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A Multi-Objective Sustainable Model For Transportation Asset Management Practices

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A MULTI-OBJECTIVE SUSTAINABLE MODEL FOR TRANSPORTATION ASSET MANAGEMENT PRACTICES

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Dedication

To my fiancé Sergio, I could not have done it without you.
Thank you for all your support and encouragement along the way.

A MULTI-OBJECTIVE SUSTAINABLE MODEL FOR TRANSPORTATION ASSET MANAGEMENT PRACTICES

by

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Abstract

Transportation Asset Management (TAM) practices have 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 because many objectives and different perspectives, often producing conflicting goals, must be considered.

This dissertation presents a Multi-Objective Sustainable (MOS) model to integrate economic, social, and environmental sustainable objectives into TAM decision-making. The objective is to develop a holistic multi-objective asset management approach integrating environmental and social sustainability related performance measures with traditional indicators, such as asset condition and agency cost, in order to improve the current decision making process in asset management practices. Examples of sustainable performance measures for TAM are on-road vehicle emissions, pedestrian safety, and multimodal livability. In the MOS model, the environmental sustainability objective is to improve air quality by reducing on-road vehicle emissions, measured by CO_2 emission savings and the social cost of CO_2. The economic sustainability objective is to improve local employment by providing jobs, measured by new jobs created as a result of maintenance scenarios. The focus of social sustainability is to foster community livability through two objectives: by preservation of the multimodal transportation system, measured by the condition of bikeways and crosswalks; and also by improving safety of vulnerable road users, measured by improvements in pedestrian crossing opportunities. 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 MOS-TAM can help agencies to prioritize projects for funding while considering the needs of motorized vehicles, bicyclists 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. It helps to answer questions like: How much CO_2 emissions can be saved by timely maintenance? Which locations are high-risk for pedestrians and how can marked crosswalks be implemented in the most cost-efficient manner? How can new bike lanes be implemented in the most cost-efficient manner? How many new jobs will be created by maintenance and construction activities? What are the levels of funding for motorized and non-motorized transportation infrastructure assets?

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Chapter 1: Introduction

Transportation Asset Management (TAM) practices have been gaining popularity in the United States (U.S.) and worldwide enabling transportation agencies to make more cost-effective investment decisions to maintain the transportation infrastructure at desired condition levels. Transportation infrastructure consists of pavements, bridges, sidewalks, bikeways, pavement markings, signs, traffic signals, crosswalks, curb ramps, and many other assets. State Departments of Transportation, as well as local transportation agencies operate with a limited budget, so it is crucial to be able to estimate the future condition and budget needed to maintain the transportation infrastructure in good state of repair. In a holistic view, also ensuring safety for all road users, improving quality of life and supporting local economy are crucial, leading to a sustainable transportation system. Therefore, a question arises: what is sustainability in the context of transportation asset management? In general terms, sustainable development 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 seen as a triple bottom line of economic, social and environmental dimension (Elkington 1997). However, sustainability considerations are often not included in the transportation asset management decision making process.

In modern Transportation Asset Management, sustainability consideration of social and environmental effects of transportation investments on communities should be integrated with the traditional cost-effectiveness and performance-based analysis. With sustainability, the decision situation becomes even more complex as many perspectives, often producing conflicting goals, need to be addressed. Furthermore, with the growing transportation funding gap, climate change issues and high numbers of road fatalities, it is vital not only to maintain the infrastructure at a certain condition, but also include incentives to promote environmental and social sustainability into the decision making. Inclusion of social and environmental factors into transportation planning is an emerging issue that this dissertation will focus on.

1.1 History of Transportation Asset Management

According to the American Association of State Highway and Transportation Officials (AASHTO), Transportation Asset Management (TAM) is *"a strategic and systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their lifecycle."* TAM evolved from Pavement Management's fundamental principles and practices. The need for a systematic maintenance of pavements arose from the boom of highway construction during 1950s and 1960s. President Eisenhower's Federal-Aid Highway Act of 1956 gave the impulse for building thousands of miles of paved roads. Back then, cities were struggling with income inequality reflected in neighborhoods, so planners were encouraged to solve these problems by building highways through those problematic parts of the city instead of building highways on the outskirts (Stromberg 2016) and as a result, *"federally funded construction of highways demolished tens of thousands of housing units each year [in 1960s], the majority in low-income and minority communities"* (USDOT 2016). The significant number of miles of new paved roads resulted in a need to maintain them in an acceptable condition in the most cost-effective manner. The AASHTO Road Test marked the beginning of Pavement Management in 1950s. During the 1970s, Pavement Management Systems (PMS) received increasing attention of academia and State Departments of Transportation (DOTs) as an approach to support funding allocation decisions.

First, PMS started as a pavement inventory with condition assessment to identify sections in need of maintenance and prioritize funding allocation using the "worst-first" approach. Later, 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).

With the advancement of computers in 1980s, pavement management was able to assist transportation agencies in solving more complicated problems. About 10 years later, management systems for other assets, such as bridges, emerged with condition prediction models, methods to identify asset needs over the planning period, and alternative maintenance

strategies to evaluate. Moving Ahead for Progress in the 21st Century (MAP-21) is a transportation bill that took effect in 2012, and mandates that pavements and bridges are maintained through a TAM process (AASHTO 2011). The National Bridge Investment Analysis System (NBIAS), developed by the Federal Highway Administration (FHWA) is a popular tool for bridge management among DOTs. 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, and MicroPAVER developed by US Army Corps of Engineers. Both PMS have been traditionally focus on pavements, however StreetSaver® is developing modules for other assets, such as curb ramps, signs, and traffic signals.

1.2 Problem Description

The problem is that not considering the economic, environmental, and social aspects in the TAM funding allocation decisions leads to a limited view of the complex situation. As the quote says, *"you cannot manage what you do not measure"* (Politico 2016). The decision situation becomes even more complex as many objectives, often in conflict, need to be addressed. Performance measures that illustrate the progress towards the agency's objectives are also an important factor and need to be chosen wisely with data availability and collection cost in mind. Overall, there is not a uniform definition of sustainability in transportation asset management and the incorporation of sustainability principles into a multi-objective model is not well structured and clear yet.

According to the International Infrastructure Management Manual (2006), *"the purpose of TAM is to meet a required level of service, in the most cost effective manner, through the management of assets for present and future customers."* As Amekudzi (2011) indicated, *"transportation infrastructure investments have long-lasting implications not only on the transportation system but also on the larger environmental, economic, and social systems with which transportation interacts."* Currently, the majority of TAM tools focus on minimizing the

agency costs required to maintain asset in a certain condition which provides a rather limited view of the complex situation. There are three specific aspects that are currently left out in the TAM decision-making:

- **Economic aspects:** Transportation asset groups (such as pavements, pavement markings, curb ramps) are often managed independently and there is rarely any coordination in maintenance practices between them which results in higher life-cycle costs.
- **Environmental aspects:** Transportation projects may have negative impacts on the environment, including air pollution, noise pollution, water pollution, as well as depletion of non-renewable resources, that need to be considered in the decision making process in order to mitigate them. Timely maintenance is important in order to maximize asset service life. Environmental sustainability in TAM can be addressed by including the real cost in the decision making, which involves not only the agency expenditures, but also social costs.
- **Social aspects:** TAM tools mostly focused on motorized road users, leaving out bicyclists and pedestrians, which results in disproportional funding allocation to assets that serve these groups. Road safety for pedestrians and cyclists should be considered in the initial design as well as during the asset lifecycle, which gives an opportunity to consider improvements of high-risk roadways in TAM to improve sections either dangerous by design or by condition. Ultimately, road safety translates into social sustainability by providing a transportation system safe for all road users. Livability is another social sustainability topic. Livability is about improving the access to transportation systems that offer multiple modes, increasing mobility and quality of life, providing connections between points of interest in a vibrant community while fostering safety, health and well-being and equity principles. It is crucial that TAM, as an approach for transportation funding allocation, considers these aspects.

In the broader context, TAM faces additional challenges resulting from limited funding, congestion, environment, social trends, technology, and transportation policy, which are discussed in Chapter 2.2.

1.3 Research Objectives

This research has the objective of developing a holistic multi-objective asset management approach integrating environmental and social sustainability related performance measures with traditional indicators (e.g. asset condition and agency cost) in order to improve the current decision making process in asset management practices. The relationship between TAM principles, sustainability aspects in transportation and the research objectives is shown in Figure 1.1.

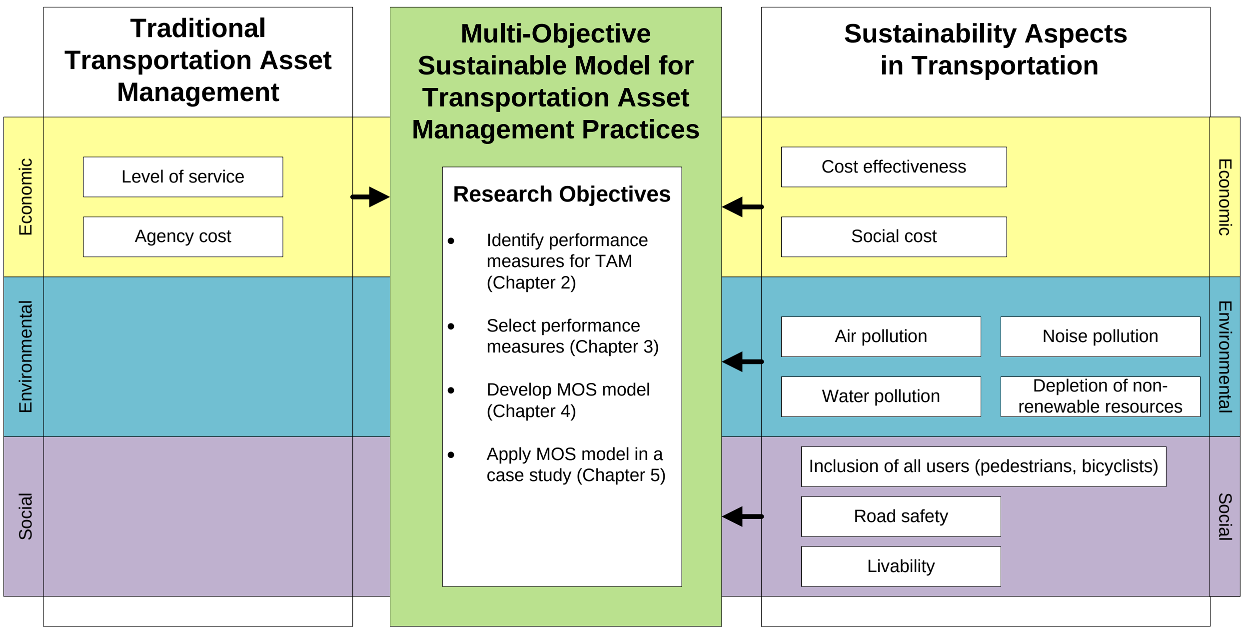


Figure 1.1: Relationship between TAM, Sustainability Aspects in Transportation and Research Objectives.

The four specific objectives of this study are to:

1. Identify performance measures for TAM to assess the environmental and social impact.
2. Use of the Quality Function Deployment Matrix to select performance measures that support environmental and social sustainability goals and objectives established by transportation agencies.
3. Develop a performance-based multi-objective sustainable (MOS) model for TAM.
4. Apply the multi-objective sustainable model in a case study for Metropolitan Transportation Commission (MTC) in San Francisco Bay Area, CA.

The multi-objective asset management model will improve decision making and contribute to a better allocation of funds while taking into account the preservation of the asset condition, providing a high-quality transportation infrastructure as well as including environmental and social factors.

This dissertation will focus on enhancing a traditional TAM, typically based on agency cost and asset condition. Environmental and social factors will be incorporated into the traditional decision making process, resulting in a multi-objective sustainable model for transportation asset management practices which addresses the social and economic effects of transportation investments on communities and environment.

1.4 Scientific Contributions

TAM would benefit from implementing the sustainability principles into the decision making process. Accounting for the consequences of transportation assets on the environment and society would lead to a more holistic approach in transportation funding allocation.

Transportation agencies will benefit from the implementation of this model in the following ways:

- Sustainable multi-objective model will help to address the needs of not only motorized users but also pedestrians and cyclists, contributing to a safer environment.
- Considering possible reduction of vehicle emissions due to pavement condition will lead to pavement maintenance plans that will have less negative impact on air quality and drivers benefit with fuel savings.
- Considering crash data and livability rating in a transportation asset management system can lead to funding allocation to streets that need an improvement in safety and livability, either by improving the asset condition or by implementing other safety and livability improvements.

1.5 Research Limitations

The research approach is based on the following assumptions:

(1) There are several aspects for economic, environmental and social sustainability in transportation, including effectiveness; wider economic benefits; air, noise, water, and light pollution; community livability; accessibility; and equity. However, for the purpose of this research, the economic sustainability is measured by creation of new jobs, agency expenditures and level of funding for non-motorized modes, the environmental sustainability is measured by on-road CO_2 emissions and the social cost of CO_2, social sustainability aims to foster livability by improving pedestrian safety and preserving multimodal transportation infrastructure.

(2) State transportation agencies manage highway and interstate infrastructure, while local transportation agencies manage transportation infrastructure in urban areas. This model is aimed towards local transportation agencies, as it focuses on transportation sustainability in urban settings. Since the social sustainability framework discussed in this dissertation focuses on non-motorized road users and highways and interstates have a limited or no access for non-motorized road users, other performance measures would be necessary to assess the social sustainability. However, the framework for environmental sustainability, which estimates emissions based on pavement condition, could be easily applied to highways and interstates.

(3) In the environmental framework for emission estimation, pavement condition index (PCI) is converted to international roughness index (IRI), while the conversion is not exact due the relationship between these indices. The emission model used also does not account for stop and go waves and idling. Lastly, the traffic volume is assumed to be constant during the 10-year analysis period. The last two aspects could be addressed by using a more complex model, such as the MOVES model by the FHWA. However, the complexity of the emissions model calculations may significantly increase the time and memory

requirements needed to run a pavement maintenance scenario, which is not desired for many local agencies.

(4) In the safety module of the social sustainability framework, only the implementation of marked crosswalks was considered for safety improvement. However, often there are other measures needed in order to address existing safety issues, such as warning signs, additional lighting, change in road geometry, road diet, bulb-outs, median islands and others. Expert judgement usually decides what the most appropriate improvement is because there are many factors to consider.

1.6 Dissertation Structure

This dissertation is organized into six 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 review of sustainability in transportation, legislature support for sustainable transportation, and 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 this research, emphasizes the contribution of the study, and provides recommendations for future research.

Chapter 2: Sustainability in Transportation Asset Management: Challenges, Goals, Objectives, and Performance Measures

This chapter aims to summarize the literature review on sustainability in transportation, challenges for sustainable TAM, and the goals, objectives and performance measures that transportation agencies can use on the way to a sustainable transportation system.

2.1 Sustainability in Transportation

Sustainability was first mentioned in 1987 when the General Assembly of United Nations called for *"a development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland 1987). The reason for such action was urgent environmental issues of *"a warming globe, threats to the Earth's ozone layer, deserts consuming agricultural land"* (Brundtland 1987) that made the United Nations call for change. A sustainable system can be defined as 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. Figure 2.1 shows examples of sustainability challenges in the transportation sector.

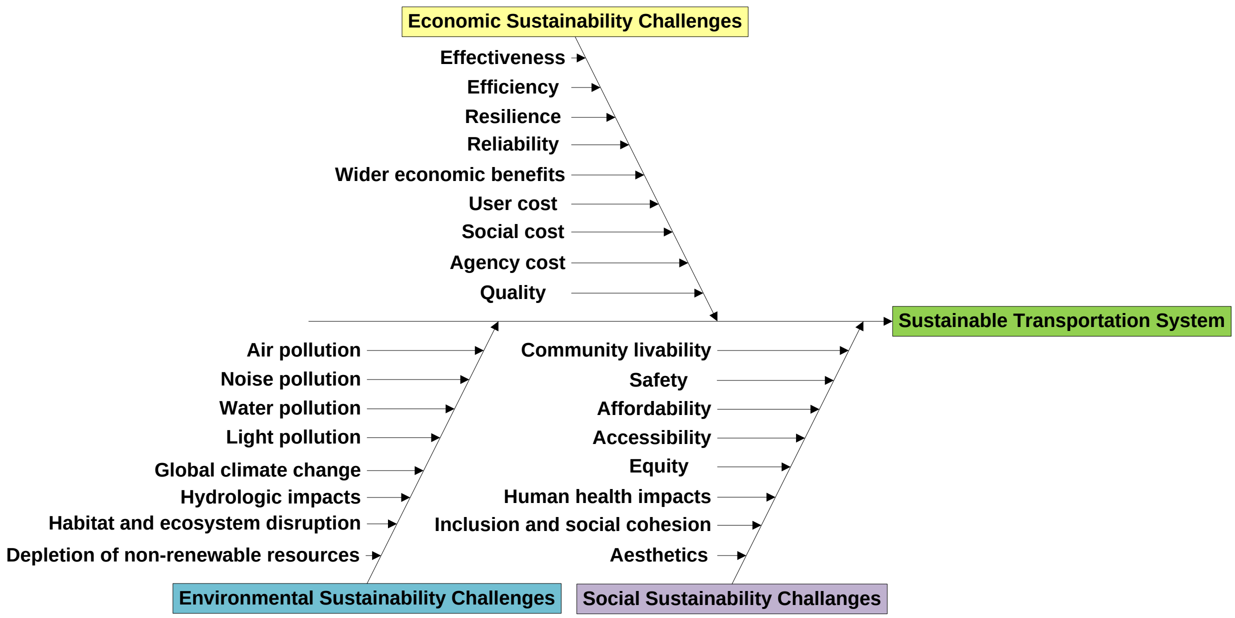


Figure 2.1: Sustainability Challenges in Transportation. (after ADD40 2008, Atkins 2008, Marsden 2015).

Economic challenges include transportation system effectiveness as well as efficiency, together with resilience to extreme weather events and overall reliability of the network. There are various costs involved: agency costs of the transportation infrastructure including construction and maintenance; user costs ranging from vehicle, insurance, vehicle operating, fuel, tolls, or costs of transportation by other means, such as mass transit or bicycle; social cost including impacts of the transportation system on air quality as well as public health and quality life; but also wider economic benefits.

Social challenges tied to transportation refer to community livability, overall safety, human health as well as affordability and accessibility for users of all ages and abilities. 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, light 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 emissions, resulting in environmental and *"social costs from pain and reduced quality of life"* (ADD40 2008).

In general terms, sustainable transportation *"includes effective and efficient system performance, with positive impacts on the social quality of life, economic competitiveness and the preservation of the natural environment"* (Amekudzi 2011).

The European Union defines a sustainable transportation system as one that:

• *"Allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations;*

• *Is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development;*

• *Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on the use of land and the generation of noise"* (Rosengren 2001).

Also the contribution to economic growth is important for sustainable transportation. Investments into transportation infrastructure play a vital role in sustainability, since these choices have profound economic, environmental and social effects. The transportation system influences transportation choice, travel time, vehicle operating costs, as well as safety of all road users (Forkenbrock and Weisbrod 2001). It also has effect on traffic noise levels, visual quality of a neighborhood, as well as community cohesion, economic development and property values (Forkenbrock and Weisbrod 2001).

NCHRP Report 541 (2005) concluded that several DOTs and MPOs consider environmental sustainability in their decisions, however they mostly focus on *"what happens during project development (with respect to environmental impacts) than with developing more environmentally sensitive plans"* (Amekudzi and Meyer 2005).

Ideally, sustainability in transportation should be measured by six sub-objectives:

- *"economic efficiency*
- *livable streets and neighborhoods*
- *protection of the environment*
- *equity and social inclusion*
- *safety"* (Black et al. 2011).

The performance in these sub-objectives can be quantified in monetary or non-monetary terms; or measured qualitatively (Black et al. 2011).

Incorporating sustainability aspects into TAM decision-making can help to address challenges that transportation decision-makers face.

2.2 Challenges for Transportation Asset Management

The following section discusses the current and future challenges from limited funding, congestion, environment, society, technology, and their impact on expectations of what TAM should be capable of in order to help transportation agencies in funding allocation decisions.

The expected service life of transportation assets ranges from several months for pavement markings, to 100 years for bridges (UK Highways Agency, 2011). Therefore, it is crucial that TAM systems are ready to face current and future challenges caused by changes in environment, technology and society to ensure that the new infrastructure planned today, as well as the existing infrastructure maintained, will meet the needs of tomorrow.

2.2.1 Limited Funding

The major source of funding for highway infrastructure is the income from gas tax which consists of federal (18.4 cents) and state (ranging from 12 to 50 cents). The federal gas tax has not been adjusted for inflation since 1993 and the purchasing power has declined. Also the vehicle miles travelled (VMT) are no longer growing every year and vehicle fuel efficiency has improved. As a result, user charges (including gas tax and vehicle registration fees) were able to fund only 45% of the highway spending in 2010 and the remaining 55% of the funding had to be

transferred from other sources, such as the General Fund (USDOT 2016). Even so, the highway infrastructure has been underfunded in the long term. According to the ASCE Infrastructure Report Card, the condition of roads in the U.S. is D, meaning poor condition (ASCE 2013). The optimal budget to meet the highway needs is estimated at $77 billion, while only $34 billion is actually funded (USDOT 2016). Many states, such as Wyoming, New Hampshire, Massachusetts, and Maryland have adjusted their state gas taxes to generate more revenues (USDOT 2016). Other potential revenue sources include charging road users tolls or mileage fees. Value capture can be another stream of revenues, especially in urban areas where new transportation infrastructure increases land value, and this newly created value can be charged to property owners who benefit from the new infrastructure.

The major challenge here for TAM is to allocate the available funding in the most efficient manner. Since the transportation infrastructure consists of many assets, including pavements, signs, pavement markings, sidewalks, transit infrastructure and many more, it is crucial that transportation agencies and metropolitan planning organizations have a tool to predict the asset condition under budget-restricted scenarios with a cross-asset allocation, as well as estimate the impacts of the funding allocation on environment and society in the long term.

2.2.2 Congestion

According to predictions of Beyond Traffic 2045 (USDOT 2016), between 2015 and 2045 the population in the United States will grow by 70 million, reaching 390 million people. *"FHWA forecasts show vehicle miles traveled (VMT) per capita remaining relatively stable, and overall VMT increasing by 23 to 27 percent over the next 30 years"* (USDOT 2016). Currently, the average annual time lost in traffic is 41 hours which costs the society $121 billion or $800 per commuter in wasted time and fuel (USDOT 2016). Until 2005 the VMT per capita increased every year however since 2006 the VMT per capita has been declining. This change can be caused by economic recession, as well as changes in the ways people commute.

Limited funding resources force agencies to carefully choose between new construction projects (that will consequently increase the overall network maintenance costs in the future) and maintenance of existing infrastructure. A phenomenon of induced traffic demand was recognized by FHWA in early 2000s, showing that building new highways and widening congested roads does not help from congestion, *"because any increase in highway capacity is quickly filled up with additional traffic"* (FHWA 2012a).

2.2.3 Environment

Due to high levels of driving per capita, *"in 2012, transportation sources directly accounted for 28 percent of total U.S. greenhouse gas emissions"* (USDOT 2016) and over half of those emissions came from *"passenger cars and light-duty trucks"* (EPA 2016). That is more than double of the levels that transportation globally accounts for (13 percent) (USDOT 2016). Carbon dioxide (CO_2) is the major greenhouse gas resulting from petroleum combustion (EPA 2016). As gases trap heat in the atmosphere, the Earth's surface gets warmer. Year 2015 was the warmest year on record since 1880, with average temperatures 1.33° F above the 20th century average (NOAA 2016). There are several consequences of changing climate for transportation. As the temperature will continue rising, the U.S. road network will be more likely to be impacted by extremes in rainfalls, temperatures, hurricanes, floods and also by gradual changes in temperature and sea level. The occurrences of unusual and extreme weather patterns are virtually certain to become more frequent and severe over the time as the global warming and climate change continue IPCC (2007). *"Higher average temperatures will raise maintenance costs across all modes. High temperatures accelerate the deterioration of pavement on roads and runways, and cause failures of railroad tracks. Heavy trucks are more prone to tire blowouts in conditions of high heat"* (USDOT 2016).

TAM can play a role both in mitigation and adaptation to climate change. Maintaining roads in good condition and smooth can improve fuel economy and decrease emissions. Also allocating transportation funding to infrastructure that promotes walking, cycling and public

transit can encourage more efficient forms of transportation that produce less or no emissions. Adaptation activities can include updating deterioration curves of assets within the TAM systems to provide reliable condition predictions.

2.2.4 Society

Also changes in society will impact the way we travel. The percentage of workforce population continues declining, as the generation of baby boomers is reaching retirement age. *"By 2045, there will be an estimated 81 million Americans older than 65 making up 21 percent of the population"*, which is twice as much as today (USDOT 2016). Many of these seniors will likely have a limited ability to drive due to vision, mental or physical limitations (USDOT 2016), and probably will seek other ways to get around, such as transit and safe infrastructure for walking. Cities with active transportation options are attractive also to young working professionals. *"A survey conducted by the American Planning Association found that only 8% of Millennials would prefer to live in an auto-dependent suburb"* (USDOT 2016). It can be caused by the increasing cost of car ownership, which is four times higher than in 1975 (AAA 2015). Economic recession during 2007-2009 and gas prices reaching up to $4/gal during 2008-2014 (USDOT 2016) can contribute to the fact that people drive less.

There are also new social trends. Mobile app taxi services such as Uber Technologies, Inc. and Lyft, and car sharing services such as Zipcar and urban bike sharing services supplement public transit and allow people to find a suitable and more affordable transportation mode for various trips without the need to own a vehicle. The most significant travel trips, to workplace and to shopping centers are also changing. Due to advancement in telecommunication technology an increasing number of Americans work from home at least one day per week (USDOT 2016) and purchases made online are also increasing, as in 2014 the 7% of all retail sales were made online (UDOT 2016) and this number is expected to grow. Consequently, this behavior is likely to cause reduction in shopping trips, while possibly increasing truck traffic.

Housing trends are also changing, as smaller homes closer to amenities are becoming more attractive than single family homes in suburbs.

People are also motivated by overall health benefits to choose active transportation, such as weight loss and lower Body Mass Index compared to people who drive to work (Andersen 2016). Additionally, the World Health Organization indicates that adults *"should do at least 150 minutes of moderate-intensity aerobic physical activity"* and encourages non-motorized transport as one of the key factors in diabetes type 2 prevention (WHO 2016). Overall, there is an apparent shift in attitudes about travel, towards reducing environmental footprint and taking advantage of health and mental benefits of an active transportation. Currently, walking accounts for more than 10 percent of all trips (including work and leisure) (USDOT 2016). Walking and bicycling to work accounts for 2.8 and 1 percent respectively, and these numbers have been rising in the last years after a continuous decrease in previous decades. The effect is more apparent in large cities. *"More than 10 percent of commuters walk to work in four American cities - Boston, Washington D.C., New York, and San Francisco. These cities also have very high public transit usage for commuting trips: New York at 56 percent, Washington, DC at 38 percent, San Francisco at 34 percent, and Boston at 33 percent. Portland, Oregon had the highest share of cycling commuters: 6.1 percent"* (USDOT 2016). With a rising number of vulnerable road users in the streets, it is crucial to ensure safety for all road users. While car fatalities have been on a decline, pedestrian and bicyclist fatalities in urban areas have rising since 2009 (USDOT 2016). Several cities in the U.S. have joined the multi-national Vision Zero movement to prevent road user fatalities by innovation in planning, engineering and education.

Consequently, there is an increasing need for TAM to focus on other assets than only pavements, in order to be able to satisfy the needs of all road users, not only drivers. By 2045 there will be tens of thousands of new bike infrastructure (USDOT 2016), therefore there is an urgent need for TAM to include these assets in the decision-making. Currently 2% of total federal transportation spending goes towards pedestrian and bicyclist facilities (USDOT 2016), which may seem low, however costs of infrastructure for active transportation are much lower

and deterioration due lighter loads is slower. TAM needs to consider bicycle traffic in its deterioration models, as they cause less damage than heavy motorized vehicles while being very sensitive to certain distresses such as cracking. Local agencies deciding the level of spending for each mode will find useful a cross-asset, multi-modal, cost-benefit analysis within TAM for estimating impacts of funding allocation. Also project coordination among various assets and various modes within a street block for the most cost-effective maintenance will be needed.

2.2.5 Technology

Corporate Average Fuel Economy (CAFE) standards have played an important role since 1975 in setting up the minimum fuel efficiency for vehicles sold in the U.S. To complement the existing standards for light duty vehicles, standards for medium and heavy duty trucks were recently added to encourage increasing fuel efficiency among new model years and reduce emissions. Vehicles with lowest emissions, such as hybrids and electric vehicles, are still in minority compared to conventional vehicles, however it may change since the Tesla 3, an affordable electric vehicle with more than 325,000 pre-orders worldwide will enter the market in 2018 (Tesla 2016). For comparison, at the end of 2014 there were total of 665,000 electric vehicles worldwide, representing 0.08% of total passenger cars (IEA 2016).

With technology progress vehicles will also be able to communicate with other vehicles as well as the infrastructure to warn about *"weather conditions, traffic, upcoming work zones, and even potholes"* (USDOT 2016). *"Automated vehicles could also make driving more accessible to people with disabilities, the young, and older adults"* (USDOT 2016).

As self-driving vehicle technology depends on good condition pavement markings and signs, the challenge for TAM will be to maintain these assets in an acceptable condition. Additionally, real-time traffic and transit data will be utilized not only for navigation but also for observing the travel behavior and apply the patterns in planning.

2.2.6 Transportation Policy

The current transportation policy has been evolving since the beginning of 20th century and has an impact on the way we view transportation today as well as on the challenges TAM is facing. Federal policies and funding opportunities indirectly determine the type of projects local transportation agencies will prioritize. TAM, as a decision-making approach, has to reflect all federal requirements, because non-compliant agencies could potentially lose its funding. Table 2.1 shows an overview of U.S. transportation bills and related legislature and their major goals related to TAM and sustainability.

Table 2.1: U.S. Legislation and Their Effect on TAM and Sustainability.

U.S. Legislation	**Major points related to TAM and sustainability**
National Environmental Policy Act (NEPA) of 1969	Set the standard of preparing Environmental Impact Statements (EIS) for major federal projects (Kershner 2011)
Clean Air Act (1970)	Focused on air pollution, established pollutant standards for vehicle tailpipe emissions. Amendments followed in 1990.
The Surface Transportation and Uniform Relocation Assistance Act (STURAA, 1987)	Environmental commitments for highway construction. (Weingoff undated)
Congestion Mitigation and Air Quality Improvement (CMAQ)	*"Implemented to support surface transportation projects and other related efforts that contribute air quality improvements and provide congestion relief"* (FHWA 2015)
The Intermodal Surface Transportation Efficiency Act (ISTEA, 1991)	Local governments can fund transit, rail, pedestrian and bicyclist projects to mitigate environmental pollution. (BTS 1991) Congestion Mitigation and Air Quality Improvement program (CMAQ) *"implemented to support surface transportation projects and other related efforts that contribute air quality improvements and provide congestion relief."* (FHWA 2015)
The National Highway System Designation Act (NHSDA, 1995)	Preventive maintenance on highways found cost-effective and eligible for federal assistance. CMAQ reauthorized. (FHWA undated)
The Transportation Equity Act for the 21st Century (TEA-21,1998)	Aimed for livable communities with multi-modal transportation options, calls for including pedestrian and bicyclist infrastructure into nation's transportation system. (Slater 1999)

Table 2.1: U.S. Legislation and Their Effect on TAM and Sustainability. (continued)

U.S. Legislation	**Major points related to TAM and sustainability**
The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU, 2005)	Largest investment in the U.S. history ($244 billion), focused on improving highway safety and environmental protection. Repair and maintenance prioritized over new construction. Safe Routes to School program enacted. (FHWA 2005a)
Moving Ahead for Progress in the 21st Century Act (MAP-21, 2012)	Agencies required to measure effectiveness of transportation investments (USDOT 2012). Established Transportation Alternatives (TAP) Program that focuses on walking and bicycling infrastructure.
Fixing America's Surface Transportation Act (FAST Act, 2016)	Allowed using highway safety funds for pedestrian safety improvements. Added non-motorized performance measures (DOT 2016)

Moving Ahead for Progress in the 21st Century (MAP-21) a transportation bill that took effect in 2012 and authorized spending in surface transportation for two years. Under MAP-21, state departments of transportation and local metropolitan planning organizations are required to establish a set of performance measures for more efficient investment decision-making in categories including safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability and reduced project delivery delays, as Table 2.2 shows (USDOT 2012).

Table 2.2: MAP-21 Performance Goals and Performance Measures. (§1203; 23 USC 150(b), FHWA 2016a)

MAP-21 Goal area	**MAP-21 National goal**	**Performance measures** (* signifies a proposed measure)
Safety	To achieve a significant reduction in traffic fatalities and serious injuries on all public roads	• Number of fatalities / serious injuries • Rate of fatalities / serious injuries per 100 million VMT • Number of non-motorized fatalities and non-motorized serious injuries
Infrastructure condition	To maintain the highway infrastructure asset system in a state of good repair	• Percentage of pavements in good / poor condition (Interstate / non-Interstate National Highway System)* • Percentage of National Highway System (NHS) bridges classified as in good / poor condition*

Table 2.2: MAP-21 Performance Goals and Performance Measures. (§1203; 23 USC 150(b), FHWA 2016a) (continued)

MAP-21 Goal area	**MAP-21 National goal**	**Performance measures** (* signifies a proposed measure)
Congestion reduction	To achieve a significant reduction in congestion on the National Highway System	Annual hours of excessive delay per capita*
System reliability	To improve the efficiency of the surface transportation system	• Percent of the Interstate System / non-interstate NHS providing for reliable travel times* • Percent of the Interstate System / non-interstate NHS where peak hour travel times meet expectations*
Freight movement and economic vitality	To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development	• Percent of the Interstate System mileage providing for reliable truck travel times* • Percent of the Interstate System mileage uncongested*
Environmental sustainability	To enhance the performance of the transportation system while protecting and enhancing the natural environment	• Total emission reductions*
Reduced project delivery delays	To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies' work practices	[Not available as of April 2016]

Fixing America's Surface Transportation Act (FAST Act), is a five-year authorization for fiscal years 2016 to 2020. This bill makes financing support of transit, walking and bicycling infrastructure more accessible. For the first time in history, state departments of transportation and metropolitan planning organization are required to accommodate safely and adequately all road users, including non-motorized users such as pedestrians and bicyclists of all abilities. Additionally, new performance measures are being discussed, such as measures of climate-related pollution from transportation, enhancing the performance-based program of MAP-21 (Grunwald 2016). Also states form legislature that aims for sustainable transportation in the long term. For example, the California Transportation Plan 2040 (CTP2040) aims *"to provide a statewide transportation system capable of meeting mobility, safety, sustainability, and economic*

objectives in the fight against climate change" (Caltrans 2016). The policy framework of the CTP2040 is shown in Figure 2.2.

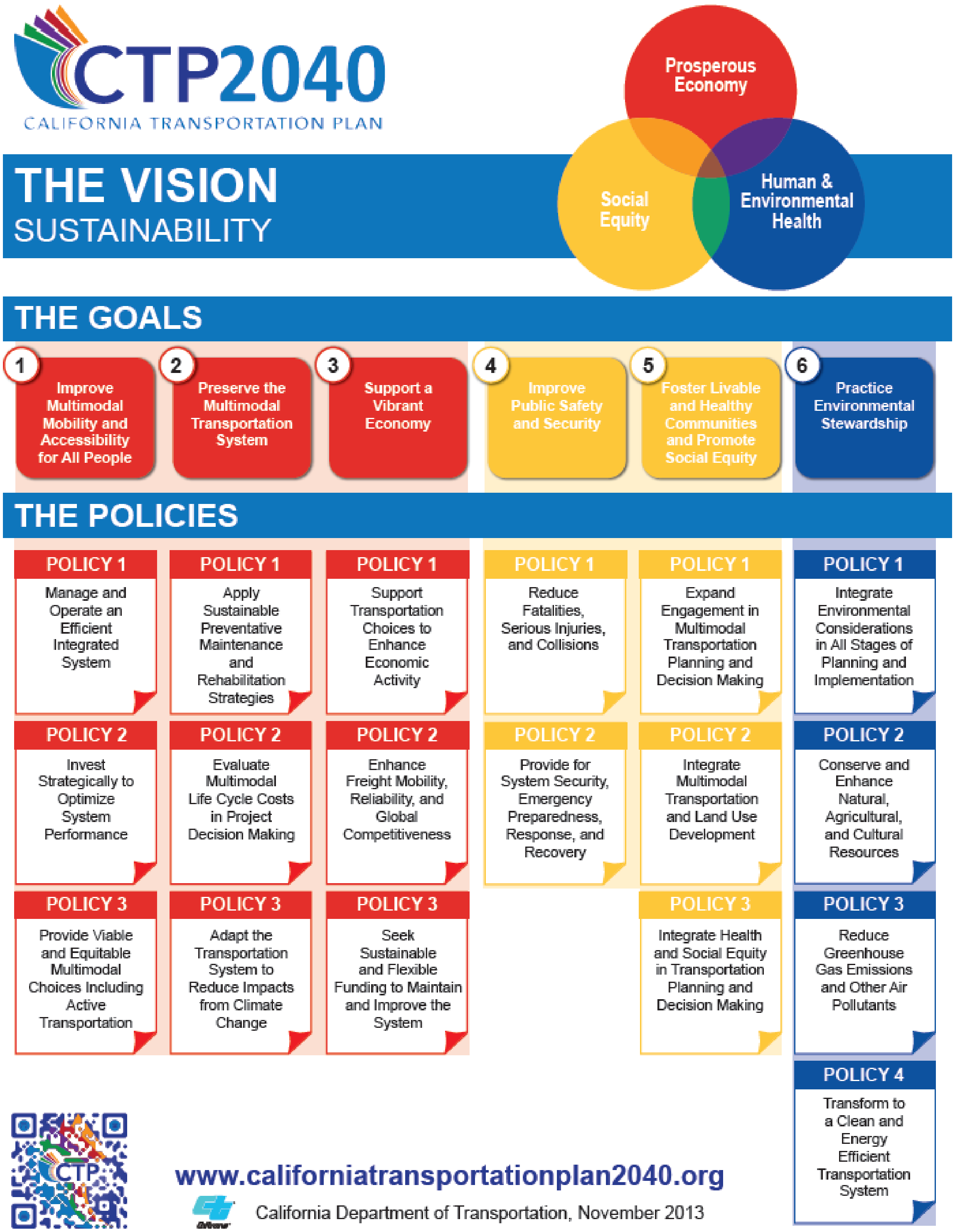


Figure 2.2: California Transportation Plan 2040 (CTP2014) Framework (Caltrans 2016).

The CTP2040 framework includes six goals addressing economic, social and environmental sustainability (Caltrans 2016):

- Improvement in multimodal mobility and accessibility for all people by managing and operating an efficient integrated system, by optimizing system performance through strategic investments, and by providing viable and equitable multimodal choices including active transportation (Caltrans 2016).
- Preservation of the multimodal transportation system by applying sustainable preventive maintenance and rehabilitation strategies, by evaluating multimodal life-cycle costs in project decision making, and by adapting the transportation system to climate change (Caltrans 2016).
- Support for a vibrant economy by supporting transportation choices that enhance economic activity, as well as freight mobility, reliability, and global competitiveness; and by seeking sustainable and flexible funding to maintain and improve the transportation system (Caltrans 2016).
- Improvement in public safety and security by reducing fatalities, serious injuries, and collisions; and by providing for system security, emergency preparedness, response, and recovery (Caltrans 2016).
- Fostering livable and healthy communities and promoting social equity by expanding engagement in multimodal transportation planning and decision making, integrating multimodal transportation and land use, and integrating health and social equity in transportation planning and decision making (Caltrans 2016).
- Practice of environmental stewardship by integrating environmental considerations in all stages of planning and implementation; by conserving and enhancing natural, agricultural, and cultural resources; by reducing greenhouse gas emissions and other air pollutants; and by transforming to a clean and energy-efficient transportation system (Caltrans 2016).

There is an apparent trend towards sustainable transportation on the federal and state level, however a project-level TAM that would incorporate sustainability performance in its scenarios is currently missing. For example, environmental sustainability can be pursued on project level via well-maintained smooth pavements which can result in lower on-road vehicle exhaust emissions. 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. Consequently, fuel consumption can be used for an estimation of emissions (Chatti and Zaabar 2010). Social sustainability in transportation can be reflected by creating livable neighborhoods that encourage non-motorized forms of transportation and are safe for all users regardless of age and ability. Streets play a significant role not only in transportation but also in the quality of life. Streets are the single largest public asset in every city, therefore the way they are designed and maintained directly affects the way they are used and by whom. There is a significant shift towards alternative modes of transportation through accommodating pedestrians, cyclist and mass transit in the urban roadways. Traditional TAM, oriented towards motorized vehicles often lacks to accommodate the other users of the roadway in safety considerations and in prioritization of funding. As funding is limited, agencies strive to allocate it in the most efficient way to ensure that economic, environmental and social needs will be met. *"Among possible transportation improvements, some may be far more effective than others in helping […] economy, preserving existing jobs, attracting employers with desirable jobs […], improving productivity and stimulating long-term economic development"* (Zhang et al. 2016).

The direction of how transportation agency funding is allocated among various assets comes from agency's goals, objectives and performance measures. Therefore, sustainability aspects can be included in TAM by defining sustainable goals, objectives and performance measures.

2.3 Transportation Asset Management, Goals, Objectives and Performance Measures

Transportation asset management (TAM) is *"a decision-making process for allocating resources"* (FHWA 2014). According to the International Infrastructure Management Manual (2006), *"the purpose of TAM is to meet a required level of service, in the most cost effective manner, through the management of assets for present and future customers."* The goal is to improve transportation asset performance at the minimum construction and preservation cost, while providing best service to tax payers (AASHTO 2011). Figure 2.3 illustrates the TAM process.

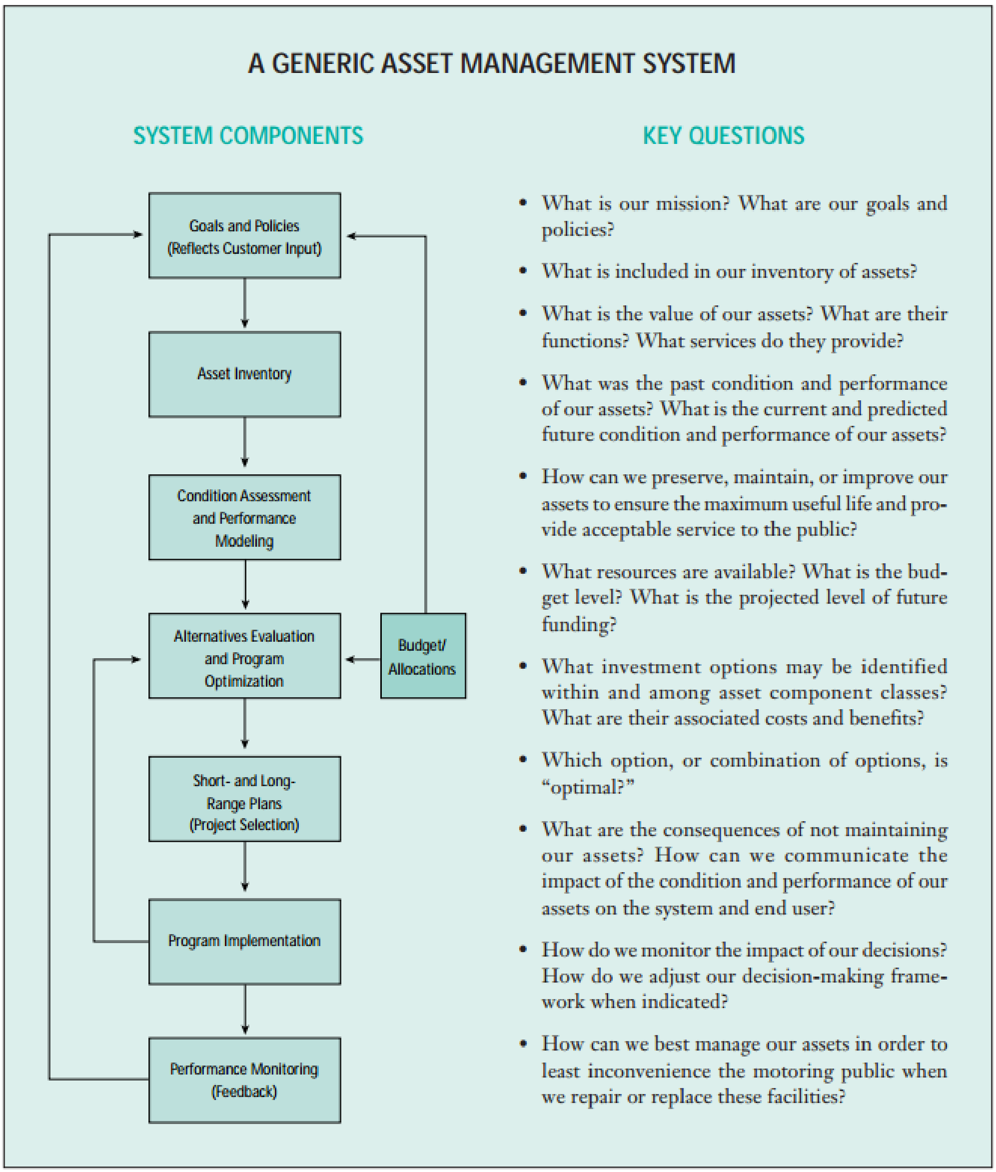


Figure 2.3: Transportation Asset Management Process (FHWA 1999a).

Goals and policies are defined by transportation agencies to indicate the direction in which the transportation network will evolve, including the most important values (condition, safety, etc.). *Asset inventory* includes information about the transportation network, such as asset location, classification, type, and work history. *Condition assessment* module contains any distress and deficiency data collected during inspections, *performance modelling* evaluates the condition data and determines the asset current condition and estimates future condition under different scenarios. During *alternatives evaluation and program optimization*, different scenarios are proposed, indicating the resulting asset performance under various levels of funding. Based on matching with agency goals, objectives and funding availability, projects are selected and formed into *short and long range plans*. It is important to *monitor performance* once the program is implemented and provide feedback of how well are the agency goals and policies met and if previous decisions have enabled the transportation infrastructure to move in the right direction.

As Figure 2.3 suggests, performance measurement plays a major role in TAM. Performance measures for TAM are derived from five core principles (NCHRP 551 2006):

- Policy-driven: performance measures provide information about changes in the transportation system in relation to policy objectives.
- Performance-based: performance measures track the changes in history and also predict the performance in the future under different funding level scenarios.
- Analysis of options and trade-offs: performance measures enable to compare different scenarios.
- Decision based on quality information: data collection should be feasible and database should be updated regularly to ensure reliability and trustworthiness.
- Monitoring to provide clear accountability and feedback: performance measures indicate both impacts and effectiveness of the resource allocation.

In general, performance measures can be categorized in ten groups (NCHRP 551 2006):

- Asset preservation: performance measures focus either on physical condition (e.g., pavement roughness, distress quantity and severity), or can be expressed by an overall

index (e.g. Pavement Condition Index), or by a non-technical index (e.g. asset value, resilience towards extreme weather events) (NCHRP 551 2006).

- Operations and maintenance: performance measures capture the effect of asset condition on fuel efficiency and user costs (NCHRP 551 2006).
- Delivery: performance measures related to delays in project delivery and projects that were identified as needed but were not funded can go into this category (NCHRP 551 2006).
- Accessibility: performance measures focus on users and their ability to access points of interest, such as employment, schools, medical care and retail (e.g. the number of households within a 0.5 mile from a transit stop, the number of retail and services within a 10-minute walk) (NCHRP 551 2006).
- Mobility: performance measures that focus on the cost and travel time of a trip (e.g. volume/capacity ratio, total travel time, delay, transit service reliability, trip cost) (NCHRP 551 2006).
- Safety: performance measures capture totals of fatal or serious injury collisions between motorized vehicles or involving vulnerable road users (pedestrians, cyclists).
- Security: performance measures that focus on resilience to terrorist actions (NCHRP 551 2006).
- Economic development: performance measures that indicate changes in employment, income and economic output as a result of transportation investments (NCHRP 551 2006).
- Environmental impacts: performance measures include air quality (carbon dioxide, volatile organic compounds), noise levels, as well as effect of transportation projects on habitat of animals and plants (NCHRP 551 2006).
- Social impacts: performance measures that capture the effect of transportation investments on mode shift and overall improvement in quality of life. Effect on community walkability and overall livability can be also included in this category.

A robust set of performance measures estimating the effect of investment on economic, environmental and social aspects is vital in order to be able to compare various funding scenarios

and also track performance over time. While increasing number of performance measures leads to a more holistic description of the decision situation, it also produces significant burden on data collection and database maintenance. Traditional TAM therefore focuses on asset preservation in restricted economic conditions while skipping on the other categories. This dissertation aims to look into the emerging topic of enhancing sustainability in TAM by assessing the social, environmental and economic effects of transportation investments on communities.

2.3.1 Economic Sustainability

The focus of economic sustainability in transportation is on innovation and design, operations and maintenance, cost effectiveness, affordability, economy and jobs, and transportation impact (Brodie et al. 2013).

2.3.1.1 Economic Sustainability Goals

Table 2.3 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 2.3: 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).

2.3.1.2 Economic Sustainability Objectives

Objectives describe specific and measurable statements that are more general than performance measures (FHWA 2013a). Table 2.4 shows examples of economic sustainability objectives.

Table 2.4: 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.

2.3.1.3 Economic Sustainability Performance Measures

Table 2.5 shows examples of performance measures for economic sustainability.

Table 2.5: Examples of 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
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	United States Government 2013
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 CO2 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 added 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.

2.3.2 Environmental Sustainability

The focus of environmental sustainability in transportation is on energy conservation, climate change, environmental protection, water conservation, waste and materials management, noise and light pollution, and on sustainable land use (Brodie et al. 2013).

2.3.2.1 Environmental Sustainability Goals

Table 2.6 shows examples of goals for environmental sustainability.

Table 2.6: 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).

2.3.2.2 Environmental Sustainability Objectives

Table 2.7 shows examples of objectives for environmental sustainability.

Table 2.7: 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 instance, 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).

2.3.2.3 Environmental Sustainability Performance Measures

Table 2.8 shows examples of performance measures for environmental sustainability.

Table 2.8: Examples of Environmental Sustainability Performance Measures.

Performance measure	Source
Total vehicle emissions	ADD40 2008
Total vehicle gas consumption	World Bank undated
Climate change emissions (CO_2, CH_4) reduction per capita	ADD40 2008, Briseno 2015
Tons of CO_2 equivalent 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 2012b
Annual hours of excessive delay per capita	MAP-21 (FHWA 2016a)
2- and 4-year total emission reductions	MAP-21 (FHWA 2016a)
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 precursor 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 2012b). Under the MAP-21 performance measures, the traffic congestion and on-road vehicle source emissions are proposed to be measured by annual hours of excessive delay per capita and all congestion mitigation projects will have to show the 2- and 4-year total emission reductions (FHWA 2016a). 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).

2.3.3 Social Sustainability

Social sustainability in transportation can be *"defined as transportation that provides equitable access to opportunities, minimizes social exclusion, and improves (or does not diminish) an individual's quality of life"* (Amekudzi 2011). Social sustainability can address various topics, such as *"access, safety, equity and inclusion, health and well-being, culture and place-making, food sustainability, and indoor environment"* (Brodie et al. 2013). Impact of transportation projects on community health can be assessed with a Transportation Health Impact Assessment Toolkit by Centers for Disease Control and Prevention. It estimates the impact on reduction in vehicle miles travelled, expansion of public transportation, promotion of active transportation, incorporation of healthy community design features, improvement in safety for all users, and ensuring equitable access to transportation networks (CDC 2015).

Initiatives that improve community quality of life can be summarized in the concept of livability. *"Livability encompasses multi-dimensional issues relative to community design, land use, environmental protection and enhancement, mobility and accessibility, public health, and economic well-being"* (FHWA 2011). It is not limited only to increasing community walkability and bikeability, but it also focuses on overall system multimodality. For example, *"livability principles for highways include strategies to get more efficiency out of the existing highway network,*

maintaining reasonable travel times through operational improvements, and multimodal enhancements (high occupancy lanes or dedicated transit lanes)" (FHWA 2011). Livability has some common goals with sustainability, like focus on social equity, human health and multimodal transportation options; while their differences are in the scope and detail (FHWA 2011). In general, livable communities are such developments that offer multi-modal transportation choices and are pedestrian-friendly and bicyclist friendly. Walkable and bikeable communities have several benefits, that include improving health by encouraging regular physical activity, enriching mobility and access by providing alternative transportation modes, improving land use, reducing air and noise pollution as well as traffic congestion, strengthening the sense of community (Amekudzi 2006).

2.3.3.1 Social Sustainability Goals

Table 2.9 shows examples of goals for social sustainability.

Table 2.9: 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).

2.3.3.2 Social Sustainability Objectives

Table 2.10 shows examples of goals for social sustainability.

Table 2.10: 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.

2.3.3.3 Social Sustainability Performance Measures

Table 2.11 shows examples of performance measures for social sustainability.

Table 2.11: 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
Improved networks that accommodate pedestrians and bicyclists	FHWA 2013b
Quality of walking/bicycle/transit infrastructure	ADD40 2008
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
Level of sidewalk/bikeway investment	DDOT 2014
Crossing opportunities	FHWA 2016b
Walk miles travelled and bicycle miles travelled	Briseno 2015
Availability of bicycle parking	FHWA 2013b
Number of new on-street bicycle facilities, trails, and sidewalks within 100 feet of parks and green space	DDOT 2014
Pedestrian Potential Index, Pedestrian Deficiency Index	FHWA 1999b
% of population within 30-minute walk, bike, or transit trip of key destinations	Dondero et al. 2013
Transportation-disadvantaged population served	FHWA 2016b
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
Number of improved crash locations within 100 feet of each approach's projects (bicycle facilities, trails, sidewalks, streets)	DDOT 2014
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), improved networks that

accommodate pedestrians and bicyclists (FHWA 2013b), 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 availability of bicycle parking (FHWA 2013b). For example, Washington D.C. measures the increase in new on-street bicycle facilities, trails, and sidewalks within 100 feet of parks and green space to ensure better accessibility to these locations. The City of Portland, OR, is a pioneer city in livability that uses a Pedestrian Potential Index and Pedestrian Deficiency Index to prioritize pedestrian projects (FHWA 1999b). The Pedestrian Potential Index is based on the presence of urban activity centers that attract pedestrians, such as shopping opportunities, parks, schools or transit; and environmental factors such as proximity, connectivity, and slope (FHWA 1999b). The Pedestrian Deficiency Index considers *"ease of street crossing (e.g., traffic speed, traffic volumes, and roadway width), sidewalk continuity (i.e., sidewalk inventory data), and street connectivity (i.e., street segment length)"* (FHWA 1999b). Both indices range from 1 (lowest rating) to 5 (highest rating) and can be used to prioritize transportation projects in regional planning (Amekudzi 2006).

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). 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 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 2002a). Los Angeles County's Model Design Manual for Living Streets recommends maximum speeds of 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). For example, Washington D.C. measures the number of improved crash locations within 100 feet of each approach's projects (bicycle facilities, trails, sidewalks, streets) (DDOT 2014).

In order to tie safety to infrastructure expenses, improvements in areas with safety problems are reported along with the prevented economic costs of injuries and fatalities.

2.4 Summary

The comprehensive literature review performed in this Chapter allowed identifying a broad variety of sustainability considerations in Transportation Asset Management as well as the goals, objectives, and performance measures that can be used to tackle the current sustainability challenges.

Goals, objectives, and performance measures help transportation agencies to manage their assets in the most effective way. Scenario planning is used to determine what actions need to be taken in order to reach agency goals and objectives.

Agencies are also required to comply with federal requirements when selecting their performance measures. For example, San Diego Association of Governments (SanDAG 2013) established 11 sustainability monitoring indicators in alignment with MAP-21 requirements for California MPOs to use, as shown in Table 2.12.

Table 2.12: California Sustainability Performance Measures (SanDAG 2013).

MAP-21 Category	Performance Monitoring Indicator	Modeled	Observed
Congestion Reduction	VMT per capita	✓	✓
	Percent of congested freeway/highway vehicle miles	✓	✓
	Mode share (travel to work)	✓	✓
	Congested arterial VMT	Proposed for future consideration	
	Bike and walk miles travelled	Proposed for future consideration	
	Mode share (non-work)	Proposed for future consideration	
Infrastructure Condition	State of good repair (highways / local streets / highway bridges / transit assets)		✓
System Reliability	Buffer Index (freeway / highway)	✓	✓
	Travel time reliability (transit / rail)	Proposed for future consideration	
Safety	Fatalities (per capita, per VMT)	✓	✓
	Serious injuries (per capita, per VMT)	✓	✓
Economic Vitality	Transit accessibility (housing and jobs within 0.5 miles of transit stops with frequent transit service)	✓	✓
	Travel time to jobs	✓	✓
	Residential and employment densities (new growth) (by Environmental Justice and Non-Environmental Justice areas)	Proposed for future consideration	
	Affordability Index (housing / transportation)	Proposed for future consideration	
Environmental Sustainability	Change in agricultural land	✓	✓
	CO_2 emissions reduction per capita	✓	

While some performance measures, such as CO_2 emissions reduction per capita are modeled, some performance measures, such as state of good repair (highways / local streets / highway bridges / transit assets), are observed. Others are both observed and modeled: VMT per capita, percent of congested freeway/highway vehicle miles, mode share (travel to work), Buffer Index (freeway / highway), fatalities (per capita, per VMT), serious injuries (per capita, per VMT), transit accessibility (housing and jobs within 0.5 miles of transit stops with frequent transit service), travel time to jobs, and change in agricultural land. Measures such as congested arterial VMT, bike and walk miles travelled, mode share (non-work), travel time reliability (transit / rail), residential and employment densities (new growth), and Affordability Index (housing / transportation) were recommended for future consideration. Recently, also the City

and County of San Francisco updated their measure of the transportation impacts of new development. Before, a Level of Service (LOS) measure was used to estimate the impact of a new development on the traffic flow delay of motorized vehicles. Since March 2016 the San Francisco County uses VMT to measure *"the amount and distance that a [new] project might cause people to drive"* in all assessments under the California Environmental Quality Act (Simi et al. 2016).

Modern TAM requires an integrated approach that connects goals, objectives and performance measures through 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. Chapter 3 focuses on selecting the right set of performance measures to reach agency's goals taking into account sustainability challenges. Chapter 4 introduces the multi-objective sustainable model that incorporates previously selected performance measures in order to measure performance in selected social and environmental objectives.

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 create a link between allocation of agency funds and the outcomes while fostering transparency and accountability (FHWA 2016c). The right 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.

Since data collection and management is expensive and time consuming, 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).

There are several methods that can be used for selection of performance measures, for example:

Analytic Hierarchy Process (AHP) is a group decision-making technique consisting of three steps. First, the problem hierarchy is defined. The goal is to find a set of performance measures, for agency objectives described by air quality, maintenance cost, asset condition, jobs creation, livability and road user safety. Then the last layer includes candidate performance measures. During the second step, every item in each layer receives a numerical weight to reflect their priority. In case of performance measures, the priority can reflect, for instance, the burden of data collection or other agency preference. Finally, in the last step performance measures are ranked based on their ability to reflect the objectives (Tang et al. 2004). Weaknesses of this method include limited ability to address interdependency between performance measures (Velasquez & Hester 2013).

Delphi Method is another group decision-making technique, based on an anonymous survey that is passed along experts. The survey has several rounds and experts are encouraged to revise their answers to previous rounds based on feedback from other participants. The process ends after a certain number of rounds or once the experts agree on a set number of performance measures. Disadvantages of this method include time requirements and limited transparency. (Linstone and Turoff 2002)

Quality Function Deployment (QFD) matrix can be used for selecting the most relevant performance measures by transferring agency needs (objectives, priority) to 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.

QFD matrix is used in this chapter to select performance measures to observe performance in environmental, social and economic sustainability aspects in TAM. This method is selected due to its visual transparency and ability to be captured in a table.

3.1 Selection of Performance Measures

The Quality Function Deployment matrix was developed in Japan in the 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.

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 (e.g. time, money, personnel) required for collection of the data for each performance measure.

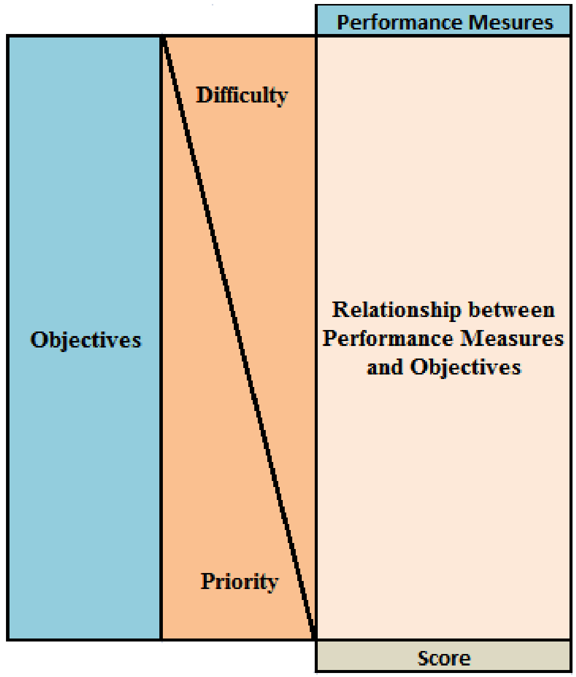


Figure 3.1: Quality Function Deployment Matrix Scheme.

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 agency 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. In this example, the environmental sustainability objective is to improve air quality by reducing on-road vehicle emissions. The economic sustainability objective is to improve local employment by providing jobs. The focus of social sustainability is to foster community livability through two objectives: by preservation of the multimodal transportation system and also by improving safety of vulnerable road users.

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. In this example, asset condition and vulnerable road user safety received the highest priority of 5, followed by livability with priority of 4, and emission reduction with job creation received priority of 3.

3. Performance Measures: While several 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 economic, environmental and social sustainability performance measures identified in Chapter 2 are used as an input to the QFD matrix.

These candidate performance measures are chosen in seven categories, depending on their focus:

- Motorized Users:
    - Total and congested vehicle miles travelled (VMT) per capita
    - Annual hours of excessive delay per capita
    - User savings from smooth pavement
- Non-Motorized Users:
    - Number of areas with a bicycle or pedestrian plan
    - Improved networks that accommodate pedestrians and bicyclists
    - Length of sidewalks / bicycle lanes per corridor mile
    - Level of non-motorized infrastructure investment
    - Availability of bicycle parking
    - Pedestrian Potential Index, Pedestrian Deficiency Index
    - Transit accessibility – housing and jobs within 0.5 mile of transit stops with frequent service
    - Percentage of population within a 30-minute walk, bike, or transit trip of key destinations
- Physical Infrastructure:
    - Asset condition
    - Pedestrian crossing opportunities
- Agency:
    - Agency expenditures on transportation infrastructure
    - Agency routine maintenance costs
    - Agency delayed maintenance costs
    - Percentage of spending on projects for transportation-disadvantaged populations
    - Jobs created

- Safety:
    - Fatalities/serious injuries per capita and per VMT
    - Number of crashes involving a driver with blood concentration of 0.08 g/dL of higher
    - Number of speeding-related fatalities
    - Number of pedestrian fatalities/incidents
    - Fatalities or injuries per mile
    - Road fatality risk as fatalities/population or registered vehicles
    - Improvements to areas that have reported fatalities and injuries
    - Traffic incident economic costs
- Pollution:
    - On-road vehicle emissions (EPA regulated pollutants: O_3, PM_{10}, $PM_{2.5}$, NO_2, CO)
    - Climate change emissions (CO_2, CH_4) reduction per capita
    - Tons of CO_2 equivalent prevented from being emitted to the atmosphere
    - Particulate matter (PM) emissions
    - Ozone related emissions (NO_x and VOCs)
    - 2- and 4-year total emission reductions
    - Travel noise levels
- Society:
    - Social cost of CO_2
    - User expenditures on transport
    - Transportation-disadvantaged population served

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 relatable to a

section, 1.1 for data possibly relatable with additional information needed, 1.2 for measures that are not applicable to section level or data is not readily available. The difficulty scale was selected based on expert judgement, because the final score is sensitive to the difficulty and therefore a refined index is needed. 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. 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, the level of non-motorized infrastructure investment has a strong relationship with neighborhood livability; a considerable effect on asset condition and safety, and a weak relationship with emission reduction.

6. 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.

			Candidate Performance Measures related to:																			
			Motorized Users				Non-Motorized Users								Physical Infrastructure			Agency				
			Total and congested vehicle miles travelled (VMT) per capita	Annual hours of excessive delay per capita	User savings from smooth pavement	Gallons of gasoline saved/displaced, based on pavement condition	Number of areas with a bicycle or pedestrian plan	Improved networks that accommodate pedestrians and bicyclists	Length of sidewalks / bicycle lanes per corridor mile	Level of non-motorized infrastructure investment	Availability of bicycle parking	Pedestrian Potential Index, Pedestrian Deficiency Index	Transit accessibility – housing and jobs within 0.5 mile of transit stops wit frequent service	% of population within 30-minute walk, bike, or transit trip of key destinati	Asset condition	Pedestrian crossing opportunities	Section Livability Characteristics	Agency expenditures on transportation infrastructure	Agency routine maintenance costs	Agency delayed maintenance costs	% of spending on projects for transportation-disadvantaged populations	Jobs created
	Objectives	**Difficulty** / **Priority**	1.2	1.2	1.1	1.0	1.2	1.1	1.1	1.0	1.2	1.2	1.2	1.2	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.0
Environmental	Reduce Vehicle Emissions	3	9	9	1	9	1	1	1	1	1	1	1	1	3		1	1	1			
Economic	Create Jobs	3																9				9
Social	Preserve Multimodal Tpt System	5					3	9		9					9	9	1	3	9	9	9	
	Improve Safety	5					3	3	3	3		1		1	1	9	9	3			1	
		Score	23	23	3	27	28	57	16	63	3	7	3	7	59	90	53	60	44	41	45	27
		% in Group	30%	30%	4%	36%	15%	31%	9%	35%	1%	4%	1%	4%	29%	45%	26%	28%	25%	28%	37%	28%
		Overall Rank	19	19	36	12	11	6	28	3	37	31	37	31	5	1	7	4	9	10	8	12

Note: The matrix was filled out during an expert brainstorming session.

Figure 3.2: QFD Matrix for Multi-Objective Sustainability Model.

Category	Objectives	Difficulty / Priority	Safety: Fatalities/serious injuries per capita and per VMT	Safety: Number of crashes involving a driver with blood concentration of 0.08 g/dl of higher	Safety: Number of speeding-related fatalities	Safety: Number of pedestrian fatalities/incidents	Safety: Fatalities or injuries per mile	Safety: Road fatality risk as fatalities / population or registered vehicles	Safety: Improvements to areas that have reported fatalities and injuries	Safety: Traffic incident economic costs	Pollution: On-road vehicle emissions	Pollution: Climate change emissions (CO2, CH4) reduction per capita	Pollution: Tons of CO2e prevented from being emitted to the atmosphere	Pollution: Particulate matter (PM) emissions	Pollution: Ozone related emissions (NOx and VOCs)	Pollution: 2- and 4-year total emission reductions	Pollution: Travel noise levels	Society: Social Cost of CO_2	Society: User expenditures on transport	Society: Transportation-disadvantaged population served
		Difficulty	1.2	1.2	1.2	1.0	1.1	1.2	1.0	1.2	1.0	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.2	1.1
Environmental	Reduce Vehicle Emissions	3									9	9	9	9	9	9		3		
Economic	Create Jobs	3																		
Social	Preserve Multimodal Tpt System	5	1	1	1	1	1	1	9								1	1	1	3
Social	Improve Safety	5	3	3	3	3	3	3	9	1										
	Score		17	17	17	20	18	17	90	4	27	23	25	25	25	25	5	14	4	14
	% in Group		8%	8%	8%	10%	9%	8%	45%	2%	18%	15%	16%	16%	16%	16%	3%	44%	13%	43%
	Overall Rank		24	24	24	22	23	24	1	34	12	19	15	15	15	15	33	29	34	30

Note: The matrix was filled out during an expert brainstorming session.

Figure 3.2: QFD Matrix for Multi-Objective Sustainability Model (continued).

3.2 Performance Measures Selected from the QFD Matrix

Motorized Users

In the Motorized Users category, "Gallons of gasoline saved/displaced, based on pavement condition" are selected as the input variables for the Multi-Objective Sustainability (MOS) model and will be used in the environmental framework to estimate CO_2 emissions saved or displaced based on the pavement condition.

Non-Motorized Users

"Level of non-motorized infrastructure investment" is selected from the Non-Motorized Users category to address the livability, safety, condition and emission objectives.

Physical Infrastructure

In the case of performance measures for Physical Infrastructure, "Asset condition" is selected. Also "Pedestrian crossing opportunities" will be used as an indicator neighborhood livability, which is here characterized by preserving multimodal transportation system and improving safety of vulnerable road users.

Agency

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

Safety

Safety related performance measures include a "Number of pedestrian fatalities/incidents" which will be used to identify sections that need a safety improvement and also is in compliance with performance measurement required by MAP-21. And then the "Improvements to areas that have reported fatalities and injuries" will be tracked to monitor the progress.

Pollutants

While "On-road vehicle emissions" are selected as to comply with MAP-21 guidance, only carbon dioxide (CO_2) is used in the model since 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).

Society

The impact on society is 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"* (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. These performance measures are used to define the multi-objective sustainable model.

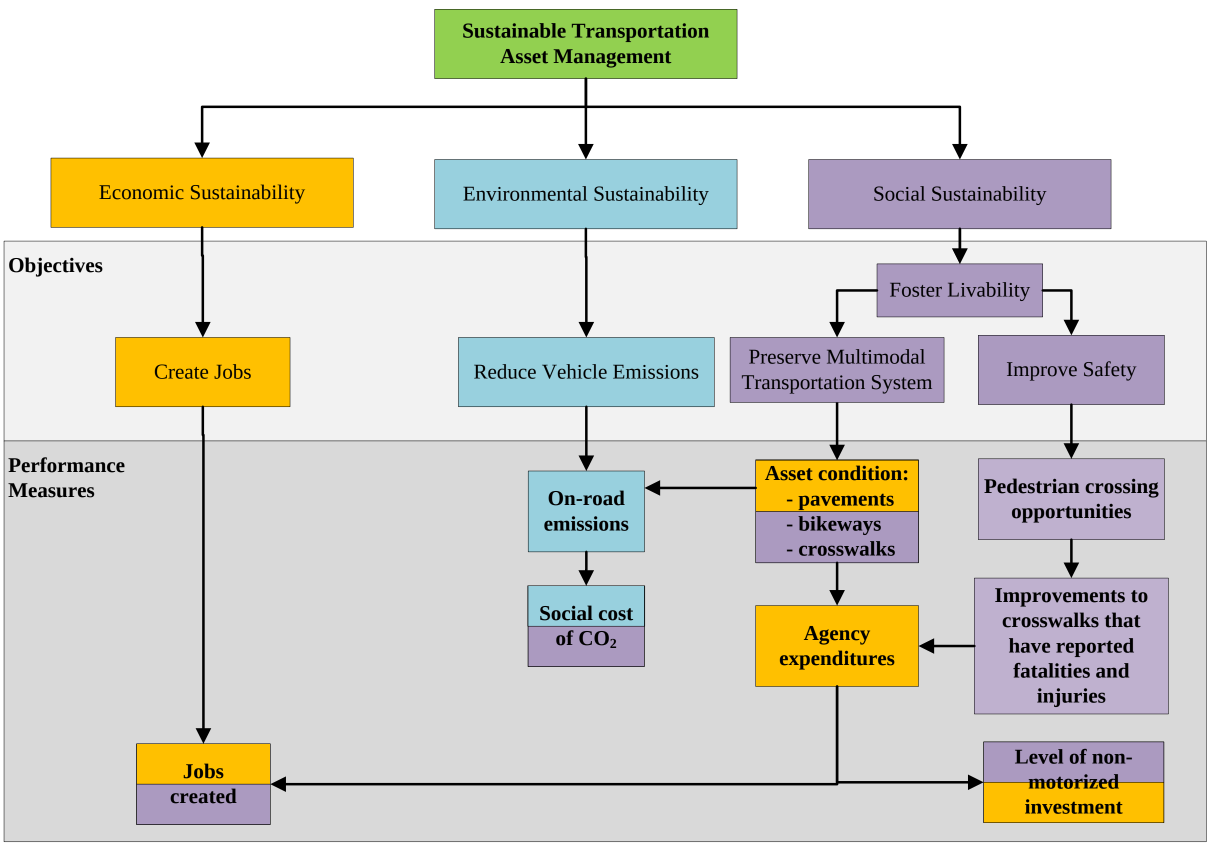


Figure 3.3: Selected Performance Measures from the QFD Matrix.

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

Pavement management systems allow local and state agencies to allocate funding in the most efficient manner to ensure required condition. Additionally, an increasing number of agencies has been adding assets such as signs, street lights, curbs and gutters, pavement markings, to their transportation asset management. There are also several assets that influence the comfort, safety and accessibility for pedestrians and bicyclists, such as sidewalks, crosswalks, median islands, curb ramps, bikeways, and hike and bike trails.

Performance measures addressing economic, environmental, and social sustainability that were selected in Chapter 3 are used in the multi-objective sustainable (MOS) model to enhance a traditional pavement management system (PMS). The traditional PMS is expanded by estimation of on-road CO_2 emissions from pavement condition while adding also assets for non-motorized users, such as pedestrians and bicyclists. This effort is aligned with the United States Environmental Protection Agency to reduce GHG emissions, as well as with the United States Department of Transportation policy to *"incorporate safe and convenient walking and bicycling facilities into transportation projects"* (FHWA 2016d).

The MOS model will focus on the following transportation assets in urban areas:

- Pavements
- Crosswalks
- Bikeways[1]

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). Crosswalks are crucial to pedestrian safety and walkability therefore the pedestrian crossing opportunities are considered in the model. Pedestrian crossing opportunities are defined for crosswalks by two factors: maximum crosswalk spacing and threshold for mid-block collisions involving pedestrians. Sections that do not satisfy the desired crosswalk

[1] For the purposes of the MOS model, the word "bikeways" is used interchangeably with "bicycle facilities", and primarily refers to bicycle lanes.

characteristics and are above the pedestrian injury threshold, become candidates for improvement. Streets where people of all ages and abilities can safely cross increase the overall neighborhood livability.

On-road bikeway facilities include bicycle boulevards, bicycle lanes, shared lanes and paved shoulders (AASHTO 2012). The MOS model focuses on bicycle lanes, which are defined as *"a proportion of roadway that has been designated for preferential or exclusive use by bicyclists by pavement [bikeway] markings"* (AASHTO 2012). Further, to enhance safety and comfort of a rising number of bicyclists, the MOS model considers the bikeway condition in the transportation asset management process.

4.1 Multi-Objective Sustainable Model Enhancement of Traditional Pavement Management System

The transportation asset management (TAM) process discussed in Chapter 2 is used to expand a traditional pavement management system adding crosswalks and bikeways, in order to address needs of both motorized and non-motorized transportation users.

Figure 4.1 shows a flowchart with the MOS model process, where a traditional pavement management system is enhanced with targets for environmental and social sustainability.

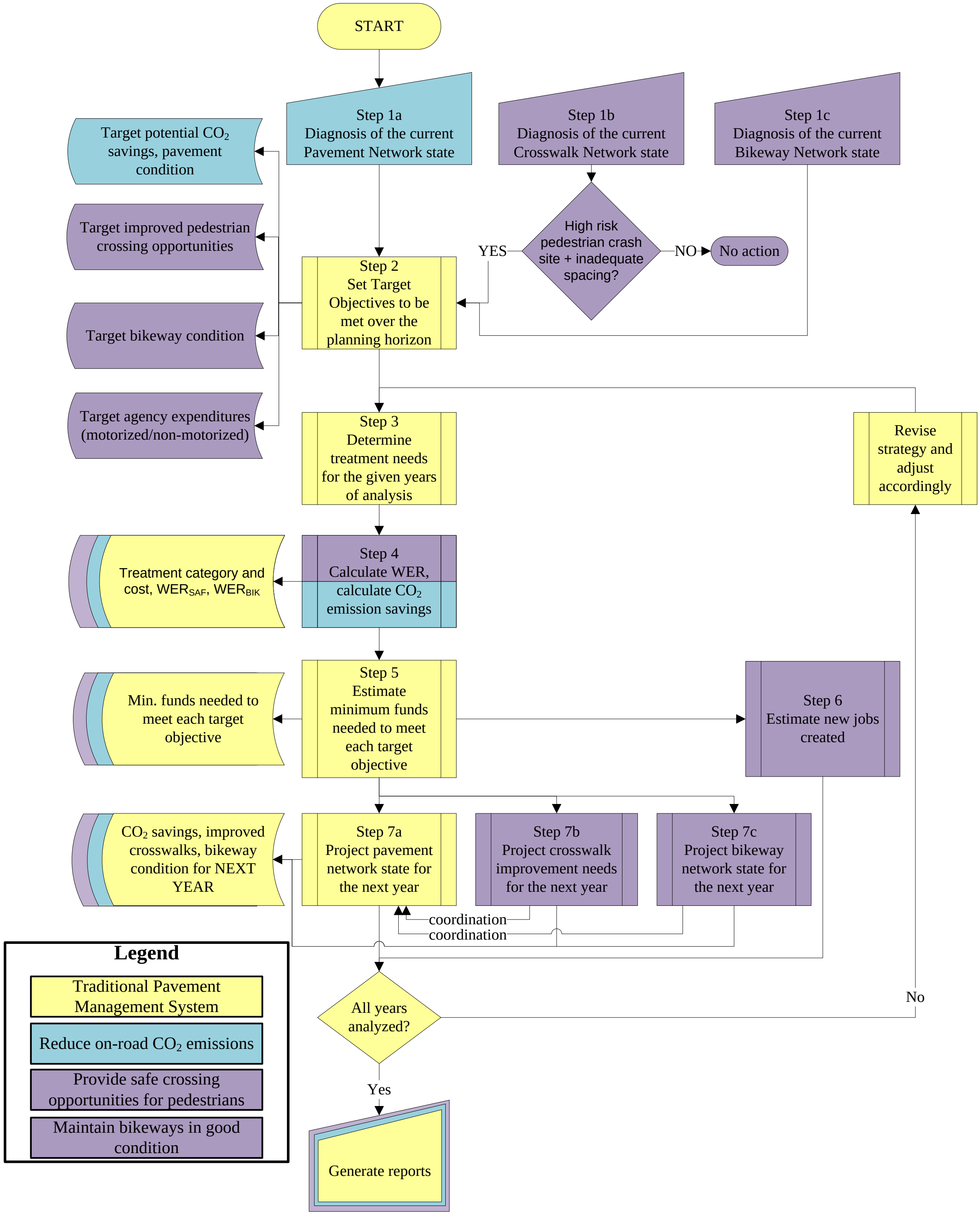


Figure 4.1: Flowchart with MOS Enhancement of a Traditional Pavement Management System. (based on Smith 2009)

The overall framework with the proposed enhancements to incorporate sustainability is shown in Figure 4.2 and builds upon the components of a TAM system defined by FHWA (1999a).

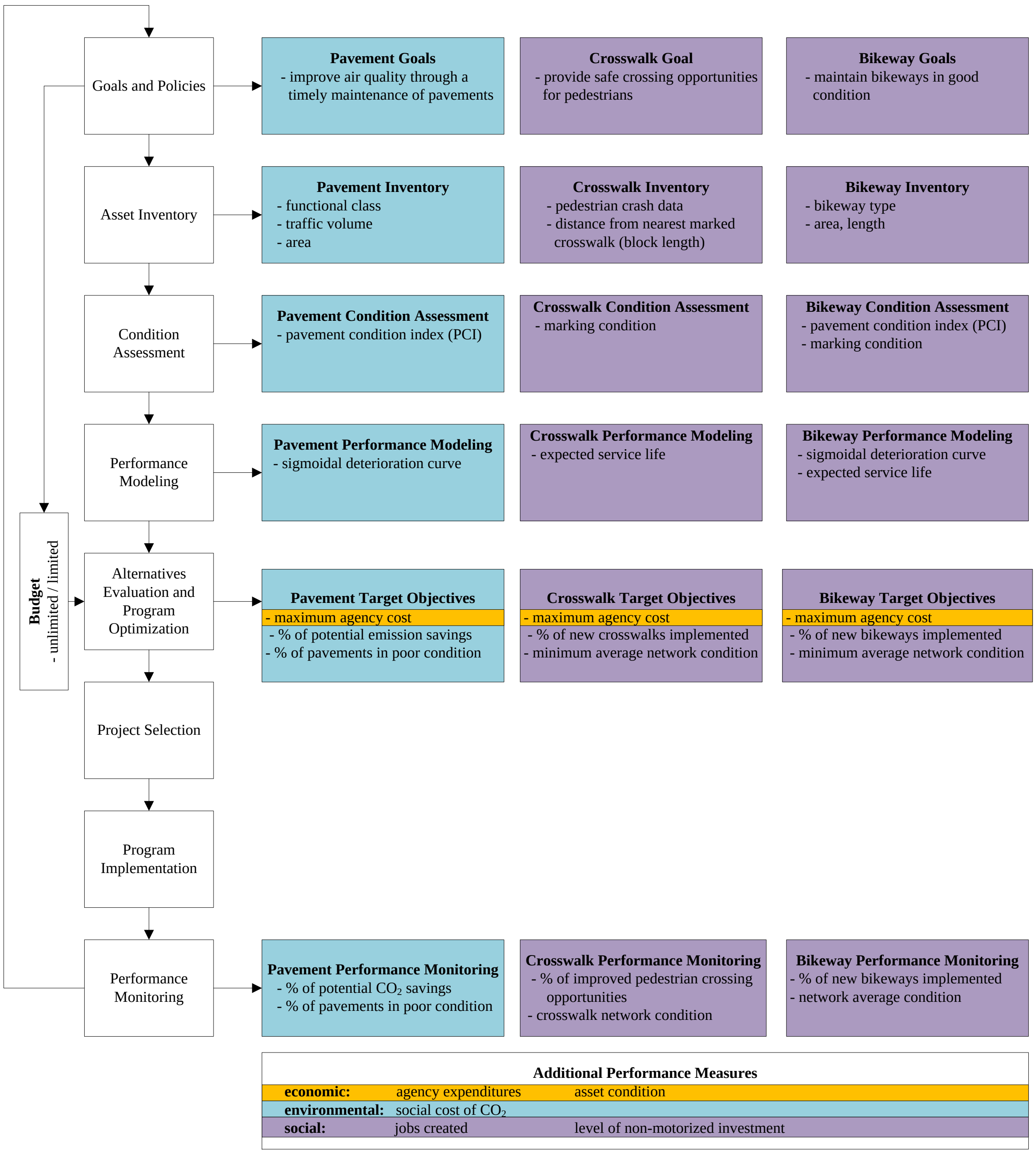


Figure 4.2: Multi-Objective Sustainable Model Overall Framework. (adapted from FHWA 1999a)

The individual modules are discussed in the following sections.

Goals and Policies

Goals and policies determine the focus of the process.

Goals describe the expectations that the TAM aims to achieve. In this case, a goal is chosen for each of the three assets (pavements, crosswalks, bikeways) considered in the analysis.

The goal for pavements is to improve air quality through a timely maintenance of pavements. While traditional pavement management systems focus on pavement condition, the MOS model focuses also on reducing on-road CO_2 emissions. Fuel consumption of a vehicle (and emissions) is correlated with pavement condition (Watanatada et al. 1987, FHWA 2000, Chatti and Zaabar 2010, Lidicker at el. 2013, Greene at al. 2013), therefore this goal will still keep the pavement network at best condition possible while also focusing on environmental aspects of air quality. The goal for crosswalks is to provide safe crossing opportunities for pedestrians by improving conditions at high risk locations. The bikeway goal is to maintain bikeways in good condition, because it affects the comfort and safety of bicyclists.

Policies reflect the agency values and often include non-engineering or non-economic factors, such as predispositions to invest into certain assets or activities (FHWA 1999a). In this case, it is considered that policies are met by the agency and are consistent with the goals.

Asset Inventory

The inventory includes information about individual pavement, crosswalk, and bikeway assets. For pavements, the main information is section area, functional class, traffic volume, and condition. For crosswalks, pedestrian crash data is used to identify high-risk locations and their distance from the nearest marked crosswalk in order to assess which crosswalks need improvement. For bikeways, the bikeway type, area and length are major data in the inventory. For all assets, inventories usually include also information about location, material, construction date, and inspection history.

Condition Assessment and Performance Modelling

Current condition of pavements and bikeways is assessed and projected to the future to identify the maintenance treatments over the planning period. There are several indices for measuring pavement condition, such as International Roughness Index (IRI), Present Serviceability Index (PSI), International Friction Index (IFI), Structural Number (SN), and Remaining Service Life (RSL). Pavement Condition Index (PCI) is used both for roadway pavements and bikeway pavements. Sigmoidal deterioration curve is used to predict deterioration of pavements, while a service life approach is used to predict deterioration of pavement markings in crosswalks and bikeways.

Alternatives Evaluation and Program Optimization

Four different types of scenarios are analyzed: All Funding, Do Nothing, Target-Driven, and Budget-Driven.

All Funding First, the asset treatments and budget needs to preserve the infrastructure transportation network in an optimal level of service over the period of analysis are identified. For pavements that means maintaining the network average condition above PCI 80. For crosswalks, that means improving all high-risk locations. For bikeways that means funding all new projects as well as maintaining the network average condition above PCI 80. No funding constraints are included in the analysis process.

Do Nothing In this scenario, where no funding is allocated during the analysis period, shows the deterioration of condition and is considered the bottom line. All other scenarios will result in asset condition and budget needs between the All Funding (ideal) and Do Nothings (worst). Target-Driven and Budget-Driven analyses are conducted to quantify the impact on performance of different maintenance strategies and funding constraints.

Target-Driven Scenario The pavement objective is to maximize CO_2 emission savings with a target % of potential emission savings (compared to All Funding and Do Nothing scenarios). For crosswalks, the objective is to maximize the safety weighted effectiveness ratio with a target of a percentage of improved pedestrian crossing opportunities. For bikeways, the

objective is to maximize the bikeway weighted effectiveness ratio with a target of minimum bikeway average condition.

Budget Scenario Budget Scenario considers a limited budget for maintenance treatments and predicts asset condition under the available budget. Pavement maintenance projects are ranked based on potential CO_2 savings. Crosswalk improvement projects are ranked based on safety weighted effectiveness ratio (WER_{SAF}) that takes into account the crosswalk importance, location, remaining service life, and cost of the improvement. Bikeway improvement projects are ranked based on bikeway weighted effectiveness ratio (WER_{BIK}) calculated as the bikeway importance, location, remaining service life, and cost of the improvement. Pavement projects, crosswalk projects, and bikeway projects are ranked separately, however crosswalk and bikeway striping is coordinated with pavement rehabilitation whenever possible.

Performance Monitoring

At the end of the analysis, the following performance measures are recommended for each scenario:

Pavements

- agency cost
- % of potential CO_2 emissions saved
- average network condition (% of pavements in poor/very poor condition)
- social cost of CO_2

Crosswalks

- agency cost
- average network condition
- % of crosswalks improved
- level of non-motorized investment

Bikeways

- agency cost
- average network condition

- % of new bikeways implemented
- level of non-motorized investment

4.2 Mathematical Formulation of the Multi-Objective Sustainable Model

Before introducing the mathematical formulation, it is necessary to describe the frameworks. The MOS model consists of 3 frameworks. The first framework incorporates environmental sustainability into pavement management by taking into account on-road CO_2 emissions as a result of pavement condition. The second framework addresses social sustainability by focusing on the assets that serve to vulnerable road users, such as pedestrians and bicyclists. The social sustainability framework consists of two modules: a module for crosswalk management that analyzes pedestrian crash data to determine high-risk locations where a marked crosswalk would improve pedestrian safety, and coordinates the new crosswalk implementation or maintenance of existing crosswalks with pavement maintenance; and a module for bikeway management searches for the optimal timing for applying new or maintaining existing bikeway markings in coordination with pavement maintenance activities. The third framework estimates new jobs created based on the costs estimated for pavement, crosswalk, and bikeway improvements analyzed in the first two frameworks. Figure 4.3 shows the frameworks with their goals and target objectives.

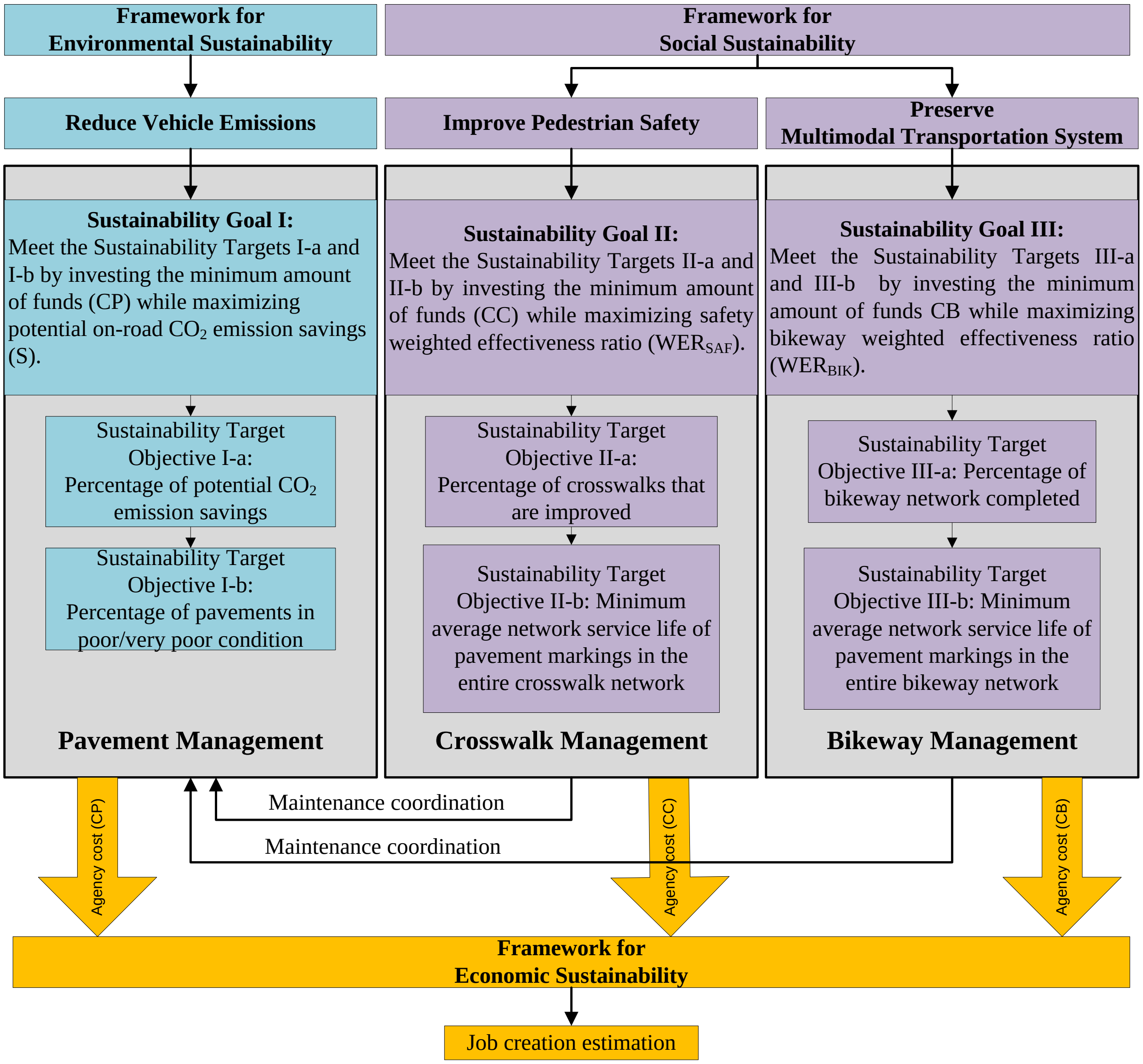


Figure 4.3: Frameworks with Their Goals and Target Objectives.

The MOS model aims to maintain the pavements, crosswalks and bikeways at the desired network state at the minimum cost, while taking into account environmental and social targets expressed in terms of potential CO_2 emissions savings, improvements in pedestrian crossing opportunities, improvements in completeness of bikeway network, as well as state of good repair of pavements, crosswalks, and bikeways. Parameters in Table 4.1 are used to characterize the transportation network state and to set targets over the planning horizon.

Table 4.1: Targets for Economic, Environmental and Social Sustainability.

	ECO-NOMIC	ENVIRONMENTAL		SOCIAL			
Asset	Agency cost	Percentage of potential CO_2 emission savings	Percentage of pavements in poor/very poor condition	Percentage of crosswalks that are improved	Minimum average network service life of crosswalk markings in the entire crosswalk network	Percentage of bikeway network completed	Minimum average network service life of bikeway markings in the entire bikeway network
Pavements	CP	b_1	b_2	-	-	-	-
Crosswalks	CC	-	-	b_3	b_4	-	-
Bikeways	CB	-	-	-	-	b_5	b_6

The sustainability enhancements in the MOS model include one goal for environmental sustainability (pavements) and two goals for social sustainability (one for crosswalks and one for bikeways). These goals are not meant to be accomplished at the same time, however there is a coordination between the assets, as Figure 4.3 suggests. The sustainability goals are as follows:

Sustainability Goal I: Meet the Sustainability Target Objectives I-a and I-b by investing the minimum amount of funds (CP) while maximizing potential on-road CO_2 emission savings (S):

Minimize CP: $\sum_{i=1}^{N} EUAC_i * X_i$

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

subject to:

Sustainability Target Objective I-a: Percentage of potential CO_2 emission savings.

$$\frac{\sum_{i=1}^{N}(E_{Ni} - E_{Ti})\, X_i}{\sum_{i=1}^{N} E_{POTENTIALi}} \geq b_1$$

Sustainability Target Objective I-b: Percentage of pavement network in poor/very poor condition.

$$\frac{\sum_{i=1}^{N} a_{i4} - q_{i4}\, X_i}{a_i} \leq \ b_2$$

where:

CP	………	objective function for minimizing pavement-related costs
$EUAC_i$	………	Equivalent Uniform Annual Cost of a treatment on pavement section i, 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 %)
X_i	………	0 if pavement section i is not selected for a treatment, 1 otherwise
S	………	objective function for maximizing potential CO_2 emission savings
ΔE_i	………	potential CO_2 emission savings resulting from a maintenance treatment
$E_{N\,i}$	………	CO_2 emissions estimated based on a pavement section i condition when a treatment is not applied
$E_{T\,i}$	………	CO_2 emissions estimated based on a pavement section i condition when a treatment is applied
$E_{POTENTIAL\,i}$	………	maximum possible CO_2 emission savings (ideal case, all funding) for pavement section i, estimated as a difference between Do Nothing scenario and All Funding scenario
b_1	………	minimum percentage of potential CO_2 savings
a_{i4}	………	area of section "i" which condition is in poor/very poor condition
q_{i4}	………	area of section "i" which is recovered from poor/very poor condition due to treatment
a_i	………	area of section "i"

b_2 ……… maximum percentage of pavement network in poor/very poor condition (below PCI 50)

Sustainability Goal II: Meet the Sustainability Target Objectives II-a and II-b by investing the minimum amount of funds (CC) while maximizing safety weighted effectiveness ratio (WER_{SAF}):

Minimize CC: $\sum_{l=1}^{R} EUAC_l * X_l$

Maximize F: $\sum_{l=1}^{R} WER_{SAF\,l}\, X_l$

subject to:

Sustainability Target Objective II-a: Percentage of crosswalks that are improved.

$$\sum_{l=1}^{R} \frac{p_l\, X_l}{c_l} \geq b_3$$

Sustainability Target Objective II-b: Minimum average network service life of crosswalk markings in the entire crosswalk network.

$$\sum_{l=1}^{R} \frac{RL_l + (\Delta RL_l\, X_l)}{R} \geq b_4$$

where:

CC	………	objective function for minimizing crosswalk-related costs
$EUAC_l$	………	Equivalent Uniform Annual Cost of a treatment on crosswalk *l*, 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 %)
X_l	………	0 if crosswalk *l* is not selected for an improvement, 1 otherwise
F	………	objective function for maximizing crosswalk safety weighted effectiveness ratio
$WER_{SAF\,l}$	………	safety weighted effectiveness ratio of crosswalk *l*
c_l	………	unmarked high-risk crosswalk *l*
p_l	………	crosswalk *l* moved to satisfactory state due to improvement
b_3	………	% of improved crossing opportunities

RL_l	………	remaining service life of crosswalk marking l
ΔRL_l	………	increase in remaining service life of crosswalk marking l due to maintenance
b_4	………	minimum average remaining life for the entire crosswalk marking network

Sustainability Goal III: Meet the Sustainability Target Objectives III-a and III-b by investing the minimum amount of funds CB while maximizing bikeway weighted effectiveness ratio (WER_{BIK}).

Minimize CB: $\sum_{k=1}^{T} EUAC_k * X_k$

Maximize B: $\sum_{k=1}^{T} WER_{BIK\ k}\ X_k$

subject to:

Sustainability Target Objective III-a: Percentage of bikeway network completed.

$$\sum_{k=1}^{T} \frac{p_k\ X_k}{c_k} \geq\ b_5$$

Sustainability Target Objective III-b: Minimum average network service life of bikeway markings in the entire bikeway network.

$$\sum_{k=1}^{T} \frac{RL_k + (\Delta RL_k\ X_k)}{T} \geq\ b_6$$

where:

CB	………	objective function for minimizing bikeway-related costs
$EUAC_k$	………	Equivalent Uniform Annual Cost of a treatment on bikeway k, 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 %)
B	………	objective function for maximizing bikeway weighted effectiveness ratio
$WER_{BIK\ k}$	………	weighted effectiveness ratio of bikeway k
X_k	………	0 if bikeway k is not selected for an improvement, 1 otherwise
p_k	………	bikeway section k to be moved from “non-existing” to

		"existing" state due to improvement
c_k	………	number of new bikeway sections *k* to be implemented
b_5	………	minimum completion level of the bikeway network
RL_k	………	remaining service life of bikeway markings on bikeway *k*
ΔRL_k	………	increase in remaining service life of bikeway markings on bikeway *k* due to maintenance
b_6	………	minimum average remaining life of bikeway markings for the entire bikeway network

In the following sections each of the frameworks is discussed in detail. Section 4.3 discusses the framework for environmental sustainability in pavement management. Section 4.4 focuses on the framework for social sustainability, which incorporates crosswalks and bikeway maintenance and synchronizes the treatments with pavement maintenance. Section 4.5 shows the framework for economic sustainability, where new jobs from maintenance activities are estimated.

4.3 Framework for Environmental Sustainability

There are several ways to address environmental sustainability in transportation, starting from urban planning and roadway engineering to resource extraction, material processing and transportation, use phase, maintenance, flora and fauna protection, and end-of life material recycling or reusing. This framework for environmental sustainability focuses entirely on pavement assets and the CO_2 that is emitted by motorized vehicles travelling on the pavement surface. Transportation produced 27% of all CO_2 emissions emitted in the U.S. in 2013 (EPA 2015a). Vehicle fuel consumption and related 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 et al. 2013) suggest a tangible relationship between pavement roughness and fuel consumption. Therefore, fuel consumption and emissions are estimated from pavement roughness condition.

Input Data

Data used to estimate CO_2 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	Pavement management system database
Speed [mph, kmph]	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 for Pavement Project Prioritization

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 downtown, commercial and residential streets, and 35-45 mph (56-72 km/h) for arterials (San Francisco Transportation Code 2008); the effect of rolling resistance is larger than internal friction or air drag as shown in Figure 4.4.

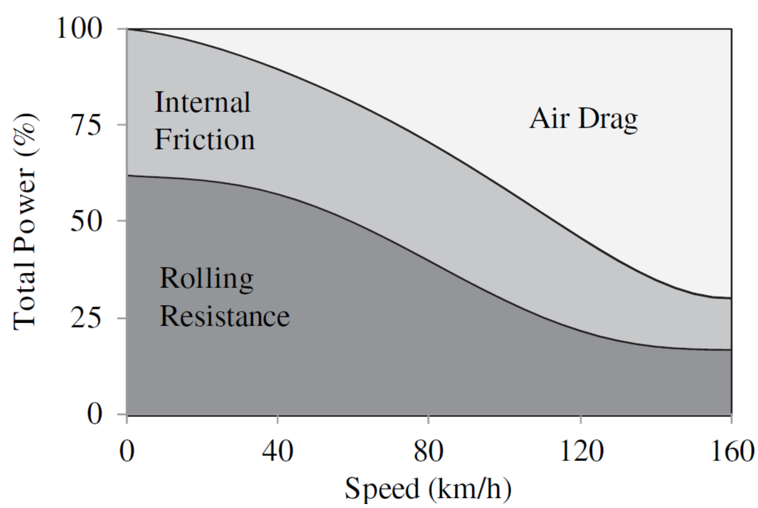


Figure 4.4: Energy Distribution in a Passenger Car versus Speed. (Chatti and Zaabar 2010)

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 of 1.4% is carried by interstates and freeways (FHWA 1996).

It is 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 CO_2 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. Figure 4.5 shows an example of pavement in poor condition.

Figure 4.5: Example of a Pavement Section in Poor Condition (section ID 7, rated PCI 43).

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≤94 as good, 94<IRI≤170 as fair, 170<IRI≤220 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.

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

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) * 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)

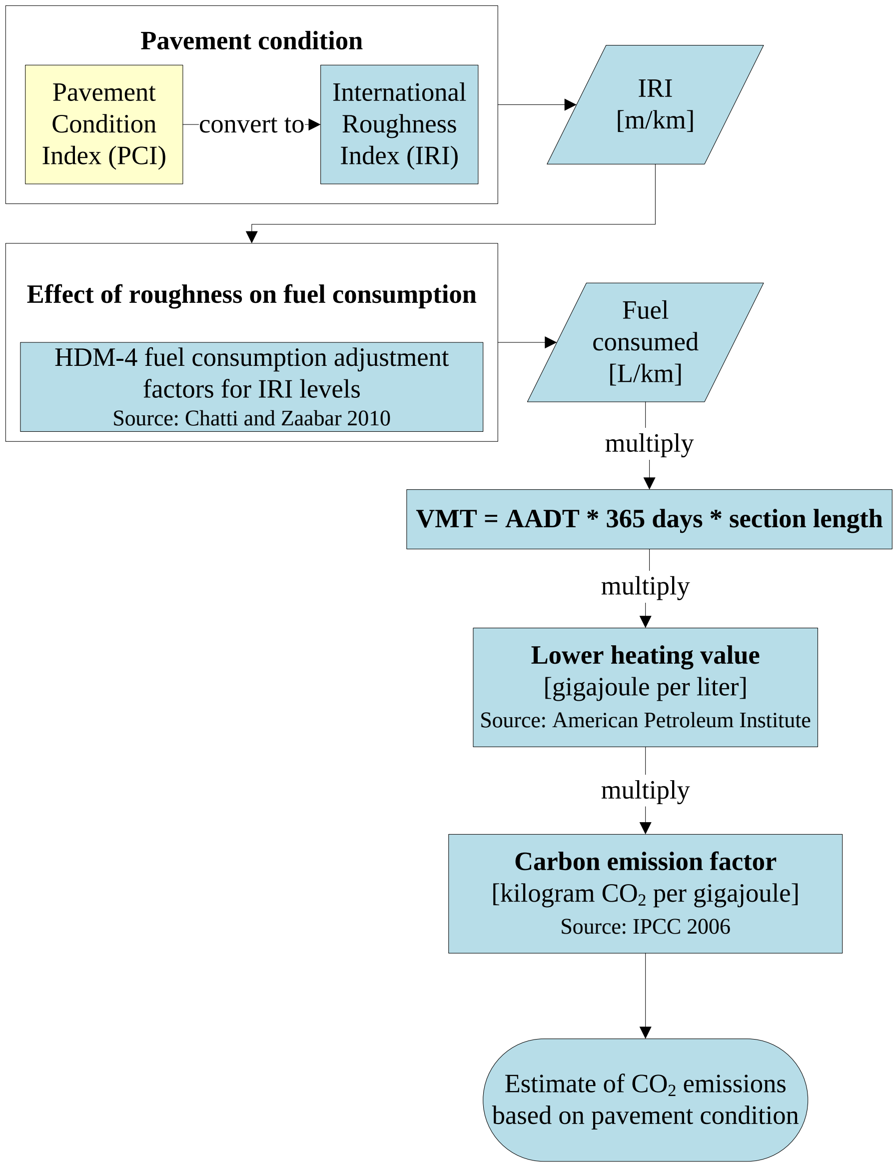
Speed	Vehicle Class	Calibrated HDM 4 model					
		Base (mL/km)	Adjustment factors from the base value				
		IRI (m/km)					
		1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13
	Van	76.99	1.01	1.02	1.03	1.04	1.05
	SUV	78.69	1.02	1.05	1.07	1.09	1.12
	Light truck	124.21	1.01	1.02	1.04	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

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

Note: The study discusses three speeds 35 mph represents a speed limit in many urban areas, while 55 mph or70 mph represent speed limits on urban interstate sections in various states in the U.S.

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, bio gasoline, biodiesel, natural gas, and propane by multiplying the fuel consumed by CO_2 emission factors established by Intergovernmental Panel on Climate Change (IPCC 2006).

Figure 4.6 summarizes the process of estimating CO_2 emissions from motorized vehicles travelling on a pavement section of a certain condition.



Note: Yellow: pavement management system data, blue: environmental sustainability

Figure 4.6: Process to Estimate CO_2 Emissions using IPCC Emissions Factors.

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

$$CO_2\ emissions = \sum_{i=1}^{N} PCI_i * length * \ fuel_{factor} \ * AADT_i * 365 * LHV * CEF$$

where:

PCI_i	....	pavement condition of section *i*
$length_i$	....	section *i* length in miles
$fuel_{factor}$	....	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. MOVES2014a 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). These models are more accurate, however as they are stand-alone, complex models, their implementation into pavement management models would be difficult and scenario runs would take considerably longer time. For that reason, the MOS uses a simplified method to estimate CO_2 emissions.

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 All Funding scenario (with 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 CO_2 emissions. Reduction in CO_2 emissions is then calculated for each pavement maintenance scenario. The agency expenditures, pavement condition, social costs of CO_2, as well as jobs created are reported in Figure 4.7.

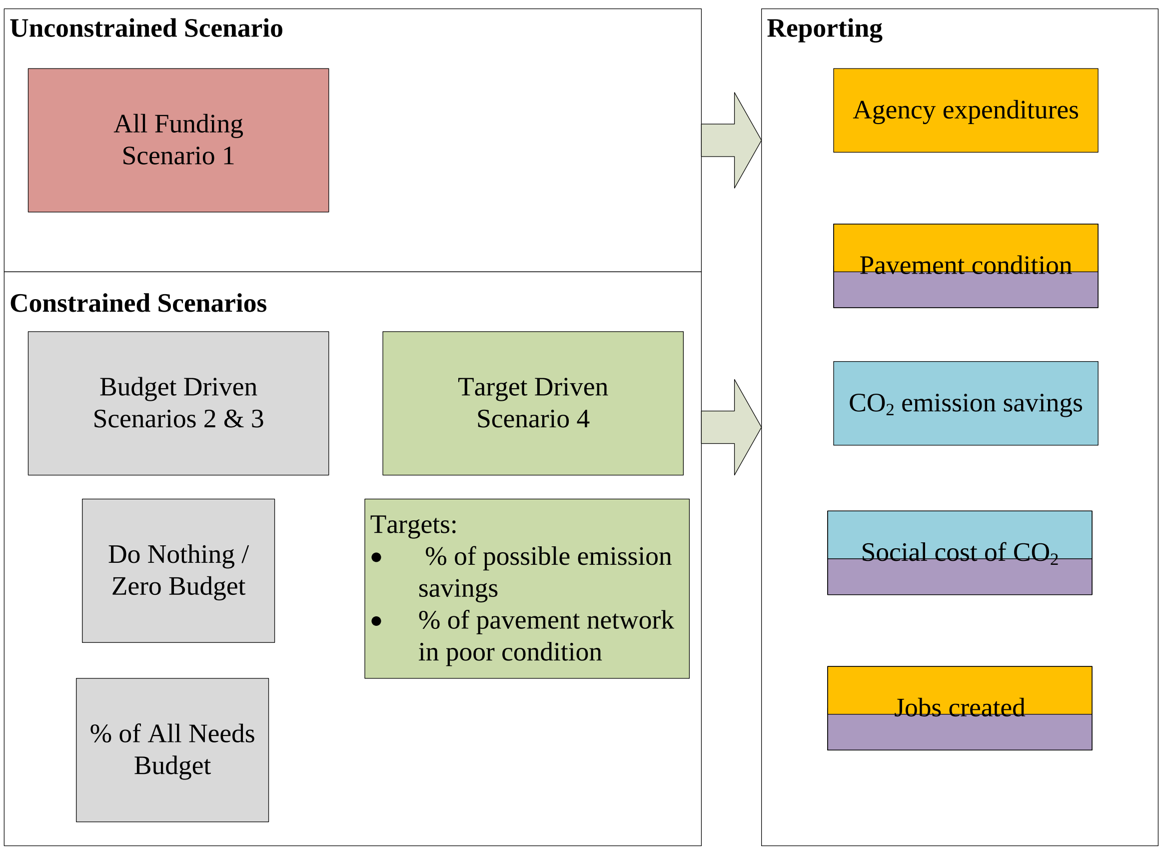


Figure 4.7: Pavement Scenarios and Performance Measures Recommended for the Reports.

4.4 Framework for Social Sustainability

The social sustainability framework brings a more holistic approach to transportation asset management decisions. When developing a sustainable model for asset management

pavement condition and resulting CO_2 emissions, as well as community livability must be considered.

"Livability" is a term that emerged among urban planners in the 1970s (Appleyard et al. 2014) and is associated with the inclusion of non-motorized transportation into urban streets in order to provide multimodal transportation options. A livable neighborhood is one which people can depend on for safe, economical transportation choices that promote public heath, reduce oil dependency, greenhouse gases, improve air quality while enhancing the unique characteristics of the community (HUD 2015). Livability in its principles refers to physical community design and land use together with choice and opportunities for its residents and is correlated with quality of life and sometimes even used synonymously (Partners for Livable Communities 2015). There is also a connection between livability, which is more localized and place-based (Godschalk 2004) and sustainability, which seeks to *"meet the needs of the present generation, without compromising the ability of future generations to meet their own needs"* (Brundtland 1987) in three dimensions including environment, economy, and social equity. In the U.S. context, Ray LaHood, U.S. Department of Transportation Secretary, in 2009 described livable communities in terms of transportation as, *"If people don't want an automobile, they don't have to have one"* (Schor 2009).

To reflect the basic livability principle of designing streets for multiple user groups, an advocacy group Smart Growth America coined the term "complete street". Complete streets are (SmartGrowth America 2015):

•*"Designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists and transit riders of all ages and abilities.*

•*"Easy to cross, walk to shops, and bicycle to work."*

•*"Allow buses to run on time and make it safe for people to walk to and from train stations."*

Several cities in the U.S. have adopted the Complete Streets 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"*.

Schlossberg (2006) describes livability by connectivity, quality, proximity and safety. The MOS model focuses on two of the aspects – quality and safety. The social sustainability framework is inspired by the Better Streets Plan and Complete Streets principles. It accommodates the needs of pedestrians and bicyclists in transportation asset decisions by including crosswalk and bikeway management into a traditional pavement management system.

The MOS model focuses on multimodal transportation and pedestrian safety as the major factors in livability that can be influenced through TAM. Improvements in multimodal transportation focus on maintaining bikeways in such condition that is safe and comfortable to ride on, while the need for safety improvements in pedestrian crossing opportunities is identified through crash data and existing marked crosswalks.

This safety and multimodal transportation improvement is used as an example to show how pavement management can be enhanced by assets that are used by non-motorized users and also how safety data can be used to improve transportation infrastructure decisions.

The following sections describe the livability framework, including multimodal transportation preservation and pedestrian safety modules.

4.4.1 Preserve Multimodal Transportation System

Multimodal transportation system provides various choices for getting from one point to the other in an efficient, timely and safe manner to users of all abilities and ages. Modes of motorized transportation include personal vehicles (both privately owned or shared), motorcycles, bus transit, light-trains, street cars, tramways, long-distance bus charters and airplanes. While non-motorized modes of transportation include walking and bicycling. This module will focus on assets that serve to a non-motorized users group of bicyclists in order to improve their safety and comfort.

For bicyclists, the riskiest time of the day is late afternoon until the end of day, since 56% of fatalities occur between 3pm and midnight (NHTSA 2015b). Total separation of bicyclists from motorized traffic is the most protective approach (GHSA 2014). However, when physical separation is not feasible, there are several bikeway designs that enhance bicyclist safety. Such as bicycle lanes; streets with calm traffic that run in parallel to major arterials, called bicycle boulevards; bicycle boxes at intersections which increase bicyclists visibility and reduce right-turn crashes (GHSA 2014).

Potholes, cracking, debris, gravel and drainage grates in the bicyclist travel way are some examples of factors that can endanger bicyclist safety. It is important to regularly sweep sections where bicycle traffic is anticipated and address any surface distresses that may force bicyclist to unexpectedly change riding path or lose control.

Parked vehicles and dooring are potentially dangerous to bicyclists and prevented by accounting for a buffer zone during road striping activities (Hunter et al. 1996, Nabors et al. 2012). Routing bicyclist traffic through well-lit streets with fewer stops, less motorized traffic and protected bicycle lanes can improve bicyclist comfort as well as overall mobility.

Crashes occurring due to motorist failing to yield to bicyclist while turning right or left, can be addressed with increasing visibility of bicyclists in intersections through painted markings and green boxes at the stop line which gives bicyclists a lead advance for their movements once the signal changes to green. Running stop signs or red lights is a frequent type of crash, where

bicyclist does not stop in attempt to conserve energy or because traffic signal detectors are not calibrated to register bicycle traffic (Nabors 2012). Intersection design with smaller radius which encourages lower speeds, as well as well marked lanes and bicycle boxes with detection of bicycles make the movements more predictable and encourage courtesy among motorists and bicyclists.

The multimodal module focuses on infrastructure quality for bicyclists, selected to represent non-motorized users. While on-road bikeway facilities include bicycle boulevards, bicycle lanes, shared lanes and paved shoulders (AASHTO 2012), the MOS model focuses on bicycle lanes, which are defined as *"a proportion of roadway that has been designated for preferential or exclusive use by bicyclists by pavement [bikeway] markings"* (AASHTO 2012). Assets that are linked to quality of bicyclist facilities include bikeway pavements, bikeway markings, lighting, and wayfinding. This study focuses on the quality of bikeways, specifically on bicycle lane pavement and marking condition. In future research, it is desirable to add other assets and bikeway types as they also play a crucial role in the safety and comfort of bicyclists.

The MOS model focuses on existing bikeways (pavements and markings), as well as installation of new bikeways according to applicable local, regional, and State Bicycle Plans, coordinated with pavement resurfacing projects.

Input Data

Figure 4.8 shows an example of the input data categories needed in the bikeway quality module. Data categories include quality and additional two categories to account for roadway sections characteristics and other features (construction cost, maintenance cost, and remaining service life).

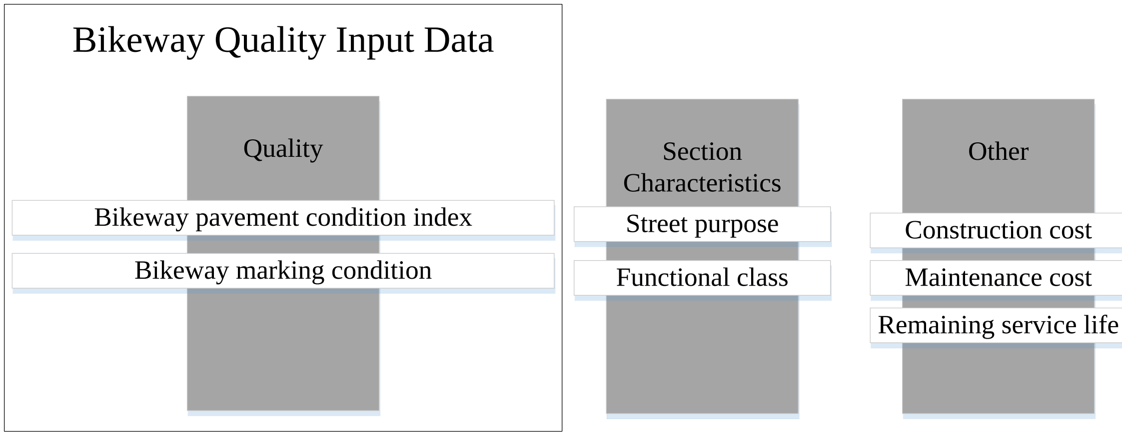


Figure 4.8: Bikeway Quality Input Data with Section Characteristics and Other Data.

Table 4.7 shows an overview of the data format for the bikeway quality module.

Table 4.7: Overview of Data Format for the Bikeway Quality Module.

Quality	
Description	**Format**
Existing bikeway pavement condition:	Good (PCI 100-85), fair (PCI 84-65), poor (64-0)
Existing bikeway marking condition:	Remaining life [years]
Section Characteristics	
Description	**Format**
Section type	Purpose: priority (part of a bikeway network) general Functional class: arterial, collector, residential
Other	
Construction cost (bikeway)	Agency records
Maintenance cost (bikeway)	Agency records
Remaining service life (bikeway)	Agency records

The data input into the bikeway quality module includes information about condition of existing bikeway pavements and bikeway striping, rated on a scale good, fair and poor. Some of the pavement distresses that bicycle tires are sensitive to include potholes and cracking, but also debris, gravel and drainage grates in the bicyclist travel can endanger bicyclist safety. Pavement condition is assessed with a Pavement Condition Index (PCI), where PCI 100-85 is considered as good condition, PCI 84-65 is considered as fair condition, and anything below that is poor condition. A surrogate performance measure is used to assess the bikeway marking condition, due to limited data on assessing pavement marking condition. Therefore, the bikeway marking condition is approximated by an average remaining life (RL), which indicates the time until next

maintenance treatment. While for individual bikeway sections the RL can range between 4 years (brand new) to 0 years (maintenance due), the network average RL is expected below 4 years.

The bikeway quality module process to prioritize projects is shown in Figure 4.9.

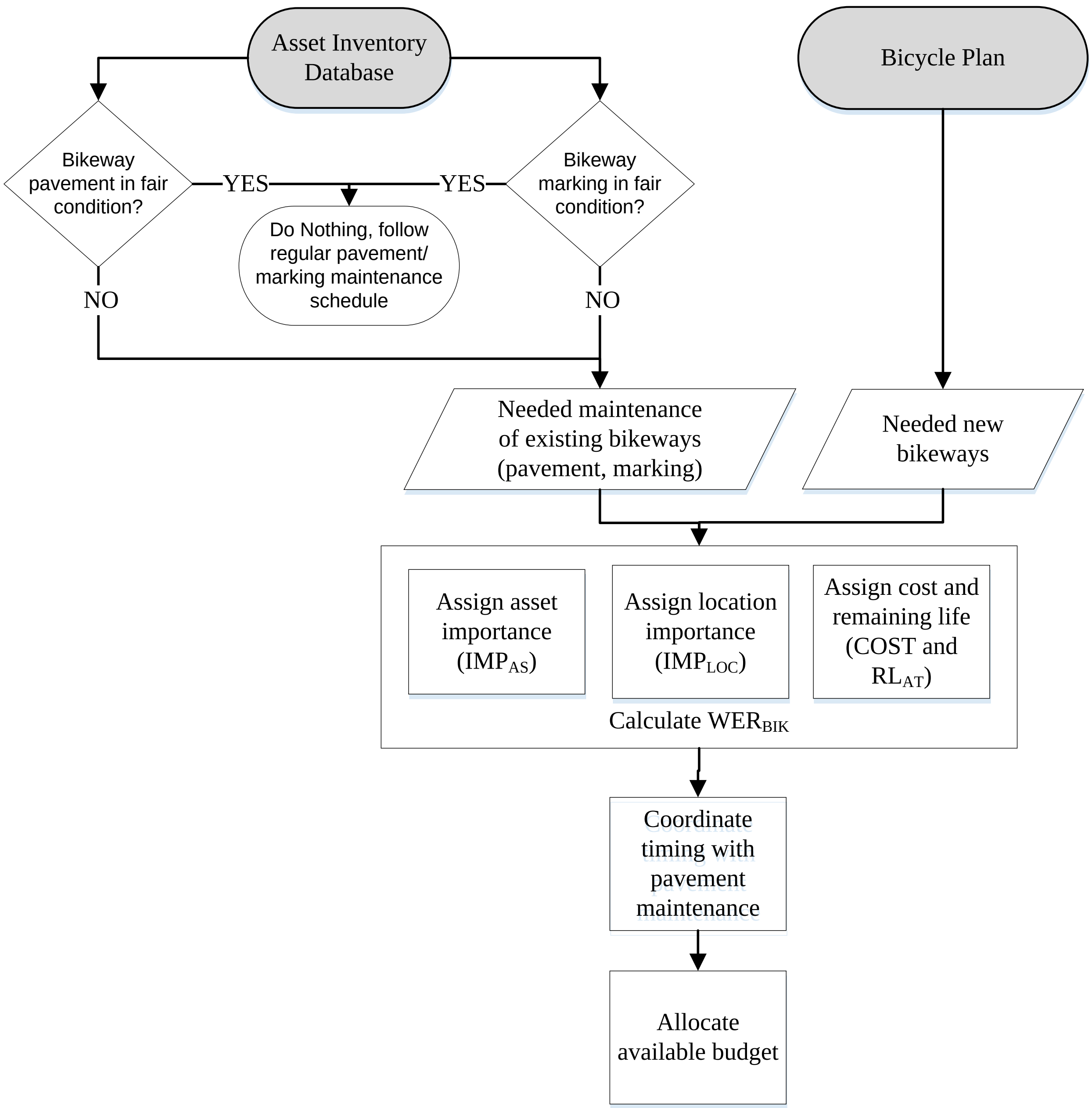


Figure 4.9: Bikeway Quality Module Processes to Prioritize Projects.

Methodology for Bikeway Project Prioritization

In the bikeway quality module, two street section purpose categories are defined:

- Priority section: bicyclist movement prioritized, includes bikeways identified in applicable local, regional, and State Bicycle Plans.
- General section: all other sections.

The bikeway quality module process for the needs analysis requires two data sources:

- Asset inventory database
- Bikeway plan

The desired bikeway quality characteristics are aimed towards providing a well-maintained pavements and striping on bikeways.

Timing of construction of new bikeways as identified in applicable local, regional, and State Bicycle Plans is coordinated with pavement resurfacing projects, to find the best timing to construct the bikeway within the planning period when funding is available. According to FHWA (2016d), *"installing bicycle facilities during roadway resurfacing projects is an efficient and cost-effective way for communities to create connected networks of bicycle facilities."*

Improvements needed on existing bikeway pavements and striping are identified through an asset inventory database. These maintenance improvements are prioritized based on a bikeway weighted effectiveness ratio (WER_{BIK}). That is calculated by using the asset importance index (IMP_{AS}), asset importance of location (IMP_{LOC}), cost and remaining service life after the improvement.

An asset importance index (IMP_{AS}) is assigned to each improvement as shown in Table 4.8. Weights for each asset distinguish between needs for maintenance of existing assets and implementation of new assets. In this example, maintaining the bikeway pavement in good condition has the highest importance, followed by new bikeway marking and bikeway marking maintenance. Since each agency has their specific priorities, decision makers are encouraged to

assign their own weights to customize the asset importance. Construction of a new pavement for bikeway is not considered in this module.

Table 4.8: Example of Asset Importance (IMP_{AS}).

Asset	Asset Importance Index (IMP_{AS})	
	New	Maintenance
Bikeway marking	0.9	0.8

In addition, the importance of location (IMP_{LOC}), is considered as shown in Table 4.9. The location importance index prioritizes improvements in street sections that would be beneficial to larger bicyclist traffic in links identified by applicable local, regional, and State Bicycle Plans.

Table 4.9: Example of Location Importance (IMP_{LOC}).

Functional class	Street purpose	Location Importance Index (IMP_{LOC})
Arterial	General	0.55
	Priority	1
Collector	General	0.55
	Priority	1
Residential	General	0.55
	Priority	1

Commonly used materials for bikeway marking include paint, epoxy resin, inlay tape and thermoplastics, each of them with different cost and expected service life. For the purpose of this study it is assumed that all bikeways are marked with thermoplastic paint. Table 4.10 shows the assumed unit costs and service life used in the MOS model for bikeway quality improvement.

Table 4.10: Example of Unit Costs and Remaining Life. (based on FHWA 2016d)

Asset	Unit Cost		Remaining Life [years]	
	New	Maintenance	New	Maintenance
Bikeway striping	$100,000/mi	$51,000/mi	4	4

Mathematical Formulation

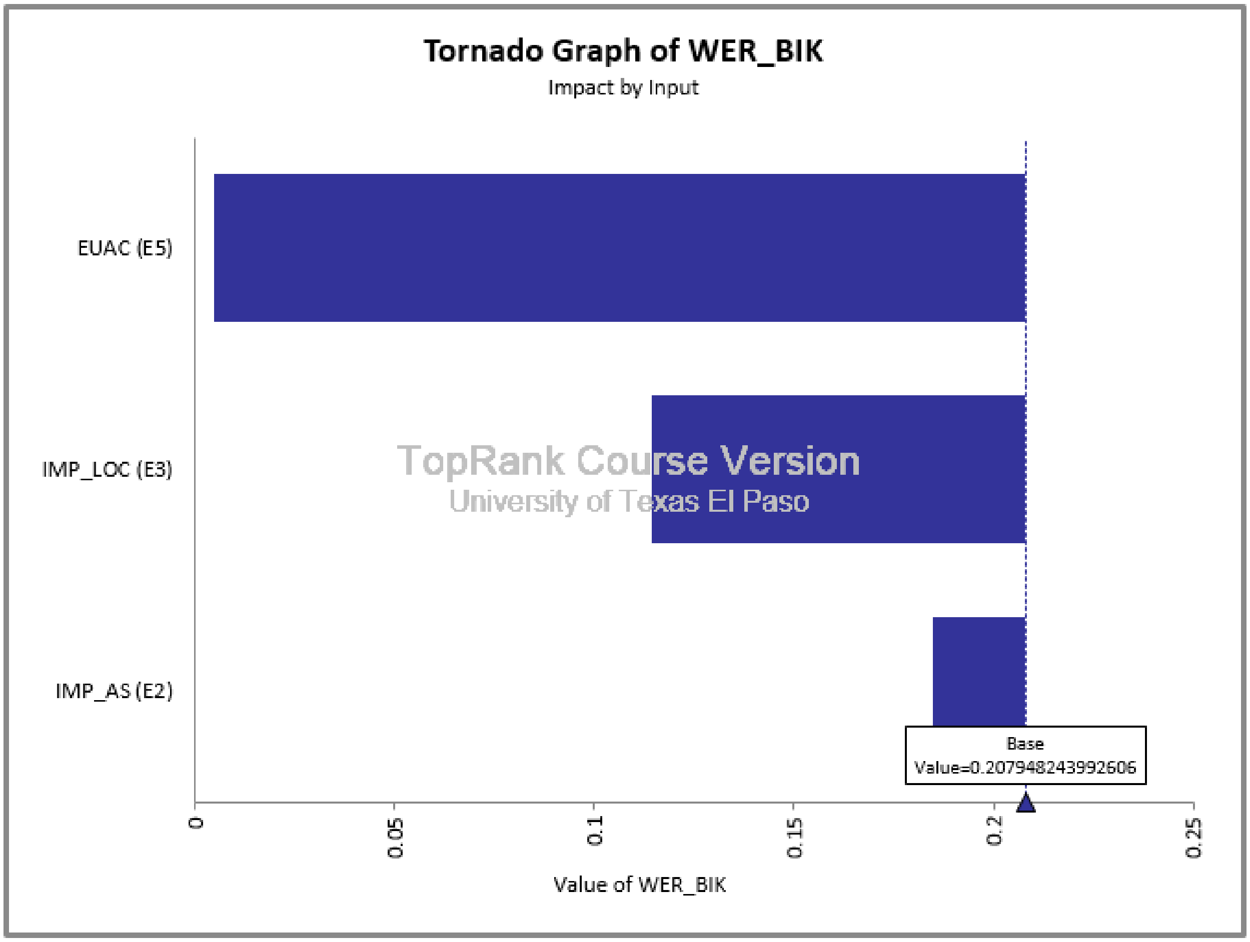
All candidate bikeway improvements, including new bikeway markings as well as maintenance of existing markings and pavements, are prioritized based on the bikeway weighted effectiveness ratio (WER_{BIK}) that can be calculated as follows:

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

where:

IMP_{AS} …….. asset importance index
IMP_{LOC} …… location importance index
RL_{AT} ……… remaining service life after implementation or maintenance
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)

Sensitivity analysis in TopRank® indicates that the equivalent uniform annual cost (EUAC), which reflects the future unit cost spread over the service life, has the greatest impact, followed by the location importance and asset importance, as Figure 4.10 shows.



What-If Analysis Summary for Output WER_BIK

Top 3 Inputs Ranked By Change in Actual Value

			Minimum			Maximum			Input
			Output		Input	Output		Input	
Rank	Input Name	Cell	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
1	EUAC (E5)	E5	0.00486718	-97.66%	46228	0.207948244	0.00%	1082	1082
2	IMP_LOC (E3)	E3	0.114371534	-45.00%	0.55	0.207948244	0.00%	1	1
3	IMP_AS (E2)	E2	0.184842884	-11.11%	0.8	0.207948244	0.00%	0.9	0.9

Figure 4.10: Sensitivity Analysis Results for WER_{BIK}.

Finally, the bikeway quality improvement projects are prioritized based on WER_{BIK}, as Figure 4.11 shows. Since the paint of bikeway markings has the best adhesion to a new pavement surface which results in better performance, it is desirable that maintenance of these two assets is synchronized. For that reason, bikeway implementation and maintenance can be delayed up to 2

years from the original due date in those cases that would lead to application of pavement maintenance and bikeway maintenance in the same year. Projects selected for funding are added to the list of budgeted improvements. City of Portland (1998) recommends conducting public meetings to discuss the identified improvements with the community. It is also important to coordinate the improvements across asset categories to ensure the optimal timing of the application. For example, bikeway markings have a longer service life when applied to a newly resurfaced pavement, therefore it is desirable to coordinate bikeway installations with paving program (FHWA 2016d). Those improvements that do not receive funding are back-logged and wait to compete for funding in the next budget cycle.

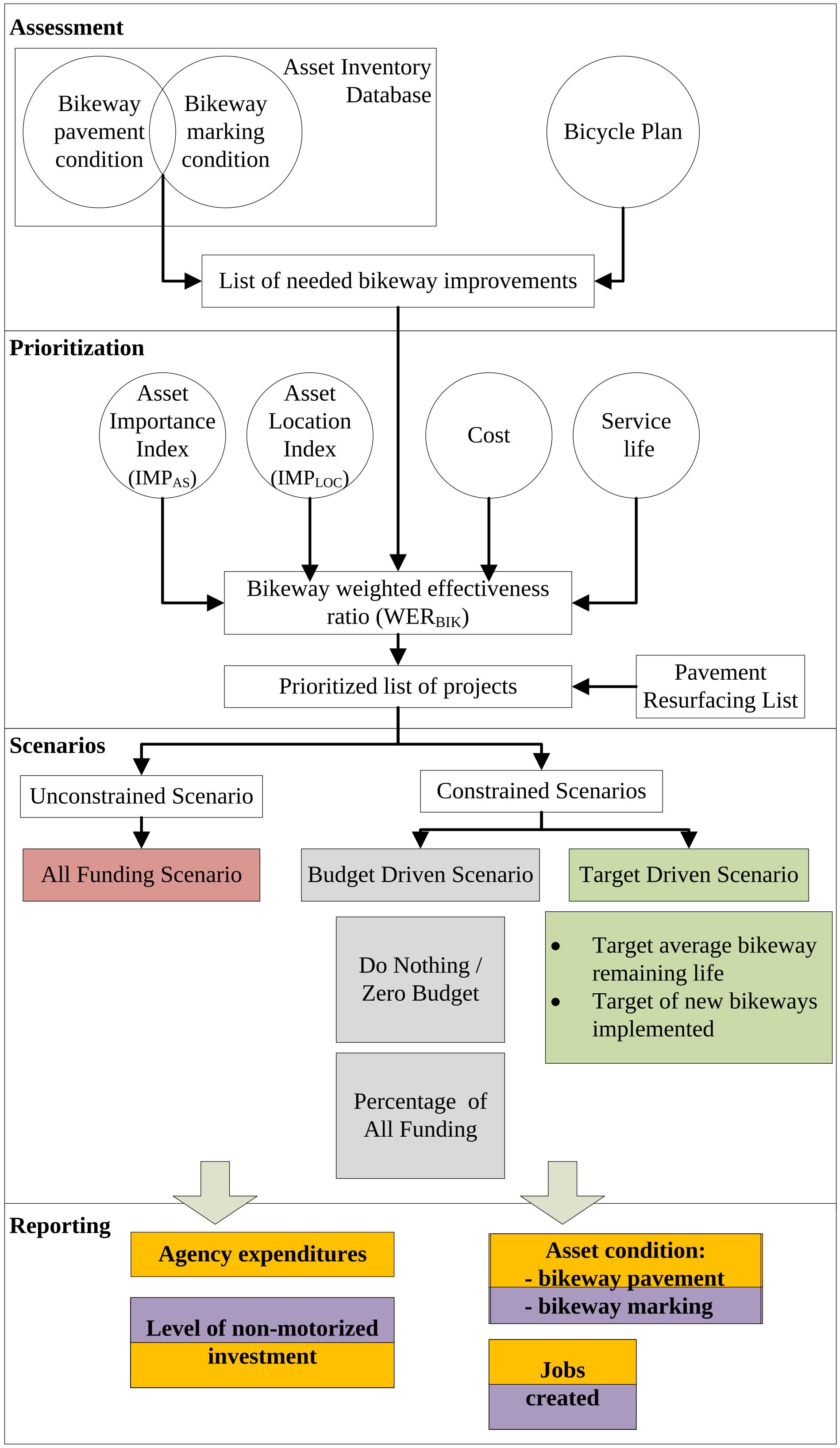


Figure 4.11: Summary of the Bikeway Quality Module.

4.4.2 Improve Pedestrian Safety

Safety is an 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).

According to the latest NHTSA report on pedestrian safety, almost 70% of pedestrian fatalities happen at non-intersections (NHTSA 2015a). Night is most risky for pedestrians, as 72% fatalities occur during dark hours (NHTSA 2015a). Majority of crash risk types for pedestrians is characterized by five crash-type categories (Hunter et al. 1996, NHTSA 2008):

Midblock: pedestrian struck while crossing midblock, as illustrated in Figure 4.12.

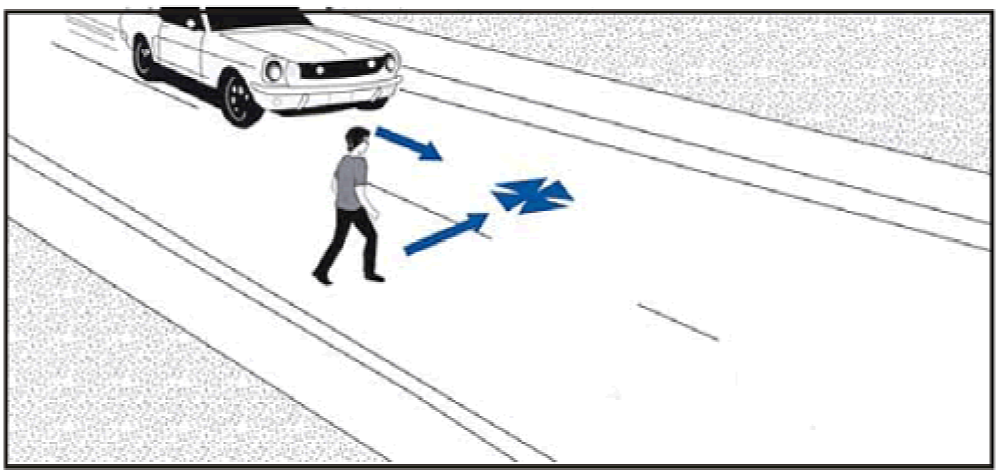


Figure 4.12: Midblock Pedestrian Crash Type (FHWA 1997, FHWA 2006).

Motorist's view could be obstructed by trees, parked vehicles, or low levels of lighting. Locations with higher risk of this crash type include neighborhood streets, proximity of a school or a park, as well as streets that do not have crossing points every 300 ft. maximum, since research has shown that pedestrians are willing to go not more than 150 ft. out of their way (Burden 2001). Likelihood of crash increases with number of lanes, since drivers in all intersecting lanes need to yield to a pedestrian in order to cross in a safe manner. Pedestrian crossing islands can provide an opportunity to cross two-way streets in two separate steps, with

the aim of reducing the risk of crash by 40% (FHWA 2006). Also an advance stop/yield line located 30 to 50 ft. before the crosswalk, accompanied by YIELD HERE TO PEDESTRIANS sign, can help to identify which cars are going to stop so that the pedestrian can safely cross (FHWA 2006). Another way to improve pedestrian safety is to reduce the roadway width at the crosswalk by using curb extensions and making pedestrians more visible by reducing the distance to cross by up to 6ft from each direction (Mead et al. 2014, FHWA 2006). Curb extensions are used in locations with parallel parking. For multilane streets with high traffic volumes a pedestrian signal is necessary to create a gap to cross for pedestrians (FHWA 2006). Streets with road diets, where the number of lanes is reduced, are easier to cross for pedestrians, due to *"shorter effective crossing, fewer lanes to cross, and slightly slower motor vehicle traffic speeds"* (FHWA 2006). For residential streets, traffic calming with *"speed tables, speed humps, traffic circles, chokers, and chicanes"* (FHWA 2006) can reduce the travel speeds to a range safer for pedestrians. Transit stops *"should be placed where it is possible for a pedestrian to cross safely at or very near the bus stop"* (FHWA 2006), in order to improve the accessibility for pedestrians.

Not in roadway: these crashes include failures to yield to pedestrians in sidewalks, driveways (as Figure 4.13 shows), parking lots and alleys.

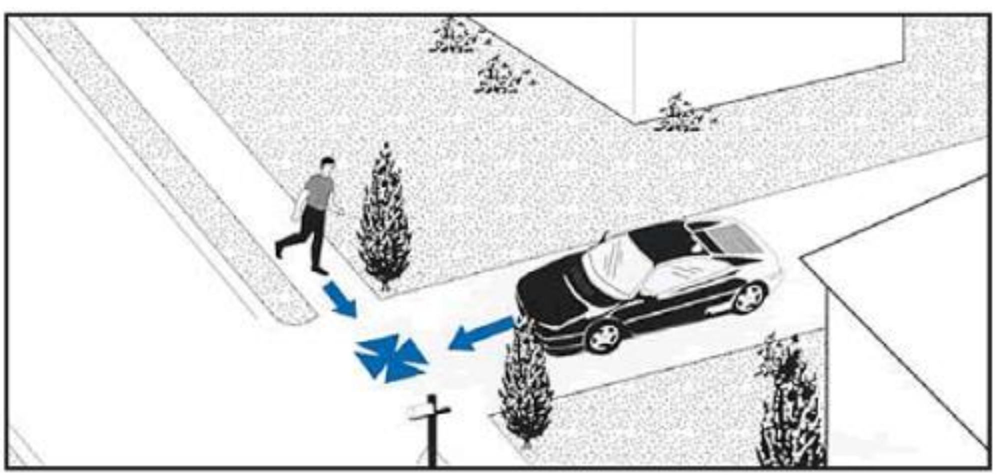


Figure 4.13: Not-in-Roadway Pedestrian Crash Type (FHWA 1997, FHWA 2006).

Sidewalks should not be interrupted in driveways and should continue with at least a 3 ft. wide level passage to comply with ADA requirements (FHWA 2006, FHWA 2002b). Driveway frequency should be minimized to reduce the construction and maintenance costs of level passages and also reduce the conflict points for pedestrians (FHWA 2006).

Walking along road: As Figure 4.14 shows, in sections without sidewalks or paved shoulders, pedestrians are forced to walk along the road, either with or against the direction of traffic.

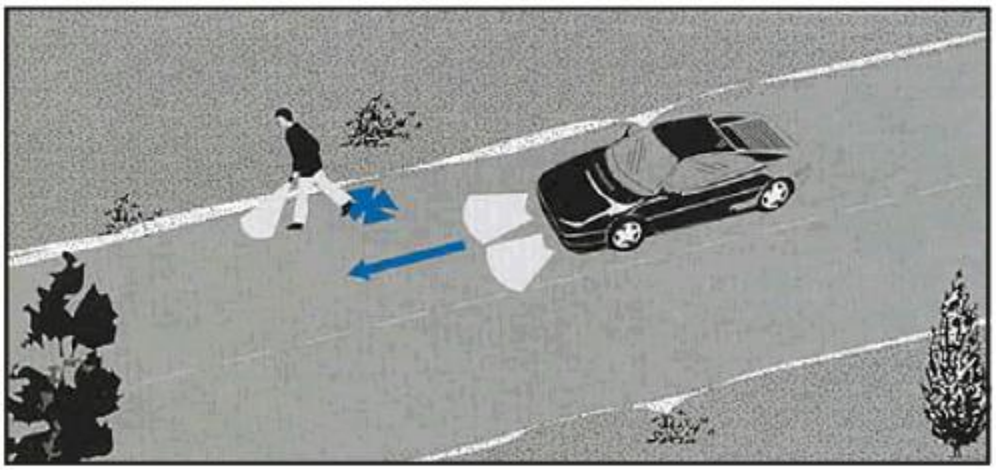


Figure 4.14: Walking Along Roadway Pedestrian Crash Type (FHWA 1997, FHWA 2006).

Width of at least 6 ft. for paved shoulders and at least 5 ft. for sidewalks (at least 6 ft. along arterials) is recommended (AASHTO 2011, FHWA 2006).

Intersection: pedestrian struck while crossing at an intersection while motorist's view was blocked. Figure 4.15 shows an example of such crash type.

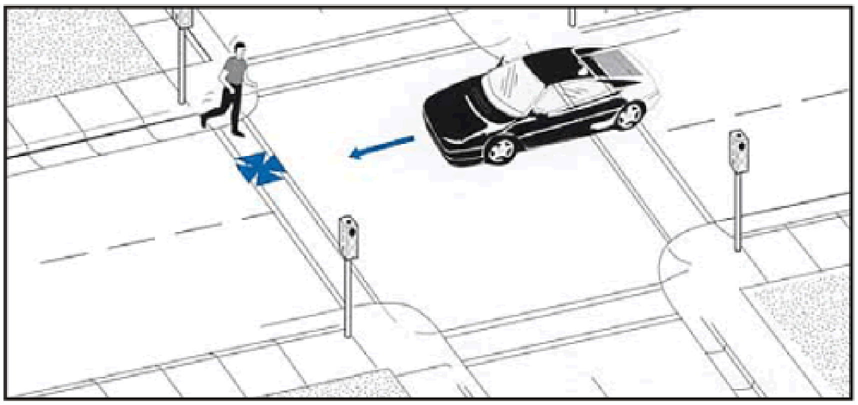


Figure 4.15: Intersection Dash Pedestrian Crash Type (FHWA 1997, FHWA 2006).

Safety improvements to make pedestrian crossing easier include pedestrian crossing islands, advance stop/yield lines, curb extensions, as mentioned in the midblock dash section (FHWA 2006). Crossing distance at intersections for pedestrians can be reduced by tighter turning radius for motorists, or by combining right-turn slip lanes with pork-chop islands (FHWA 2006). Single ADA ramps leading to the middle of intersection should be avoided and rather ramps at each corner with a maximum radius of 25 ft. are preferred (FHWA 2006). Right-turn slip lanes with pork-chop islands give pedestrians an opportunity to check first for incoming vehicles in the red-turn lane, stop at the island and then check for a gap in the other lanes.

Vehicle turn/merge: pedestrian struck at a crosswalk while vehicle was turning or merging, as Figure 4.16 illustrates.

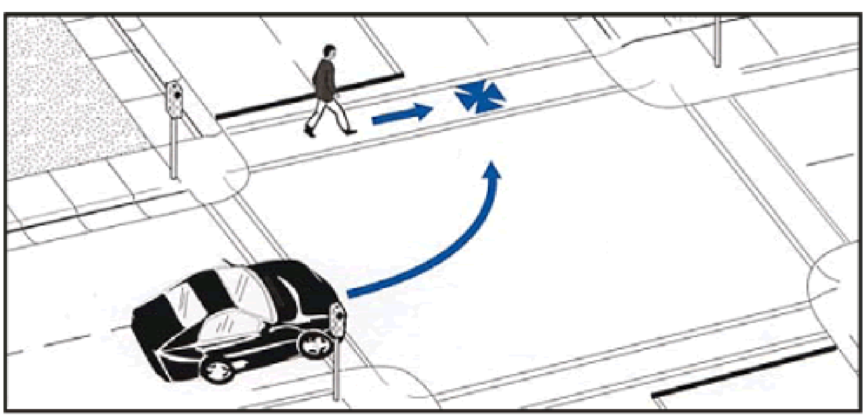


Figure 4.16: Vehicle Turn/Merge Pedestrian Crash Type (FHWA 1997, FHWA 2006).

This crash type is frequent at intersections with allowed right turn on red, when motorist fails to yield to pedestrian who is crossing on green signal. Conflicts between turning vehicles and pedestrians can be minimized by giving walk signal 3 to 7 seconds before the conflicting phase (Barnes 2014).

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), as well as reducing the crossing distance with curb extensions. 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). Figure 4.17 shows pedestrians who took the shortest route regardless of a nearby crosswalk, potentially due to faded paint of the crosswalk markings.

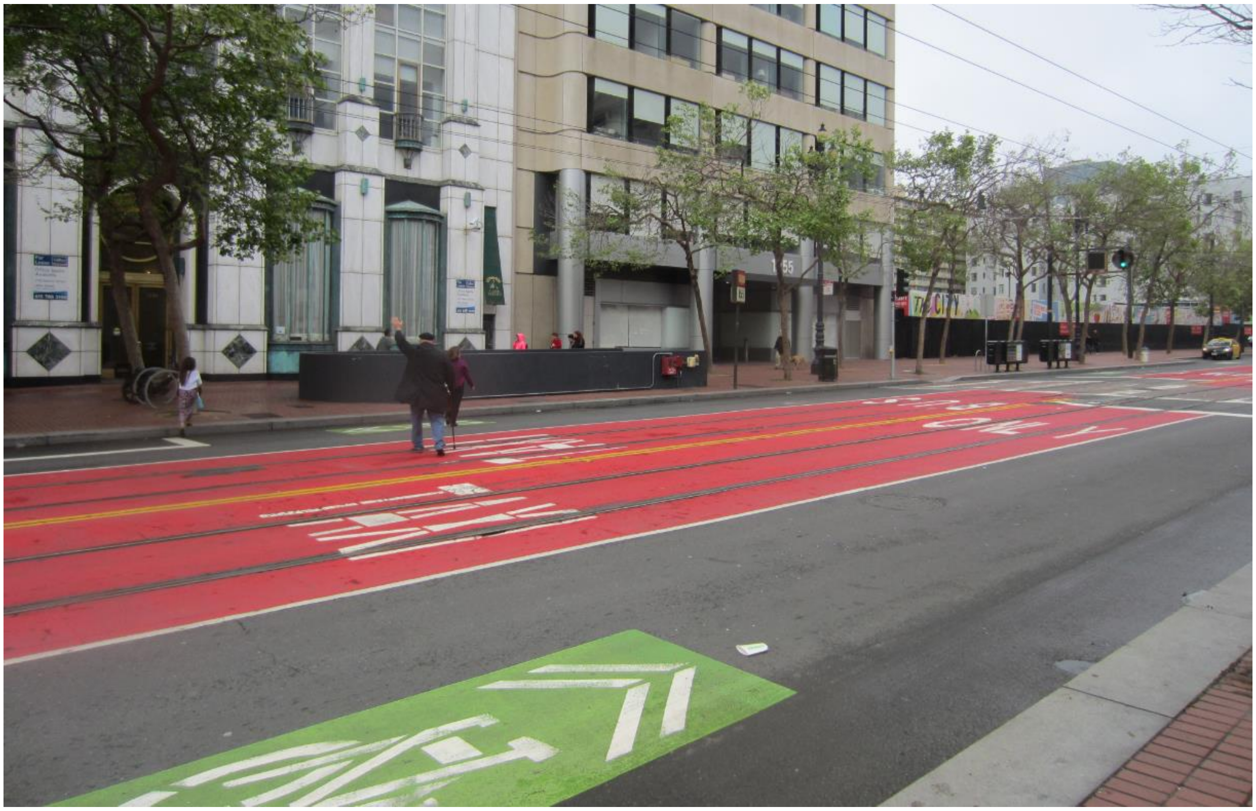


Figure 4.17: Pedestrians in San Francisco Crossing Outside of a Crosswalk.

Input Data

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 safety module focuses on pedestrian safety by analyzing safety data to determine where pedestrian crossing opportunities could be improved by striping of new marked crosswalks as well as maintaining the existing ones.

Figure 4.18 shows an example of the input data categories needed in the safety module. Data categories include safety, and additional two categories to account for roadway characteristics and other features such as the construction cost, maintenance cost, and remaining service life of the crosswalk.

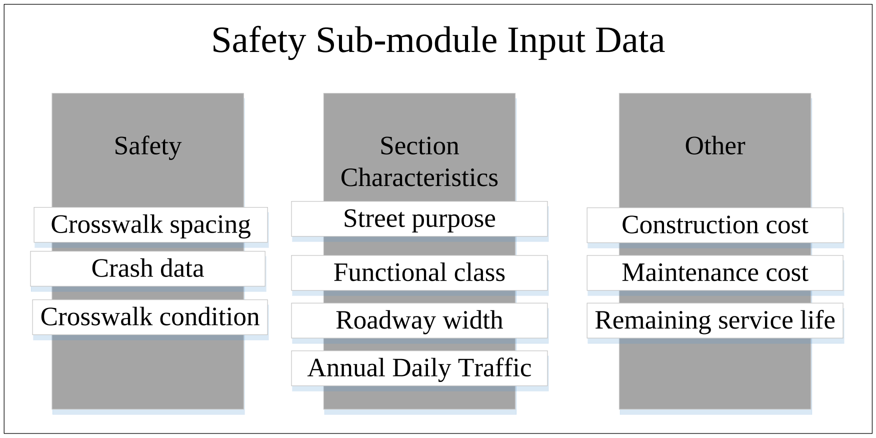


Figure 4.18: Livability Input Data with Section Characteristics and Other Data.

Table 4.11 shows an overview of the data format for the safety module.

Table 4.11: Overview of Data Format for Safety Module.

Safety	
Description	**Format**
Existing crosswalk condition:	Remaining service life [years]
Existing crosswalk characteristics:	Spacing [ft.]
Desired crosswalk characteristics:	For purpose types and functional classes – desired spacing
Pedestrian safety trigger:	Maximum number of mid-block pedestrian collisions in the last 5 years
Crash data for roadway section:	Transportation Injury Mapping System (TIMS), TransBase
Section Characteristics	
Description	**Format**
Section type	Purpose: priority (proximity of school /hospital / transit / retail), general Functional class: arterial, collector, residential Roadway width [ft.], traffic volume [ADT], posted speed [mi/hr]
Other	
Construction cost (crosswalk)	Agency records
Maintenance cost (crosswalk)	Agency records
Remaining service life (crosswalk)	Agency records

The data input into the safety module includes information about condition of existing crosswalk markings. A surrogate performance measure is used to assess the crosswalk marking condition, due to limited data on assessing pavement marking condition. Therefore, the crosswalk marking condition is approximated by an average remaining life (RL), which indicates the time until next maintenance treatment.

The need for new crosswalks is identified on sections with two or more mid-block pedestrian crashes, and existing crosswalk characteristics above the desired crosswalk spacing which is setup to 300 ft. in the MOS model for all functional classes (after VDOT 2004). The source of crash data for San Francisco is the Transportation Injury Mapping System (TIMS) and TransBase. Alternatively, not only crash data but also neighborhood needs requests can be considered when assessing the need for crosswalk improvements (City of Portland 1998).

The process to prioritize projects in the pedestrian safety module is shown in Figure 4.19, which is discussed in the following section.

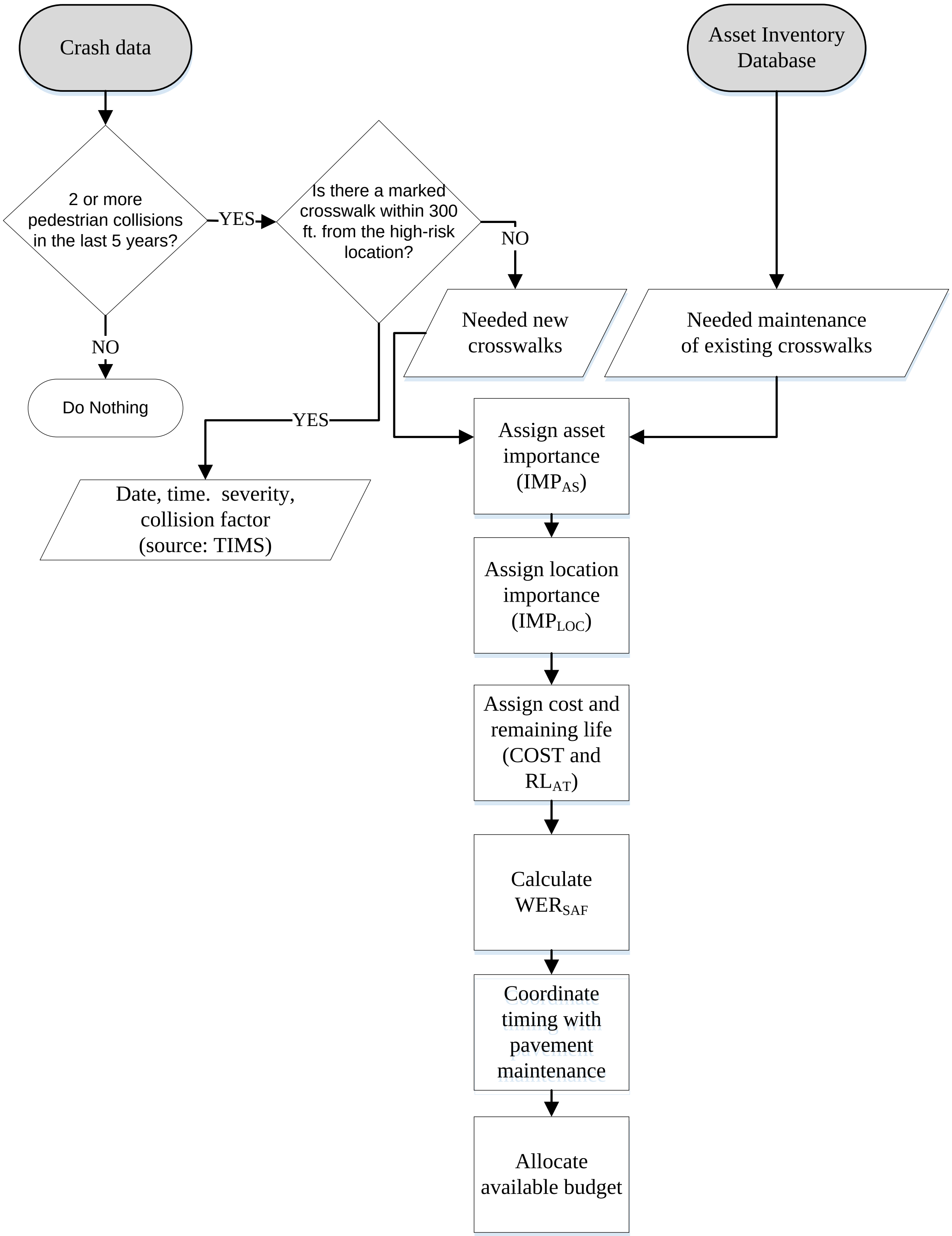


Figure 4.19: Safety Module Processes to Prioritize Projects.

Methodology for Crosswalk Project Prioritization

The safety `module process for identifying the needed improvements uses two data sources:

- Crash data (Transportation Injury Mapping System (TIMS), TransBase)
- Asset inventory database

The aim is to identify sites where the pedestrians are most at risk, therefore crash data, such as date, time, location, severity and collision cause are extracted from the TIMS and TransBase databases. Sections with more than two mid-block crashes involving a pedestrian in the last five years are checked for compliance with crosswalk spacing requirements. If the crosswalk spacing is above the required maximum, then a need for a new marked crosswalk is created. *"Striped crosswalks indicate a legal and preferred crossing for pedestrians, and may be installed at intersections or midblock locations. Motorists often fail to yield to pedestrians at these crossing points so marked crosswalks are often installed to warn motorists to expect a pedestrian crossing ahead and also to indicate a preferred crossing location to pedestrians"* (FHWA 2013c).

Table 4.12 shows the desired crosswalk spacing and the pedestrian collision thresholds for different functional classes and street purpose categories.

Streets are categorized into two zones, depending on their purpose:

- Priority zone: includes streets in the proximity of schools, parks, hospitals, transit stops, and retail, where pedestrian movement is prioritized.
- General zone: all other streets.

The crosswalk spacing targets are chosen to follow the crosswalk spacing of 300 ft. recommended by Burden (2001). General zones do not have any desired crosswalk spacing. Sections with two or more collisions involving pedestrians are considered as not meeting the desired crosswalk characteristics, regardless of their zone. Additionally, for streets with more than 3 lanes and ADT above 9,000 vehicles; or streets with ADT above 12,000, FHWA (2005b) recommends complementing new marked crosswalks with other improvements such as warning

signs, flashers, raised medians, traffic signals, raised crossings, street narrowing, nighttime lighting.

Table 4.12: Desired Crosswalk Characteristics by Functional Class and Street Purpose.

Functional class	Zone	Crosswalk	Pedestrian safety
		Desired crosswalk spacing	**Pedestrian collision threshold**
Arterial	General	-	2 or more collisions
	Priority	300 ft.	2 or more collisions
Collector	General	-	2 or more collisions
	Priority	300 ft.	2 or more collisions
Residential	General	-	2 or more collisions
	Priority	300 ft.	2 or more collisions

The desired crosswalk characteristics are aimed towards providing opportunities for pedestrians to safely cross the street. In order to improve pedestrian safety, more factors could be included such as sidewalk width, buffer zone between sidewalks and travel lanes, lighting, tree coverage, and crossings at intersections.

Improvements needed on existing crosswalks are identified through an asset inventory database. These maintenance improvements are prioritized based on a safety weighted effectiveness ratio (WER_{SAF}). That is calculated by using the asset importance index (IMP_{AS}), asset importance of location (IMP_{LOC}), cost and remaining service life after improvement.

An asset importance index (IMP_{AS}) is assigned to each improvement as shown in Table 4.13. Weights for each asset distinguish between needs for maintenance of existing assets and implementation of new assets. In this example, the painting of a new crosswalk is assigned with the highest importance. However, since each agency has their specific priorities, decision makers are encouraged to assign their own weights to customize the asset importance.

Table 4.13: Example of Asset Importance (IMP_{AS}).

Asset	Asset Importance Index (IMP_{AS})	
	New	Maintenance
Crosswalk	1	0.8

In addition, the importance of location (IMP_{LOC}), is considered as shown in Table 4.14. The location importance index prioritizes improvements in crosswalks located at street sections that would be beneficial to larger pedestrian traffic in the proximity of schools, parks, hospitals, transit stops, or retail.

Table 4.14: Example of Location Importance (IMP_{LOC}).

Functional class	Street zone	Location Importance Index (IMP_{LOC})
Arterial	General	0.55
	Priority	1
Collector	General	0.55
	Priority	1
Residential	General	0.55
	Priority	1

Commonly used materials for crosswalks include paint, epoxy resin, inlay tape and thermoplastics, each of them with different cost and expected service life. For the purpose of this study it is assumed that all crosswalks are marked with paint. Table 4.15 shows the assumed unit costs and service life used in the MOS model. The crosswalk striping is expected to last 3 years, after which needs to be re-painted. It is assumed that the cost of re-painting is equal to the cost of implementation of a new crosswalk.

Table 4.15: Example of Unit Costs and Service Life.

Asset	Median Unit Cost [each] Source: FHWA 2013c		Service Life [years] Source: FHWA 2013d	
	New	Maintenance	New	Maintenance
Crosswalk	$340	$340	3	3

Mathematical Formulation

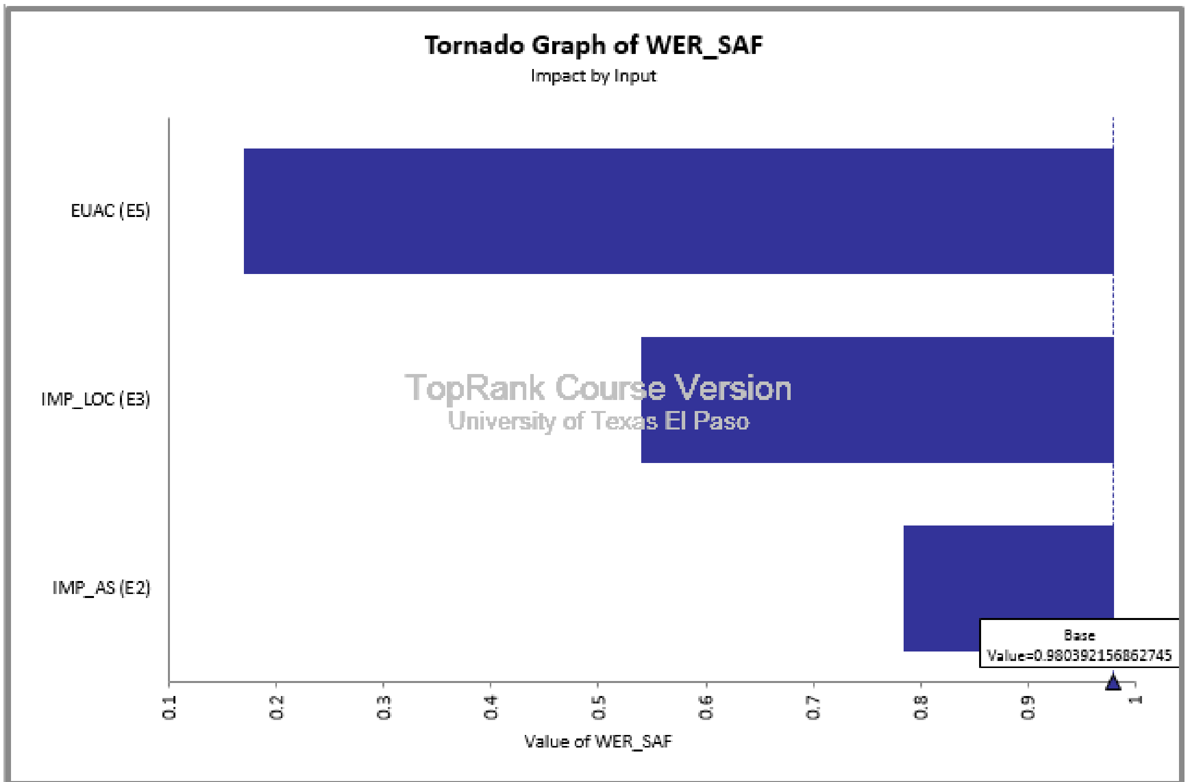
All candidate crosswalk improvements, including new marked crosswalks as well as maintenance of existing crosswalks, are prioritized based on the safety weighted effectiveness ratio (WER_{SAF}) that can be calculated as follows:

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

where:

IMP_{AS} ……..	asset importance index
IMP_{LOC} ……	location importance index
RL_{AT} ………	remaining service life after implementation or maintenance project
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)

Sensitivity analysis in TopRank® indicates that equivalent uniform annual cost (EUAC), which reflects the future unit cost spread over the service life, has the greatest impact, followed by the location importance and asset importance, as Figure 4.20 shows.



What-If Analysis Summary for Output WER_SAF

Top 3 Inputs Ranked By Change in Actual Value

					Minimum			Maximum			
					Output		Input	Output		Input	Input
Rank	Input Name	Workbook	Worksheet	Cell	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
1	EUAC (E5)	Book1.xlsx	Sheet1	E5	0.170068027	-82.65%	1960	0.980392157	0.00%	340	340
2	IMP_LOC (E3)	Book1.xlsx	Sheet1	E3	0.539215686	-45.00%	0.55	0.980392157	0.00%	1	1
3	IMP_AS (E2)	Book1.xlsx	Sheet1	E2	0.784313725	-20.00%	0.8	0.980392157	0.00%	1	1

Figure 4.20: Sensitivity Analysis Results for WER_{SAF}.

Finally, the crosswalk improvement projects are prioritized based on WER_{SAF}, as Figure 4.21 shows. Similarly to bikeway markings, the paint for crosswalk markings has the best adhesion to a new pavement surface which results in better performance, and it is desirable that maintenance of these two assets is synchronized. For that reason, crosswalk implementation and maintenance can be delayed by 1 year from the original due date in those cases that would lead to application of pavement and crosswalk treatments in the same year. Projects selected for funding are added to the list of budgeted improvements. City of Portland (1998) recommends

conducting public meetings to discuss the identified improvements with the community. It is also important to coordinate the improvements across asset categories to ensure the optimal timing of the application. For example, a marked crosswalk 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.

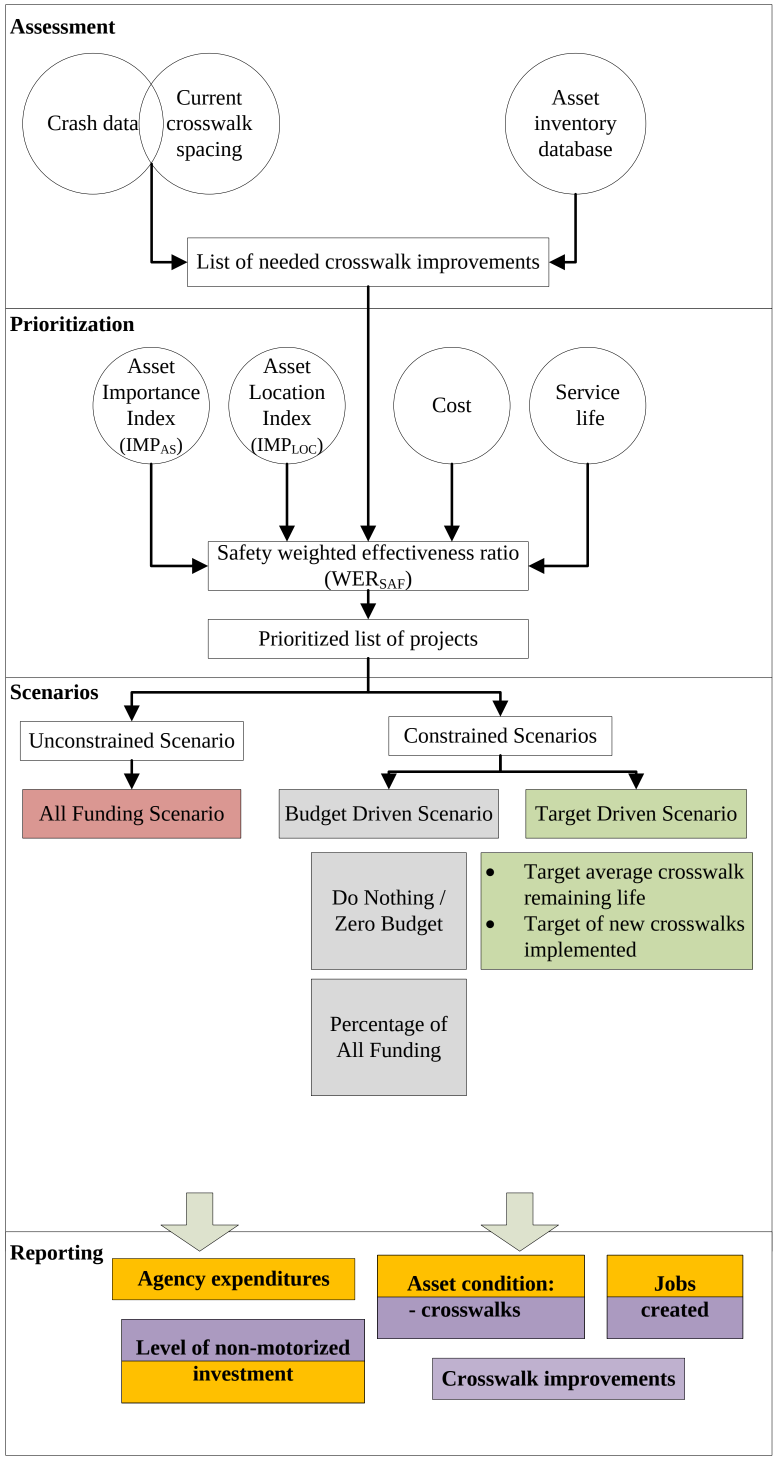


Figure 4.21: Summary of the Safety Module.

4.5 Framework for Economic Sustainability

The economic sustainability framework focuses on estimating how many new jobs are created based on the level of funding that pavements, bikeways, and crosswalks receive.

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

Input Data

Data used for the estimates are shown in Table 4.16.

Table 4.16: 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)

Methodology for Job Creation Estimates

As Figure 4.20 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 can be reported for each of the maintenance strategies or budget scenarios, as shown in Figure 4.21.

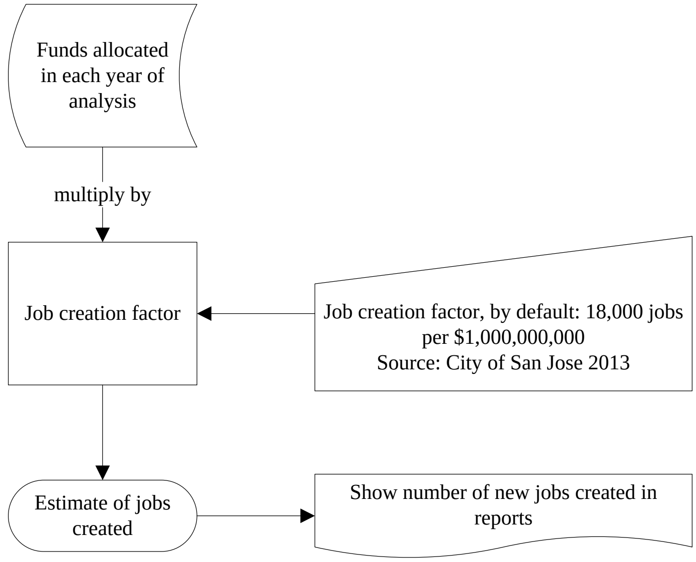


Figure 4.22: Process of Job Creation Estimation.

City of

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 4.23: Example of Potential Reporting of Job Creation Estimation in StreetSaver®.

Mathematical Formulation

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

4.6 Summary

This chapter has reviewed and summarized how sustainability aspects can be implemented into transportation asset management, namely pavement management, as well as bikeway and crosswalk management systems.

There are several ways to address sustainability in transportation, starting from urban planning and roadway engineering to resource extraction, material processing and transportation, use phase, maintenance, flora and fauna protection, and end-of life material recycling or reusing. The MOS model framework for environmental sustainability focuses entirely on pavement assets and the CO_2 that is emitted by motorized vehicles travelling on the pavement surface.

There are several aspects to economic, environmental and social sustainability, as discussed in Figure 2.1, including effectiveness; wider economic benefits; air, noise, water, and light pollution; community livability; accessibility; and equity. However, for the purpose of the MOS model, the economic sustainability is measured by creation of new jobs, agency expenditures, and level of funding for non-motorized modes; the environmental sustainability is measured by on-road CO_2 emissions and the social cost of CO_2; while social sustainability aims to foster livability by improving pedestrian safety and preserving multimodal transportation infrastructure. The MOS model focuses on multimodal transportation and pedestrian safety as the major factors in livability that can be influenced through TAM by enhancing a pavement management by other assets, such as crosswalks and bikeways. Improvements in multimodal transportation focus on maintaining bikeways in such condition that is safe and comfortable to ride on, while the need for safety improvements in pedestrian crossing opportunities is identified through crash data and existing marked crosswalks. This safety and multimodal enhancement is used as an example to show how pavement management can be enhanced by assets that are used by non-motorized users and also how safety data can be used to improve transportation infrastructure.

Chapter 5: Application of the Multi-Objective Sustainability Model

The MOS model introduced in Chapter 4 is used to complement an existing pavement management system StreetSaver® developed by the Metropolitan Transportation Commission in Oakland, CA. The MOS model adds crosswalks and bikeways into the management process and provides a more holistic view on transportation asset management that takes into account not only motorized vehicles, but also pedestrians and bicyclists.

5.1 Integration of the Multi-Objective Sustainable Model into StreetSaver® Pavement Management System

The MOS model enhances StreetSaver's pavement management by estimating CO_2 emissions resulting from network condition, as well as jobs creation based on funding allocated to maintenance activities.

"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 5.1.

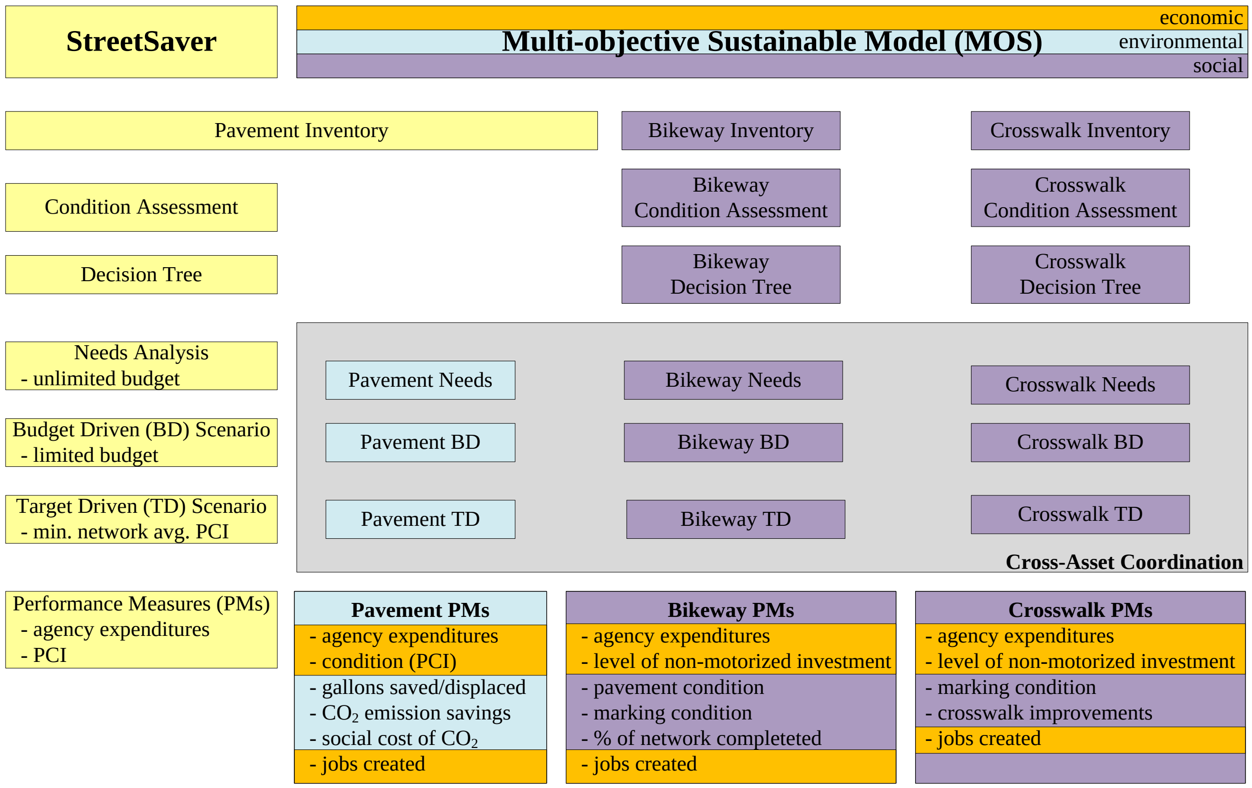


Figure 5.1: Multi-Objective Sustainable Model Enhancement for StreetSaver®.

The individual modules are discussed in the following section.

Inventory and Condition Assessment

An inventory includes information about individual assets, such as their location, material, construction date, inspection history, and condition. The StreetSaver® pavement inventory information that is used in the MOS model includes: section ID, year of construction, surface type, length, area, and condition. Bikeway inventory information that was collected for the MOS model includes: bikeway ID, remaining service life, and length. Crosswalk inventory

information that was collected for the MOS model includes: crosswalk ID, and remaining service life.

Current condition is assessed and projected to the future to identify the maintenance needs over the planning period. The StreetSaver® pavement condition model is based on a sigmoidal deterioration curve for deterioration. The MOS model assumes linear condition deterioration based on the asset age for bikeway markings and crosswalk markings.

Needs Analysis

The first step in the analysis is to identify the network treatment and budget needs to preserve the infrastructure transportation network in an optimal condition over the period of analysis. No funding constraints are included in the analysis process, therefore the scenario that reflects that is called All Funding. StreetSaver® only considers the pavement condition in the criteria for the All Funding Scenario and aims to maintain the network average condition at PCI 80 or above. For crosswalks, the unconstrained All Funding scenario means improving all high-risk locations. For bikeways, the All Funding scenario provides funding to all new projects as well as maintains the network average condition above PCI 80.

After establishing the All Funding scenario, alternative Target-Driven, and Budget-Driven scenarios analyses are conducted to quantify the impact on performance of different condition and funding constraints. The opposite of All Funding scenario is the Do Nothing scenario.

Budget-Driven Scenario

StreetSaver® Budget-Driven scenario considers a limited budget for maintenance treatments and predicts asset condition under the available budget. Maintenance actions are ranked based on weighted-effectiveness ratio (WER) and compete for available budget. WER takes into account the functional class, treatment annualized cost (EUAC), and treatment effectiveness (condition improvement and service life extension after treatment) (Smith 1996).

In the MOS model, pavement maintenance projects are ranked based on potential CO_2 savings. Crosswalk improvement projects are ranked based on safety weighted effectiveness ratio (WER_{SAF}) that takes into account the crosswalk importance, location, remaining service life, and cost of the improvement. Bikeway improvement projects are ranked based on bikeway weighted effectiveness ratio (WER_{BIK}) calculated as the bikeway importance, location, remaining service life, and cost of the improvement.

Target-Driven Scenario

Traditional StreetSaver® Target-Driven scenarios include four individual targets: minimum pavement condition index (PCI), minimum remaining service life, minimum percentage of network in very good condition, and maximum percentage of network in poor condition.

In the MOS model, the goal for pavements is to maximize CO_2 emission savings with a target objective % of potential emission savings (compared to All Funding and Do Nothing scenarios) and a target objective % of pavements in poor and very poor condition. For crosswalks, the goal is to maximize the safety weighted effectiveness ratio with a target objective of a percentage of improved pedestrian crossing opportunities and a target objective of minimum average network service life. For bikeways, the goal is to maximize the bikeway weighted effectiveness ratio with a target objective of minimum bikeway average condition and a target objective of minimum average network service life.

Performance Measures

StreetSaver® uses three performance measures: PCI, remaining service life, and agency expenditures. The MOS model reports for each pavement scenario also on-road CO_2 emission savings, social cost of CO_2, and jobs created. For bikeway scenarios the MOS model indicates not only the agency expenditures but also the level of investment into non-motorized transportation infrastructure, as well as the condition on bikeway pavements and markings, the percentage of completed bikeway network, and jobs created. In crosswalk scenarios are reported

agency expenditures, level of investment into non-motorized transportation infrastructure, crosswalk marking condition, funded crosswalk improvements, and jobs created.

Solving Technique

Approaches to solving multi-objective problems can range from ranking techniques to optimization. Many pavement management systems prefer ranking to prioritize funding allocation, as *"optimization techniques are often perceived as too complex, and answers provided by these methodologies are not well understood by local agencies"* (Chang 2007). A ranking technique, called the Dynamic Bubble-Up (Chang 2007) is used to prioritize the projects in the MOS model. Projects are ranked based on their potential CO2 emission savings (pavements), safety weighted effectiveness (crosswalks), or bikeway weighted effectiveness (bikeways). Then for each year of the analysis projects are selected starting with the project with the highest potential benefits until the target objectives are reached or the funds are exhausted for each of the three asset types.

The analyses are performed for a 10-year period. 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.

5.2 Case example of MOS Application for the City of San Francisco

The case example shows the application of the MOS model on selected sections from the City of San Francisco database. San Francisco is a city that is interested in approaches that incorporate sustainability into transportation asset management decisions and is in the process of implementing the use of crash data in transportation planning. Data retrieved from San Francisco StreetSaver® database, Google Earth, TransBase crash database, Transportation Injury Mapping System (TIMS) database, as well as from on-site visits are taken as a reference to build the case example.

The application of the Multi-Objective Sustainability (MOS) model is demonstrated in an example including 77 block-long sections (74 arterial, 1 collector, and 2 residential streets) and

three different assets: pavements, crosswalks and bikeways. The pavement sections are selected based on the location of crosswalks and bikeways that can be analyzed in the MOS model. Each of the pavement sections has a crosswalk or a bikeway associated with it.

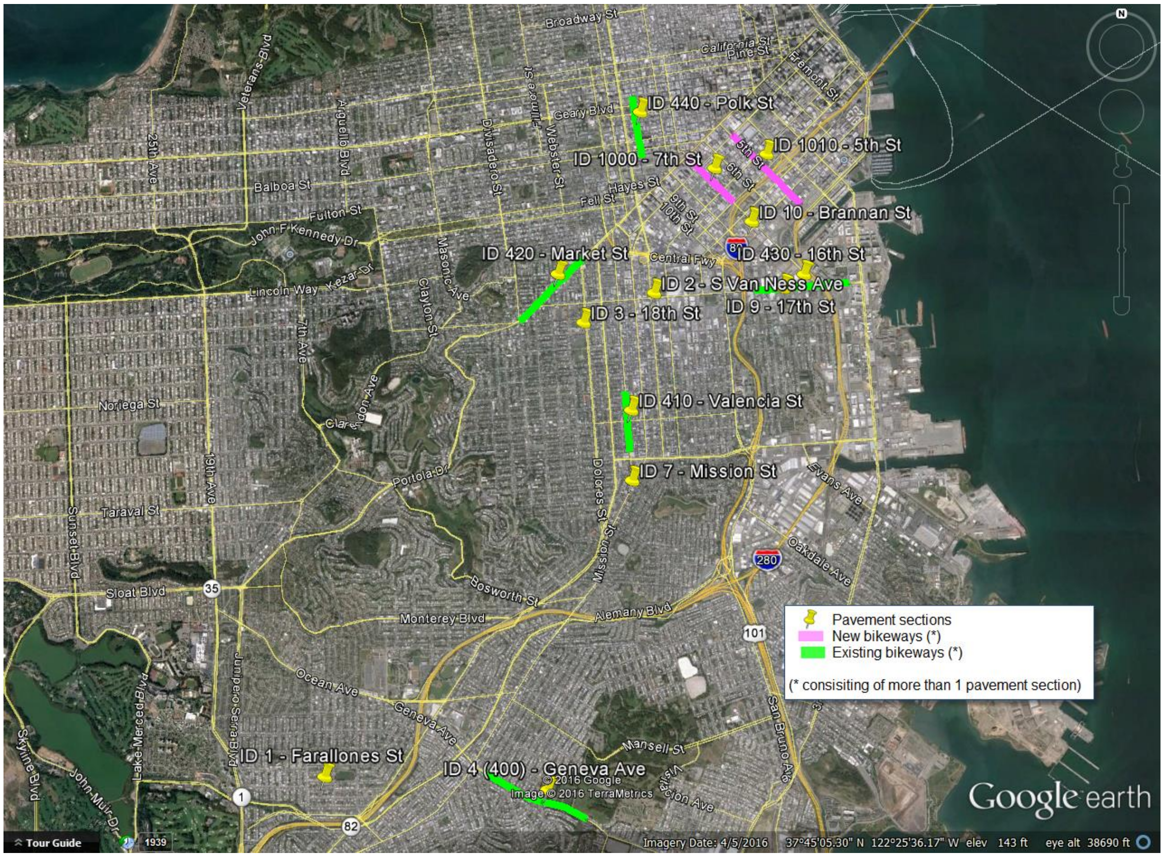


Figure 5.2: Location of Pavement Sections, Crosswalks and Bikeways (New and Existing).

Table 5-1 shows the selected sections with assets including pavements, crosswalks and bikeways.

Table 5.1: Sections and Assets Selected for the Case Study.

MOSM ID	Street	Functional Class (FC)	Pavement	Crosswalk	Bikeway
1	Farallones St	Residential	Existing	Existing	
2	S. Van Ness Ave	Arterial	Existing	Existing	
3	18th St	Collector	Existing	Existing, New	
4	Geneva Ave	Arterial	Existing	Existing, New	Existing
7	Mission St	Arterial	Existing	New	
9	17th St	Residential	Existing	New	
10	Brannan St	Arterial	Existing	Existing, New	
400a	Geneva Ave	Arterial	Existing		Existing
400b			Existing		Existing
400c			Existing		Existing
400d			Existing		Existing
400e			Existing		Existing
400f			Existing		Existing
400g			Existing		Existing
400h			Existing		Existing
400i			Existing		Existing
410a	Valencia St	Arterial	Existing		Existing
410b			Existing		Existing
410c			Existing		Existing
410d			Existing		Existing
410e			Existing		Existing
420a	Market St	Arterial	Existing		Existing
420b			Existing		Existing
420c			Existing		Existing
420d			Existing		Existing
420e			Existing		Existing
420f			Existing		Existing
420g			Existing		Existing
420h			Existing		Existing
430a	16th St	Arterial	Existing		Existing
430b			Existing		Existing
430c			Existing		Existing
430d			Existing		Existing
430e			Existing		Existing
430f			Existing		Existing
430g			Existing		Existing
430h			Existing		Existing
430i			Existing		Existing
430j			Existing		Existing
430k			Existing		Existing
430l			Existing		Existing

Table 5.1: Sections and Assets Selected for the Case Study (continued).

MOSM ID	Street	Functional Class (FC)	Pavement	Crosswalk	Bikeway
440a	Polk St	Arterial	Existing		Existing
440b			Existing		Existing
440c			Existing		Existing
440d			Existing		Existing
440e			Existing		Existing
440f			Existing		Existing
440g			Existing		Existing
440h			Existing		Existing
440i			Existing		Existing
440j			Existing		Existing
440k			Existing		Existing
440l			Existing		Existing
440m			Existing		Existing
1000a	7th St	Arterial	Existing		New
1000b			Existing		New
1000c			Existing		New
1000d			Existing		New
1000e			Existing		New
1000f			Existing		New
1000g			Existing		New
1000h			Existing		New
1010a	5th St	Arterial	Existing		New
1010b			Existing		New
1010c			Existing		New
1010d			Existing		New
1010e			Existing		New
1010f			Existing		New
1010g			Existing		New
1010h			Existing		New
1010i			Existing		New
1010j			Existing		New
1010k			Existing		New
1010l			Existing		New
1010m			Existing		New
1010n			Existing		New
1010o			Existing		New

The case example includes a comparison of various scenarios incorporating sustainability goals, target objectives, and budget constraints as described in Chapter 4. The MOS finds the

minimum budget to reach the target objectives (Target-Driven Scenarios), or prioritize funding allocation for given budgets (Budget-Driven).

The case study focuses on three types of assets: pavements, crosswalks and bikeways, in order to showcase how transportation assets can be handled in a holistic approach that includes also pedestrians and bicyclists to the traditionally motorized-vehicle oriented decision-making. Pavement sections are analyzed in the environmental sustainability model, where the maintenance cost and on-road vehicle CO_2 emissions resulting from pavement condition are analyzed under various scenarios. Existing and planned crosswalks and bikeways are analyzed in the social sustainability model. The analysis period is 10 years to illustrate the process.

5.2.1 Environmental Sustainability

The model for environmental sustainability is applied to maintenance practices of the previously selected 77 pavement sections in order to estimate CO_2 emissions for various maintenance scenarios. General data description for the 77 pavement sections, that were selected as an example to illustrate the MOS model, is shown in Table 5.2. There are 74 arterial, 1 collector, and 2 residential sections. All sections are asphalt concrete overlay of a rigid pavement (AC/PCC), and are one block long with their actual length ranging from 56 ft. to 2,393 ft. The total length of all 77 sections is about 5.3 center miles. The width of the pavement sections ranges from 24 ft. to 77 ft. accommodating between 2 and 5 travel lanes. The Average Daily Traffic (ADT) ranges between 1300 vehicles per day to 53,515 vehicles, depending on the section. The total ADT on these sections is about 1,114,057 vehicles per day. The current pavement network condition is described by the Pavement Condition Index (PCI), where PCI 100 is the best condition and PCI 0 is the worst condition. For this network the initial PCI ranges from 31 to 90, with an average PCI of 69.

Table 5.2 General Data for Pavement Sections.

MOSM ID	Functional Class (FC)	Surface Type	Length [ft.]	Width [ft.]	Average Daily Traffic (ADT) [vehicles/day]	Initial Pavement Condition Index (PCI)
1	Residential	AC-PCC	1028	36	1300	36
2	Arterial	AC-PCC	588	58	8000	52
3	Collector	AC-PCC	660	38	12200	75
4	Arterial	AC-PCC	2393	37	9900	75
7	Arterial	AC-PCC	553	56	12000	34
9	Residential	AC-PCC	281	46	8400	83
10	Arterial	AC-PCC	905	60	4100	56
400a	Arterial	AC-PCC	277	34	9418	71
400b			278	35	9730	71
400c			276	34	9384	68
400d			276	32	8832	64
400e			277	38	10526	71
400f			279	34	9486	71
400g			275	34	9350	52
400h			262	35	9170	62
400i			276	36	9936	71
410a	Arterial	AC-PCC	581	63	36603	77
410b			584	62	36208	77
410c			584	62	36208	77
410d			584	62	36208	79
410e			285	63	17955	69
420a	Arterial	AC-PCC	711	25	17775	45
420b			452	26	11752	31
420c			519	25	12975	35
420d			135	26	3510	67
420e			778	24	18672	49
420f			93	25	2325	61
420g			857	27	23139	53
420h			844	24	20256	47
430a	Arterial	AC-PCC	541	72	38952	74
430b			695	77	53515	75
430c			533	64	34112	72
430d			280	59	16520	76
430e			186	60	5580	75
430f			93	60	2790	67
430g			92	59	5428	71
430h			180	59	10620	65
430i			288	59	16992	72
430j			280	59	16520	72
430k			280	59	16520	58
430l			278	60	16680	37

Table 5.2 General Data for Pavement Sections (continued).

MOSM ID	Functional Class (FC)	Surface Type	Length [ft.]	Width [ft.]	Average Daily Traffic (ADT) [vehicles/day]	Initial Pavement Condition Index (PCI)
440a	Arterial	AC-PCC	190	49	9310	70
440b			171	46	7866	70
440c			173	45	7785	69
440d			171	45	7695	68
440e			344	48	16512	69
440f			172	49	8428	70
440g			170	50	8500	71
440h			174	50	8700	65
440i			169	50	8450	66
440j			174	49	8526	74
440k			170	48	8160	70
440l			172	48	8256	72
440m			173	48	8304	63
1000a	Arterial	AC-PCC	240	48	11520	76
1000b			408	51	20808	73
1000c			219	62	13578	90
1000d			190	62	11780	89
1000e			226	61	13786	88
1000f			633	61	38613	79
1000g			226	61	13786	86
1000h			407	61	24827	87
1010a	Arterial	AC-PCC	224	70	15680	75
1010b			191	68	12988	75
1010c			218	63	13734	76
1010d			217	63	13671	76
1010e			196	62	12152	73
1010f			221	62	13702	75
1010g			224	62	13888	79
1010h			56	62	3472	90
1010i			76	62	4712	90
1010j			58	62	3596	90
1010k			219	62	13578	81
1010l			219	63	13797	78
1010m			413	62	25606	77
1010n			322	62	19964	74
1010o			313	60	18780	77
			Total: 30,149	**Average: 51**	**Average: 15,418**	**Average: 69**

5.2.1.1 Pavements: All Funding and Do-Nothing Scenarios

The All Funding Scenario is assumed to yield the maximum CO_2 emission savings possible since there are no budget restrictions. Pavement treatments are assigned based on the decision tree, as Figure 5.3 shows. The needed pavement treatments over the 10-year analysis

period include mill and fill, as well as mill and fill with base repairs. While this maintenance policy can be applicable for a particular agency, in general it is recommended to apply also preventive maintenance treatments in the condition interval between PCI 100 and PCI 70. Preventive maintenance, when properly applied, can extend pavement service life (FHWA 2004). Table 5.3 shows the optimal timing of treatments for the selected sections.

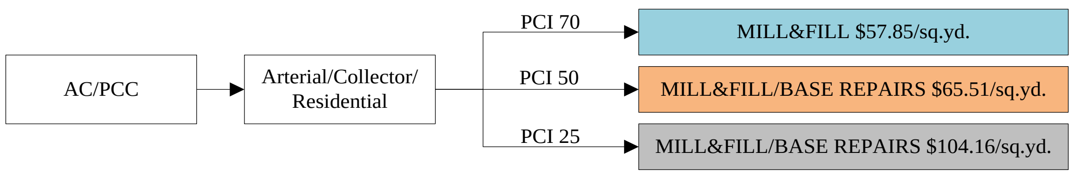


Figure 5.3: Decision Tree for Treatments, AC/PCC Pavement Type.

Table 5.3: Optimal Timing of Maintenance Treatments.

Section	FC	beginning	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	R	PCI 37	PCI 34	PCI 30	PCI 26	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
2	A	PCI 51	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
3	C	PCI 75	PCI 73	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
4	A	PCI 74	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
7	A	PCI 31	PCI 27	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
9	R	PCI 83	PCI 81	PCI 79	PCI 77	PCI 75	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87
10	A	PCI 54	PCI 51	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
400a	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400b	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400c	A	PCI 68	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400d	A	PCI 64	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400e	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400f	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400g	A	PCI 52	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
400h	A	PCI 62	PCI 59	PCI 56	PCI 54	PCI 51	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
400i	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
410a	A	PCI 77	PCI 74	PCI 72	PCI 70	PCI 100 MILL & FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
410b	A	PCI 77	PCI 74	PCI 72	PCI 70	PCI 100 MILL & FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
410c	A	PCI 77	PCI 74	PCI 72	PCI 70	PCI 100 MILL & FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
410d	A	PCI 79	PCI 76	PCI 74	PCI 73	PCI 71	MILL & FILL 100	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
410e	A	PCI 69	PCI 100 MILL & FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
420a	A	PCI 45	PCI 39	PCI 35	PCI 32	PCI 28	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
420b	A	PCI 31	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
420c	A	PCI 35	PCI 28	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
420d	A	PCI 67	PCI 100 MILL & FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
420e	A	PCI 49	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
420f	A	PCI 61	PCI 57	PCI 54	PCI 52	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82

Table 5.3: Optimal Timing of Maintenance Treatments (continued).

Section	FC	beginning	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
430a	A	PCI 74	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
430b	A	PCI 75	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
430c	A	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430d	A	PCI 76	PCI 74	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
430e	A	PCI 75	PCI 73	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
430f	A	PCI 67	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430g	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430h	A	PCI 65	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430i	A	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430j	A	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
430k	A	PCI 58	PCI 54	PCI 51	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
430l	A	PCI 37	PCI 30	PCI 26	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
440a	A	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440b	A	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440c	A	PCI 69	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440d	A	PCI 68	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440e	A	PCI 69	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440f	A	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440g	A	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440h	A	PCI 65	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440i	A	PCI 66	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440j	A	PCI 74	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
440k	A	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440l	A	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79	PCI 77
440m	A	PCI 63	PCI 59	PCI 57	PCI 54	PCI 52	PCI 100 MILL&FILL/BASE RE	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
1000a	A	PCI 76	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
1000b	A	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
1000c	A	PCI 90	PCI 89	PCI 88	PCI 87	PCI 86	PCI 85	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80
1000d	A	PCI 89	PCI 88	PCI 87	PCI 86	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80	PCI 79	PCI 78
1000e	A	PCI 88	PCI 86	PCI 85	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80	PCI 78	PCI 77	PCI 76
1000f	A	PCI 79	PCI 76	PCI 74	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
1000g	A	PCI 86	PCI 84	PCI 83	PCI 81	PCI 80	PCI 79	PCI 77	PCI 76	PCI 74	PCI 73	PCI 71
1000h	A	PCI 87	PCI 85	PCI 84	PCI 83	PCI 81	PCI 80	PCI 79	PCI 78	PCI 76	PCI 75	PCI 73
1010a	A	PCI 75	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
1010b	A	PCI 75	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
1010c	A	PCI 76	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
1010d	A	PCI 76	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
1010e	A	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
1010f	A	PCI 75	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80
1010g	A	PCI 79	PCI 77	PCI 75	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83
1010h	A	PCI 90	PCI 89	PCI 88	PCI 87	PCI 86	PCI 85	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80
1010i	A	PCI 90	PCI 89	PCI 88	PCI 87	PCI 86	PCI 85	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80
1010j	A	PCI 90	PCI 89	PCI 88	PCI 87	PCI 86	PCI 85	PCI 84	PCI 83	PCI 82	PCI 81	PCI 80
1010k	A	PCI 81	PCI 79	PCI 77	PCI 76	PCI 74	PCI 72	PCI 70	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87

Table 5.3: Optimal Timing of Maintenance Treatments (continued).

Section	FC	beginning	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1010l	A	PCI 78	PCI 76	PCI 74	PCI 72	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
1010m	A	PCI 77	PCI 75	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82
1010n	A	PCI 74	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82	PCI 80	PCI 79
1010o	A	PCI 77	PCI 74	PCI 73	PCI 71	PCI 100 MILL&FILL	PCI 91	PCI 89	PCI 87	PCI 85	PCI 83	PCI 82

In the All Funding Scenario, all sections receive the treatment that they need at the right time, which maintains them in the best condition possible and yields the highest CO_2 emission savings. On the other hand, the Do Nothing Scenario estimates the CO_2 emissions when no pavement treatments are applied to the sections. Table 5.4 shows the CO_2 emissions generated under each scenario and the potential CO_2 emissions savings over the 10-year analysis period. In years 2021, 2023, 2024 and 2025 there are no treatments due for the All Funding scenario, because all sections have PCI above 70, and according to the decision tree in Figure 5.3, no treatments are scheduled for a PCI between 100 and 71.

Table 5.4: CO_2 Emissions for the All Funding and Do Nothing Scenarios (2016-2025 Total).

Year	All Funding Scenario 1-P		Do Nothing Scenario 2-P		Comparison	
	Budget	Network Average PCI	Budget	Network Average PCI	Maximum Potential CO_2 Savings from On-Road Vehicles [tons/year]	CO_2 Savings "All Funding" vs. "Do Nothing" Scenario [% of total CO_2 Savings from On-Road Vehicles]
2016	$2,671,102	77	$ 0	66	147	1.5%
2017	$1,372,849	79	$ 0	64	243	2.5%
2018	$1,925,273	84	$ 0	61	270	2.8%
2019	$1,823,232	88	$ 0	59	333	3.5%
2020	$903,110	88	$ 0	57	365	3.8%
2021	$ 0	86	$ 0	54	325	3.4%
2022	$170,363	84	$ 0	51	320	3.3%
2023	$ 0	83	$ 0	49	346	3.6%
2024	$ 0	81	$ 0	46	343	3.5%
2025	$ 0	79	$ 0	43	377	3.9%
	Total: $8,865,929	Average: PCI 83	Total: $0	Average: PCI 55	Total: 3,068 tons	

Note: On-road vehicle emissions were estimated based on the traffic volume (AADT, annual average daily traffic) which did not distinguish between vehicle categories, since the data was used for network-level decisions.

In the case of All Funding Scenario 1-P, the total budget of $8.9 million is spent over 10 years, which results in average network PCI of 83 and 93,400 tons of CO_2 emissions produced over the analysis period. The Do Nothing Scenario 2-P assumes that no treatments are applied during the analysis period and the network deteriorates, which cause higher pavement roughness, which leads to higher CO_2 emissions from on-road vehicles. For this case, the network PCI in the last year of analysis is as low as 43 and the resulting CO_2 emissions produced are 96,468 tons. In comparison, by applying maintenance treatments when they are due (All Funding Scenario), up to 3,068 tons of CO_2 (3% of the total) can be saved over the 10-year analysis period. The performance of other scenarios will be measured towards the maximum possible savings of 3,068 tons is assumed as 100% savings. Figure 5.4 shows the budget and PCI over the analysis period for both scenarios.

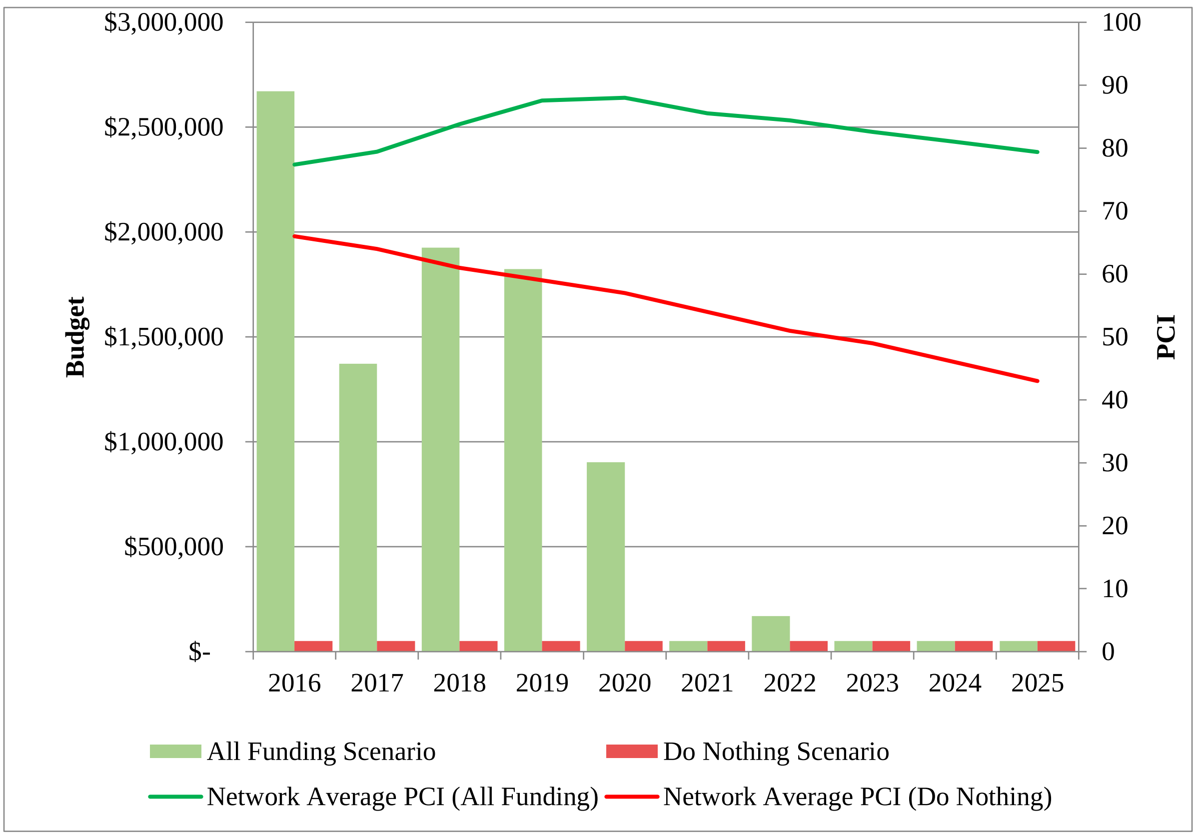


Figure 5.4: Impact of Budget on PCI in All Funding Scenario and Do Nothing Scenario.

5.2.1.2 Pavements: 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 3-1-P: available budget is 84% of the total 10-year budget Needs
- Scenario 3-2-P: available budget is 69% of the total 10-year budget Needs
- Scenario 3-3-P: available budget is 49% of the total 10-year budget Needs
- Scenario 3-4-P: available budget is 34% of the total 10-year budget Needs

The available funding was selected based on a percentage of the desired scenario with unlimited funding. The percentage of 84%, 69%, 49%, and 34% were randomly selected to represent different funding levels. Pavement sections with the highest potential for CO_2 emission savings are selected using the Dynamic Bubble Up ranking method. Table 5.5 shows the summary of CO_2 emission savings for each scenario.

Table 5.5: Budget-Driven CO_2 Emission Saving Scenarios Inputs and Outputs.

INPUT		OUTPUT				
Scena -rio	**Available Budget or Agency Cost (% of All Funding)**	**Emission Savings (% of maximum possible throughout the analysis period)**	**Average % of Pavements in Poor or Very Poor Condition (throughout the analysis period)**	**Average Network Remaining Life (throughout the analysis period)**	**Critical Remaining Life (Year)**	**Backlog at the end of 2025**
3-1-P	$ 7,457,173 (84%)	76%	9%	24.02	20.06 (2016)	$1,408,756
3-2-P	$ 6,098,411 (69%)	47%	19%	23.26	20.06 (2016)	$2,780,152
3-3-P	$ 4,330,157 (49%)	32%	23%	22.47	20.06 (2016)	$3,408,584
3-4-P	$ 3,046,625 (34%)	22%	25%	21.92	19.23 (2024)	$4,056,030

Figure 5.5 shows CO_2 emission savings and percentage of pavement sections in good/fair/poor and very poor condition for each of the budget scenarios.

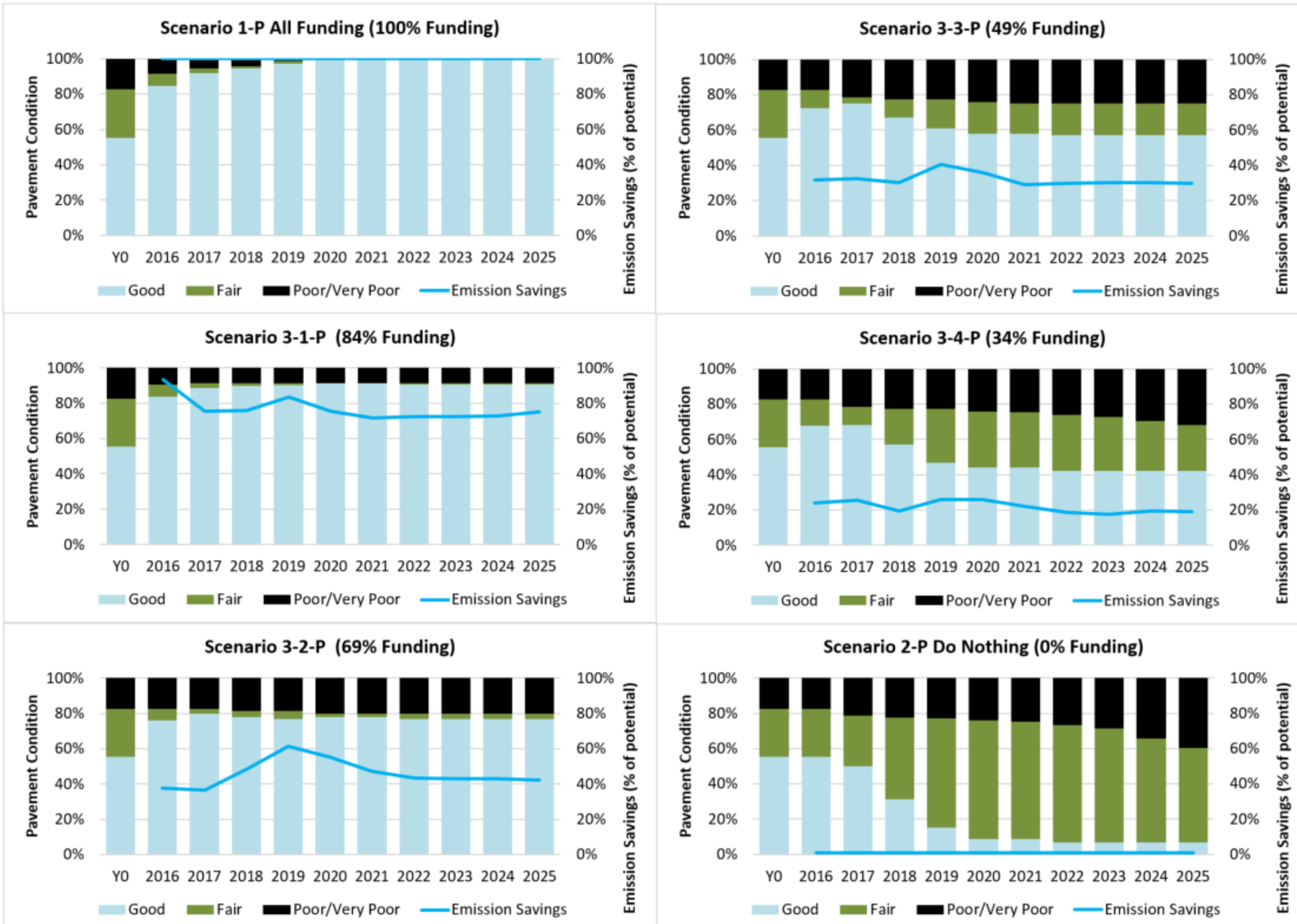


Figure 5.5: Pavement Network Condition and CO2 Emission Savings for Different Budget-Driven Scenarios.

Under Scenario 1 (All Funding) the condition of the pavement network improves to 100% in good condition by year 2020 and also the emission savings are 100%.

Scenario 2 (Do Nothing) causes the pavement condition to deteriorate, so by year 2025, 40% of pavements are in poor condition and there are no emission savings due to maintenance.

Scenario 3-1 (84% Funding) partially improves the network condition to 90% in good condition, however 9% stay in poor/very poor condition as there is not sufficient funding to apply all needed maintenance treatments. The average emission savings during the analysis period from Scenario 3-1 are on average 76% compared to the ideal emission savings in the All Funding Scenario 1.

Scenario 3-2 (69% Funding) partially improves the network condition to 77% in good condition; however, 20% stay in poor/very poor condition as there is not sufficient funding to apply all needed maintenance treatments. The average emission savings during the analysis period from Scenario 3-2 are on average 47% compared to the ideal emission savings in the All Funding Scenario 1. The spike in emission savings in year 2019, which is most visible in this scenario, is caused by the many delayed sections that are finally improved in 2019. This spike can be also observed in Scenarios 3-1 ,3-3, and 3-4.

Scenario 3-3 (49% Funding) maintains the percentage of pavements in good condition around its initial level; however, the number in poor/very poor condition increases to 25% as there is not sufficient funding to apply all needed maintenance treatments. The average emission savings during the analysis period from Scenario 3-3 are on average 32% compared to the ideal emission savings in the All Funding Scenario 1.

Scenario 3-4 (34% Funding) causes the percentage of pavements in good condition to decrease to 42% from initial 55%, and the number in poor/very poor condition increases to 32% as there is not sufficient funding to apply all needed maintenance treatments. The average emission savings during the analysis period from Scenario 3-4 are on average 22% compared to the ideal emission savings in the All Funding Scenario 1.

A non-linear relationship between agency costs and emission savings is observed for Budget-Driven Scenarios. Figure 5.6 indicates an exponential relationship and it this particular case, the steepest increase in emission savings is for funding levels between 69 and 84 percent.

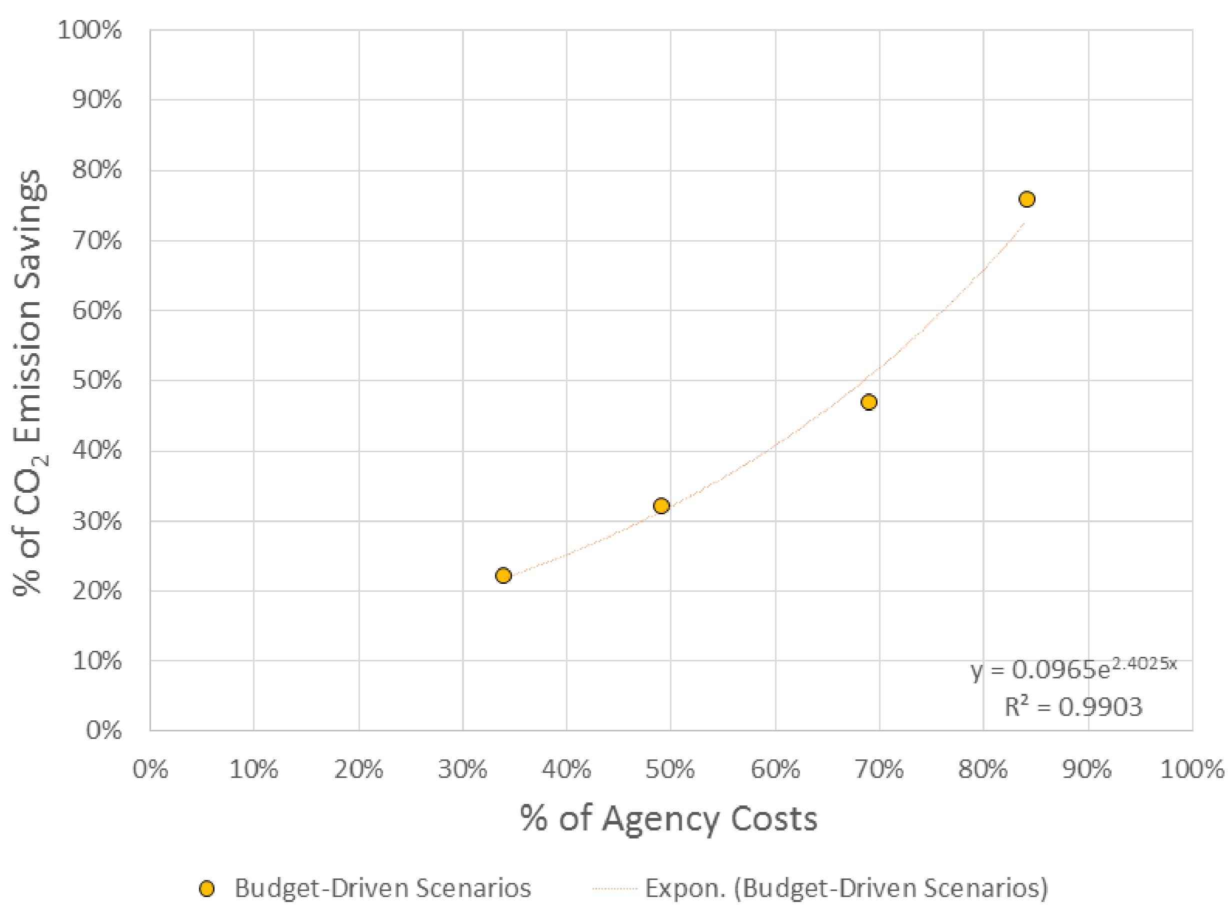


Figure 5.6: Exponential Relationship Between Agency Costs and Emission Savings.

A non-linear relationship is also observed between agency costs and pavement condition for Budget-Driven Scenarios. Figure 5.7 indicates an exponential relationship and it this particular case, the steepest improvement in pavement condition is for funding levels between 69 and 84 percent.

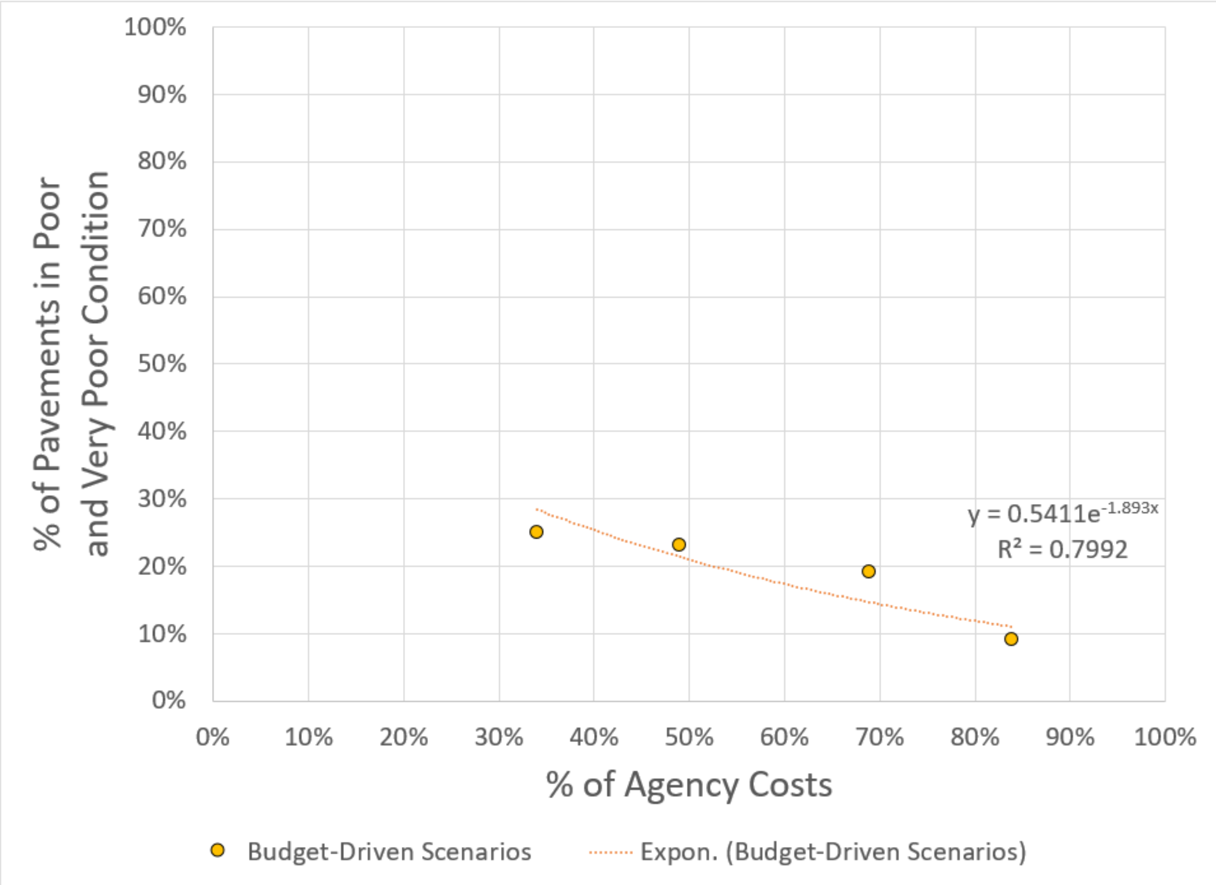


Figure 5.7: Exponential Relationship Between Agency Costs and Pavement Condition.

5.2.1.3 Pavements: Target-Driven Scenarios

Target-Driven Scenarios aim to reach a target objective, expressed in terms of CO_2 emission savings and maximum percentage of pavements in poor and very poor condition, with the minimum budget. Three Target-Driven scenarios are run using the MOS model:

- Scenario 4-1-P: at least 90% of possible maximum emissions are saved compared to Do Nothing Scenario, and the percentage of pavements in poor or very poor condition (PCI below 50) is no more than 10%
- Scenario 4-2-P: at least 80% of possible maximum emissions are saved compared to Do Nothing Scenario, and the percentage of pavements in poor or very poor condition (PCI below 50) is no more than 10%

- Scenario 4-3-P: at least 40% of possible maximum emissions are saved compared to Do Nothing Scenario, and the percentage of pavements in poor or very poor condition (PCI below 50) is no more than 15%

Table 5.6 shows the summary of funding allocated and emission savings.

Table 5.6: Target-Driven Scenarios Inputs and Outputs.

TARGET OBJECTIVES			**OUTPUT**			
Scena-rio	**Emission Savings (% of maximum possible)**	**Average % of Pavements in Poor or Very Poor Condition**	**Allocated Budget or Agency Costs (% of All Funding)**	**Resulting Emission Savings (% of maximum possible)**	**Resulting Average % of Pavements in Poor or Very Poor Condition (throughout the analysis period)**	**Backlog at the end of 2025**
4-1-P	90%	10%	$ 8,021,292 (90%)	93%	6%	$844,637
4-2-P	80%	10%	$ 6,815,587 (77%)	84%	8%	$1,050,353
4-3-P	40%	15%	$ 5,993,824 (68%)	47%	15%	$2,252,443

Figure 5.8 shows CO_2 emission savings for each of the Target-Driven scenarios. Scenarios 1 (All Funding) and 2 (Do Nothing) are shown for reference when comparing what is the best and worst possible condition.

Scenario 4-1, with a target objective of no more than 10% of pavements in poor/very poor condition and a target objective of at least 90% of possible emission savings, maintains the percentage of pavements in poor condition at 6% and emission savings at 93% on average during the analysis period. The total allocated budget in this scenario is $8.0 million, which is 90% of the ideal cost in Scenario 1 (All Funding).

Scenario 4-2, with a target objective of not more than 10% of pavements in poor/very poor condition and a target objective of at least 80% of possible emission savings, maintains the percentage of pavements in poor condition at no more than 9% during the analysis period, and emission savings are 84% compared to the ideal emission savings in the All Funding Scenario 1.

The total allocated budget in this scenario is \$6.8 million, which is 77% of the ideal cost in Scenario 1 (All Funding).

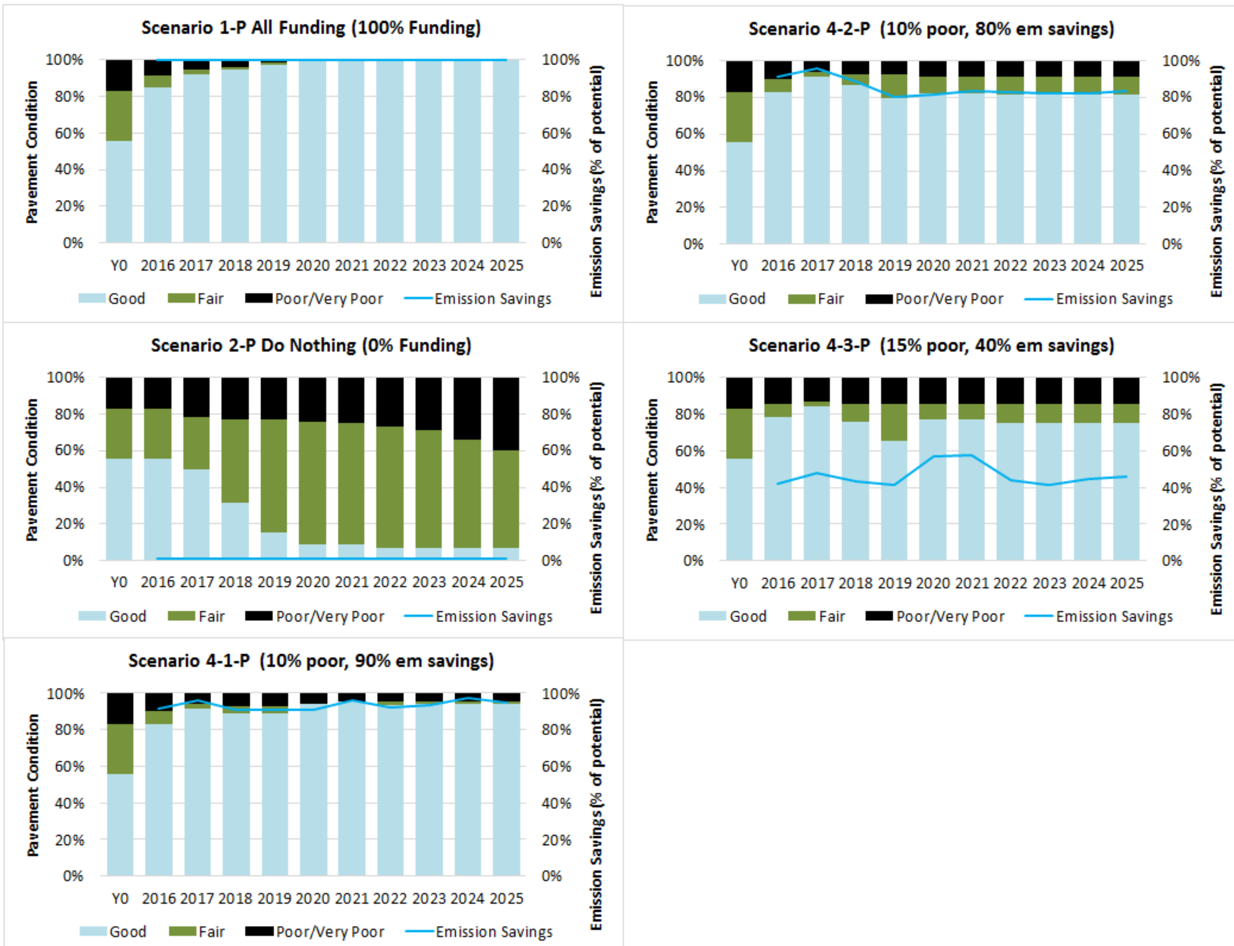


Figure 5.8: Minimum Budget for Target-Driven CO2 Emission Savings Scenarios.

Scenario 4-3, with a target objective of not more than 15% of pavements in poor/very poor condition and a target objective of at least 40% of possible emission savings, maintains the percentage of pavements in poor condition at 15% and emission savings at 47% on average during the analysis period. The total allocated budget in this scenario is \$6.0 million, which is 68% of the ideal cost in Scenario 1 (All Funding).

Similar plots as for the Budget Driven in Figure 5.7 could be developed also for Target-Driven scenarios. However, in this situation, the challenge is showing three variables together: emission savings, pavement condition, and agency cost.

5.2.1.4 Pavements: Interpretation of the Results

Since the 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 CO_2 emissions are. Figure 5.9 shows the funding levels in accumulated budget allocated throughout the 10-year analysis period, as well as the performance in emission savings and pavement network condition.

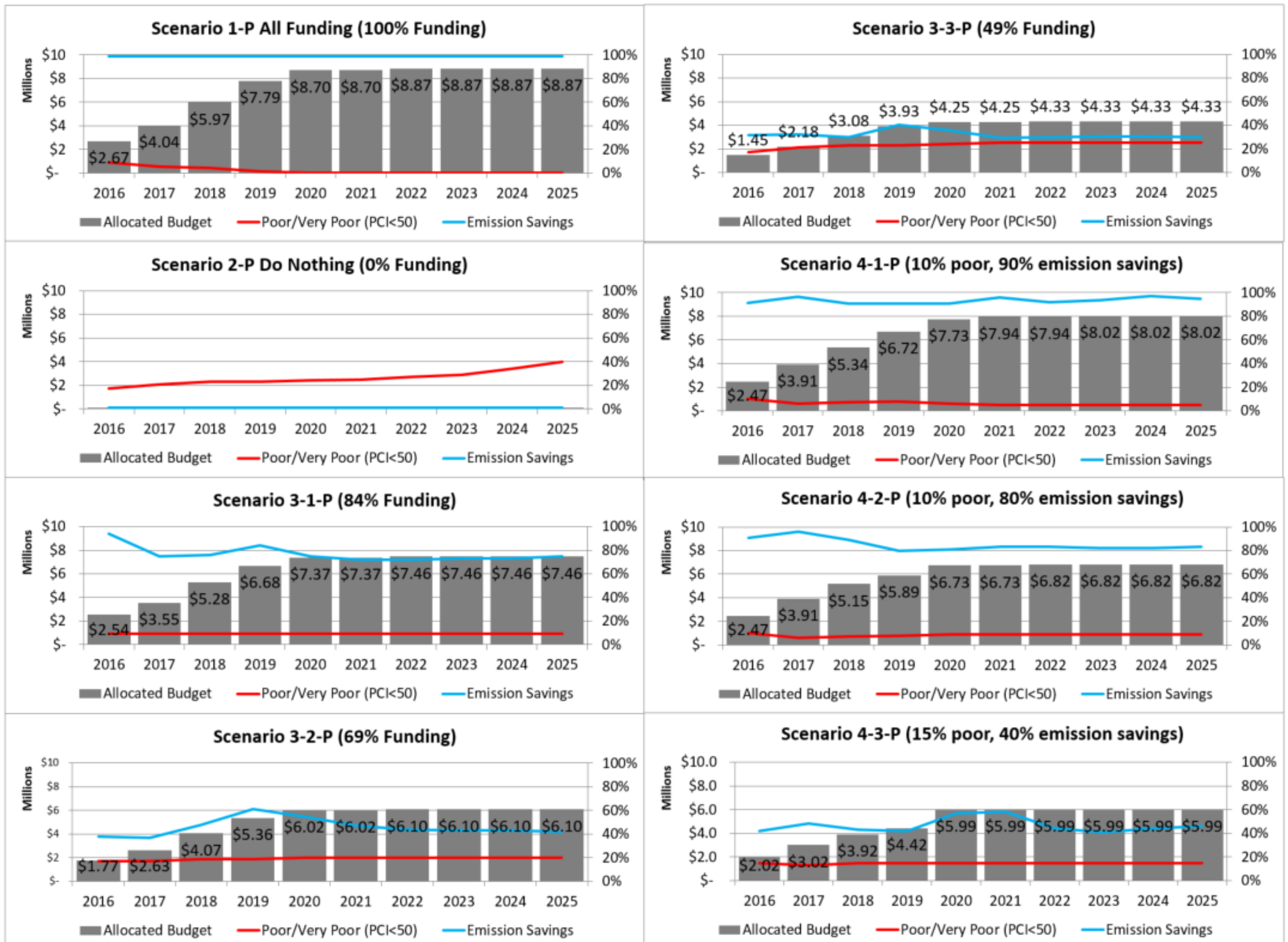


Figure 5.9: Performance in Emission Savings and Condition versus Allocated Budget for Pavement Scenarios.

Table 5.7 shows the overview of agency expenditures, average pavement condition (PCI), total on-road emissions, and social cost of CO_2 for each of the six scenarios.

Scenario 1-P shows the desired scenario where all needed treatments are applied in a timely manner. It costs $8.8 million to maintain the average network PCI at 83 throughout the analysis period. Good condition of the pavement leads to the lowest on-road CO_2 emissions of 93,400 tons which can be translated into the social cost of CO_2 equal to $4.02 million.

Scenario 2-P maintains the average network PCI at 55 and results in the maximum on-road CO_2 emissions, 96,486 tons. They are 3.2% higher than the minimum emissions achieved in Scenario 1-P. The difference in social cost between these two scenarios is also 3.2%. Since the social cost of CO_2 is calculated as on-road emissions multiplied by the cost, it is observed that these two measures are correlated. Converting CO_2 emissions to the social cost of CO_2 allows a direct comparison with agency pavement maintenance costs. Anytime when agency costs are lower than the resulting social cost of CO_2, it is an indicator of underfunding, where pavements are not maintained in good condition. While the social cost of CO_2 can be hardly avoided, it is recommended that an agency chooses such maintenance scenario where agency expenditures are higher than the social cost of CO_2.

Budget-driven scenarios 3-1-P, 3-2-P and 3-3P show that with decreasing budget also the average network condition worsens while on-road vehicle emissions and social cost of CO_2 increase. Scenario 3-3-P is very close to the limit where the social cost could become higher than agency expenditures.

Target-driven scenarios 4-1-P, 4-2-P, and 4-3-P use targets of maximum share of pavement area in poor condition and the minimum on-road emission savings.

Table 5.7: Summary of Results of Pavement Scenarios.

Scenario	Agency Expenditures	Avg. PCI (throughout the analysis period)	On-road CO_2 Emissions [tons]	Social Cost of CO_2 (total over analysis period)
Scenario 1-P All Funding (100% Funding)	$ 8,865,929	83	93,400	$ 4,016,184
Scenario 2-P Do Nothing (0% Funding)	$ -	55	96,468	$ 4,148,112
Scenario 3-1-P (84% Funding)	$ 7,457,173	78	94,139	$ 4,047,992
Scenario 3-2-P (69% Funding)	$ 6,098,411	71	95,039	$ 4,086,696
Scenario 3-3-P (49% Funding)	$ 4,330,157	66	95,486	$ 4,105,897
Scenario 4-1-P (10% poor, 50% em. savings)	$ 7,138,941	76	94,347	$ 4,056,921
Scenario 4-2-P (10% poor, 80% em. savings)	$ 6,815,587	77	93,881	$ 4,036,881
Scenario 4-3-P (15% poor, 40% em. savings)	$ 5,993,824	72	95,032	$ 4,086,365

There is an apparent relationship between the pavement network condition and environmental consequences, in this case the on-road CO_2 emissions. It is recommended that local agencies be aware of this fact and incorporate it in their decision-making, especially agencies that tend to under-fund their infrastructure. The on-road CO_2 emissions ranged around 90 thousand tons with a potential of saving up to 3.2% (3,068 tons) in a 10-year analysis period for a pavement network that has 5.3 center-miles and carries a total of 1.1 million vehicle volume per day, representing 0.6% of the total street network that City of San Francisco manages and 2.2% of the daily traffic in the City of San Francisco, respectively. In comparison, according to the World Bank (2011), the U.S. produces annually 17 tons of CO_2 emissions per capita. In that case, the maximum emission saving produced by the Scenario 1-P are equivalent to annual CO_2 emissions of 18 people.

5.2.2 Social Sustainability: Bikeway Quality

The bikeway quality module is a part of the social sustainability framework. The MOS model allocates available funds for improvements in bikeways with the goal of improving their condition, as well as optimally timing the implementation of new bikeways. This case study

includes maintenance of existing bikeways on five different streets (sections 400 through 440) as well as implementation of new bikeway striping on two streets (sections 1000 and 1010). The timing of treatments is coordinated with maintenance on pavement sections to maximize the effectiveness of durability and cost. General data description for the seven bikeways is shown in Table 5.8.

Table 5.8: General Data for Bikeways.

MOSM ID	Length [ft.]	IMP_{AS} for new	IMP_{AS} for maintenance	IMP_{LOC}	WER_{SAF} for new	WER_{SAF} for maintenance
400a	277	-	0.8	0.55	-	0.0204
400b	278	-	0.8	0.55	-	0.0206
400c	276	-	0.8	0.55	-	0.0206
400d	276	-	0.8	0.55	-	0.0619
400e	277	-	0.8	0.55	-	0.0203
400f	279	-	0.8	0.55	-	0.0198
400g	275	-	0.8	0.55	-	0.0107
400h	262	-	0.8	0.55	-	0.0126
400i	276	-	0.8	0.55	-	0.0237
4	2393	-	0.8	0.55	-	0.0140
410a	581	-	0.8	1	-	0.0473
410b	584	-	0.8	1	-	0.0545
410c	584	-	0.8	1	-	0.0458
410d	584	-	0.8	1	-	0.0164
410e	285	-	0.8	1	-	0.0458
420a	711	-	0.8	1	-	0.0254
420b	452	-	0.8	1	-	0.0462
420c	519	-	0.8	1	-	0.0542
420d	135	-	0.8	1	-	0.0475
420e	778	-	0.8	1	-	0.0477
420f	93	-	0.8	1	-	0.0528
420g	857	-	0.8	1	-	0.0468
420h	844	-	0.8	1	-	0.0462
430a	541	-	0.8	1	-	0.1849
430b	695	-	0.8	1	-	0.1362
430c	533	-	0.8	1	-	0.1785
430d	280	-	0.8	1	-	0.0473
430e	186	-	0.8	1	-	0.0473
430f	93	-	0.8	1	-	0.0251
430g	92	-	0.8	1	-	0.0322
430h	180	-	0.8	1	-	0.0331
430i	288	-	0.8	1	-	0.0395
430j	280	-	0.8	1	-	0.0043
430k	280	-	0.8	1	-	0.0178
430l	278	-	0.8	1	-	0.0177

Table 5.8: General Data for Bikeways (continued).

MOSM ID	Length [ft.]	IMP_{AS} for new	IMP_{AS} for maintenance	IMP_{LOC}	WER_{SAF} for new	WER_{SAF} for maintenance
440a	190	-	0.8	1	-	0.0177
440b	171	-	0.8	1	-	0.0177
440c	173	-	0.8	1	-	0.0146
440d	171	-	0.8	1	-	0.0199
440e	344	-	0.8	1	-	0.1113
440f	172	-	0.8	1	-	0.0191
440g	170	-	0.8	1	-	0.0149
440h	174	-	0.8	1	-	0.0370
440i	169	-	0.8	1	-	0.0557
440j	174	-	0.8	1	-	0.0370
440k	170	-	0.8	1	-	0.0372
440l	172	-	0.8	1	-	0.0595
440m	173	-	0.8	1	-	0.0598
1000a	240	0.9	0.8	1	0.0070	0.0123
1000b	408	0.9	0.8	1	0.0076	0.0133
1000c	219	0.9	0.8	1	0.0216	0.0376
1000d	190	0.9	0.8	1	0.0069	0.0121
1000e	226	0.9	0.8	1	0.0215	0.0375
1000f	633	0.9	0.8	1	0.0341	0.0595
1000g	226	0.9	0.8	1	0.0351	0.0613
1000h	407	0.9	0.8	1	0.0330	0.0575
1010a	224	0.9	0.8	1	0.0440	0.0767
1010b	191	0.9	0.8	1	0.0347	0.0605
1010c	218	0.9	0.8	1	0.0639	0.1113
1010d	217	0.9	0.8	1	0.0215	0.0375
1010e	196	0.9	0.8	1	0.0173	0.0301
1010f	221	0.9	0.8	1	0.0343	0.0598
1010g	224	0.9	0.8	1	0.0208	0.0363
1010h	56	0.9	0.8	1	0.0349	0.0609
1010i	76	0.9	0.8	1	0.0345	0.0602
1010j	58	0.9	0.8	1	0.0349	0.0609
1010k	219	0.9	0.8	1	0.0347	0.0605
1010l	219	0.9	0.8	1	0.0313	0.0545
1010m	413	0.9	0.8	1	0.0214	0.0374
1010n	322	0.9	0.8	1	0.0214	0.0372
1010o	313	0.9	0.8	1	0.0345	0.0602

The section length was obtained from the StreetSaver® database. The existing bikeways were identified via Google Earth and matched with existing StreetSaver pavement sections. The new bikeways to be implemented were identified via City of San Francisco Capital Improvement Plan for fiscal year 2015-2019. Safety weighted effectiveness ratios (WER_{SAF}) were determined based on asset importance and asset location as discussed in Chapter 4 in Tables 4.8 and 4.9. Figure 5.10 shows that a bikeway (in this case a bike lane) consists of a pavement section painted with white stripes and bicycle symbols and arrows.

Figure 5.10: Example of a Bikeway in San Francisco, CA.

5.2.2.1 Bikeways: All Funding and Do-Nothing Scenarios

The All Funding Scenario assumes unlimited funding for the maintenance of existing bikeways as well as the implementation of new bikeways. The assumed service life of bikeway markings is between 48 and 72 months (FHWA 2016d). Therefore, the maintenance treatment of repainting is scheduled every four years. Since the paint of bikeway markings has the best adhesion to a new pavement surface which results in better performance, it is desirable that the

maintenance of these two assets is synchronized. For that reason, the bikeway implementation and maintenance can be delayed up to two years from the original due date in those cases that would lead to the application of the pavement maintenance and bikeway maintenance in the same year, as Figure 5.11 suggests.

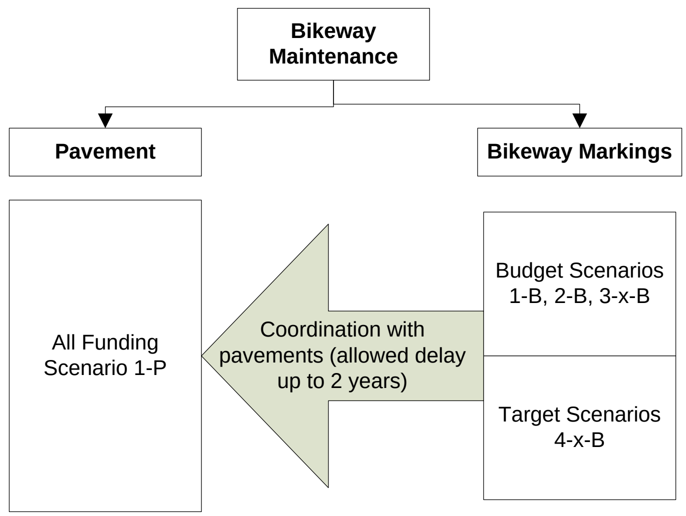


Figure 5.11: Example of Coordination Between Pavement and Bikeway Maintenance.

The total cost of a new bikeway is assumed to be \$100,000/mi (FHWA 2016d). The average maintenance present cost to repaint bikeway marking is assumed to be \$51,000/mi (FHWA 2016d). The cost details are discussed in Chapter 4 Section 4.4.1.

For the All Funding Scenario 1-B, the total cost including the implementation of the two new bikeways (1.1 mi in each direction) and the maintenance of the existing five bikeways (3.4 mi in each direction) over ten years of analysis is worth \$1,023,358.

The Do Nothing Scenario 2-B simulates a situation where no funding is allocated to bikeways. Under such scenario, no new bikeways are implemented, nor the existing bikeway markings are maintained.

Table 5.9 shows the initial construction cost of new bikeways, the maintenance cost of existing bikeway markings, the remaining life and the percentage of the new bikeways funded.

Table 5.9: All Funding and Do Nothing Scenario Summary (2016-2025 Total).

Year	All Funding Scenario				Do Nothing Scenario			
	Cost of New Bikeways	Cost of Maintenance	Average Remaining Life throughout the analysis period	% New Bikeway Striping Funded	Cost of New Crosswalks	Cost of Maintenance	Average Remaining Life throughout the analysis period	% New Bikeway Striping Funded
2016	$131,780	$47,832	2.39	61%	$0	$0	1.17	0%
2017	$44,167	$75,128	3.06	78%	$0	$0	0.38	0%
2018	$40,568	$150,141	3.24	100%	$0	$0	0.10	0%
2019		$50,092	2.92	100%	$0	$0	0.00	0%
2020		$25,017	2.15	100%	$0	$0	0.00	0%
2021		$110,809	2.42	100%	$0	$0	0.00	0%
2022		$101,884	3.10	100%	$0	$0	0.00	0%
2023		$170,831	3.34	100%	$0	$0	0.00	0%
2024		$50,092	2.96	100%	$0	$0	0.00	0%
2025		$25,017	2.16	100%	$0	$0	0.00	0%
	Total New: $216,515	Total Maintenance $808,843	RL Average: 2.77 years		Total New: $0	Total Maintenance $0	RL Average: 0.16 years	
	Total Spent: $1,023,358				Total Spent: $0			

In the case of All Funding Scenario 1-B, the total budget of $1,023,358 is spent over 10 years, which results in funding all needed the new bikeways while also improving the average remaining life (RL) from 1.17 years at the beginning of the analysis up to RL 3.34 years in year 2023, RL 2.96 years in year 2014 and RL 2.16 years in 2025. The Do Nothing Scenario 2-B assumes that no treatments are applied during the analysis period and the network deteriorates, which causes all the existing bikeways to reach the end of their life by the year 2019.

5.2.2.2 Bikeways: Budget-Driven Scenarios

Transportation agencies often do not have sufficient funding to cover all costs. In that case, is useful to predict asset condition under a limited budget. Four Budget-Driven scenarios are run using the MOS model:

- Scenario 3-1-B: available budget is $858,397 (85% of the total 10-year budget Needs)
- Scenario 3-2-B: available budget is $704,358 (70% of the total 10-year budget Needs

- Scenario 3-3-B: available budget is \$508,738 (50% of the total 10-year budget Needs)
- Scenario 3-4-B: available budget is \$355,959 (35% of the total 10-year budget Needs)

The implementation and maintenance projects compete for limited funding based on their ranking by bikeway weighted effectiveness ratio WER_{BIK} as described in Chapter 4, Section 4.4.1.

Table 5.10 shows the summary of effects of limited funding on bikeway condition.

Table 5.10: Budget-Driven Scenarios for Bikeways.

INPUT		OUTPUT				
Scena-rio	**Available Budget or Agency Cost (% of All Funding)**	**Percentage of New Bikeways Completed**	**Average Remaining Life**	**Critical Remaining Life (Year)**	**Critical Annual Backlog (in Year)**	**Backlog at the end of 2025**
3-1-B	\$ 858,397 (85%)	96%	2.69	1.99 (2020)	\$106,505 (2020)	\$70,206
3-2-B	\$ 704,358 (70%)	91%	2.55	1.91 (2020)	see year 2025	\$183,406
3-3-B	\$ 508,738 (50%)	74%	2.33	1.77 (2020)	\$287,669 (2022)	\$281,642
3-4-B	\$ 355,959 (35%)	70%	1.82	1.42 (2020)	\$380,238 (2022)	\$357,323

Figure 5.12 shows the consequences of limited funding on bikeway marking condition.

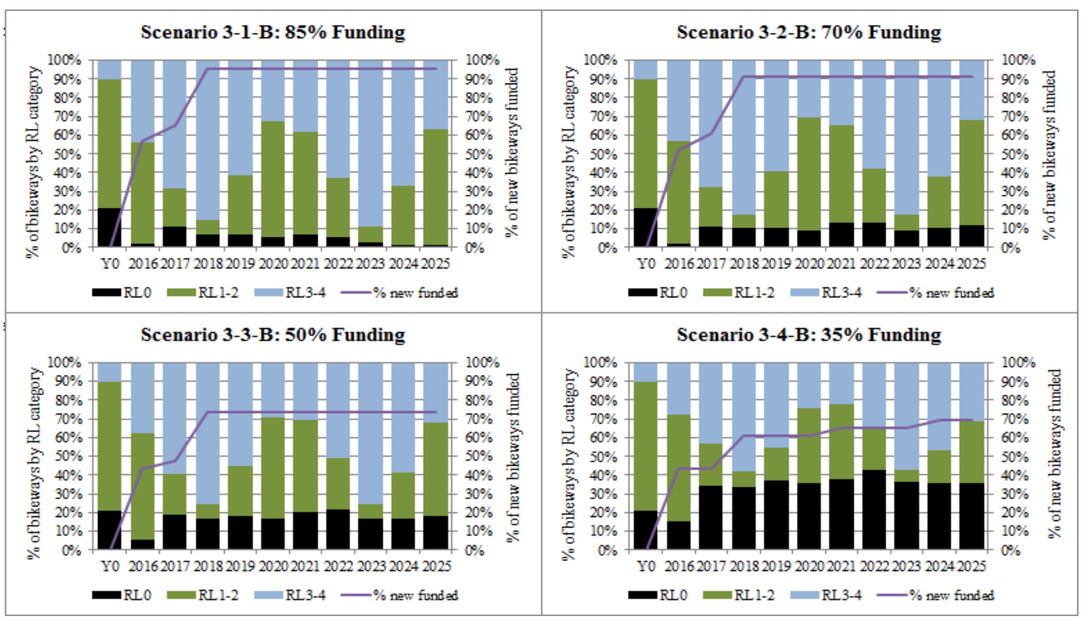


Figure 5.12: Remaining Life and New Bikeways Funded – Budget Scenarios.

With 85% of funding (Scenario 3-1-B) up to 11% of markings have no remaining life and need maintenance during the analysis period and only 96% of new bikeways get implemented. In Scenario 3-2-B (70% funding) up to 13% of markings have no remaining life and need maintenance during the analysis period and only 91% of new bikeways get implemented. With even more limited budgets of 50% and 35%, up to 22% and 43% of markings (respectively) have no remaining life and need maintenance during the analysis period and only about 70% of new bikeways get implemented.

Limited budget scenarios result in the delaying maintenance treatments that are due and also not all planned new bikeways get implemented. Limited funding of 85% and 70% resulted in not more than 11% and 13% of markings with no remaining life while 96% and 91% of new bikeways were implemented.

A non-linear relationship between agency costs and new bikeways implemented is observed for Budget-Driven Scenarios. Figure 5.13 indicates an exponential relationship and it this particular case, the steepest increase in fraction of new bikeways funded is for funding levels between 50 and 70 percent.

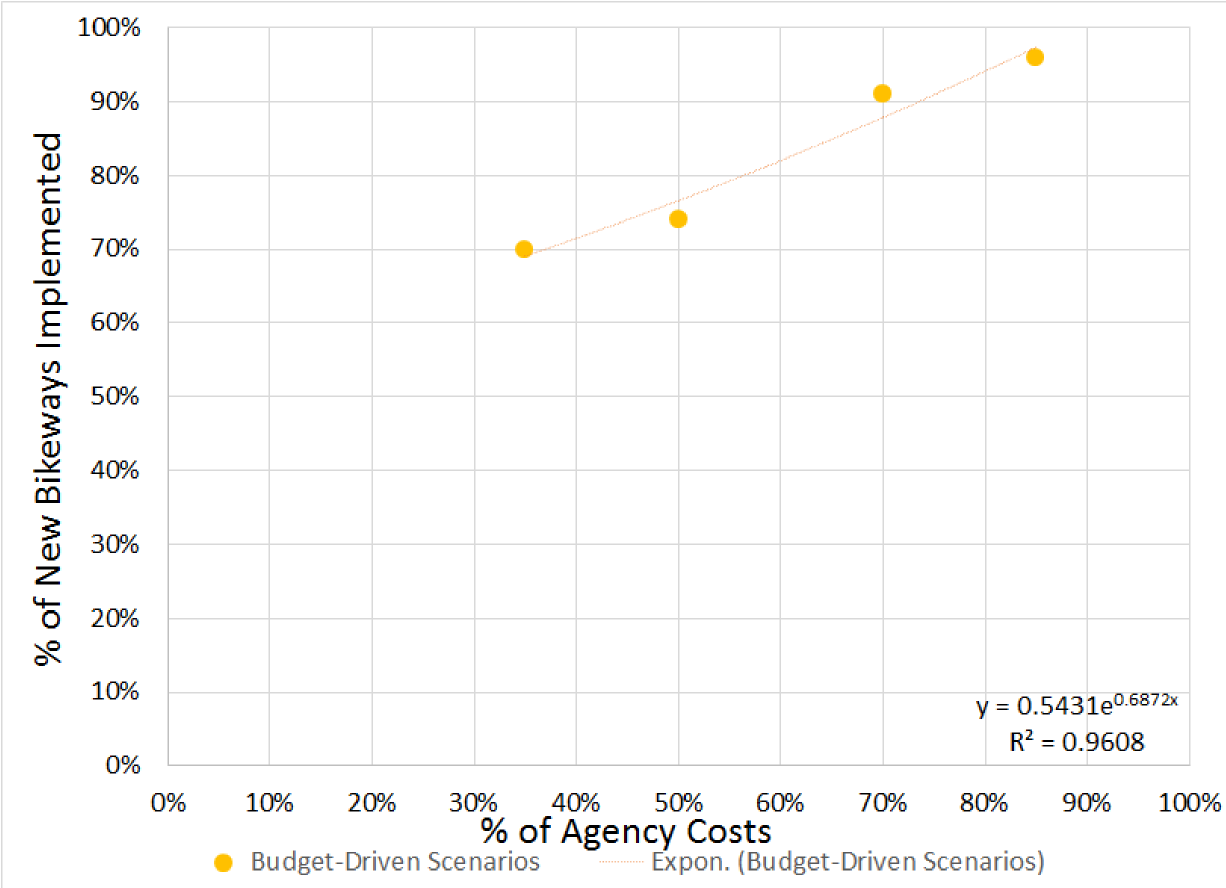


Figure 5.13: Exponential Relationship Between Agency Costs and New Bikeways Implemented.

A non-linear relationship is also observed between agency costs and bikeway network average remaining life for Budget-Driven Scenarios. Figure 5.14 indicates an exponential relationship and it this particular case, the steepest improvement in remaining life is for funding levels between 35 and 50 percent.

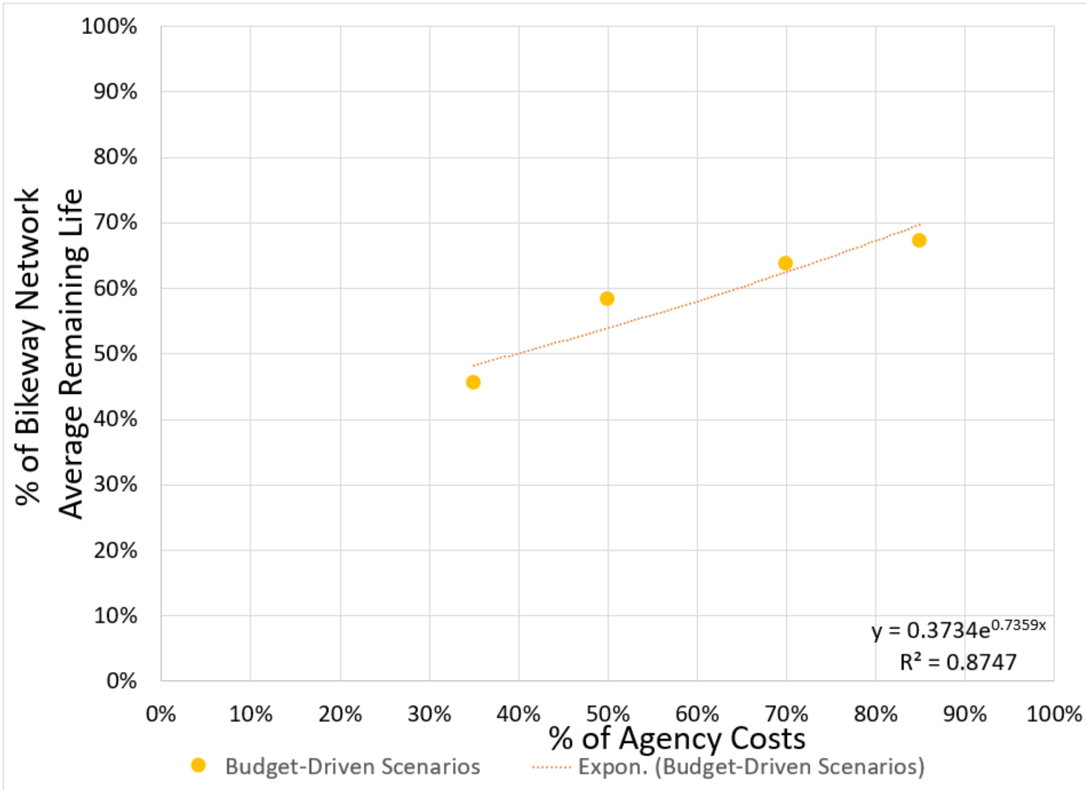


Figure 5.14: Exponential Relationship Between Agency Costs and Bikeway Network Average Remaining Life.

5.2.2.3 Bikeways: Target-Driven Scenarios

Target-Driven Scenarios give the option to select separate target objectives for the completion of the network of new bikeways and for the existing network condition. The minimum budget required to reach the target objectives is calculated. Three Target-Driven scenarios are run using the MOS model:

- Scenario 4-1-B: no new bikeways, the best remaining life possible
- Scenario 4-2-B: 52% of the new bikeways funded, the best remaining life possible
- Scenario 4-3-B: 52% of the new bikeways funded, remaining life 2 years

Table 5.11 shows the summary of target objectives used in the scenarios and the funding allocated.

Table 5.11: Target-Driven Livability Scenarios Inputs and Outputs.

TARGET OBJECTIVES			OUTPUT			
Scena-rio	**Average Remaining Life**	**Percentage of New Bikeways Completed**	**Allocated Budget or Agency Cost (% of All Funding)**	**Critical Remaining Life (in Year)**	**Critical Backlog (in Year)**	**Backlog at the end of 2025**
4-1-B	2.73	0%	$ 696,420 (68%)	1.92 (2016)	see year 2025	$216,515
4-2-B	2.77	52%	$ 826,434 (81%)	1.92 (2016)	see year 2025	$137,538
4-3-B	2.01	52%	$ 400,352 (39%)	1.92 (2016)	$352,878 (2024)	$351,120

Figure 5.15 shows the resulting bikeway marking condition for Target-Driven Scenarios.

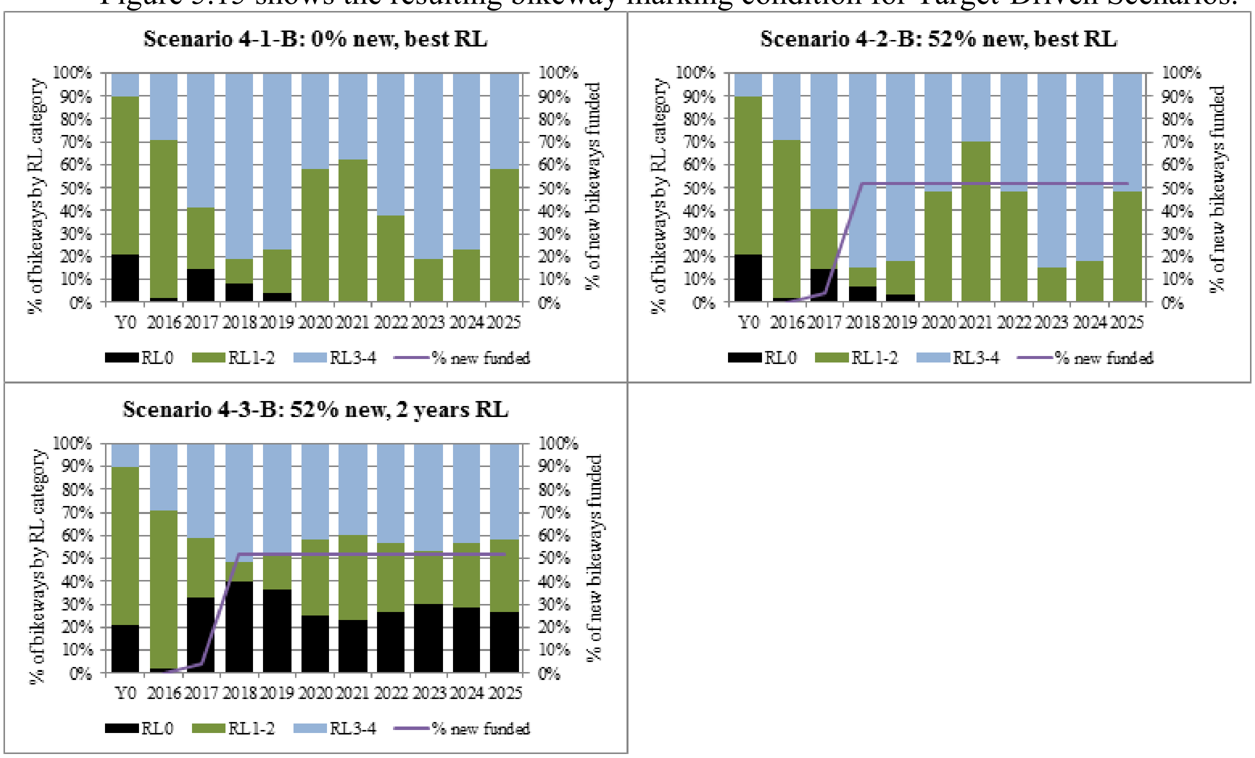


Figure 5.15: Remaining Life and New Bikeways Funded – Target-Driven Scenarios.

Similar plots as for the Budget Driven in Figure 5.14 could be developed also for Target-Driven scenarios. However, in this situation, the challenge is showing three variables together: average remaining life, percentage of bikeways completed, and agency cost.

5.2.2.4 Bikeways: Interpretation of the Results

The bikeway network quality is correlated with allocated funding. The more funding allocated to the improvement and maintenance projects, the higher are the remaining service life and network completeness. Not only bikeways in good condition with adequate connectivity improve mobility, quality of life, safety and potentially health of the population, but also decrease on-road emissions. Zahabi et al. (2016) report that *"a reduction of close to 2% in GHG emissions is observed for an increase of 7% in the length of the bicycle network."* Therefore, the maintenance of the existing bikeways as well as construction of new facilities have potentially significant consequences on the environmental and social sustainability.

With unlimited budget (All Funding Scenario 1-B) a total of $1,023,358 is spent over a period of 10 years to fund all the needed new bikeways and also to improve the average remaining life (RL) of the network from 1.17 years at the beginning of the analysis to an average of 2.77 years. The Do Nothing Scenario 2-B assumes that no treatments are applied during the analysis period and the network deteriorates, which causes all existing bikeways to reach the end of their life by the year 2019, while no new bikeways are implemented. Figure 5.16 shows the funding levels in accumulated budget allocated throughout the 10-year analysis period, as well as the performance in remaining life and new bikeways funded.

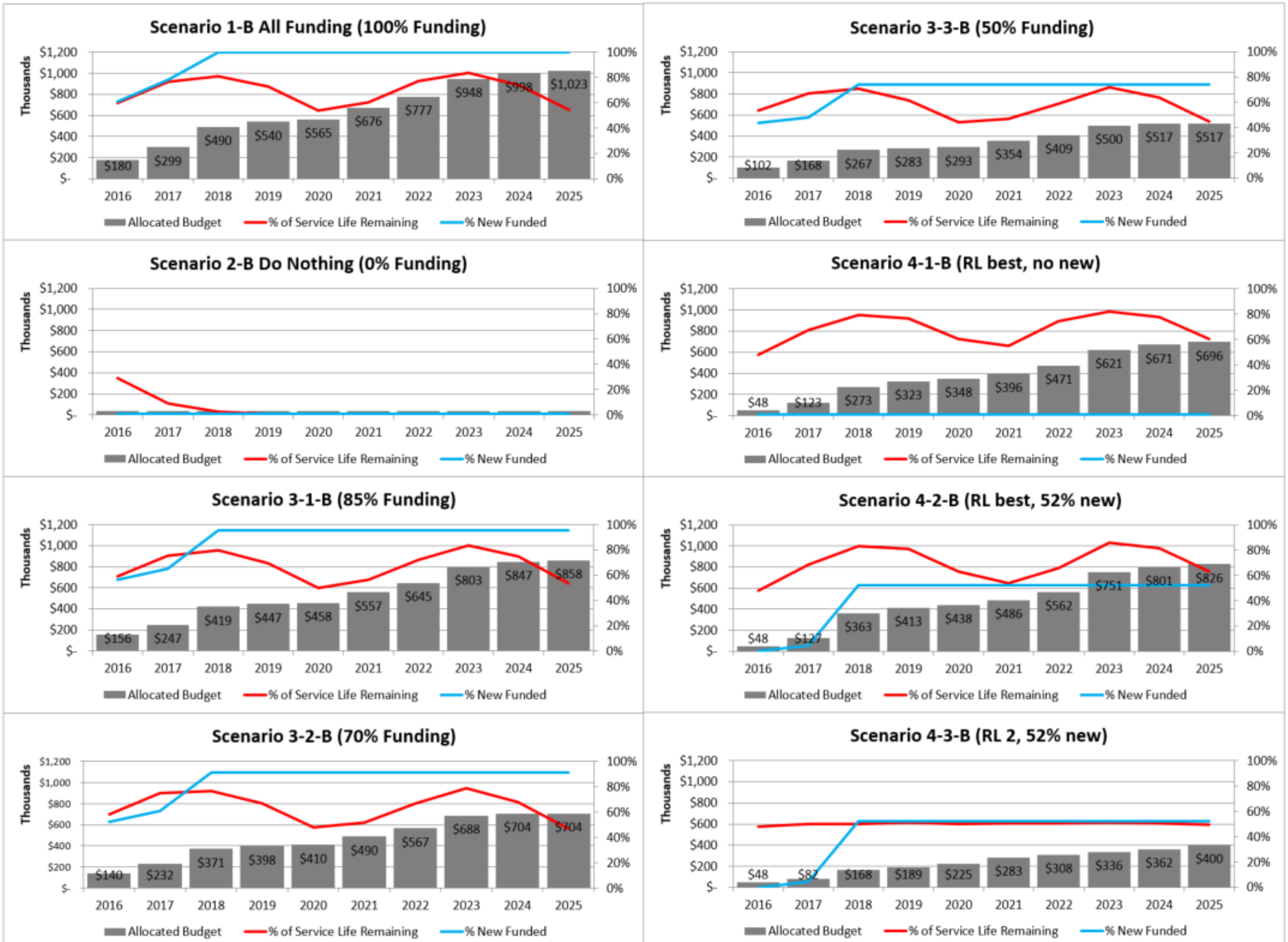


Figure 5.16: Performance in Remaining Life and New Bikeways Funded versus Allocated Budget for Bikeway Scenarios.

The overall performance and comparison of the scenarios can be illustrated in a radar plot, as Figure 5.17 shows. Comparison between pavement and bikeway marking condition, as well as expenditures for their scenarios showing the level of investment in non-motorized transportation is discussed in Section 5.2.4.

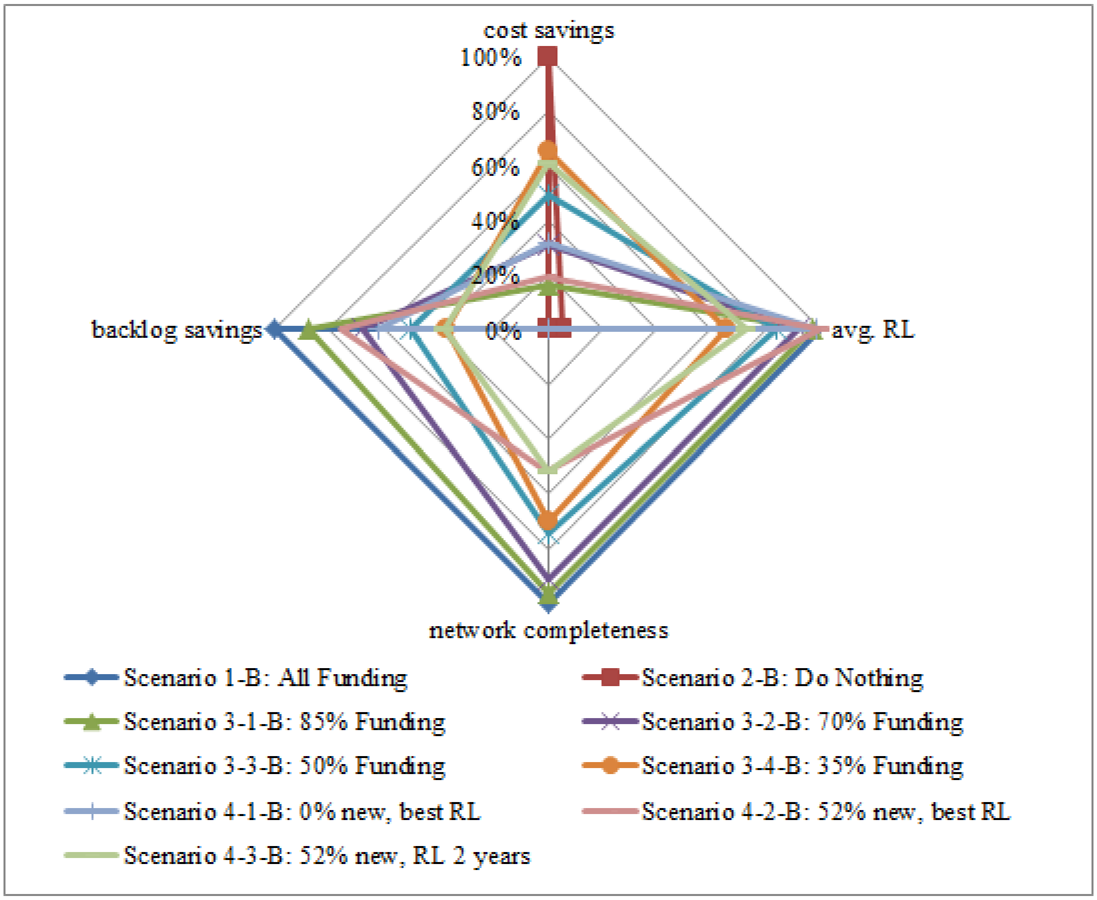


Figure 5.17: Scenario Comparison for Bikeways.

As no money is spent in Scenario 2-B (Do Nothing), the cost savings are naturally largest. However, it is at the expense of the network condition. Backlog savings are assumed to be highest for Scenario 1-B (All Funding), where backlog is $0. Average remaining life indicates that the condition of the network by how many years are left till the maintenance will be needed. While the assumed service life of bikeways markings is 4 years, the best remaining service life during the 10-year analysis period averages at 2.77 years throughout the analysis period (in

Scenarios 1-B, 4-1-B and 4-2-B). The network completeness indicates how many of the planned new bikeways are implemented in each scenario, where 100% means that all 23 sections of two new bikeways are completed.

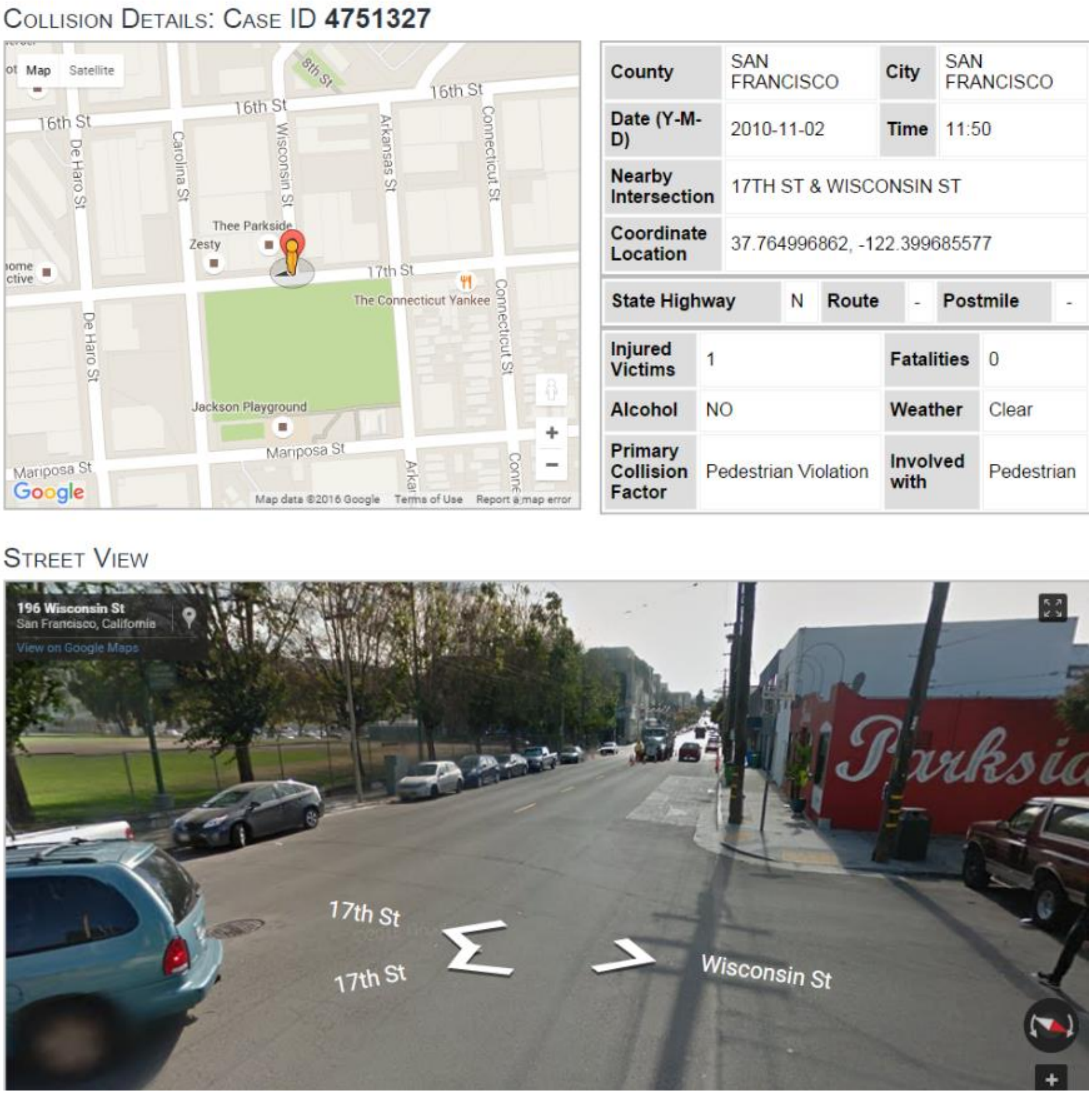
5.2.3 Social Sustainability: Crosswalk Safety

The crosswalk safety module is a part of the social sustainability framework. The MOS model allocates available funds for improvements in crosswalks with the goal of maximizing pedestrian safety. The needs for 6 new crosswalks and maintenance of 4 existing crosswalks are prioritized in coordination with the maintenance on pavement sections in order to maximize the overall effectiveness. General data description for the 11 crosswalks is shown in Table 5.12.

Table 5.12: General Data for Crosswalks.

MOSM ID	Average Daily Traffic (ADT) [vehicles/day]	No. of crashes	Block length	IMP_{AS}	IMP_{LOC}	WER_{SAF} in 2016	WER_{SAF} in 2017	Notes
1-C-1	1,300	-	1,000	0.8	1	-	2.2	
1-C-N	1,300	2	1,000	1	1	0.5	-	Church, mid-block
2-C-1	8,000	-	560	0.8	0.55	-	1.2	
3-C-1	12,200	-	600	0.8	0.55	-	1.2	
3-C-N	12,200	2	600	1	1	0.5	-	School, mid-block
4-C-1	9,900	-	1,000	0.8	0.55		1.2	
4-C-N	9,900	2	1,000	1	1	0.5	-	Park, mid-block
7-C-N	12,000	3	620	1	1	0.5	-	Parking lot, mid-block
9-C-N	8,400	2	230	1	1	2.8	-	Park, intersection
10-C-N	4,100	2	880	1	0.55	0.3	-	Commercial, mid-block

The ADT was obtained from the StreetSaver® database, while the number of crashes involving pedestrians between years 2010 and 2014 were obtained from a Transportation Injury Mapping System (TIMS). Figure 5.18 shows an example of the TIMS report, indicating that at an intersection leading to a children’s playground in 2010 was a crash between a motorized vehicle and a pedestrian, and the primary collision factor is indicated as pedestrian violation.



County	SAN FRANCISCO	City	SAN FRANCISCO
Date (Y-M-D)	2010-11-02	Time	11:50
Nearby Intersection	17TH ST & WISCONSIN ST		
Coordinate Location	37.764996862, -122.399685577		

State Highway	N	Route	-	Postmile	-

Injured Victims	1	Fatalities	0
Alcohol	NO	Weather	Clear
Primary Collision Factor	Pedestrian Violation	Involved with	Pedestrian

Figure 5.18: Example of a TIMS Report, Section ID 9 in MOSM.

Figure 5.19 shows the same location during a site visit, showing that drivers disregard the ADA ramps and park in the area of the unmarked crosswalk which creates a potentially risky situation for pedestrians trying to cross the street, especially the children from the adjacent playground or the handicapped individuals.

Figure 5.19: MOSM Section ID 9 – Candidate Location for a New Marked Crosswalk.

More information about the exact location of crashes is in Appendix A. The block length was estimated based on the Google Earth measurements. As Burden (2001) has indicated, locations with higher risk include neighborhood streets, streets in the proximity of a school or a park, as well as streets that do not have crossing points at every 300 ft. maximum, since pedestrians are willing to go not more than 150 ft. out of their way (Burden 2001). The observed block length (distance between legal opportunities to cross, whether marked or unmarked) is far above the 300 ft. threshold, between 560 ft. and 1,000 ft. An exception is, however, section 9-C-N which is currently an unmarked crosswalk at the entrance to a playground with existing ADA ramps but no marking. It is a site of 2 pedestrian crashes in the last 4 years. Therefore, even though the block length here is less than 300 ft., this crosswalk was selected to be marked. Seven

new crosswalks were identified in places where there is high pedestrian activity, such as proximity to church, school, park, access to parking lot, or commercial street. Location and asset importance were assigned. Tables 4.13 and 4.14 were used to calculate the safety weighted effectiveness ratio (WER_{SAF}). It is assumed that once a new crosswalk is implemented, it is registered in the database of existing crosswalks that receive maintenance according to the schedule in Table 4.15. Similarly to bikeway markings, the paint for crosswalk markings has the best adhesion to a new pavement surface which results in better performance, and it is desirable that maintenance of these two assets is synchronized. For that reason, crosswalk implementation and maintenance can be delayed by 1 year from the original due date in those cases that would lead to application of pavement maintenance and crosswalk maintenance in the same year.

5.2.3.1 Crosswalks: All Funding and Do-Nothing Scenarios

The All Funding Scenario assumes unlimited funding and implementation of new crosswalk markings in the year 2016, while all existing crosswalks are re-painted at the end of their service life, which is the year 2017. After that, every 3 years, a maintenance treatment, which in this case is re-painting of the markings is applied. The total cost of a new crosswalk is assumed to be $340 if ADA curb ramps are already present, otherwise additional $1620 is added for the construction of two ADA curb ramps (FHWA 2013c). The cost of maintenance (re-painting) is assumed to be $340. For the All Funding scenario, the total budget including implementation of six new crosswalks and maintenance of existing crosswalks over 10 years of analysis is $20,356.

On the other hand, the Do Nothing Scenario simulates a situation where no funding is allocated to crosswalks. Under such scenario no new crosswalks are implemented, nor arebthe existing markings re-painted once they reach their service life.

Table 5.13 shows the optimal timing of implementing new marked crosswalks as well as maintenance.

Table 5.13: Optimal Timing of Crosswalk Improvements and Maintenance.

Section	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	Total Cost
1-C-1	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	$ 1,020
1-C-N	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	$ 2,980
2-C-1	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	$ 1,020
3-C-1	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	$ 1,020
3-C-N	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	$ 2,980
4-C-1	RL 1	RL0 (shift)	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	$ 1,020
4-C-N	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	$ 2,980
7-C-N	(shift)	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	$ 2,640
9-C-N	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	$ 2,980
10-C-N	(shift)	RL 3 NEW	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	RL 0 -> RL 3 MAINTENANCE	RL 2	RL 1	$ 2,640
										Σ	$ 21,280

Table 5.14 shows the cost of new crosswalks, cost of maintenance, and average remaining life and the percentage of improved crosswalks.

Table 5.14: All Funding and Do Nothing Scenario Summary (2016-2025 Total).

Year	All Funding Scenario				Do Nothing Scenario			
	Cost of New Crosswalks	Cost of Maintenance	Average Remaining Life (throughout analysis period)	% Improved Crosswalks	Cost of New Crosswalks	Cost of Maintenance	Average Remaining Life	% Improved Crosswalks
2016	$7,840	$0	2.00	100%	$0	$0	1.0	0%
2017	$3,920	$,020	2.30	-	$0	$0	0.0	0%
2018	$0	$340	1.70	-	$0	$0	0.0	0%
2019	$0	$1,360	1.90	-	$0	$0	0.0	0%
2020	$0	$1,700	2.40	-	$0	$0	0.0	0%
2021	$0	$340	1.70	-	$0	$0	0.0	0%
2022	$0	$1,360	1.90	-	$0	$0	0.0	0%
2023	$0	$1,700	2.40	-	$0	$0	0.0	0%
2024	$0	$340	1.70	-	$0	$0	0.0	0%
2025	$0	$1,360	1.90	-	$0	$0	0.0	0%
	Total: $11,760	Total: $9,520		Total: 100%	Total: $0	Total: $0		Total: 0%

In the case of All Funding Scenario, the total budget of $21,280 is spent over 10 years, which results in all needed new crosswalks funded while also maintaining the average remaining life between 1.7 and 2.4 years.

The Do Nothing Scenario assumes that no treatments are applied during the analysis period and network deteriorates, which causes all existing crosswalks to reach the end of their life in the year 2017.

5.2.3.2 Crosswalks: Budget-Driven Scenarios

Transportation agencies often do not have sufficient funding to cover all costs. In that case is useful to predict asset condition under a limited budget. Four Budget-Driven scenarios are run using the MOS model:

- Scenario 3-1-C: available budget is $18,300 (86% of the total 10-year budget Needs)
- Scenario 3-2-C: available budget is $14,980 (70% of the total 10-year budget Needs)
- Scenario 3-3-C: available budget is $10,640 (50% of the total 10-year budget Needs)
- Scenario 3-4-C: available budget is $7,660 (36% of the total 10-year budget Needs)

Implementation and maintenance projects compete for limited funding based on their ranking by safety weighted effectiveness ratio WER_{SAF} as described in Chapter 4, Section 4.4.2.

Table 5.15 shows the summary of effects of limited funding on bikeway condition.

Table 5.15: Budget-Driven Scenarios for Bikeways.

INPUT		**OUTPUT**				
Scena -rio	**Available Budget or Agency Cost (% of All Funding)**	**Percentage of New Crosswalks Completed at the end of the analysis**	**Average Remaining Life**	**Critical Remaining Life (Year)**	**Critical Backlog (Year)**	**Backlog at the end of 2025**
3-1-C	$ 18,300 (86%)	83%	1.94	1.44 (2018)	$2,300 (2018)	$1,960
3-2-C	$ 14,980 (70%)	67%	1.84	1.38 (2018)	$4,260 (2018)	$4,260
3-3-C	$ 10,640 (50%)	50%	1.41	0.86 (2021)	$6,900 (2020)	$6,560
3-4-C	$ 7,660 (36%)	33%	1.32	0.83 (2021)	$8,860 (2022)	$8,860

Figure 5.20 shows the consequences of limited funding on the condition of the network of crosswalks.

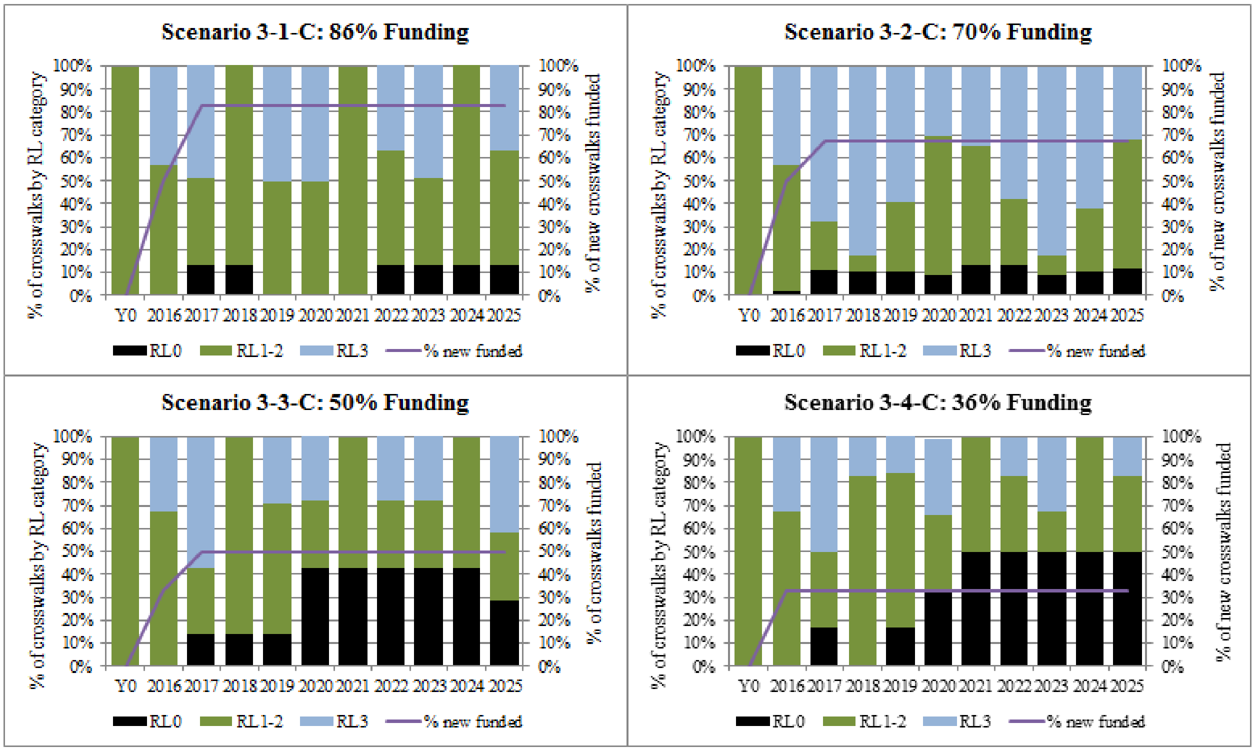


Figure 5.20: Remaining Life and New Crosswalks Funded – Budget Scenarios.

With 85% of funding (Scenario 3-1-B) up to 13% of crosswalks have no remaining life and need maintenance during the analysis period and only 83% of new crosswalks get implemented. In Scenario 3-2-B (70% funding) up to 13% of crosswalks have no remaining life and need maintenance during the analysis period and only 67% of new crosswalks get implemented. With even more limited budgets of 50% and 36%, up to 43% and 50% of crosswalks (respectively) have no remaining life and need maintenance during the analysis period and only about 50% and 33% of new bikeways (respectively) get implemented.

Limited budget scenarios result in delaying maintenance treatments that are due and also not all planned new crosswalks get implemented. Limited funding of 86% and 70% resulted in not more than 12% of crosswalks with no remaining life while 83% and 67% of new crosswalks were implemented.

A non-linear relationship between agency cost and new crosswalks implemented is observed for Budget-Driven Scenarios. Figure 5.21 indicates an exponential relationship and it

this particular case, the steepest increase in fraction of new crosswalks funded is for funding levels between 36 and 50 percent.

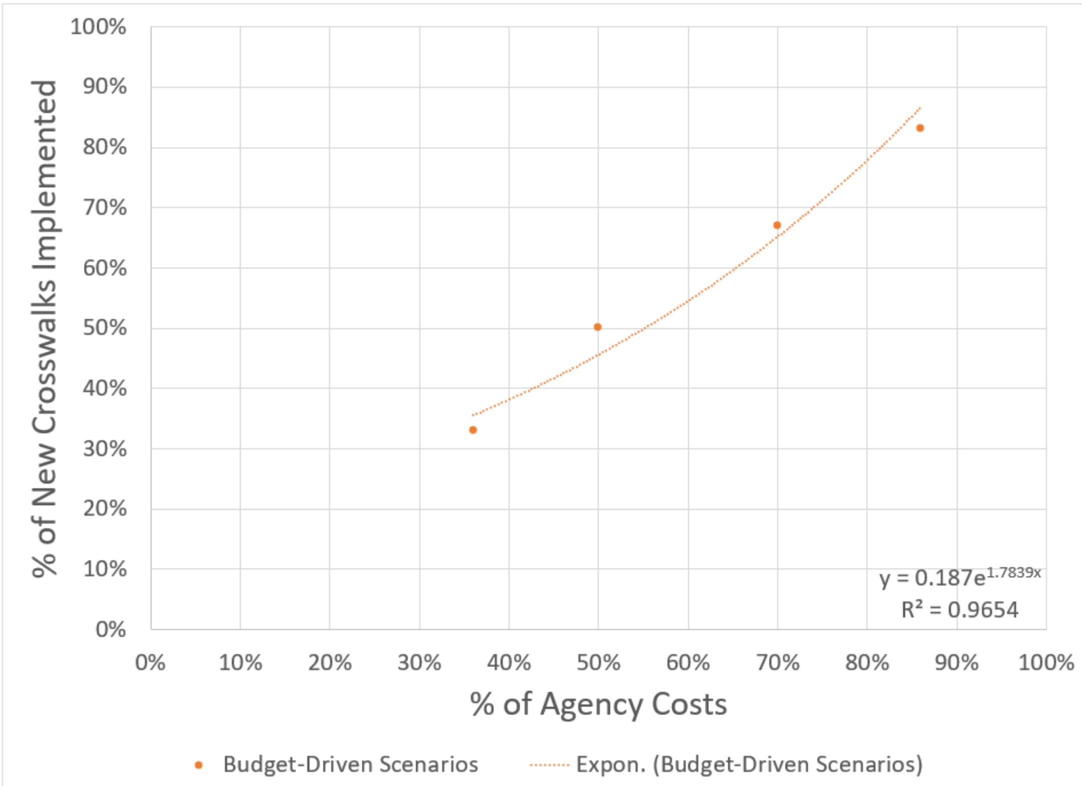


Figure 5.21: Exponential Relationship Between Agency Costs and New Crosswalks Implemented.

A non-linear relationship is also observed between agency costs and crosswalk network average remaining life for Budget-Driven Scenarios. Figure 5.22 indicates an exponential relationship and it this particular case, the steepest improvement in remaining life is for funding levels between 50 and 70 percent.

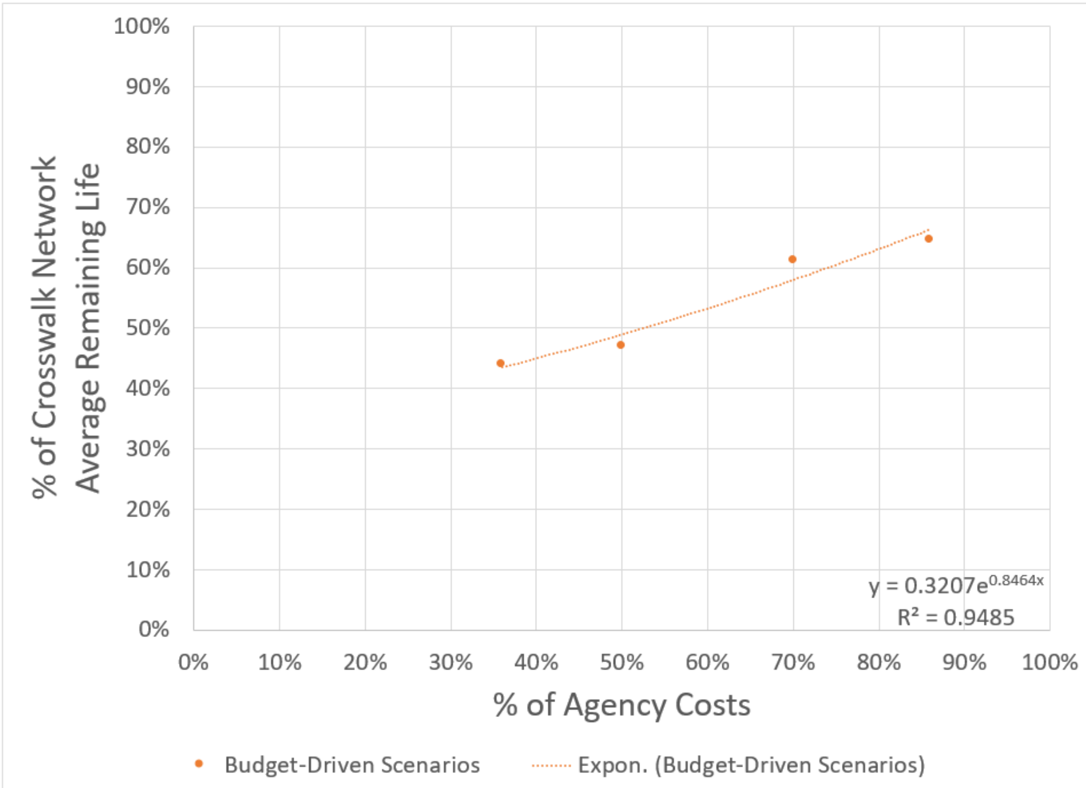


Figure 5.22: Exponential Relationship Between Agency Costs and Crosswalk Network Average Remaining Life.

5.2.3.3 Crosswalks: Target-Driven Scenarios

Target-Driven Scenarios give the option to select separate target objectives for completion of the network of new crosswalks and for existing network condition. The minimum budget required to reach the target objectives is calculated. Three Target-Driven scenarios are run using the MOS model:

- Scenario 4-1-B: no new crosswalks, the best remaining life possible
- Scenario 4-2-B: 50% new crosswalks funded, the best remaining life possible
- Scenario 4-3-B: 50% new crosswalks funded, remaining life 1.5 years

Table 5.16 shows the summary of target objectives used in the scenarios and the funding allocated.

Table 5.16 Target-Driven Livability Scenarios Inputs and Outputs.

TARGET OBJECTIVES			**OUTPUT**			
Scena-rio	**Average Remaining Life**	**Percentage of New Crosswalks Completed**	**Allocated Budget or Agency Cost (% of All Funding) throughout the analysis period**	**Critical Remaining Life (Year)**	**Critical Backlog (Year)**	**Backlog at the end of 2025**
4-1-C	1.88	0%	$ 4,080 (19%)	1.00 (2016)	$11,760 (2018)	$11,760
4-2-C	1.95	50%	$ 14,640 (69%)	1.67 (2016)	$5,880 (2018)	$5,880
4-3-C	1.68	50%	$ 13,620 (64%)	1.67 (2016)	$6,220 (2019)	$6,220

Figure 5.23 shows the resulting bikeway marking condition for Target-Driven Scenarios.

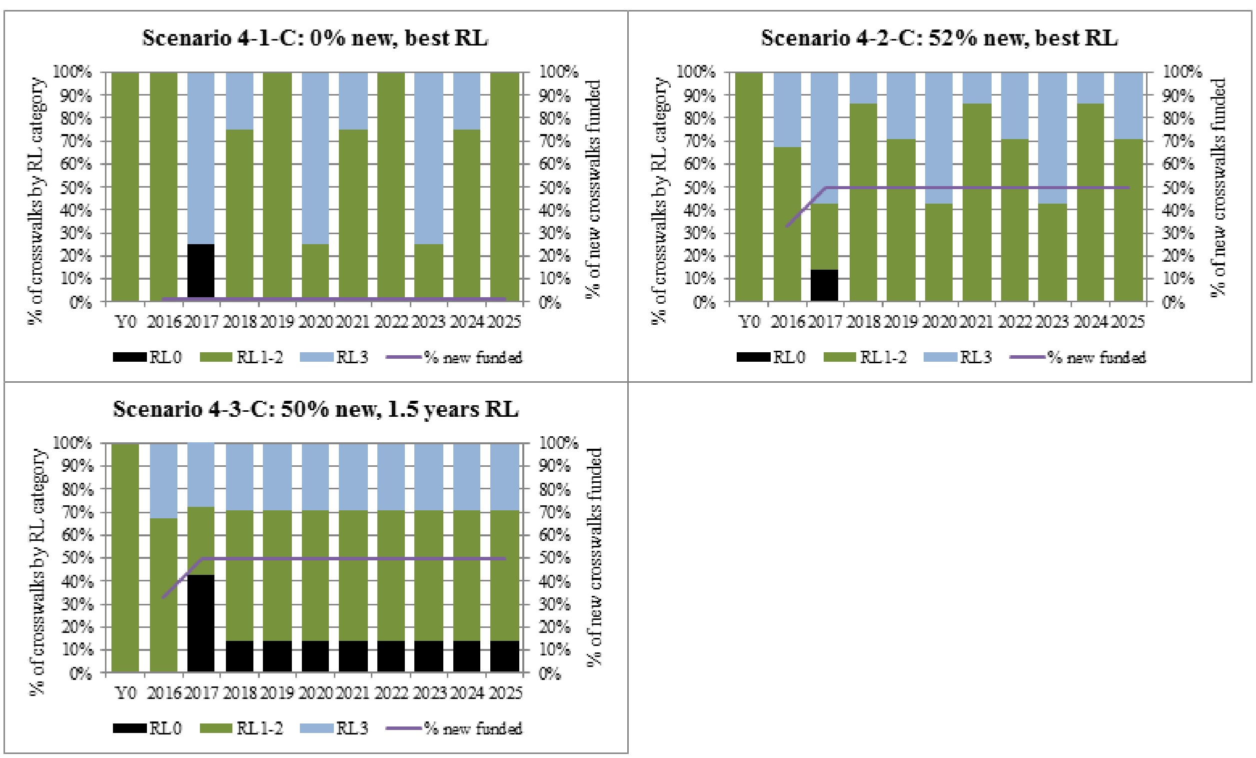


Figure 5.23: Remaining Life and New Crosswalks Funded – Target-Driven Scenarios.

Similar plots as for the Budget Driven in Figure 5.22 could be developed also for Target-Driven scenarios. However, in this situation, the challenge is showing three variables together: average remaining life, percentage of crosswalks completed, and agency cost.

5.2.3.4 Crosswalks: Interpretation of the Results

Crosswalk network quality is correlated with allocated funding. The more funding allocated to the improvement and maintenance projects, the higher remaining service life and network completeness.

With unlimited budget (All Funding Scenario 1-C) the total expenditures of $21,280 are spent over 10 years to fund all needed new crosswalks and also to improve the average remaining life (RL) of the network from 1.00 years at the beginning of the analysis to an average of 1.99 years. The Do Nothing Scenario 2-C assumes that no treatments are applied during the analysis period and network deteriorates, which causes all existing crosswalks to reach the end of their life by year 2017, while no new crosswalks are implemented. Figure 5.24 shows the funding levels in accumulated budget allocated throughout the 10-year analysis period, as well as the performance in remaining life and new crosswalks funded.

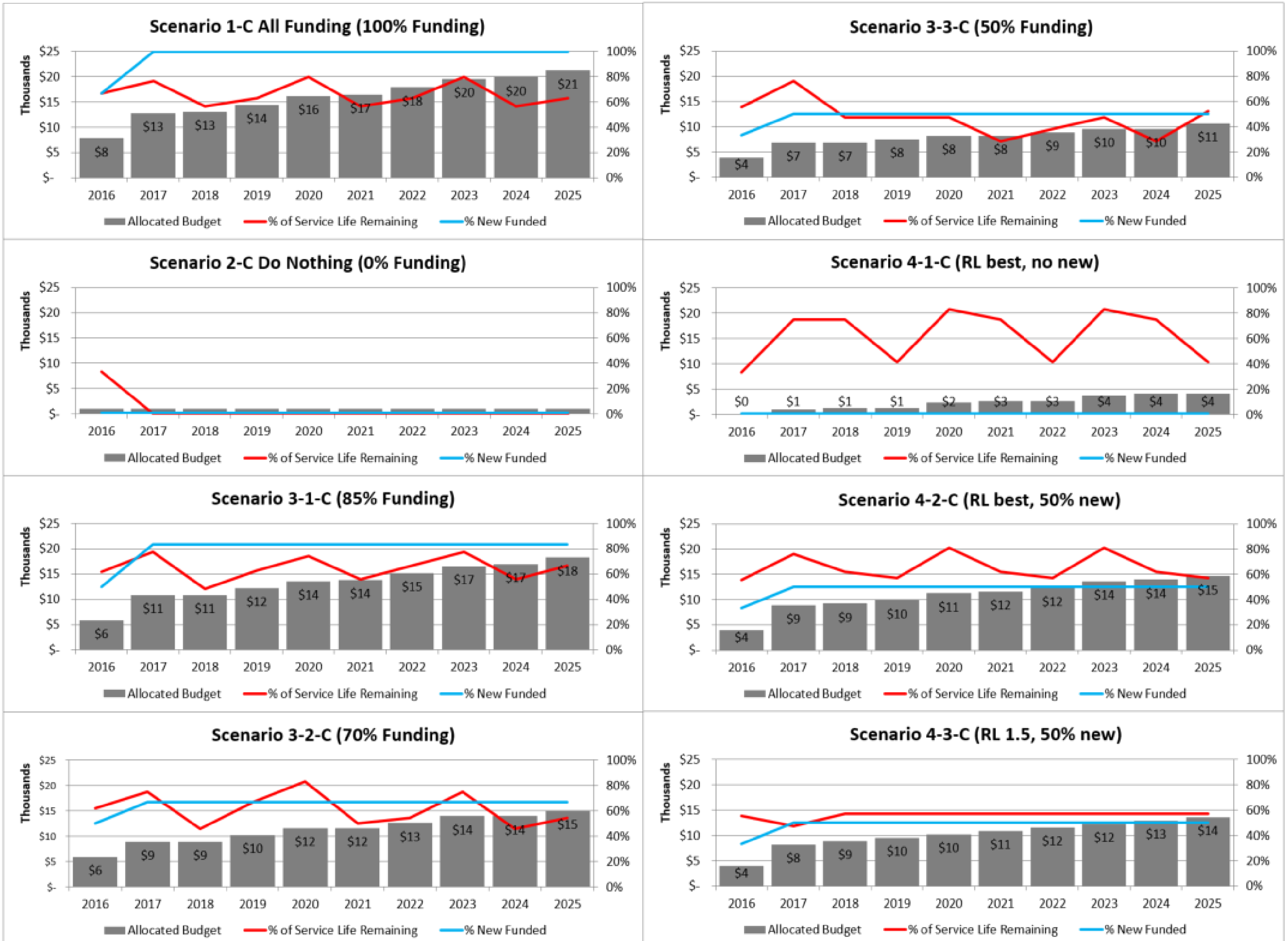


Figure 5.24: Performance in Remaining Life and New Crosswalks Funded versus Allocated Budget for Crosswalk Scenarios.

The overall performance and comparison of the scenarios can be illustrated in a radar plot, as Figure 5.25 shows.

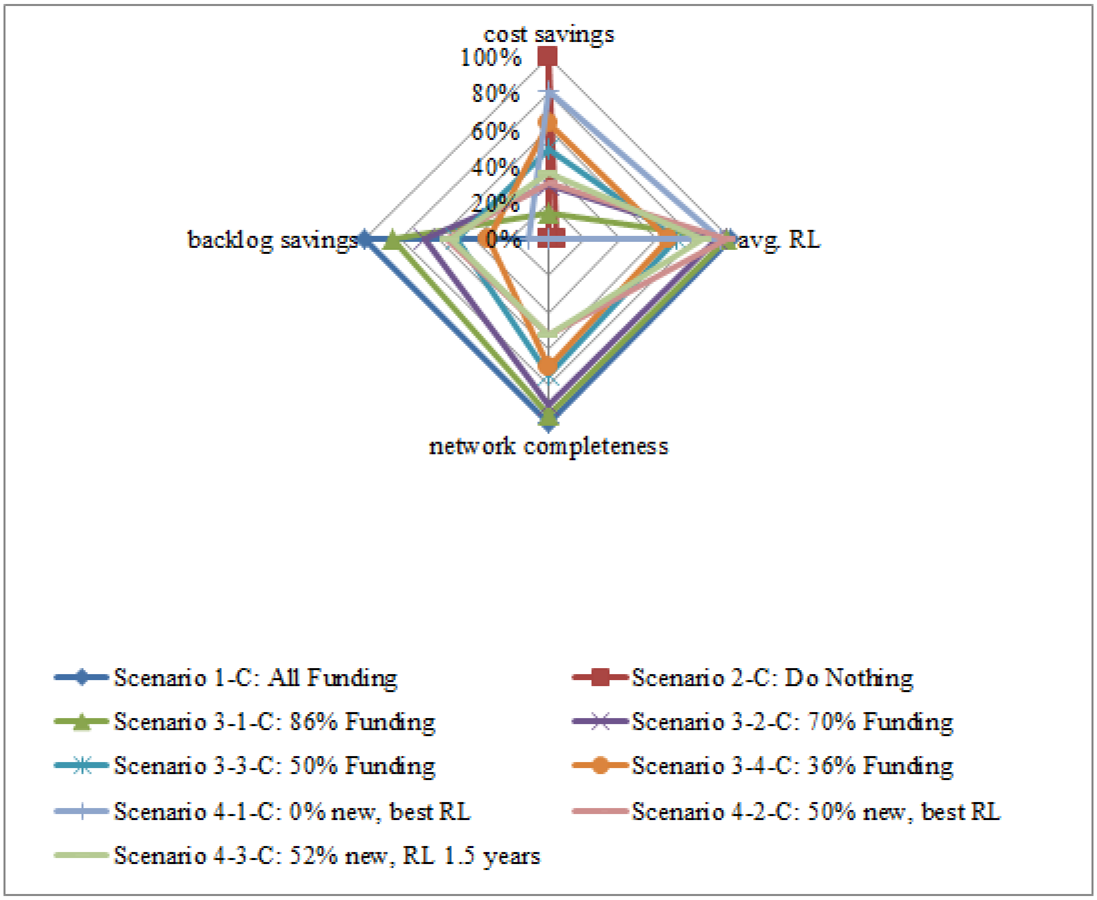


Figure 5.25: Scenario Comparison for Crosswalks.

Theoretically, cost savings are assumed to be the highest in Scenario 2-C (Do Nothing), as no money is spent, however it is at the expense of network condition. Backlog savings are assumed to be highest for Scenario 1-C (All Funding), where backlog is $0. Average remaining life indicates the condition of the network by how many years are left until maintenance will be needed. While assumed service life of crosswalks is 3 years, the best remaining service life during the 10-year analysis period averages at 1.99 years throughout the analysis period. The network completeness indicates how many of the planned new crosswalks are implemented in each scenario, where 100% means that all 6 new crosswalks are completed.

Safe places for pedestrians to cross streets are crucial for cities that aim for a walkable environment. Marked crosswalks help pedestrians to be more visible and indicate to drivers where frequent places to cross are. Well-maintained crosswalk markings are important for crosswalk visibility; therefore, it is crucial that they are re-painted in adequate intervals, because faded crosswalks do not fulfill their safety function.

5.2.4 Economic Sustainability

Following the method described in Chapter 4, creation of new jobs is estimated based on the funding allocated to pavement maintenance, as well as bikeways and crosswalks. Table 5.17 summarizes the agency's expenditures on pavements, bikeways, and crosswalks; the level of investment into non-motorized transportation, as well as the new jobs created. Since crosswalk and bikeway maintenance activities are coordinated with pavement maintenance for maximum effectiveness, the example in Table 5.18 assumes that pavements are maintained following the All Funding Scenario, while funding levels for crosswalks and bikeways vary to show the consequences of limited funding. For that reason, even a "Do Nothing" scenario for crosswalks and bikeways, where no funding is spent on these assets during the analysis period, shows 160 jobs created, because these jobs come from the pavement maintenance.

Table 5.17: Summary of Agency Expenditures, Condition and Jobs Created.

Scenario Pavements	Scenario Bikeways	Agency Expenditures		Condition	
		Pavements	Bikeways	Pavements (PCI, 100 max)	Bikeways (Avg. RL, ESL 4)
Scenario 1-P: All Funding	Scenario 1-B: All Funding	$ 8,865,929	$ 1,023,358	83	2.77
	Scenario 2-B: Do Nothing		$ -		0.16
	Scenario 3-1-B: 85% Funding		$ 858,397		2.69
	Scenario 3-2-B: 70% Funding		$ 704,358		2.55
	Scenario 3-3-B: 50% Funding		$ 516,698		2.33
	Scenario 4-1-B: 0% new, best RL		$ 696,420		2.73
	Scenario 4-2-B: 52% new, best RL		$ 826,434		2.77
	Scenario 4-3-B: 52% new, RL 2 years		$ 400,352		2.01

Scenario Pavements	Scenario Crosswalks	Agency Expenditures		Condition	
		Pavements	Crosswalks	Pavements (PCI, 100 max)	Crosswalks (Avg. RL, ESL 3)
Scenario 1-P: All Funding	Scenario 1-C: All Funding	$ 8,865,929	$ 21,280	83	1.99
	Scenario 2-C: Do Nothing		$ -		0.10
	Scenario 3-1-C: 86% Funding		$ 18,300		1.94
	Scenario 3-2-C: 70% Funding		$ 14,980		1.84
	Scenario 3-3-C: 50% Funding		$ 10,640		1.41
	Scenario 4-1-C: 0% new, best RL		$ 4,080		1.88
	Scenario 4-2-C: 50% new, best RL		$ 14,640		1.95
	Scenario 4-3-C: 50% new, RL 1.5 years		$ 13,620		1.68

Scenario Pavements	Scenario Bikeways & Crosswalks	Agency Expenditures			Jobs created (after San Jose 2013)
		Pavements	Bikeways + Crosswalks	Level of Non-Motorized Investment	
Scenario 1-P: All Funding	Scenario 1-C: All Funding	$ 8,865,929	$ 1,044,638	12%	178
	Scenario 2-C: Do Nothing		$ -	0%	160
	Scenario 3-1-C: 85% & 86% Funding		$ 876,697	10%	175
	Scenario 3-2-C: 70% Funding		$ 719,338	8%	173
	Scenario 3-3-C: 50% Funding		$ 527,338	6%	169
	Scenario 4-1-C: 0% new, best RL		$ 700,500	8%	172
	Scenario 4-2-C: 50% new, best RL		$ 841,074	9%	175
	Scenario 4-3-C: 50% new, RL 2& 1.5 years		$ 413,972	5%	167

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Transportation Asset Management (TAM) evolved from Pavement Management as a strategic approach 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. Performance measures can be forecasted to analyze the impact of TAM programs on on-road emissions, agency expenditures, funding for new bikeway striping and crosswalks, and on other selected performance measures under various scenarios. Modern TAM requires an integrated approach that connects these three key elements through the adoption of sustainability principles to balance economic, environmental, and social aspects. In this context, the selection of performance measures that better fit the decision making process of the agency to assess the current and desired state is a very important decision, especially since data collection is costly.

The literature review in Chapter 2 discusses the challenges, goals, objectives, and performance measures that can be used to incorporate sustainability in TAM and balance economic, environmental, and social aspects.

A decision-making technique, called the Quality Function Deployment (QFD) matrix is used in Chapter 3 for selecting a set of performance measures that will help to reach the agency's goals while taking into account sustainability challenges. The QFD matrix relates 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 asset condition, fuel consumption based on pavement condition, agency expenditures, level of non-motorized infrastructure investment, on-road CO_2 emissions, social cost of CO_2 emissions, new jobs created, pedestrian-related crashes, and improvements to high crash risk areas.

The following can be concluded from this study:

a) The MOS model developed in Chapter 4 focuses on three assets: pavements, bikeways and crosswalks, and incorporates multimodality into a traditionally motorist-centered TAM with three frameworks addressing economic, environmental, and social sustainability.

b) The framework for environmental sustainability estimates on-road CO_2 emission savings as a consequence of good pavement condition, promoting a state of good repair as one of the options to reduce gas emissions, improve local air quality, and slow down climate change.

c) The framework for social sustainability focuses on multimodal transportation and pedestrian safety as the major factors in livability that can be influenced through TAM. Improvements in multimodal transportation focus on maintaining bikeways in such condition that is safe and comfortable to ride on, while the need for safety improvements in pedestrian crossing opportunities is identified through crash data and existing marked crosswalks. This safety and multimodal enhancement is used as an example to show how pavement management can be enhanced by assets that are used by non-motorized users and also how safety data can be used to improve transportation infrastructure. Once high-risk locations, where marked crosswalks are needed, are identified, then the implementation of a crosswalk is synchronized with pavement maintenance activities.

d) The framework for economic sustainability looks into the motorized and non-motorized transportation funding levels, as well as job creation estimation.

e) The case study presented in Chapter 5, shows how the MOS model can be used to enhance an existing pavement management system StreetSaver® by taking into account CO_2 emission savings in pavement maintenance practices, pedestrian crash data to determine high-risk locations that need safety improvements as marked crosswalks, and also bikeway condition to ensure all road users have access to safe and multimodal transportation. Outputs can help local transportation agencies to decide among strategies under limited funding.

f) The MOS model is solved in Chapter 5 with a ranking method, which looks for the maximum CO_2 emission savings and maximum safety, bikeway weighted effectiveness ratio for a given budget, or to minimize the budget to reach the target objectives based on emission

savings, bikeway and crosswalk network completeness, and asset condition. The ranking technique is used to solve the Target and Budget-Driven scenarios. Ranking is a practical method that is often preferred by local transportation agencies, as other optimization techniques may seem too complex and their results difficult to understand.

g) 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 decisions on roadway users, environment, and the overall transportation network sustainability. The following performance measures are recommended:

Pavements

- agency cost of maintenance over the analysis period
- % of potential CO_2 emissions saved
- average network condition (% of pavements in poor/very poor condition)
- social cost of CO_2

Crosswalks

- agency cost of initial construction and maintenance over the analysis period
- average network condition
- % of crosswalks improved
- level of non-motorized investment

Bikeways

- agency cost of initial construction and maintenance over the analysis period
- average network condition
- % of new bikeways implemented
- level of non-motorized investment

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. Following the quote, *"you cannot manage what you do not measure"* (Politico 2016), the inclusion of performance measures for environmental and social sustainability into TAM systems fosters a transportation network that minimizes the impact on the environment, while addressing the needs of motorized users as well as pedestrians and bicyclists.

Running Target-Driven and Budget-Driven scenarios with MOS provides helpful insights into the environmental and social consequences of maintenance and construction decisions that local transportation agencies make daily under limited budgets. It helps answer questions like: How much CO_2 emissions can be saved by timely maintenance? Which locations are high-risk for pedestrians and how can marked crosswalks be implemented in the most cost-efficient manner? How can be new bike lanes implemented in the most cost-efficient manner? How many new jobs will be created by maintenance and construction activities? What are the levels of funding for motorized and non-motorized transportation infrastructure assets? Therefore, the MOS model enhances the traditional TAM methods that are typically based only on pavement condition.

The results of this study indicate a relationship between the pavement network condition and environmental consequences, in this case the on-road CO_2 emissions. It is recommended that transportation agencies consider CO_2 emissions and its cost to society in their funding decision-making process.

Beyond these contributions, this research presents an overall framework for inclusion of pedestrian crash data into TAM decisions. The goal is to help transportation agencies manage an infrastructure network that is better connected and safer for all road users through the maintenance of existing assets as well as identification of new improvements.

6.3 Recommendations for Future Research

The following research topics are recommended for future consideration:

a) The MOS model assumes an independent budget for pavements, bikeways, and crosswalks. It is recommended to consider cross-asset funding allocation for trade-offs between investments into motorized versus non-motorized transportation to assess the impact on the overall sustainability performance. Also, it is recommended that pavement sections with bikeways receive higher priority for maintenance under constrained budget by incorporating a global index that incorporates sustainability principles.

b) A ranking method was used as a solving technique in the case study, however there are a number of optimization techniques that could potentially find more cost-effective funding allocation solutions under constrained budget or multiple target objectives.

c) In order to improve accuracy of on-road CO_2 emissions, it is recommended to determine a relationship between pavement condition (PCI) and fuel consumption (currently there is only estimated relationship between roughness (IRI) and fuel consumption), or improve the accuracy of the PCI-IRI conversion. Also the emissions should account for stop and go waves and idling which are additional sources of emissions that could be calculated by emission models, such as MOVES2014.

d) While the MOS model assumes a constant traffic volume for all years of analysis, more research is recommended to determine the relationship between pedestrian and bicyclist network completeness, mode-share shifts, and potential emission savings.

e) Further research is recommended for determining the impact of bicycle-only traffic on pavement loading, as potentially pavements undergoing lighter traffic loads could deteriorate slower than pavements that face heavy vehicles. Additionally, bicyclists are more sensitive to certain pavement distresses and their safety can be endangered on poorly maintained surface, therefore future research is recommended to adjust pavement condition ratings from the perspective of a bicyclist.

f) In the MOS model bikeway sections correspond with street blocks and are prioritized for maintenance or implementation as a block, and not as a bikeway consisting of several blocks, which may not be the real case. Further research is recommended on how to improve the connectivity of bikeway networks while coordinating striping with pavement maintenance in the most cost-effective way.

g) In order to visually describe the relationship between the variables in Budget-Driven and Target-Driven scenarios, it is recommended to explore graphical representation of the model parameters by multi-dimensional plots (e.g. 3-D).

References

ADD40, Sustainable Transportation Indicators Subcommittee of the Transportation Research Board. 2008. Sustainable Transportation Indicators a Recommended Research Program for Developing Sustainable Transportation Indicators and Data. <http://www.vtpi.org/sustain/sti.pdf>

Amekudzi, A. and M. Mayer. 2005. NCHRP Report 541: Consideration of Environmental Factors in Transportation Systems Planning. Transportation Research Board. Washington, D.C

Amekudzi, A. 2006. Georgia Guidebook for Pedestrian Planning. Prepared for Georgia Department of Transportation.

Amekudzi, A. 2011. Transportation Planning for Sustainability Guidebook. Prepared for US DOT Federal Highway Administration.

American Automobile Association, 2015. Your Driving Costs (Heathrow, FL: Annual Issues), <http://www.aaapublicaffairs.com> Accessed on Apr 6, 2016.

American Association of State Highway and Transportation Officials. AASHTO. 2008. Mechanistic-Empirical Pavement Design Guide.

American Association of State Highway and Transportation Officials. AASHTO. 2011. Transportation Asset Management Guide. Focus on Implementation.

American Association of State Highway and Transportation Officials. AASHTO. 2012. Guide for the Development of Bicycle Facilities. Washington, D.C.

American Society of Civil Engineers. ASCE. 2013. 2013 Report Card for America's Infrastructure.

Andersen, L.B. 2016. Active commuting: an easy and effective way to improve health. The Lancet Diabetes & Endocrinology.

Appleyard, B., C.E. Ferrell, M.A. Carroll, M. Taecker. A Framework to Guide Planning, Design, and Engineering Decisions. Transportation Research Record: Journal of the Transportation Research Board, No. 2403, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 62–71.

Atkins, S. 2008. Transport and Social Sustainability. <http://www.tsu.ox.ac.uk/events/ht08_seminars/satkins080117.pdf>

Australian Asset Management Collaborative Group. AAMCOG. 2008. Public Sector Asset Performance Measurement and Reporting.

Barnes, M. 2014. Pedestrian and Bicycle Crash Types and Countermeasures. MnDOT Office of Traffic, Safety and Technology.

Bennett, C. 2000. Asset Valuation Draft Specifications.

Black, J.A., A. Paez, and P.A> Suthanaya. 2011. Sustainable Urban Transportation: Performance Indicators and Some Analytical Approaches. the Journal of Urban Planning and Development, Vol. 128, No. 4, December 1, 2002. ©ASCE, ISSN 0733-9453/2002/4-184–209.

Briseno, C. 2015. California MAP-21 Performance Management Efforts. Presented at 94th Transportation Research Board Annual Meeting.

Brodie, S., A. Ingles, Z. Colville, A. Amekudzi, R.W. Peters and V. Sisiopikou. 2013. A Review of Sustainability Rating Systems for Transportation and Neighborhood-Level Developments. In Green Streets, Highways, and Development.

Brundtland, G.H. et al. 1987. Our Common Future. World Commission on Environment and Development. <http://www.un-documents.net/our-common-future.pdf> Accessed July 22, 2014.

Burden, D. 2001. Building Communities with Transportation. Transportation Research Record: Journal of the Transportation Research Board, No. 1773, Transportation Research Board of the National Academies, Washington, D.C., pp. 5–20.

Bureau of Transportation Statistics. BTS. 1991. Intermodal Surface Transportation Efficiency Act of 1991 – Summary. http://ntl.bts.gov/DOCS/ste.html

Caltrans. 2014. California Transportation Plan (CTP) 2040 Final - Focus Group Summary Report, prepared by VRPA Technologies, Inc.

Caltrans. 2015. Interregional Transportation Strategic Plan, Draft ITSP Vision-Goals Comparison. <http://www.dot.ca.gov/hq/tpp/offices/oasp/ITSP_Draft_Vision_Goals_ Objectives_Matrix.pdf>

Caltrans, 2016. California Transportation Plan 2040. Final Review Draft Feb 29, 2016.

Cambridge Systematics. 2008. Best Practice Methodology for Calculating Return on Investment for Transportation Programs and Projects. NCHRP Report 8-36, Task 62. Final Report.

Cambridge Systematics. 2010. Transportation Performance Management: Insight from Practitioners. National Cooperative Highway Research Report 660, Washington, D.C., USA.

Centers for Disease Control and Prevention (CDC). 2015. Transportation Health Impact Assessment Toolkit For Planning and Health Professionals. <http://www.cdc.gov/healthyplaces/transportation/hia_toolkit.htm>

Chang, C. 2007. Development of a Multi-Objective Strategic Management Approach to Improve Decisions for Pavement Management Practices in Local Agencies. Dissertation. Texas A&M University, College Station, Texas.

Chatti, K. and I. Zaabar. 2010. Estimating the Effects of Pavement Condition on Vehicle Operating Costs. NCHRP Report 720. National Cooperative Highway Research Program, Washington, D.C.

City of Portland. 1998. Pedestrian Master Plan. < https://www.portlandoregon.gov/transportation/article/90244>

City of San Francisco. 2010. Better Streets Plan. Policies and Guidelines for the Pedestrian Realm.

City of San Jose, Transportation and Environment Committee. 2013. Pavement Maintenance Program Update and Funding Strategy. Memorandum.

District Department of Transportation. DDOT. 2014. MoveDC, Multimodal Long-Range Transportation Plan. Appendix 1.1 Goals and performance Measures <http://www.wemovedc.org/resources/DraftPlan/Appendix_1-1_Performance_Criteria.pdf>

Department of Transportation. DOT. 2016. National Performance Management Measures: Highway Safety Improvement Program; Final Rule Federal Register / Vol. 81 , No. 50 / Tuesday, March 15, 2016 / Rules <https://www.gpo.gov/fdsys/pkg/FR-2016-03-15/html/2016-05202.htm>

Derrible, S., C.D. Cottryl. 2013. How new technologies can contribute to measuring sustainable mobility. TRB 2013 Annual Meeting.

Dewan, S. A. 2002. Development of an Effective Asset Management Approach for Managing a Local Agency Pavement Network. Dissertation. Texas A&M University, College Station, Texas.

Dondero, G., K. Rodgers, P.T. Hurley. 2013. Developing A Comprehensive Sustainable Transportation Analysis Framework. TRB 2013 Annual Meeting.

Elkington, J. 1997. Cannibals With Forks: The Triple. Bottom Line of 21st Century Business. Capstone,. Oxford, 1997, 402 pp. ISBN 1-900961-27-X.

Environmental Protection Agency. 2015a. Inventory of U.S. Greenhouse Gas 7 Emissions and Sinks: 1990-2013.

Environmental Protection Agency. 2015b. MOVES2014a User Guide.

Environmental Protection Agency. 2016. Sources of Greenhouse Gas Emissions. <https://www3.epa.gov/climatechange/ghgemissions/sources/transportation.html>

Ewing, R., & Greene, W. 2003. Travel and Environmental Implications of School Siting. U.S. Environmental Protection Agency, EPA 231-R-03-004.

Ewing, R., and R. Cervero. 2010. Travel and the Built Environment. Journal of the American Planning Association, Vol. 76, No. 3, pp. 265–294.

Federal Highway Administration, FHWA. Undated. NEPA Documentation: Environmental Impact Statement (EIS). < https://www.environment.fhwa.dot.gov/projdev/docueis.asp> Accessed on Apr 11, 2016.

Federal Highway Administration, FHWA. 1996. Flexibility in Highway Design. U.S. Department of Transportation.

Federal Highway Administration, FHWA. 1997. Pedestrian Crash Types: A 1990's Informational Guide. U.S. Department of Transportation. FHWA-RD-96-163.

Federal Highway Administration, FHWA. 1999a. Asset Management Primer. U.S. Department of Transportation.

Federal Highway Administration, FHWA. 1999b. Guidebook on Methods to Estimate Non-Motorized Travel: Overview of Methods. U.S. Department of Transportation. FHWA-RD-98-165.

Federal Highway Administration. FHWA. 2000. WesTrack Track Roughness, Fuel Consumption, and Maintenance Costs. FHWA-RD-00-052. Research, Development and Technology Turner-Fairbank Highway. McLean, VA.

Federal Highway Administration. FHWA. 2002a. Pedestrian Facilities User Guide – Providing Safety and Mobility. Publication No. FHWA-RD-01-102.

Federal Highway Administration. FHWA. 2002b. An Analysis of Factors Contributing to "Walking Along Roadway" Crashes: Research Study and Guidelines for Sidewalks and Walkways. FHWA-RD-01-101.

Federal Highway Administration. FHWA. 2004. Memorandum: ACTION: Preventive Maintenance Eligibility.

Federal Highway Administration. FHWA 2005a. A Summary of Highway Provisions in SAFETEA-LU, , Office of Legislation and Intergovernmental Affairs, Program Analysis Team http://www.fhwa.dot.gov/safetealu/summary.htm

Federal Highway Administration. FHWA. 2005b. Safety Effects of Marked versus Unmarked Crosswalks at Uncontrolled Locations: Final Report and Recommended Guidelines. C.V. Zeeger, J.R. Stewart, H.H. huang, P.A. Lagerwey, J. Feaganes, and B.J. Campbell. FHWA–HRT–04–100.

Federal Highway Administration. FHWA. 2006. Federal highway Administration University Course on Bicycle and Pedestrian Transportation, Lesson 3: Pedestrian and Bicyclist Safety. U.S. Department of Transportation.

Federal Highway Administration. FHWA. 2011. The Role of FHWA Programs In Livability: State of the Practice Summary.

Federal Highway Administration. FHWA. 2012a. Induced Travel: Frequently Asked Questions. <http://www.fhwa.dot.gov/planning/itfaq.cfm>

Federal Highway Administration. FHWA. 2012b. Relationships Between Asset Management and Travel Demand: Findings and Recommendations from Four State DOT Site Visits. U.S. Department of Transportation.

Federal Highway Administration. FHWA. 2013a. Performance Based Planning and Programming Guidebook. U.S. Department of Transportation.

Federal Highway Administration. FHWA. 2013b. 2013 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance. U.S. Department of Transportation.

Federal Highway Administration. FHWA. 2013c. Costs for Pedestrian and Bicyclist Infrastructure Improvements, A resource for Researchers, Engineers, Planners, and the general Public. M.A. Bushell, B.W. Poole, C.V. Zeeger, and D.A. Rodriguez. UNC Highway Safety Research Center.

Federal Highway Administration. FHWA. 2013d. Guide for Maintaining Pedestrian Facilities for Enhanced Safety Research Report. T. Huber, K. Luecke, M. Hintze, V. Coffman, J. Toole, and M. VanOosten.

Federal Highway Administration. FHWA. 2014. Asset Management Guide. < https://www.fhwa.dot.gov/research/deployment/asset.cfm>

Federal Highway Administration. FHWA. 2015. Congestion Mitigation and Air Quality Improvement (CMAQ) Program http://www.fhwa.dot.gov/environment/air_quality/cmaq/

Fort Worth. 2009. Street Development Standards, Roadway Standards and Master Thoroughfare Plan. Fort Worth, Texas.

Federal Highway Administration. FHWA. 2016a. Assessing Performance of the National Highway System, Freight Movement on the Interstate System, and the Congestion Mitigation and Air Quality Improvement Program. Overview Presentation. <http://www.fhwa.dot.gov/tpm/rule/prespmoverview200416.pdf >

Federal Highway Administration. FHWA. 2016b. Guidebook for Developing Pedestrian & Bicycle Performance Measures. FHWA-HEP-16-037.

Federal Highway Administration. FHWA. 2016c. Transportation Alternatives Program Performance Management Guidebook. FHWA-HEP-16-026.

Federal Highway Administration. FHWA. 2016d. Incorporating On-Road Bicycle Networks into Resurfacing Projects. FHWA-HEP-16-025.

Federal Highway Administration. FHWA Undated. Title III – Miscellaneous Highway Provisions. http://www.fhwa.dot.gov/legsregs/title3.html#309

Forkenbrock, D.J. and G.E. Weisbrod. 2001. Guidebook for Assessing the Social and Economic Effects of Transportation Projects. NCHRP Report 456.

Galehouse, L., J.S. Moulthrop, and R.G. Hiks. 2006. Principles of Pavement Preservation. Pavement Preservation Compendium II, September 2006. Federal Highway Administration.

GHSA, Governors Highway Safety Association. 2014. Bicyclist Safety. Governors Highway Safety Association, prepared by Dr. Allan Williams.

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

Greene,S., M. Akbarian, F.J. Ulm, J. Gregory. 2013. Pavement Roughness and Fuel Consumption. Concrete Sustainability Hub, Massachusetts Institute of Technology.

Grunwald, M. 2016. A new Obama emissions play. Politico, April 18, 2016. <http://www.politico.com/agenda/story/2016/04/a-new-obama-emissions-play-000095>

HUD, U.S. Department of Housing and Urban Development. Six Livability Principles. <http://portal.hud.gov/hudportal/HUD?src=/program_offices/economic_resilience/Six_Livability_Principles> Accessed Jul. 7, 2015.

Hunter, W.W., J.C. Stutts, W.E. Pein, C.L. Cox. 1996. Pedestrian and Bicycle Crash Type of the Early 1990's. FHWA-RD-95-163.

IEA, International Energy Agency. 2016. Global EV Outlook 2015. <http://www.iea.org/evi/Global-EV-Outlook-2015-Update_2page.pdf>

Interagency Working Group on Social Cost of Carbon, United States Government. 2013. Technical Support Document: - Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866.

Intergovernmental Panel on Climate Change. IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Table 1.4, Pg. 1.23

International Infrastructure Management Manual. 2006. National Asset Management Steering Group.

Kershner, J. 2011. NEPA, the National Environmental Policy Act. http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=9903, Accessed on Apr 11, 2016.

Lane, B.W. and C.P.Sherman. 2012. Using the Kaldor-Hicks Tableau to Assess Sustainability in Cost-Benefit Analysis in Transport: An Example Framework for Rail Transit. Master in Public Administration – University of Texas at El Paso Working Paper Series.

Lidicker, J., N. Sathaye, and A. Horvath. 2013. Pavement Resurfacing Policy for Minimization of Life-Cycle Costs and Greenhouse Gas Emissions. ASCE Journal of Infrastructure Systems. American Society of Engineers. Vol. 19, pg. 129-137.

Linstone, H.A. and M. Turoff. 2002. The Delphi Method Techniques and Applications.

Los Angeles County. 2011. Model Design Manual for Living Streets.

Marsden, G. 2015. Sustainable Transportation: Indicators, Frameworks and Performance Management. < http://www.slideshare.net/ITSLeeds/sustainable-transport-will-it-ever-really-count>

Maurer, L. K., T.J. Mansfield, L.B. Lane, J. Hunkins. 2013. Blueprint for Sustainability, One Department of Transportation's Pursuit of Performance-Based Accountability. Transportation Research Record: Journal of the Transportation Research Board, No. 2357, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 13–23. DOI: 10.3141/2357-02

McPherson, E.G. and J. Muchnick. 2005. Effects of Street Tree Shade on Asphalt Concrete Pavement Performance. Journal of Arboriculture 31(6).

Mead, J., C. Zegeer, and M. Bushell. 2014. Evaluation of Pedestrian-Related Roadway Measures: A Summary of Available Research. Federal Highway Administration DTFH61-11-H-00024.

Nabors, D., E. Goughnour, L. Thomas, W. DeSantis, M. Sawyer. 2012. Bicycle Road Safety Audit Guidelines and Prompt Lists. FHWA-SA-12-018.

NHTSA. 2008. Evaluation of the Miami-Dade Pedestrian Safety Demonstration Project. By Ch. Zeeger, D. Henderson, R. Blomberg, et al.

NHTSA. 2009. Traffic Safety Performance Measures for States and Federal Agencies.

NHTSA. (2015a). Traffic Safety Facts, 2013 Data, Bicyclists and Other Cyclists. DOT HS 812 151.

NHTSA. (2015b). Traffic Safety Facts, 2013 Data, Pedestrians. DOT HS 812 124.

National Renewable Energy Laboratory. NREL. 2013. Clean Cities 2013 Annual Metrics Report. Prepared by Caley Johnson and Mark Singer.

NCHRP Report 551. Cambridge Systematics, Inc., PB Consult, Inc. and Texas Transportation Institute. 2006. Performance Measures and Targets for Transportation Asset Management. National Cooperative Highway Research.

NOAA National Centers for Environmental Information, State of the Climate: Global Analysis for Annual 2015, published online January 2016, retrieved on March 31, 2016 from http://www.ncdc.noaa.gov/sotc/global/201513.

NYSDOT. Jobs Created and Employment Reporting. retrieved on August 6, 2015 from <https://www.dot.ny.gov/recovery/jobs>

OECD. 2001. Performance Indicators for Road Sector.

Park, K., N.E. Thomas, K.W. Lee. 2007. Applicability of the International Roughness Index as a Predictor of Asphalt Pavement Condition. ASCE Journal of Transportation Engineering. Vol. 133, No. 12.

Park, N., E. Deakin and J.S. Lee. 2014. Perception-Based Walkability Index to Test Impact of Microlevel Walkability on Sustainable Mode Choice Decisions. Transportation Research Record: Journal of the Transportation Research Board, No. 2464, Transportation Research Board of the National Academies, Washington, D.C., pp. 126–134. DOI: 10.3141/2464-16.

Partners for Livable Communities. < http://www.livable.org/index.php> Accessed Jun 3, 2015.

Politico. 2016. "A new Obama emissions play. The administration floats a rule governing transportation projects." Article by Michael Grunwald. <http://www.politico.com/agenda/story/2016/04/a-new-obama-emissions-play-000095#ixzz4JznHCBGw> Accessed Aug 14, 2016.

Ramani, T.L., J. Zietsman, K. Ibarra, and M. Howell. 2013. Addressing Sustainability and Strategic Planning Goals Through Performance Measures Study of Bus Rapid Transit Systems in El Paso, Texas. Transportation Research Record: Journal of the Transportation Research Board, No. 2357, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 33–40. DOI: 10.3141/2357-04

Rosengren, B. 2001. 2340th Council meeting - Transport/ Telecommunications - Luxembourg, 4-5 April 2001. <http://corporate.skynet.be/sustainablefreight/trans-counci-conclusion-05-04-01.htm> Accessed Mar 14, 2016.

SanDAG (San Diego Association of Governments). 2013. Statewide Performance Monitoring Indicators for Transportation Planning. Final Report.

San Francisco Transportation Code. 2008. Article 700. 702 Designated Speed Limits.

Simi, G., P. Rose, and E. Young. 2016. San Francisco Planning Commission adopts resolution to immediately update the environmental review process. Press release, March 3, 2016. <http://sf-

planning.org/article/san-francisco-planning-takes-lead-modernizing-environmental-review-new-development-projects>

SHRP 2. 2012. Interactions Between Transportation Capacity, Economic Systems, and Land Use. Strategic Highway Research Program, Report S2-C03-RR-1.

SHRP 2. 2012. Interactions Between Transportation Capacity, Economic Systems, and Land Use.

SHRP 2 Report S2-CO9-RW-2. PB Americas, Inc., Cambridge Systematics, Inc., E.H. Pechan & Associates, Inc., Euquant, Inc. 2013. Practitioners Guide to Incorporating Greenhouse Gas Emissions into the Collaborative Decision-Making Process. The Second Strategic Highway Research Program. Transportation Research Board, Washington D.C.

Smith, R. 1996. Conceptual Description of Prioritization and Impact Analysis (Scenario) by MTCPMS Software.

Smith, R. 2009. Conceptual Description of PCI Target-Driven Scenario for MTC StreetSaver PMP Software.

Smith, R. 2014. Conceptual Description of Non-pavement Asset Management For the MTC StreetSaver™ StreetSaver PMP Software.

Schlossberg, M. 2006. From TIGER to Audit Instruments: Measuring Neighborhood Walkability with Street Data Based on Geographic Information Systems. In Transportation Research Record: Journal of the Transportation Research Board, No. 1982, Transportation Research Board of the National Academies, Washington, D.C., pp. 48–56.

Schor, E. LaHood's Twelve-Word Definition of "Livability." StreetsBlog USA, Oct. 5, 2009. <http://dc.streetsblog.org/2009/10/05/lahood-defineslivability-in/> Accessed Jun. 5, 2015.

Slater, R.E. 1999. TEA-21 , One Year Anniversary Highlights of Accomplishments. http://www.fhwa.dot.gov/tea21/oneyrhl.htm

Smart Growth America. 2015. What are complete streets? <http://www.smartgrowthamerica.org/complete-streets/complete-streets-fundamentals/complete-streets-faq> Accessed Jul. 23, 2015.

Stromberg, Joseph. 2016. Highways gutted American cities. So why did they build them?, Mar 18,2016 http://www.vox.com/2015/5/14/8605917/highways-interstate-cities-history Accessed Mar 19,2016.

Tang, S.L.,I.U. Ahmad, S.M. Ahmed and M. Lu. 2004. Quantitative Techniques for Decision Making in Construction. Hong Kong University Press.

Tesla Motors. 2016. The Week that Electric Vehicles Went Mainstream. <https://www.teslamotors.com/blog/the-week-electric-vehicles-went-mainstream?utm_campaign=Blog_Model3_040716&utm_source=Twitter&utm_medium=social> Accessed Apr 7, 2016.

Thompson, P.D., K.M. Ford, M.H.R. Arman, S. Labi, K.C. Sinha, A.M. Shirole. 2012. Estimating Life Expectancies of Highway Assets. NCHRP Report 713, Volume 1.

UK Highways Agency. 2011. Climate Change Risk Assessment August.

USDOT (United States Department of Transportation). 2012. Moving Ahead for Progress in the 21st Century Act (MAP-21), A Summary of Highway Provisions.

United States Department of Transportation, 2016. Beyond Traffic 2045, Trends and Choices. Draft.

United States Government, Interagency Working Group on Social Cost of Carbon. 2013. Technical Support Document: - Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866.

U.S. Energy Information Administration. EIA. 2015."Frequently Asked Questions: How much carbon dioxide is produced by burning gasoline and diesel fuel?" < http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11> Accessed Jun 11, 2015.

Virginia Department of Transportation. VDOT. 2004. Guidelines for the installation of Marked Crosswalks. L.E. Dougald. FHWA/VTRC 05-R18

Velasquez, M., and P.T. Hester. 2013. An Analysis of Multi-Criteria Decision Making Methods. International Journal of Operations Research Vol. 10, No. 2, 56-66.

Watanatada, T. C.G. Harral, W.D.O. Paterson, A.M. Dhareshwar, A. Bhandari, and K. Tsunokawa. 1987. The Highway Design and Maintenance Standards Model, Volume 1, Description of the HDM-III Model. A World Bank Publication.

Weingroff, R. undated. President Ronald Reagan and the Surface Transportation and Uniform Relocation Assistance Act of 1987. https://www.fhwa.dot.gov/infrastructure/rw01e.cfm

Witczak, M. 1978. Determination of Flexible Pavement Life, Report No. FHWA/MD/R-79/1, Federal Highway Administration, Washington, DC.

World Bank. undated. Measuring Road Transport Performance. < http://www.worldbank.org/transport/roads/rdt_docs/annex1.pdf>

World Bank. 2011. CO2 emissions (metric tons per capita), Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States. < http://data.worldbank.org/indicator/EN.ATM.CO2E.PC>

World Health Organization. WHO. 2016. Global Report on Diabetes. <http://apps.who.int/iris/bitstream/10665/204871/1/9789241565257_eng.pdf?ua=1>

Zahabi, S.A.H., A. Chang, L.F. Miranda-Moreno, and Z. Patterson. 2016. Exploring the link between typologies, bicycle infrastructure and commuting cycling over time and the potential impact on commuter GHG emissions. Transportation Research Part D 47 (2016) 89-103.

Zhang, M., and N. Kukadia. Metrics of Urban Form and the Modifiable Areal Unit Problem. In Transportation Research Record: Journal of the Transportation Research Board, No. 1902, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 71–79.

Zietsman, J., T. Ramani. 2011. Sustainability Performance Measures for State DOTs and Other Transportation Agencies. NCHRP Report 708.

Zietsman, J., T. Ramani, J. Potter, J. Reeder, J. DeFloria. 2011. A Guidebook for Sustainability Performance Measurement for Transportation Agencies, National Cooperative Highway Research Report 708, Washington, D.C., USA.

Appendix A: Crosswalk Locations

The following figures show the locations that were identified as high-risk sites for pedestrians through a crash data analysis in the Transportation Injury Mapping System (TIMS) and are candidates for new crosswalk markings in the MOS model.

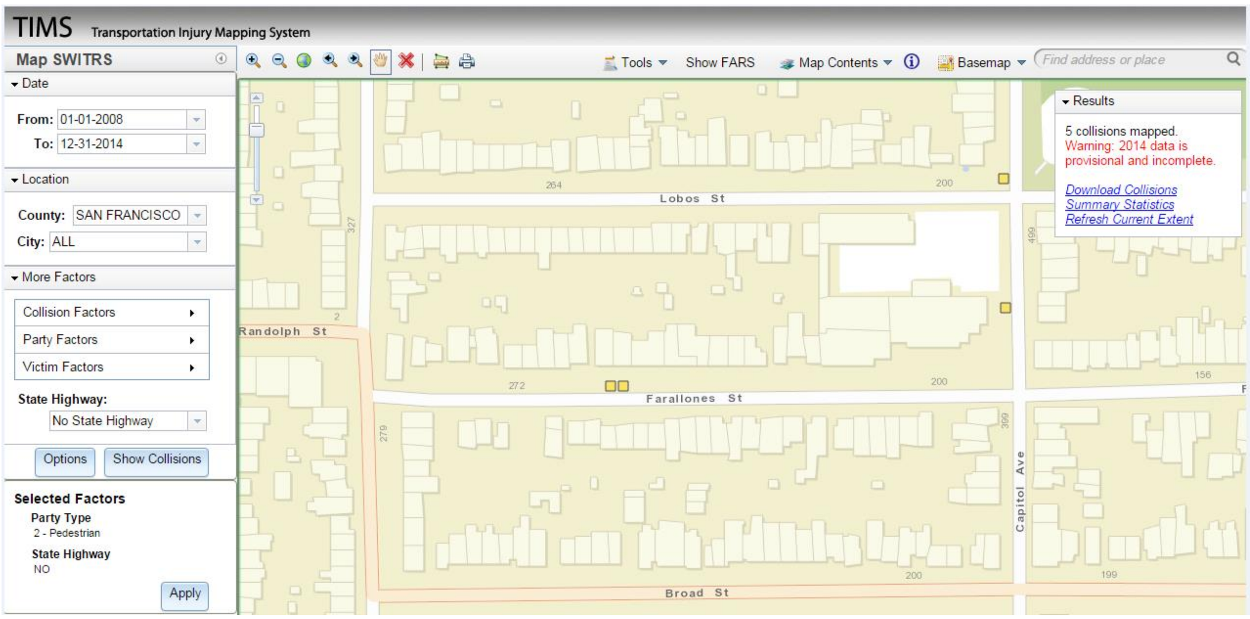


Figure A.1: Section ID 1 (source: TIMS)

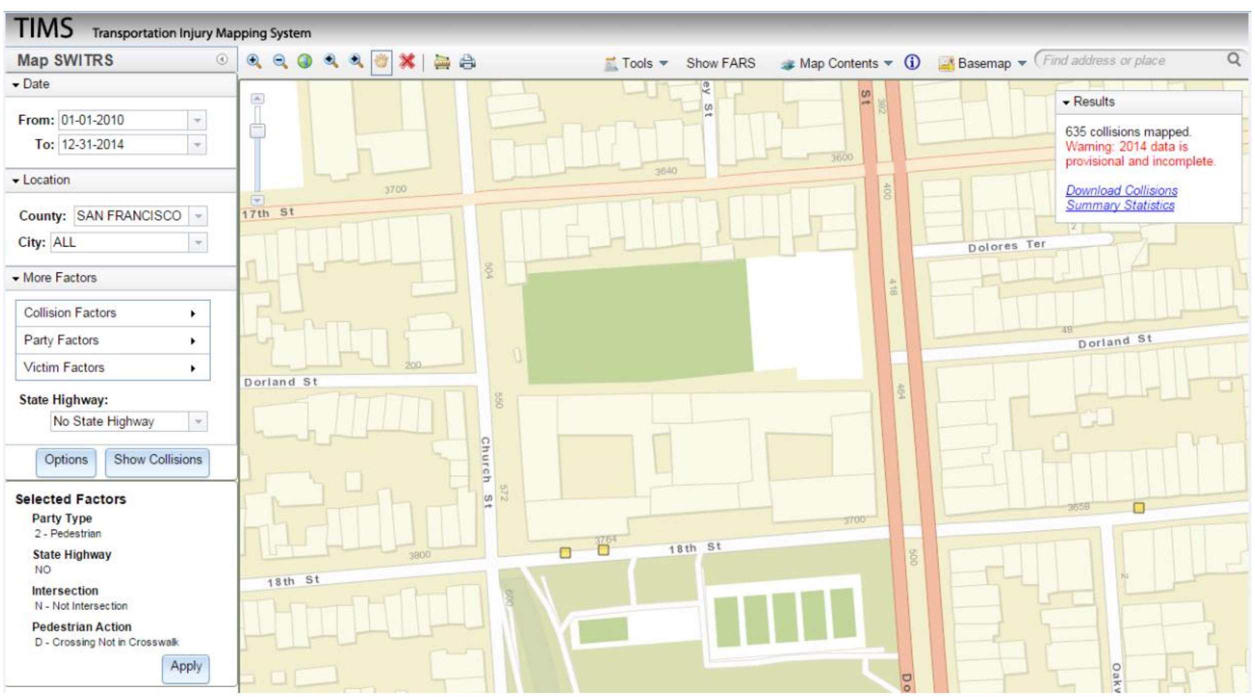


Figure A.2: Section ID 3 (source: TIMS)

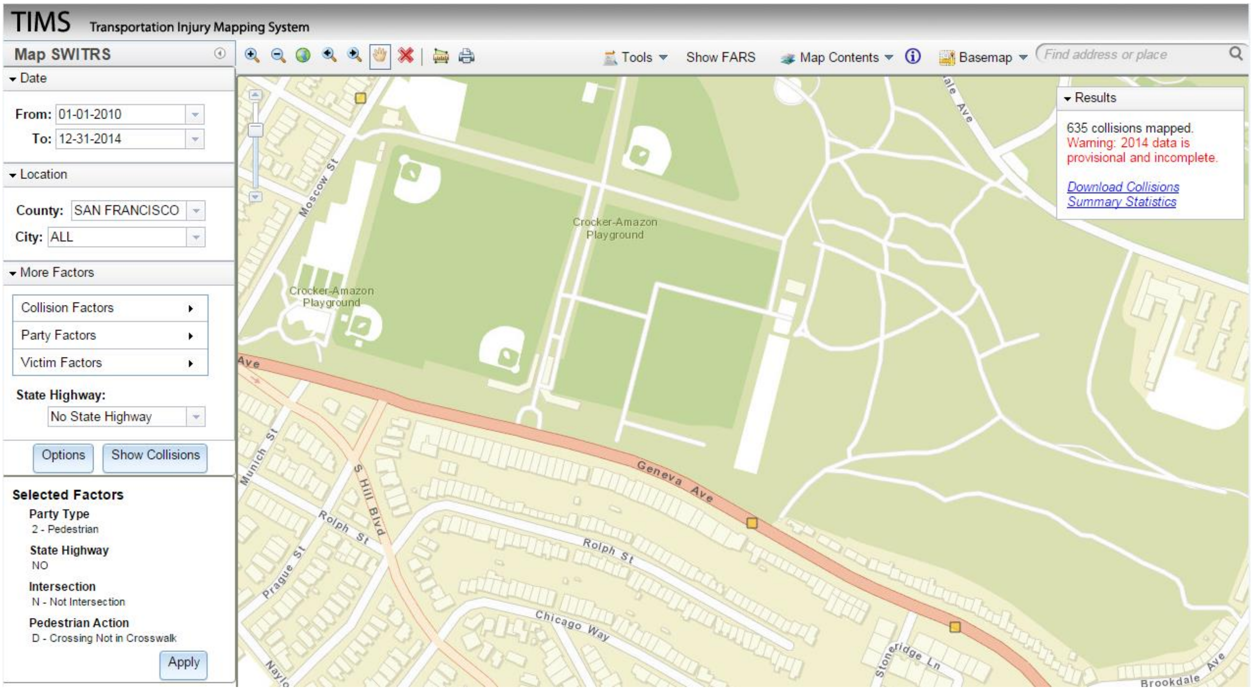


Figure A.3: Section ID 4 (source: TIMS)


Figure A.4: Section ID 4, a teenager crossing a high-volume 4-lane road with a 35 mph speed limit to access the playground, in the place where previously in 2014 a pedestrian was hit

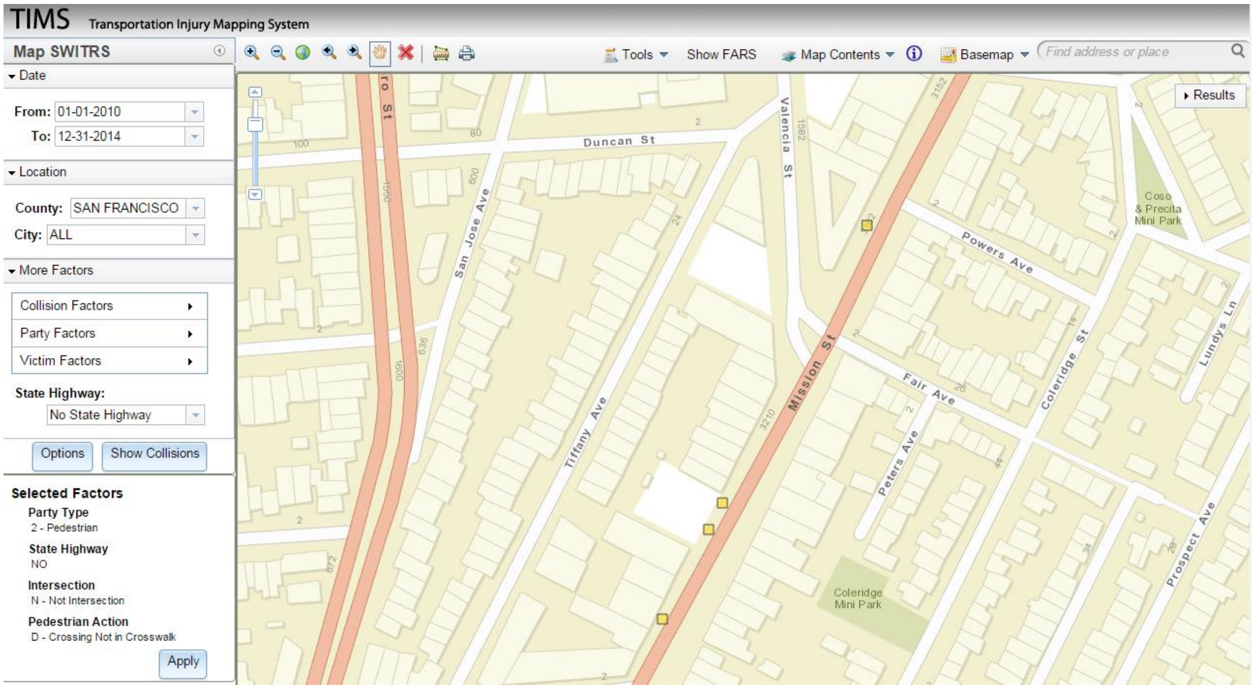


Figure A.5: Section ID 7 (source: TIMS)

Figure A.6: Section ID 7, as TIMS indicates, there have been two crashes at the entrance of this parking lot where pedestrians wanted to cross to the other side of the street without going 330 feet to the nearest crosswalk

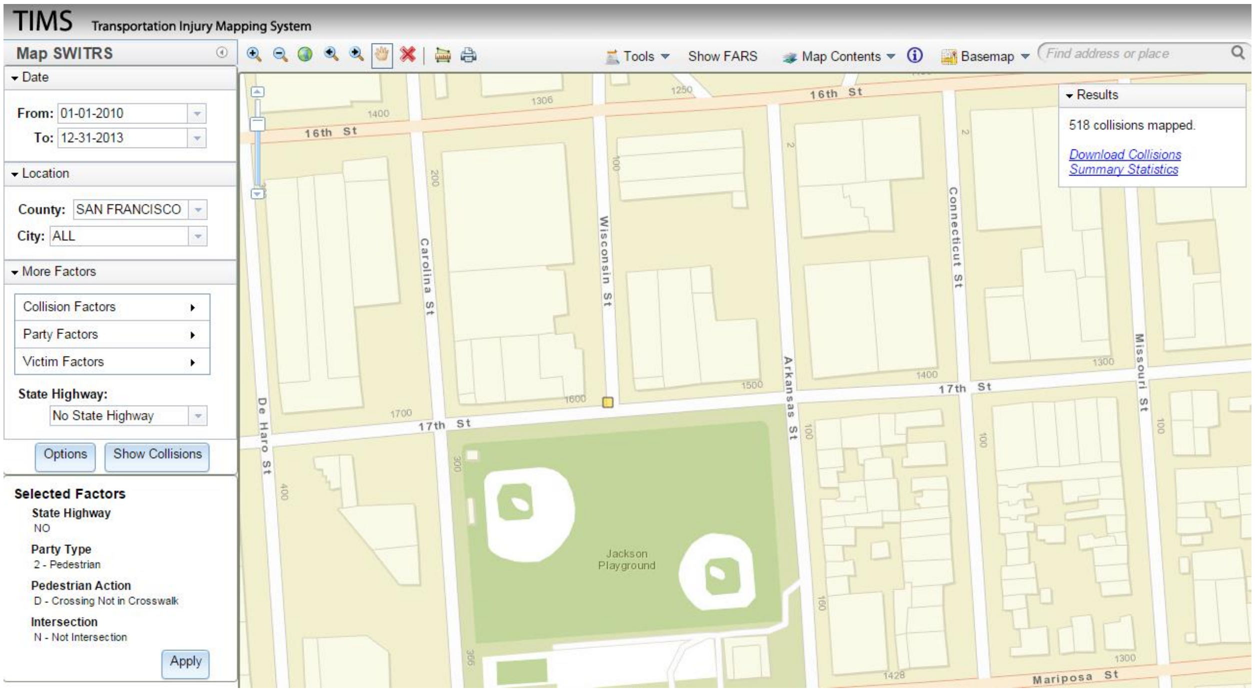


Figure A.5: Section ID 9 (source: TIMS)

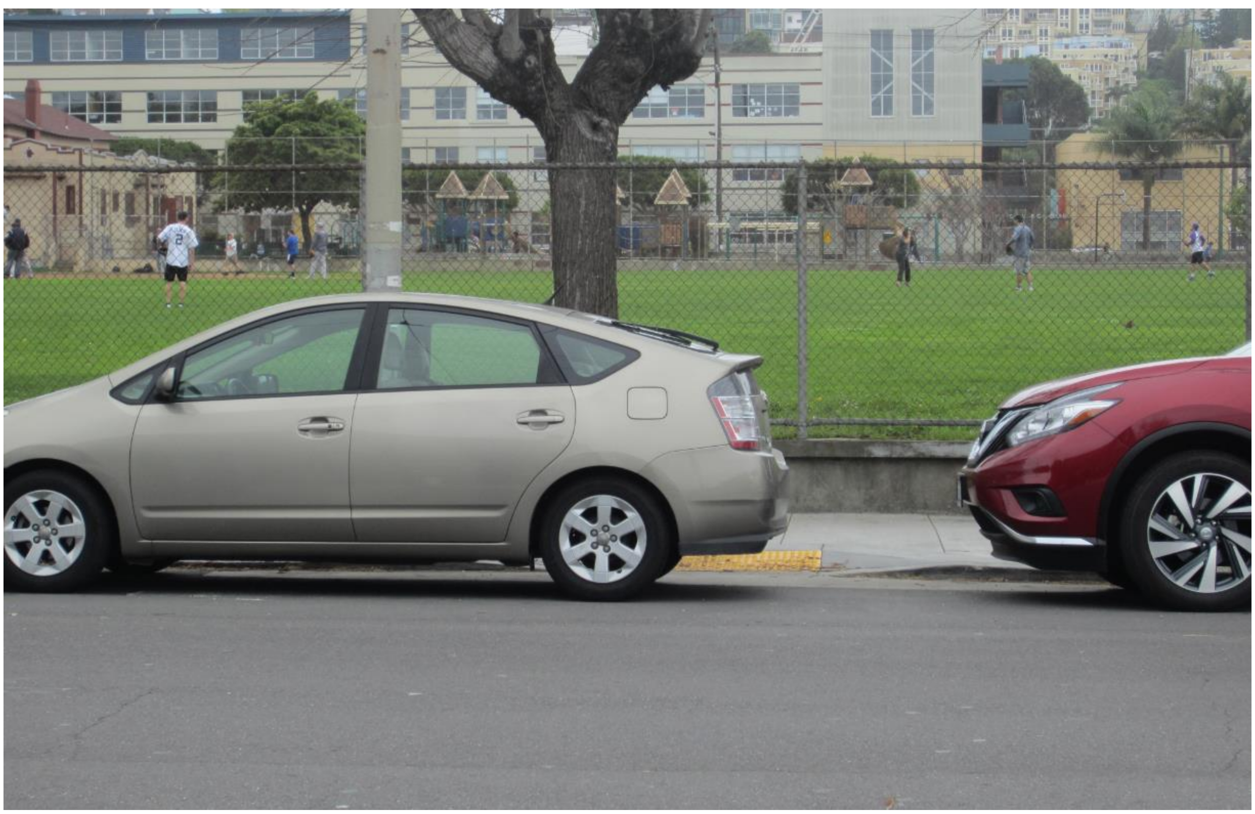


Figure A.6: Section ID 9, unmarked crosswalk in front of a playground blocked by parked vehicles

Vita

Markéta Vavrová was born in Kadan, Czech Republic. In 2010 she received her Bachelor's Degree of Transportation Engineering in Automation and Informatics from the Czech Technical University in Prague. She was awarded with a scholarship from the European Commission's Directorate General for Education and Culture to pursue a dual Master's degree at the Czech Technical University in Prague (CTU) and the University of Texas at El Paso (UTEP).

She graduated in 2012 with a Master's Degree in Civil Engineering from UTEP and a Master's Degree in Transport and Logistics Systems from CTU. Her master thesis, titled "Development of an electronic vehicle miles traveled toll model," presented a distance-based fee as an alternative to the fuel tax, and received the Friedrich List Award as an outstanding scientific paper in the field of transportation in the European Union.

In the same year, she started working as a research associate at the Center for Transportation Infrastructure Systems at UTEP under the guidance of Dr. Carlos Chang. She conducted research for National Cooperative Highway Research, Tier I University Transportation Center Consortium led by Rutgers Center for Advanced Infrastructure and Transportation, as well as Metropolitan Transportation Commission in Oakland, CA. She received the International Road Federation Executive Leadership Fellowship in Washington D.C. and became the president of Class 2014. In her research, she focuses on ways to implement sustainability into transportation asset management decisions, leading to livable and safe streets for all road users.

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