioritization of street improvements include high crash areas, transit hubs, schools, senior centers, deficient neighborhoods, areas with accessibility gaps, and areas with high pedestrian volume such as tourist destinations and recreational facilities (City of San Francisco 2010).

The desired livability characteristic targets are chosen to follow the minimum width recommendations for sidewalk zones (City of San Francisco 2010) in a simplified manner. Crosswalk spacing target for access sections is set to 300 ft. (Burden 2001). General sections do not have any livability target for buffers and crosswalks. The desired state is compared with the current state of the assets. If the current state is below the desired state, the need of improvement is added to the list of "New assets" or "Upgrade of existing assets".

An asset importance index (IMP_{AS}) is assigned to each improvement as shown in Table 4.10. Weights for each asset distinguish between needs for new assets, updates, and maintenance of existing assets. In this example, the construction of a new sidewalk is assigned with the highest importance and the maintenance of a buffer with the lowest. Decision makers can assign their own weights to customize the asset importance.

Table 4.10 Example of Asset Importance (IMP_{AS})

Asset	Asset Importance Index (IMP_{AS})		
	New	**Update**	**Maintenance**
Sidewalk	1	0.5	0.6
Crosswalk	0.9	-	0.7
Buffer	0.8	0.4	0.3

In addition, the importance of location is considered as shown in Table 4.11. The location importance index prioritizes improvements in street sections that would be beneficial to larger pedestrian traffic.

Table 4.11 Example of Location Importance

Functional class	Street purpose	Location Importance Index
Arterial	General	0.55
	Access	1
Collector	General	0.55
	Access	1
	Downtown	1
Residential	General	0.55
	Access	1

In the next step, costs are related to an estimated remaining life for each improvement. Table 4.12 shows a simplified approach to relate costs and remaining life.

Table 4.12 Example of unit costs and remaining life

Asset	Unit Cost [$/sq. ft.]			Remaining Life [years]		
	New	**Update**	**Maintenance**	**New**	**Update**	**Maintenance**
Sidewalk	12	12	5	20	20	15
Crosswalk	10	10	10	3	3	3
Buffer	30	30	15	15	15	15

Mathematical Formulation

Once construction, maintenance costs, and remaining life are determined a weighted effectiveness ratio is calculated as follows:

$$WER_{LIV} = 1000 * IMP_{AS} * \ IMP_{LOC} * \frac{1}{RL_{AT}} * \frac{1}{EUAC}$$

where:

IMP_{AS} ……..	asset importance index
IMP_{LOC} ……	location importance index
RL_{AT} ………	remaining life after treatment or construction
EUAC……..	Equivalent Uniform Annual Cost, calculated as $EUAC = COST_F * \frac{f(1+f)^n}{(1+f)^n-1}$ where $COST_F = COST_P \left(\frac{100+f}{100}\right)^n$
n …………..	years of analysis, equals to RL_{AT} or number of years from first analysis year to year of treatment
f …………...	inflation rate (in %)
$COST_F$……..	future inflated costs (unit costs at analysis date)
$COST_P$……..	present costs (unit costs current at the first analysis year)

Finally, the construction and maintenance projects are ranked from highest to lowest WER_{LIV}, and the available budget is allocated using the Dynamic Bubble Up technique (DBU) (Chang 2007). Projects selected for funding are added to the list of budget improvements. It is important to coordinate the improvements across asset categories to ensure the optimal timing of the application. For example, pavement markings should not be placed right before a pavement overlay scheduled in the same section. Those improvements that do not receive funding are back-logged and wait to compete for funding in the next budget cycle.

Chapter 5: Application of the Multi-Objective Sustainability Model

The application of the Multi-Objective Sustainability (MOS) model is demonstrated in an example including 10 block-long sections (2 arterial, 3 collector, and 5 residential streets). Data extracted from San Francisco StreetSaver® database and Google Earth are taken as a reference to build the case example. The example includes a comparison of various scenarios incorporating sustainability goals, target objectives, and budget constraints as described in Chapter 4. MOS finds the minimum budget to reach the targets (Target-Driven Scenarios), or prioritize funding allocation for given budgets (Budget-Driven). Two different techniques are used to solve the models:

- Optimization: Excel add-in Solver is used to minimize cost in the Target-Driven scenarios, or to maximize the emission savings or livability characteristics in the Budget-Driven scenarios.
- Dynamic Bubble-Up (DBU): Projects are ranked based on their potential CO_2 emission savings or increase in livability, then projects are selected starting with the project with the highest potential benefits until the target is reached or the funds are exhausted.

The analyses are performed only for one year to illustrate the process. Any sections in need of a treatment that do not receive funding are deferred to future years until receiving or exhausting the funds. This process is repeated over the period of analysis.

5.1 Environmental Sustainability

General data description for the 10 pavement sections are shown in Table 5.1. The current pavement network condition has an average PCI of 45. If there were enough funds to apply all the treatments needed, the PCI could increase to a PCI of 99. The recommended pavement treatments include mill and fill, micro surfacing, mill and thin overlay, and reconstruction.

Table 5.1 General data for pavement sections

Section ID	Functional Class	Length [ft.]	ADT [veh./day]	PCI Untreated	PCI Treated	Treatment	Cost of Treatment	WER
1	Arterial	597	5,100	25	100	MILL & FILL	$ 179,642	39
2	Arterial	297	33,429	22	100	MILL & FILL	$ 130,617	39
3	Collector	423	7,800	14	100	MILL & FILL	$ 166,448	39
4	Collector	524	5,215	70	100	MILL & FILL	$ 84,204	26
5	Collector	281	7,700	50	100	MILL & FILL	$ 112,496	36
6	Residential	592	200	84	91	MICRO-SURF	$ 23,105	10
7	Residential	317	8,860	48	100	MILL & FILL	$ 89,989	36
8	Residential	208	1,200	43	100	MILL,T.OVERL	$ 41,584	36
9	Residential	294	1,700	47	100	RECONSTR.	$ 143,811	33
10	Residential	290	5,000	50	100	MILL & FILL	$ 105,544	35
			Average	45	99	**Total**	$ 1,077,440	330

5.1.1 Optimal and Do-Nothing Scenarios

The Optimal Scenario (also referred to as Needs) yields the maximum CO_2 emission savings possible since there are no budget restrictions. In the optimal scenario, all sections receive the treatment that they need. On the other hand, the Do Nothing Scenario estimates the CO_2 emissions when no pavement treatments are applied to the sections. Table 5.2 shows the CO_2 emissions generated under each scenario and the potential savings.

Table 5.2 CO_2 emissions for the Optimal and Do Nothing scenarios

Section ID	Functional Class	Optimal Scenario: CO_2 Emissions [tons/year]	Do Nothing Scenario: CO_2 Emissions [tons/year]	Potential CO_2 Emission Savings [tons/year]
1	Arterial	281,282	309,411	28,128
2	Arterial	917,229	1,008,952	91,723
3	Collector	304,813	335,294	30,481
4	Collector	252,454	260,028	7,574
5	Collector	199,892	209,886	9,995
6	Residential	10,938	11,266	328
7	Residential	259,47	280,230	20,758
8	Residential	23,059	24,904	1,845
9	Residential	46,174	49,868	3,694
10	Residential	133,957	140,655	6,698
	Total	**2,429,271**	**2,630,494**	**201,223**

The allocated budget for treatments in the Optimal Scenario is $1,077,440, and $ 0 in the Do Nothing Scenario. Maximum potential savings on CO_2 emissions are 201,223 tons in one year if the all the pavement sections in need of treatment are funded.

5.1.2 Target-Driven Scenarios

Target-Driven Scenarios aim to reach a target objective, expressed in terms of gas emission savings, with the minimum budget. Four Target-Driven scenarios are run using the MOS model:

- Scenario PAV-TD-A: at least 60,367 tons CO_2 emissions are saved compared to Do Nothing Scenario (30% of possible maximum emission savings)
- Scenario PAV-TD-B: at least 100,612 tons CO_2 emissions are saved compared to Do Nothing Scenario (50% of possible maximum emission savings)
- Scenario PAV-TD-C: at least 140,856 tons CO_2 emissions are saved compared to Do Nothing Scenario (70% of possible maximum emission savings)
- Scenario PAV-TD-D: at least 181,101 tons CO_2 emissions are saved compared to Do Nothing Scenario (90% of possible maximum emission savings)

Table 5.3 shows the summary of funding allocated and emission savings.

Table 5.3 Target-Driven scenarios inputs and outputs

INPUT			OUTPUT		
Scenario		Target Objective: CO_2 Emission Saved (% of possible maximum emission savings)	Minimum Budget Needed to reach the target	Sections Funded	Checking CO_2 Emission Saved [tons/year] (% of possible maximum emission savings)
Optimization	PAV-TD-A-O	60,367 tons (30%)	$ 130,617	2	91,723 (46%)
	PAV-TD-B-O	100,612 tons (50%)	$ 220,606	2,7	112,481 (56%)
	PAV-TD-C-O	140,856 tons (70%)	$ 387,054	2,3,7	142,962 (71%)
	PAV-TD-D-O	181,101 tons (90%)	$702,297	1,2,3,5,6,7	181,413 (90%)
DBU	PAV-TD-A-BU	60,367 tons (30%)	$ 130,617	2	91,723 (46%)
	PAV-BD-B-BU	100,612 tons (50%)	$ 297,065	2,3	122,204 (61%)
	PAV-BD-C-BU	140,856 tons (70%)	$ 476,707	1,2,3	150,332 (75%)
	PAV-BD-D-BU	181,101 tons (90%)	$763,396	1,2,3,4,5,7	188,658 (94%)

Figures 5.1 and 5.2 show CO_2 emission savings using the optimization and DBU ranking methods for each of the Target-Driven scenarios.

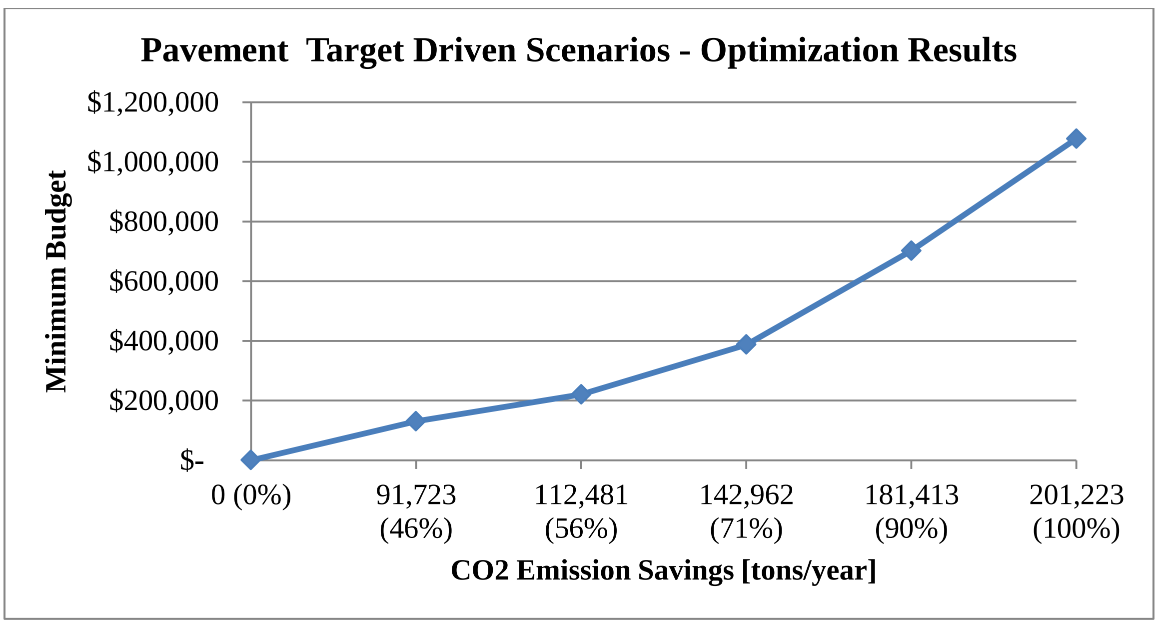


Figure 5.1 Minimum Budget for Target-Driven CO_2 Emission Savings Scenarios – Optimization

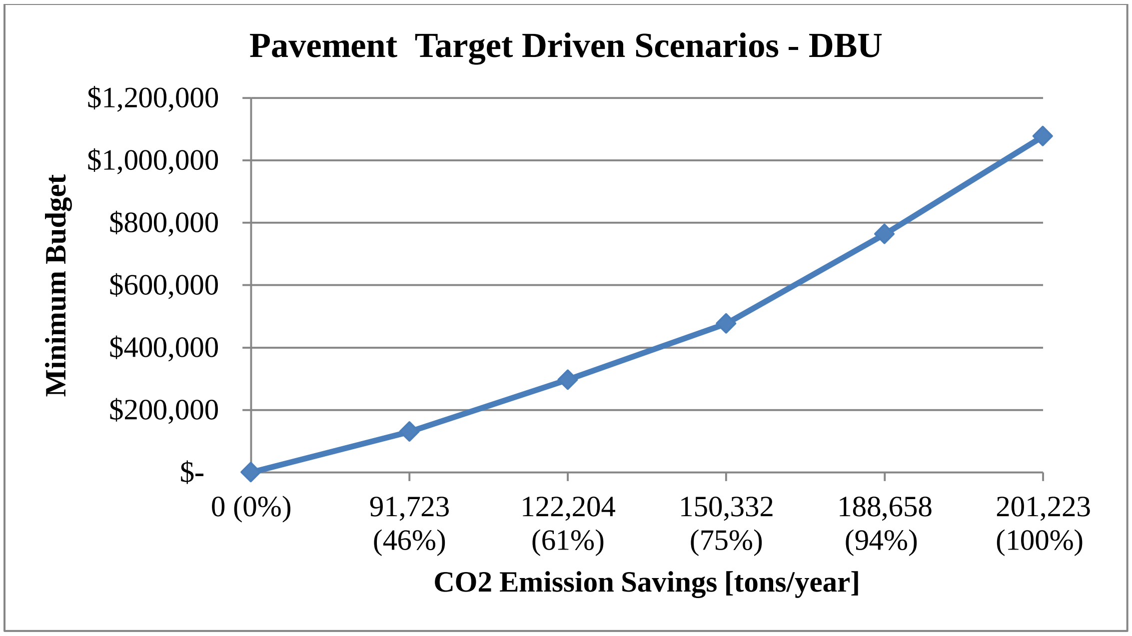


Figure 5.2 Minimum Budget for Target-Driven CO_2 Emission Savings Scenarios – DBU ranking

5.1.3 Budget-Driven Scenarios

Budget-Driven Scenarios aim to maximize the CO_2 emission savings under a limited budget. Four Budget-Driven scenarios are run using the MOS model to maximize CO_2 emission savings for the available funds:

- Scenario PAV-BD-A: available budget is 30% of the budget Needs
- Scenario PAV-BD-B: available budget is 50% of the budget Needs
- Scenario PAV-BD-C: available budget is 75% of the budget Needs
- Scenario PAV-BD-D: available budget is 90% of the budget Needs

Pavement sections with the highest potential for gas emissions savings are selected using the optimization and DBU ranking methods. Table 5.4 shows the summary of gas emission savings for each scenario.

Table 5.4 Budget-Driven gas emission saving scenarios inputs and outputs

INPUT			OUTPUT		
Scenario		Available Budget	CO_2 Emission Savings [tons/year] (% of possible maximum emission savings)	Sections Funded	Checking Allocated Budget
Optimization	PAV-BD-A-O	$ 323,232 (30%)	122,532 (61%)	2,3,6	$ 320,170
	PAV-BD-B-O	$ 538,720 (50%)	153,285 (76%)	3,3,5,6,7	$ 522,655
	PAV-BD-C-O	$ 808,080 (75%)	190,503 (95%)	1,2,3,4,5,7,8	$ 804,980
	PAV-BD-D-O	$ 969,696 (90%)	197,529 (98%)	1,2,3,4,5,6,7,8,10	$ 933,629
DBU	PAV-BD-A-BU	$ 323,232 (30%)	122,204 (61%)	2,3	$ 297,065
	PAV-BD-B-BU	$ 538,720 (50%)	150,332 (75%)	1,2,3	$ 476,707
	PAV-BD-C-BU	$ 808,080 (75%)	188,658 (94%)	1,2,3,4,5,7	$ 763,396
	PAV-BD-D-BU	$ 969,696 (90%)	195,356 (97%)	1,2,3,4,5,7,10	$ 868,940

Figures 5.3 and 5.4 show CO_2 emission savings using optimization and DBU methods for each of the budget scenarios.

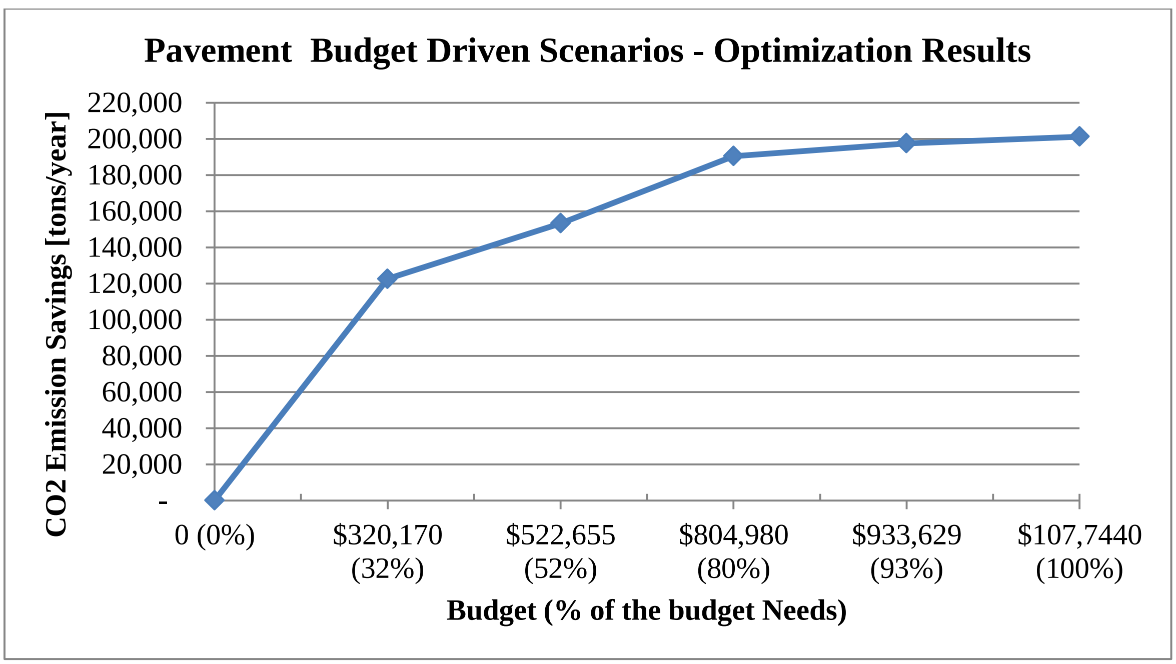


Figure 5.3 CO_2 Emission Savings for Different Budget-Driven Scenarios – Optimization

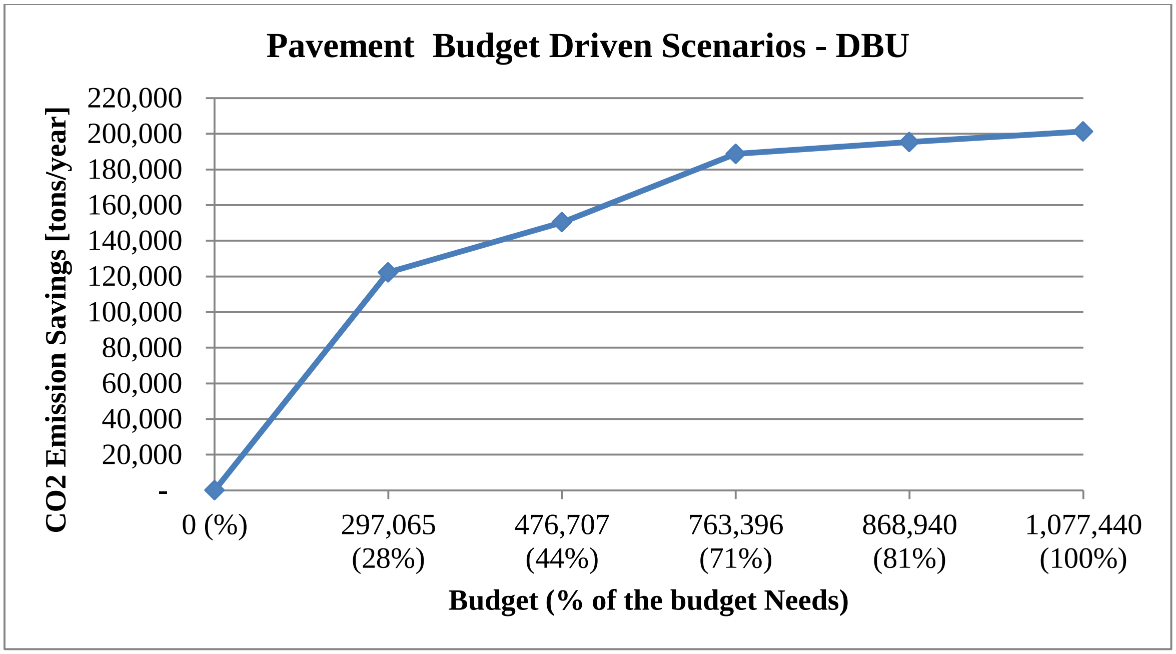


Figure 5.4 CO_2 Emission Savings for Different Budget-Driven Scenarios – DBU ranking

5.1.4 Interpretation of the Results

Since fuel consumption depends on the pavement condition, the emission savings are correlated with the level of funding allocated for pavement treatments. The more funding is allocated to maintenance, the lower the gas emissions are. It is also observed, that optimization provided better allocation of available funds and the emission savings are 1% higher than the results obtained with the DBU ranking technique. With 30% of the optimal funding, 61% of the total potential maximum emissions are saved; but with 75% of the optimum funding, 95% of the potential emissions are saved. Target-Driven scenarios confirmed the funding levels needed to meet the different levels of gas emission savings.

5.2 Social Sustainability

5.2.1 Livability

In the livability sub-model, more scenarios are run using the MOS model to allocate available funds for improvements in 10 sidewalk sections with the goal of maximizing livability characteristics. The case study focused only on the livability characteristics, which in this case is whether sidewalk width was in compliance with the minimum desired width or not. While usually streets have sidewalks on both sides, only sidewalks on the west-side or north-side of the streets are evaluated for illustration purposes. Sidewalk lengths are the same as the pavement section length. Remaining service life is assumed 20 years after the improvement. Excel add-in Solver is used to find the minimum budget to reach the livability targets (Target-Driven) or the best selection of sections to maximize the WER_{LIV} when there are budget constraints.

5.2.1.1 Optimal and Do-Nothing Scenarios

The Optimal Scenario (also referred to as Needs) yields the maximum livability characteristics enhancements since there are not budget restrictions. The unit cost of sidewalk is assumed as $12/sq. ft. For the optimum scenario, the total budget is $136,596. On the other hand, the budget for the Do Nothing Scenario is $ 0 since the current widths are not improved. Table 5.5 shows the livability characteristics, cost of improvement, and WER_{LIV} for each section.

Table 5.5 Livability sidewalk sections data with optimal cost of improvements

Section ID	Functional Class	Street Purpose	Width Actual	Width Desired	Cost of Improvement	WER_{LIV}
1	Arterial	Access	10	12	$ 28,656	9
2	Arterial	General	7	10	$ 32,076	5
3	Collector	General	9	10	$ 5,076	28
4	Collector	Access	10	12	$ 25,152	10
5	Collector	Access	11	12	$ 3,372	75
6	Residential	General	5	6	$ 7,104	20
7	Residential	Access	8	10	$ 15,216	17
8	Residential	Access	9	10	$ 2,496	56
9	Residential	General	5	6	$ 3,528	39
10	Residential	Access	8	10	$ 13,920	18
				TOTAL	$ 136,596	277

5.2.1.2 Target-Driven Scenarios

Target-Driven Scenarios find the minimum budget required to reach the livability target objective. Four Target-Driven scenarios are run using the MOS model:

- Scenario SID-TD-A: 20% sidewalk network meet desired livability characteristics
- Scenario SID-TD-B: 40% sidewalk network meet desired livability characteristics
- Scenario SID-TD-C: 60% sidewalk network meet desired livability characteristics
- Scenario SID-TD-D: 80% sidewalk network meet desired livability characteristics

Table 5.6 shows the summary of funding allocated and resulting livability (WER_{LIV}).

Table 5.6 Target-Driven livability scenarios inputs and outputs.

INPUT			OUTPUT		
Scenario		Livability Target: % of sidewalks that meet the desired livability	Minimum Budget to Reach the Livability Target	Sections Funded	WER_{LIV}
Optimization	SID-TD-A-O	20%	$9,396	5,8,9	170
	SID-TD-B-O	40%	$19,080	3,5,6,9	162
	SID-TD-C-O	60%	$46,728	3,4,5,6,8,9	228
	SID-TD-D-O	80%	$89,304	1,3,4,5,6,8,9,10	255
DBU	SID-TD-A-BU	20%	$9,396	5,8,9	170
	SID-TD-B-BU	40%	$21,576	3,5,8,9,10	218
	SID-TD-C-BU	60%	$50,712	1,2,4	253
	SID-TD-D-BU	80%	$104,520	1.3.4.5.6.7.8.9.10	272

Figures 5.5 and 5.6 show the relationships between livability targets and budgets for the optimization and DBU ranking methods.

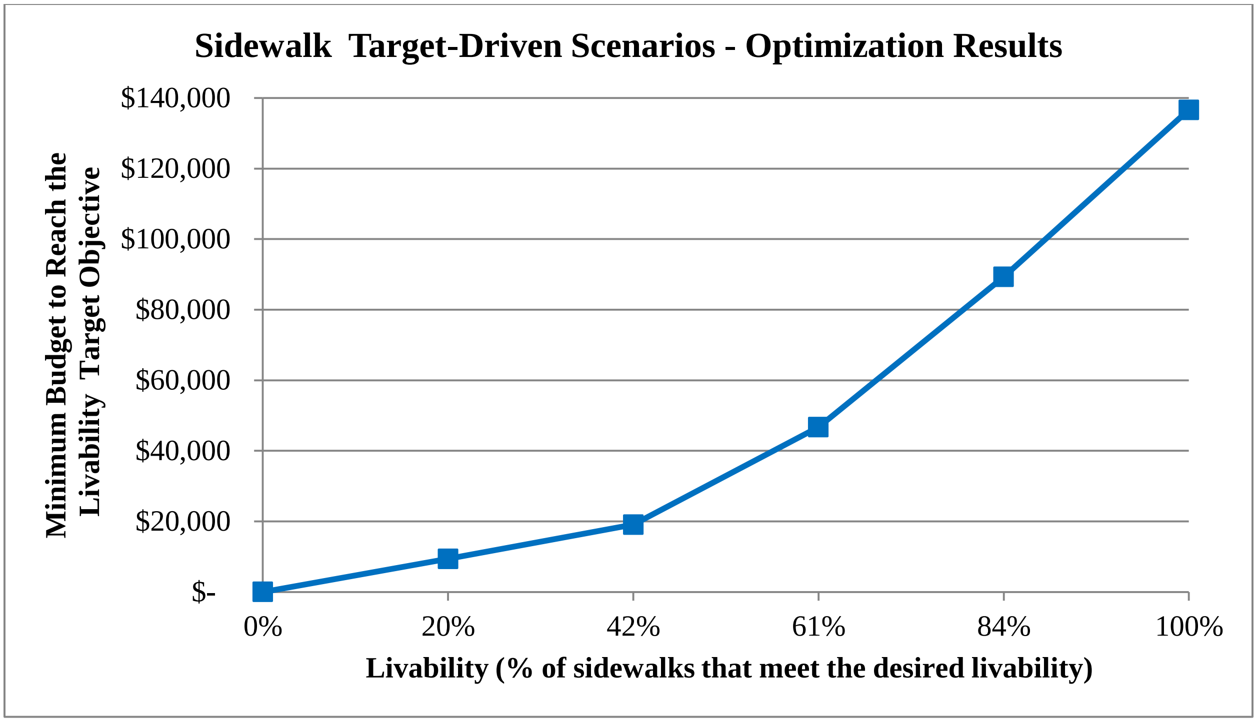


Figure 5.5 Minimum Budget for Target-Driven Livability Scenarios – Optimization

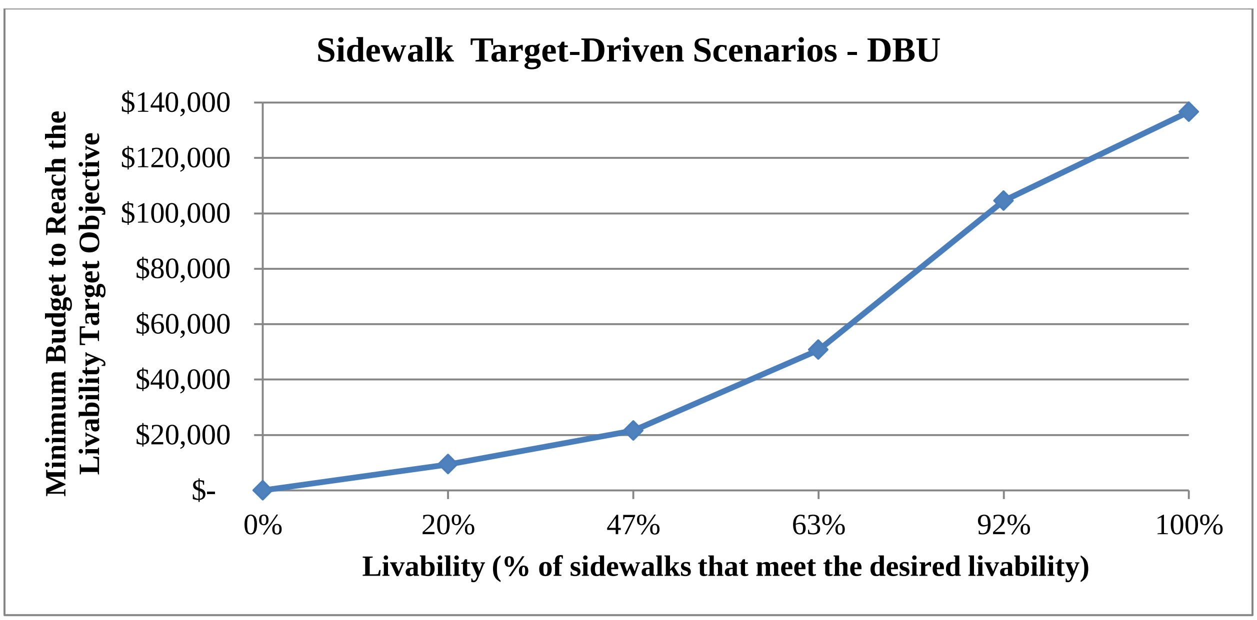


Figure 5.6 Minimum Budget for Target-Driven Livability Scenarios – DBU Ranking

5.2.1.3 Budget-Driven Scenarios

Budget-Driven Scenarios maximizes the livability characteristics (WER_{LIV}) for a given budget. Four Budget-Driven scenarios are run using the MOS model:

- Scenario SID-BD-A: available budget is $40,979 (30% of the Optimal Budget)
- Scenario SID-BD-B: available budget is $68,298 (50% of the Optimal Budget)
- Scenario SID-BD-C: available budget is $102,447 (75% of the Optimal Budget)
- Scenario SID-BD-D: available budget is $122,936 (90% of the Optimal Budget)

Table 5.7 shows the summary of funding allocated and resulting livability (WER_{LIV}).

Table 5.7 Budget-Driven Livability Scenarios Inputs and Outputs

INPUT			OUTPUT			
Scenario		Available Budget (% of Optimal Budget)	Percentage of sidewalks that meet the desired livability	Sections Funded	WER_{LIV}	Checking Allocated Budget
Optimization	SID-BD-A-O	$ 40,979 (30%)	55%	3,5,6,7,8,9	236	$ 35,496
	SID-BD-B-O	$ 68,298 (50%)	63%	3,5,6,7,8,9,10	253	$ 50,712
	SID-BD-C-O	$ 102,447 (75%)	77%	3,4,5,6,7,8,9,10	263	$ 75,864
	SID-BD-D-O	$ 122,936 (90%)	92%	1,3,4,5,6,7,8,9,10	272	$ 104,520
DBU	SID-BD-A-BU	$ 40,979 (30%)	55%	3,5,6,8,9,10	236	$ 35,496
	SID-BD-B-BU	$ 68,298 (50%)	63%	3,5,6,7,8,9,10	253	$ 50,712
	SID-BD-C-BU	$ 102,447 (75%)	77%	3,4,5,6,7,8,9,10	263	$ 75,864
	SID-BD-D-BU	$ 122,936 (90%)	92%	1,3,4,5,6,7,8,9,10	272	$ 104,520

Figures 5.7 and 5.8 show the correlation between funding allocated and percentage of sidewalks that meet the desired livability using the optimization and DBU ranking method.

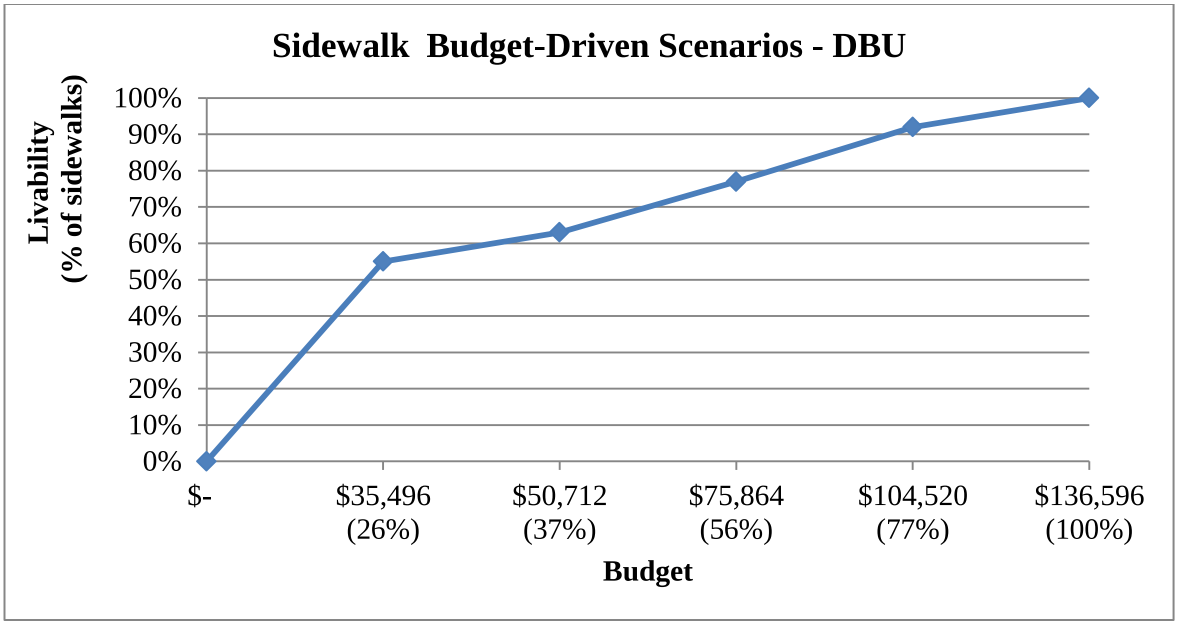


Figure 5.7 Livability for Different Budget-Driven Scenarios – Optimization

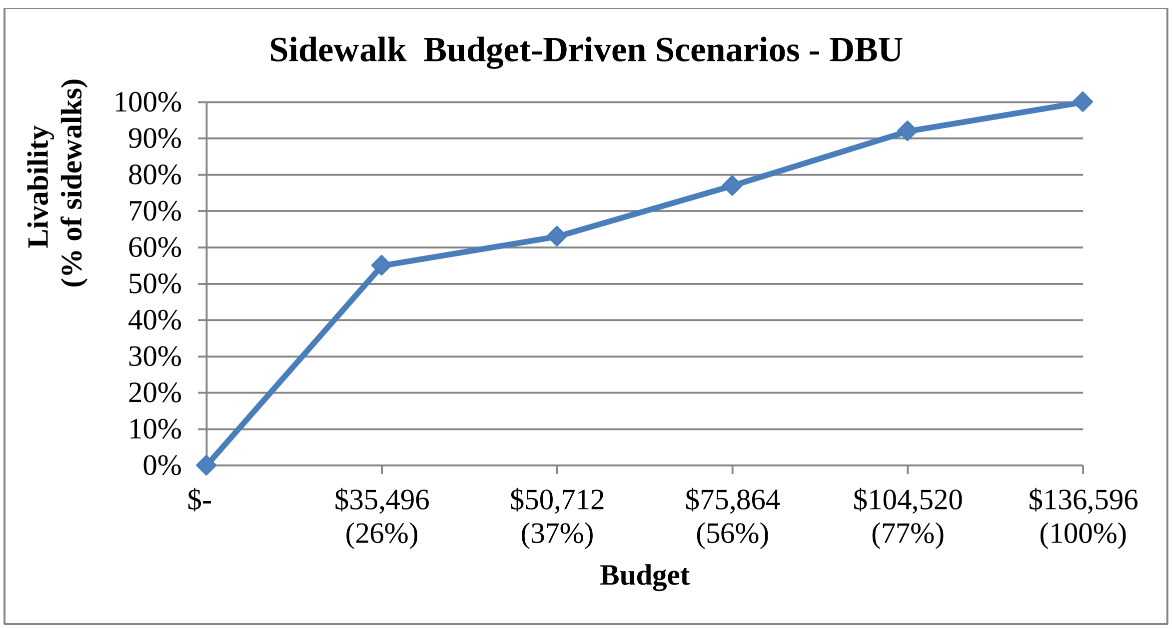


Figure 5.8 Livability for Different Budget-Driven Scenarios – DBU ranking

5.2.1.4 Interpretation of the Results

Improvements in livability characteristics are correlated with allocated funding. The more funding allocated to the improvement projects, the higher the percentage of sidewalk network that meet the desired livability characteristics. All 10 sections had a width below the desired level and became candidates for improvements. With 30% of the optimal funding, six sections could be brought up to the desired standard, while with 75% of the optimal funding eight sections could be brought up to the desired standard. Target-Driven scenarios indicated that in order to have 80% of the network to meet the livability requirements, eight sections need an improvement. It is also observed that DBU ranking technique provided very close results to the optimization method.

5.2.2 Job Creation

Following the method described in Chapter 4, creation of new jobs is estimated based on the funding allocated to pavement treatments. Table 5.8 summarizes the jobs created under each of the pavement maintenance and sidewalk improvement scenarios.

Table 5.8 Estimation of new jobs created for pavement scenarios

Scenario	Funding Finally Allocated	New Jobs Created (San Jose 2013)
PAV-BD-A-O	$ 320,170	26
PAV-BD-B-O	$ 522,655	42
PAV-BD-C-O	$ 804,980	64
PAV-BD-D-O	$ 933,629	75
PAV-TD-A-O	$ 130,617	10
PAV-TD-B-O	$ 220,606	18
PAV-TD-C-O	$ 387,054	31
PAV-TD-D-O	$ 702,297	56
SID-BD-A-O	$ 35,496	3
SID-BD-B-O	$ 50,712	4
SID-BD-C-O	$ 75,864	6
SID-BD-D-O	$ 104,520	8
SID-TD-A-O	$ 9,396	1
SID-TD-B-O	$ 19,080	2
SID-TD-C-O	$ 46,728	4
SID-TD-D-O	$ 89,304	7

5.3 Project Coordination

The aim of the project coordination is to consider pavement treatment needs and sidewalk widening improvements when evaluating the sections for funding.

5.3.1 Optimal and Do-Nothing Scenarios

The Optimal Scenario (also referred to as Needs) yields the maximum emissions savings and maximum livability characteristics without any budget constraints. Table 5.9 shows optimal costs of pavement maintenance and sidewalk improvements. Details about the pavement and sidewalk sections are found in the previous sections (Tables 5.1 and 5.5). For the Optimum

Scenario, the total budget for both pavement maintenance and sidewalk improvements is $1,214,036.

Table 5.9 Optimal gas emission savings and livability improvements project data

Section ID	Functional Class	Street Purpose	Cost of Pavement Treatments	Cost of Sidewalk Improvements	Total Cost of Improvement	WER	WER_{LIV}	WER_{COMB}
1	Arterial	Access	$ 179,642	$ 28,656	$ 208,298	39	9	48
2	Arterial	General	$ 130,617	$ 32,076	$ 162,693	39	5	44
3	Collector	General	$ 166,448	$ 5,076	$ 171,524	39	28	67
4	Collector	Access	$ 84,204	$ 25,152	$ 109,356	26	10	36
5	Collector	Access	$ 112,496	$ 3,372	$ 115,868	36	75	111
6	Residential	General	$ 23,105	$ 7,104	$ 30,209	10	20	30
7	Residential	Access	$ 89,989	$ 15,216	$ 105,205	36	17	53
8	Residential	Access	$ 41,584	$ 2,496	$ 44,080	36	56	92
9	Residential	General	$ 143,811	$ 3,528	$ 147,339	33	39	72
10	Residential	Access	$ 105,544	$ 13,920	$ 119,464	35	18	53
		Total	$1,077,440	$ 136,596	$1,214,036	330	277	607

5.3.2 Target-Driven Scenarios

Target-Driven Scenarios minimizes the cost for given simultaneous targets of emission savings and sidewalks meeting livability requirements. Two Target-Driven scenarios are run using the MOS model:

- Scenario COM-TD-A: target 50% emission savings and 50% of sidewalks meeting livability requirements
- Scenario COM-TD-B: target 80% emission savings and 80% of sidewalks meeting livability requirements

Table 5.10 shows the summary of the budgets needs for each Target-Driven scenario using the optimization solving technique.

Table 5.10 Target-Driven project coordination scenarios inputs and outputs

INPUT		**OUTPUT**				
Scenario	**Targets**	**Minimum Budget**	**Sections Funded**	**WER_{COMB}**	**Checking Emission Savings**	**Checking % of sidewalks**
SID-BD-A	50% emission savings, 50% of sidewalks that meet desired livability)	$451,543	2,4,6,7,8	255	122,227 (61%)	51%
SID-BD-B	80% emission savings, 80% of sidewalks that meet desired livability)	$895,173	1,2,4,5,6, 7,8,10	468	167,047 (83%)	81%

5.3.3 Budget-Driven Scenarios

Budget-Driven Scenarios prioritize funding allocation selecting the combination of sections that maximizes the combined weight effectiveness ratio (WER_{COMB}) under a budget constraint. Two Budget-Driven scenarios are run using the MOS model:

- Scenario COM-BD-A: available budget is $607,018 (50% of Optimal Budget)
- Scenario COM-BD-B: available budget is $971,229 (80% of Optimal Budget)

Table 5.11 shows the summary of the sections prioritized for funding using the optimization method, and the maximum WER_{COMB} obtained for that given budget.

Table 5.11 Budget-Driven project coordination scenarios inputs and outputs

INPUT		**OUTPUT**				
Scenario	**Budget**	**Sections Funded**	**Checking Budget**	**WER_{COMB}**	**Emission Savings**	**% of sidewalks meeting livability requirements**
SID-TD-A	$607,018 (50% of Optimal Budget)	5,6,7,8,9,10	$562,165	412	43,317 (22%)	52%
SID-TD-B	$971,229 (80% of Optimal Budget)	1,3,5,6,7,8,9,10	$941,987	527	101,926 (51%)	79%

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Transportation Asset Management (TAM) evolved from Pavement Management as a tool to manage transportation assets in the most cost-effective way. Goals, objectives, and performance measures help transportation agencies to assess the current state of their assets and predict future condition as well as maintenance needs under various scenarios. Modern TAM requires an integrated approach that connects these three key elements though the adoption of sustainability principles to balance economic, environmental, and social aspects. In this context, the selection of the right performance measures to assess the current and desired state is an important decision, especially since data collection is costly.

Quality Function Deployment matrix is recommended to relate objectives with performance measures in order to track network performance and help to ensure that goals be met in the long-term. The performance measures selected for the Multi-Objective Sustainable (MOS) model included Pavement Condition Index, Remaining Service Life, fuel consumption based on pavement condition, annual daily traffic, agency expenditures, estimated CO_2 emissions, social cost of CO_2 emissions, new jobs created, crashes involving pedestrians, bicyclists, and livability requirements.

The MOS model enhances the existing StreetSaver® pavement management process by taking into account gas emission savings and livability requirements. The MOS model can be solved with optimization or ranking methods such as the Dynamic Bubble-Up (DBU) technique. The optimization approach looks for the maximum CO_2 emission savings and/or to maximize livability for a given budget, or to minimize the budget to reach the target objectives set by the agency. The DBU technique is used an alternative simplified method to solve Target and Budget-Driven scenarios defined in terms of desired emission savings or livability requirements.

Results from the case study show that using MOS to consider environmental and social aspects into transportation asset management can help in understanding the consequences of maintenance and construction decision on users, environment, and the overall transportation network sustainability. Performance in the target categories is depicted in the radar graph shown in Figure 6.1 where the further from the center is the point, the better the performance. The highest emission savings is reached in scenario DB-B, while the highest livability and combined weight effectiveness ratio (WER_{COMB}) is achieved in scenario TD-B. When scenario BD-B (target 80% emissions, 80% livability) is compared to TD-B (80% Optimal Budget); it is observed that a 4% funding increase results in an increase of 10% in WER_{COMB} , 32% in emission savings, and 2% in livability.

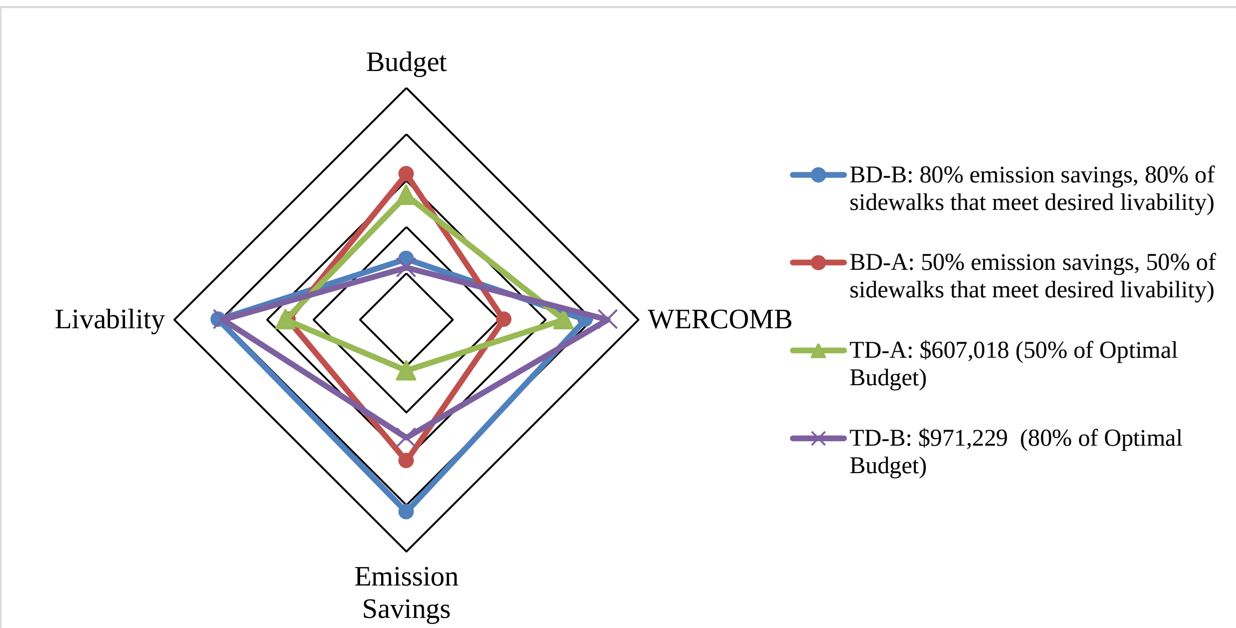


Figure 6.1 Comparison of Scenarios for Project Coordination

6.2 Major Contributions of the Research

The major contribution of this research is the development of a Multi-Objective Sustainable (MOS) model that incorporates environmental and social sustainability aspects into the asset management decision-making process. The inclusion of sustainable characteristics into TAM systems fosters a transportation network that addresses the needs of motorized users as well as pedestrians, while minimizing the impact on environment. Running Target-Driven and Budget-Driven scenarios with MOS provides helpful insights of the environmental and social consequences of maintenance and construction decisions that local transportation agencies daily make under limited budgets. Therefore, the MOS model enhances the traditional TAM methods that are typically based only on pavement condition.

6.3 Recommendations for Future Research

TAM-MOS would benefit transportation agencies from integrating sustainability principles into the funding allocation decision-making process. Currently, the MOS model uses target objectives related to emissions or livability, but more objectives could be added to represent other livability concepts, such as proximity and connectivity, and social cost of CO_2. Budget-Driven scenarios with additional constraints can also be run to ensure minimum condition, maximum emissions, and minimum livability for different functional classes or groups of sections.

The livability sub-model case study could be extended to incorporate crash data, safety and livability audit data and condition data in order to address the real-world needs of transportation agencies.

A larger database should also be used to apply MOS into real-world scenarios. Running Target-Driven and Budget-Driven scenarios in a larger database makes the solution of MOS model more cumbersome. In this study, only optimization and DBU ranking methods were used as solving techniques, however there are other solving heuristic techniques to address more complex multi-objective problems. Another recommendation is related to the need of running scenarios with multi-year optimization since the case study shows runs for one year. Results from multi-year optimization will allow consider long-term effects on sustainability.

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