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A Multi-Objective Asset Management Approach to Evaluate Maintenance Strategies for Funding Allocation

Carlos M. Chang*, Ph.D., P.E., Associate Professor, Department of Civil Engineering, The University of Texas at El Paso, El Paso, TX, USA

Marketa Vavrova, MSc, Research Assistant, Department of Civil Engineering, The University of Texas at El Paso, El Paso, TX, USA

Roger E. Smith, Ph.D., P.E.., Professor, Retired, Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, USA

Sui Tan, P.E., MTC Pavement Management Program Manager, Metropolitan Transportation Commission, Oakland, CA, USA

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* Corresponding author

ABSTRACT

Modern asset management aims to provide the user's expected level of service in the transportation infrastructure assets in the most cost-effective manner while also accounting for broader social and enviromental impacts. The decision-making process is complex due to many potential conflicting goals that need to be balanced in the final solution. This paper describes a holistic multi-objective asset management approach to integrate environmental related measures with traditional perfomance measures. A robust framework for managing infrastructure assets is proposed for implementation, and a case study focused on asphalt concrete (AC) pavements demonstrates its applicability, evaluating various maintenance strategies from a multi-objective perspective. The case study shows that timely applied preservation leads to lower emissions and lower fuel consumption. In the example, savings estimates of 662,310,738 kg CO2 over a 20 year period that are equivalent to $31 million in social costs for a 940 mile network. By considering economic, environmental, and social impacts; the multi-objective asset management approach improves the decision making process and contribute to better balanced funding allocation decisions when developing maintenance strategies.

INTRODUCTION

Transportation Asset Management (TAM) has been gaining popularity in the United States (U.S.) and worldwide enabling to provide the required level of service for the transportation infrastructure assets in the most cost-effective manner. In modern transportation asset management, sustainability considering the environmental and social factors 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 considered. 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 in a cost-effective manner at a certain level of service, but also to incorporate into the decision making process environmental and social sustainability factors. Emissions from on-road vehicles is one of the factors that can be added into the traditional decision making analysis when developing a pavement management strategy. A strategy that maintains a road in good condition has lower emissions and fuel consumption for users.

BACKGROUND

Asset management is a decision-making process based on business, economic, and engineering principles to make cost-effective investments to preserve, operate, maintain, repair, and renew aging infrastructure assets. From a stakeholder's perspective, there are fundamental system performance dimensions including: environmental health, community livability, mobility, safety, service levels, and vehicle operating costs among others. From an agency's perspective, these system performance dimensions belong to asset class domains in which interdependency among infrastructure assets exist. Each asset class domain can be associated with a performance dimension to be managed by the agency. As the number of individual asset performance dimensions included in the analysis increases, the complexity of the multi-dimensional problem also increases.

Traditional TAM creates maintenance plans based on the asset condition and the funding available. In order to expand the limited view of the complex decision situation and make better informed cost-effective decisions, the impact on environmental and social sustainability can be added. Condition of the transportation infrastructure impacts the economics, resident's quality of life as well as the environment.

It was demonstrated that it is more cost-effective to maintain pavements in good condition than to let them deteriorate (Witczak 1987), as the cost of rehabilitation or reconstruction can be 6 to 10 times more expensive than timely preventive maintenance (Galehouse et al. 2006). Lately, it is observed an apparent trend toward sustainability, both in road construction practices and in the outcomes from the transportation modes.

Due to issues with air pollution and limited non-renewable resources, there is an ongoing effort to improve fuel efficiency of vehicles. One of the many ways to achieve that is to preserve roads in acceptable condition. A numer of 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). Emissions from transportation can be addressed as an environmental issues. On the other hand, social aspects reflect the efforts to increase livability in neighborhoods and improve safety. There is a significant shift towards alternative modes of transportation through accommodating pedestrians, cyclist and mass transit in the urban roadways. Although, traditional TAM is usually oriented towards motorized vehicles, and often lack to accommodate the other user's needs of the roadway.

MULTI-OBJECTIVE ASSET MANAGEMENT APPROACH

Metropolitan Transportation Comission (MTC) in Oakland, California is exploring ways to address the environmental and social sustainability impacts within its Pavement Management System (PMS), StreetSaver. One of the options taken into consideration is to address sustainability through four objectives:

- Objective I: Reduce Vehicle Emissions
- Objective II: Synchronize Utility Cuts and Bikeway Maintenance
- Objective III: Improve Safety of Drivers, Pedestrians and Bicyclists
- Objective IV: Foster Livability

A possible approach is shown in a block diagram of the current StreetSaver process and sustainability objectives in **Figure 1**. Environmental sustainability is addressed through the impact of pavement condition on fuel consumption and emissions. Economic sustainability is inherent in the decision making process since it is a key reason for maintaining a good state of repair while balancing costs and benefits of maintenance treatments. The benefits can include savings in fuel, emissions, vehicle operating costs as well as health benefits from multi-modal transportation network. Total costs can include maintenance treatment costs, travel time delay, and environmental costs due to gas emissions. Optimal maintenance timing is fostered through the coordination of pavement maintenance with utility works and bikeway works. Social sustainability is addressed through improving roadway safety for all users and fostering livability.

Therefore, sustainable Target Driven Scenario objectives can include:

- Minimize emissions and fuel consumption of on-road vehicles.
- Not exceed emissions of the optimal maintenance program by more than a given limit.
- Minimum PCI for sections that carry mass transit lines, on-road bikeways or are in the proximity of hospitals, schools, parks and commercial centers.

Additionally, the following prioritization choices are considered:

- Synchronize pavement maintenance with utility works.
- Synchronize pavement maintenance with on-road bikeway maintenance.
- Synchronize pavement maintenance with safety and livability improvements.

The multi-objective model aims to take into account performance, available funds, as well as sustainability. Further study should identify the most important sustainability features for a particular agency to assimilate social and environment sustainability related measures into its pavement management practices.

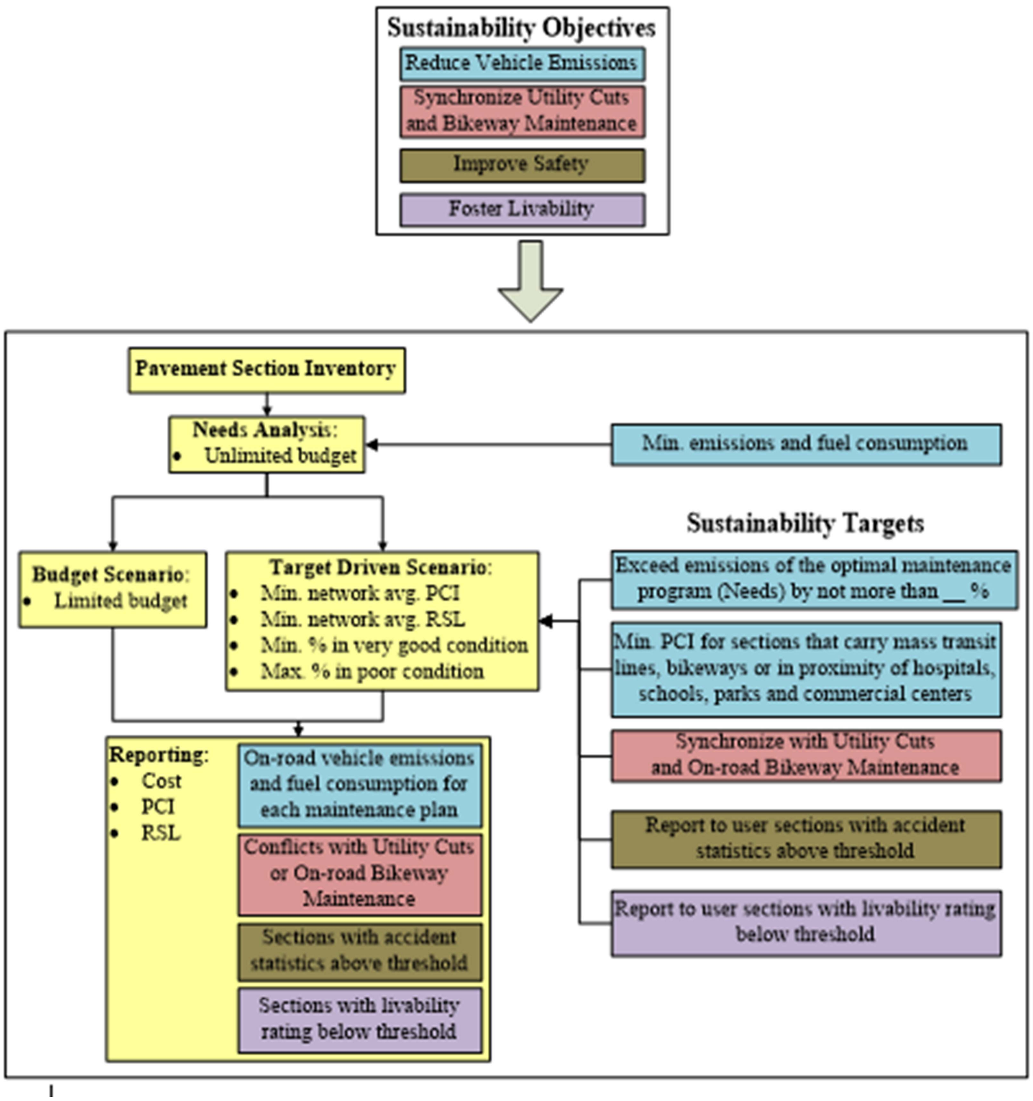

Figure 1. StreetSaver decision-making process with expanded sustainability objectives.

Current thinking is to accommodate the following features in the sustainable multi-objective model:

Economic measure:

- Agency and user costs due to pavement condition.

Environmental measures:

- On-road vehicle fuel consumption estimated from pavement roughness.
- Emission (CO_2) reduction from on-road vehicles estimated from pavement roughness, pavement maintenance scenario compared to Do-Nothing.
- Change in emissions (CO_2) from on-road vehicles, pavement maintenance scenario compared to Needs (unlimited budget scenario).

Social measures:

- Change in condition of sections carrying mass transportation lines.
- Change in condition of sections carrying bikeways.
- Optionally, social cost of CO_2 can be estimated.

Framework for estimation of CO2 emissions from use phase

The framework presented in this paper compares CO_2 emissions based on the pavement condition resulting from different maintenance strategies as shown in **Figure 2**.

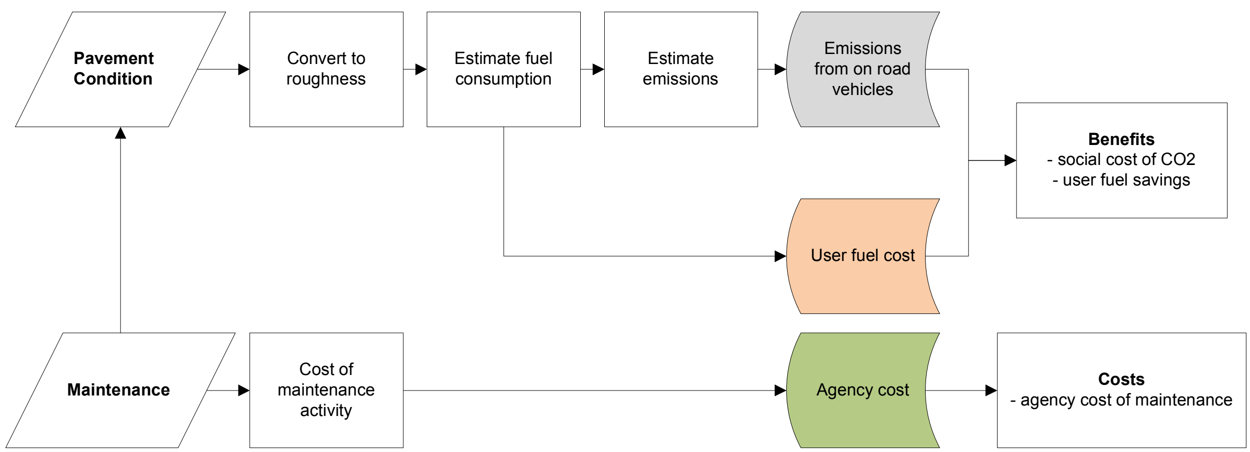

Figure 2. Framework for evaluating maintenance strategies based on pavement condition.

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). The assumption is that better pavement condition (lower roughness) reduces fuel consumption and corresponding emissions. There are several other factors influencing the fuel consumption such as fuel, engine, vehicle weight, tire pressure, speed, driving style. For the purpose of showing an example, generalizations will be made in order to make the estimate.

Pavement condition can be described by several indices, and the most popular are Pavement Condition Index (PCI) and International Roughness Index (IRI). 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).

PCI can be converted to IRI using for example the equation developed by multilinear regression analysis of 39 AC highway pavement datasets in the San Francisco Bay area (Dewan 2005):

$$IRI\ [m/km] = 0.0171*(153-PCI)$$

IRI can be associated with fuel consumption levels by HDM-4 estimates that were calibrated in 2010 for U.S. conditions (Chatti and Zaabar 2010), as **Table 1** shows.

Table 1. Effect of Roughness on Fuel Consumption. (Chatti and Zaabar 2010)

		Calibrated HDM 4 model					
		Base (mL/km)	Adjustment factors from the base value				
		IRI (m/km)					
Speed	Vehicle Class	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

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

As CO2 accounts for 95% of mobile-source emissions (SHRP 2013), it can be chosen to represent the overall emissions. CO2 emissions can be obtained by multiplying the fuel consumed by emission factors established by the Intergovernmental Panel on Climate Change (IPCC 2006). In this manner, CO2 emissions can be calculated for gasoline, diesel, biogasoline, biodiesel, natural gas, and propane.

Figure 3 summarizes the process of estimating CO2 emissions from motorized vehicles on a pavement section of a certain condition, expressed by IRI.

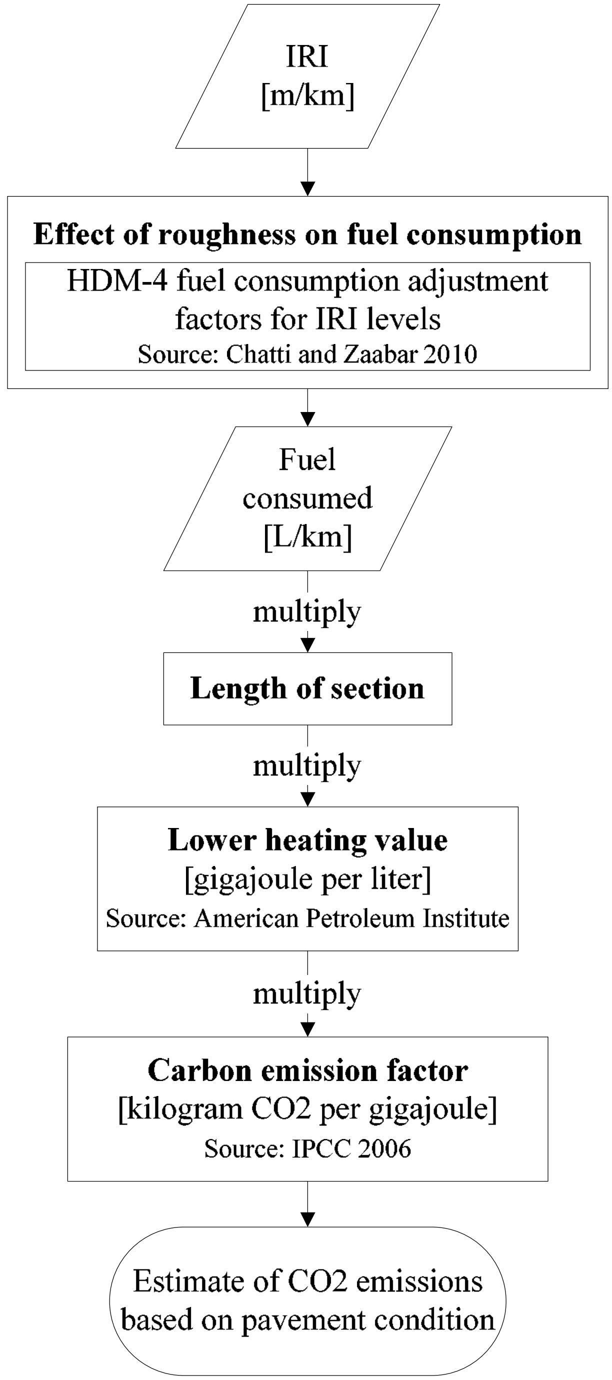

Figure 3. Process of CO_2 Estimation using IPCC Emissions Factors.

A more accurate estimate of emissions, not limited to CO_2, can be obtained by modelling them in MOVES2010b (Motor Vehicle Emission Simulator). Environmental Protection Agency (EPA) develops MOVES 2010b and the model considers variable speed and acceleration. AADT can be multiplied by section length and converted to VMT which is an input into EMFAC2011 in California, or MOVES2010b in the rest of U.S.; then emissions can be estimated based on the specific regional fleet. Wang (2013) describes the process of updating rolling resistance parameter in MOVES2010b based on pavement condition.

Social cost of CO_2

Additionally, CO_2 emissions can be converted to dollars, using for example the social cost of CO_2 for 2010-2050 (Interagency Working Group on Social Cost of Carbon, United States Government 2013). "The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions that impact cumulative global emissions. 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 take into account changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (Interagency Working Group on Social Cost of Carbon, United States Government 2013). Federal agencies such as EPA use the SCC to estimate the benefits (value of damages avoided) of CO_2 reductions. Table 2 shows an example of the SCC for discount rates 5%, 3% and 2.5%,

Table 2. 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

Reduced emissions can be calculated either towards Do-Nothing scenario or between multiple scenarios under analysis. It is expected that the Optimal Maintenance Scenario with unlimited funding will yield the highest reduction in CO_2 emissions (compared to Do-Nothing). Other scenarios can have the reduction in CO_2 calculated and reported to the user. The total cost in a planning period can include the agency costs (currently reported in all PMS) as well as the social cost of CO_2 (SCC). This approach leads to a benefit-cost ratio for each maintenance scenario under analysis. Benefits can be expressed in terms of treatment effectiveness as well as savings in social cost and vehicle operating costs based on pavement condition.

When comparing maintenance scenarios from an environmental perspective, the following performance measures can be used:

- GHG emissions from preservation, rehabilitation and reconstruction activities
- On-road vehicle fuel consumption estimated from pavement roughness
- Emission (CO_2) reduction from on-road vehicles estimated from pavement roughness, pavement maintenance scenario compared to a Do-Nothing scenario
- Change in emissions (CO_2) from on-road vehicles, a given pavement maintenance scenario compared to Needs (unlimited budget scenario)
- Social cost of CO_2

CASE STUDY

A case study was prepared to illustrate the enhanced asset management decision-making process, incorporating environmental performance measures in terms of SCC, in a pavement network of 940 miles with asphalt concrete (AC) sections withstanding an annual average daily traffic (AADT) of 20,0000 vehicles. Figure 4 shows a decision tree with five condition levels and recommended treatments.

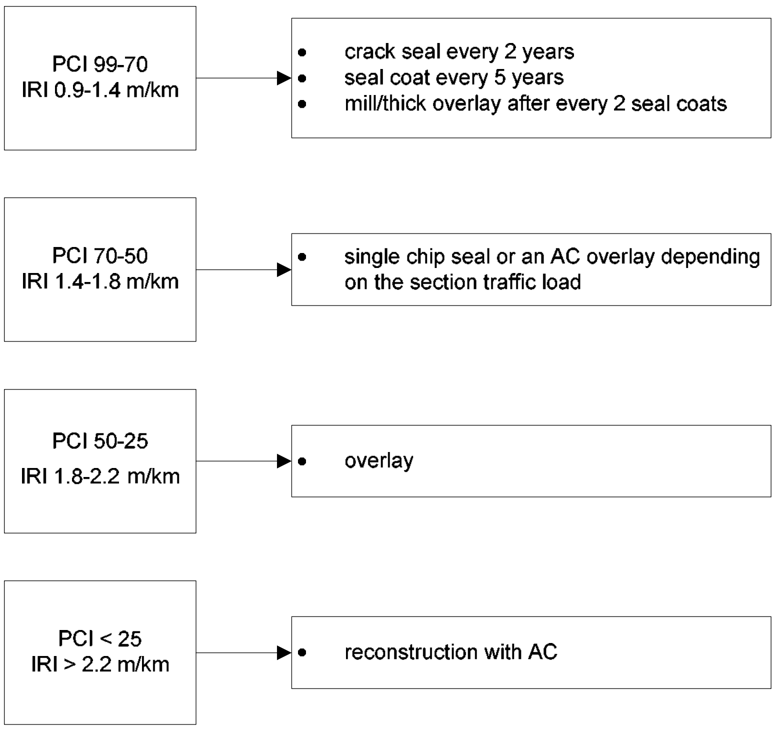

Figure 4. Treatments in Optimal Maintenance scenario.

The following scenarios were considered in the analysis:

- Optimal Maintenance (unlimited funding)
- Do-Nothing
- No Preventive Maintenance (PCI 99-70, IRI 0.9-1.4)

Figures 5, 6 and **7** show the results of the scenarios analyses. Optimal maintenance scenario is the ideal situation when an agency has sufficient funds to apply all maintenance treatments identified as needed by the Pavement Management System. Do Nothing scenario assumes no funding over the 20 year analysis period and results in 3% overall cost increase due to fuel consumption, emissions, and social costs when compared to the optimal scenario.

Optimal Maintenance (unlimited funding)										
Year	Agency Cost per Year		PCI	Asset Value	International Roughness Index [in/mi]	Fuel consumption [gallon per mile]	CO2 Emissions [kg per vehicle-mi]	Network fuel consumption per year [gal]	Emissions per year [kg CO2 per network]	Social cost of CO2 [USD] at 3% discount rate
	PM	Rehab								
2014	$ 7,600,000	$ 140,991,000	94	$ 507,600,000	196.9	0.04585	0.389	314,634,797	2,670,607,816	$ 101,483,097
2015	$ -	$ -	87	$ 469,800,000	213.6	0.04594	0.390	315,264,067	2,675,949,031	$ 101,686,063
2016	$ 203,000	$ -	86	$ 464,400,000	216.1	0.04594	0.390	315,264,067	2,675,949,031	$ 101,686,063
2017	$ -	$ -	84	$ 453,600,000	221.2	0.04604	0.391	315,893,337	2,681,290,247	$ 101,889,029
2018	$ 285,000	$ -	83	$ 448,200,000	223.8	0.04604	0.391	315,893,337	2,681,290,247	$ 101,889,029
2019	$ 17,211,000	$ -	87	$ 469,800,000	213.6	0.04594	0.390	315,264,067	2,675,949,031	$ 101,686,063
2020	$ -	$ 8,790,000	91	$ 491,400,000	203.9	0.04594	0.390	315,264,067	2,675,949,031	$ 115,065,808
2021	$ 49,000	$ -	85	$ 459,000,000	218.6	0.04604	0.391	315,893,337	2,681,290,247	$ 115,295,481
2022	$ 88,000	$ -	83	$ 448,200,000	223.8	0.04604	0.391	315,893,337	2,681,290,247	$ 115,295,481
2023	$ 85,000	$ -	82	$ 442,800,000	226.4	0.04604	0.391	315,893,337	2,681,290,247	$ 115,295,481
2024	$ 7,632,000	$ -	83	$ 448,200,000	223.8	0.04604	0.391	315,893,337	2,681,290,247	$ 115,295,481
2025	$ -	$ -	81	$ 437,400,000	229.0	0.04604	0.391	315,893,337	2,681,290,247	$ 128,701,932
2026	$ 27,778,000	$ 10,334,000	89	$ 480,600,000	208.7	0.04594	0.390	315,264,067	2,675,949,031	$ 128,445,554
2027	$ -	$ -	82	$ 442,800,000	226.4	0.04604	0.391	315,893,337	2,681,290,247	$ 128,701,932
2028	$ 90,000	$ -	81	$ 437,400,000	229.0	0.04604	0.391	315,893,337	2,681,290,247	$ 128,701,932
2029	$ 27,791,000	$ -	82	$ 442,800,000	226.4	0.04604	0.391	315,893,337	2,681,290,247	$ 128,701,932
2030	$ 101,000	$ -	80	$ 432,000,000	231.7	0.04604	0.391	315,893,337	2,681,290,247	$ 139,427,093
2031	$ 2,125,000	$ -	79	$ 426,600,000	234.4	0.04613	0.392	316,522,606	2,686,631,463	$ 139,704,836
2032	$ 55,556,000	$ 10,334,000	90	$ 486,000,000	206.3	0.04594	0.390	315,264,067	2,675,949,031	$ 139,149,350
2033	$ 27,807,000	$ -	86	$ 464,400,000	216.1	0.04594	0.390	315,264,067	2,675,949,031	$ 139,149,350
TOTAL	$ 174,401,000	$ 170,449,000					7.809	6,312,832,577	53,583,075,216	$2,387,250,985

Figure 5. Optimal Maintenance scenario.

Do Nothing										
Year	Cost per Year		PCI	Asset Value	International Roughness Index [in/mi]	Fuel consumption [gallon per mile]	CO2 Emissions [kg per vehicle-mi]	Network fuel consumption per year [gal]	Emissions per year [kg CO2 per network]	Social cost of CO2 [USD] at 3% discount rate
	PM	Rehab								
2014	$ -	$ -	71	$ 383,400,000	257.5	0.04622	0.392	317,151,876	2,691,972,678	$ 102,294,962
2015	$ -	$ -	68	$ 367,200,000	266.8	0.04631	0.393	317,781,145	2,697,313,894	$ 102,497,928
2016	$ -	$ -	66	$ 356,400,000	273.3	0.04631	0.393	317,781,145	2,697,313,894	$ 102,497,928
2017	$ -	$ -	64	$ 345,600,000	279.9	0.04631	0.393	317,781,145	2,697,313,894	$ 102,497,928
2018	$ -	$ -	62	$ 334,800,000	286.8	0.04640	0.394	318,410,415	2,702,655,110	$ 102,700,894
2019	$ -	$ -	60	$ 324,000,000	293.9	0.04640	0.394	318,410,415	2,702,655,110	$ 102,700,894
2020	$ -	$ -	58	$ 313,200,000	301.2	0.04640	0.394	318,410,415	2,702,655,110	$ 116,214,170
2021	$ -	$ -	56	$ 302,400,000	308.8	0.04649	0.395	319,039,685	2,707,996,325	$ 116,443,842
2022	$ -	$ -	54	$ 291,600,000	316.6	0.04649	0.395	319,039,685	2,707,996,325	$ 116,443,842
2023	$ -	$ -	52	$ 280,800,000	324.8	0.04649	0.395	319,039,685	2,707,996,325	$ 116,443,842
2024	$ -	$ -	50	$ 270,000,000	333.3	0.04659	0.395	319,668,954	2,713,337,541	$ 116,673,514
2025	$ -	$ -	48	$ 259,200,000	342.1	0.04659	0.395	319,668,954	2,713,337,541	$ 130,240,202
2026	$ -	$ -	45	$ 243,000,000	356.0	0.04659	0.395	319,668,954	2,713,337,541	$ 130,240,202
2027	$ -	$ -	42	$ 226,800,000	370.9	0.04668	0.396	320,298,224	2,718,678,756	$ 130,496,580
2028	$ -	$ -	39	$ 210,600,000	387.0	0.04668	0.396	320,298,224	2,718,678,756	$ 130,496,580
2029	$ -	$ -	37	$ 199,800,000	398.3	0.04677	0.397	320,927,493	2,724,019,972	$ 130,752,959
2030	$ -	$ -	34	$ 183,600,000	416.6	0.04677	0.397	320,927,493	2,724,019,972	$ 141,649,039
2031	$ -	$ -	32	$ 172,800,000	429.7	0.04691	0.398	321,871,398	2,732,031,796	$ 142,065,653
2032	$ -	$ -	29	$ 156,600,000	451.0	0.04691	0.398	321,871,398	2,732,031,796	$ 142,065,653
2033	$ -	$ -	27	$ 145,800,000	466.4	0.04704	0.399	322,815,302	2,740,043,619	$ 142,482,268
TOTAL	$ -	$ -					7.905	6,390,862,007	54,245,385,955	$2,417,898,881
								1%	1%	1%

Figure 6. Do Nothing scenario.

No Preventive Maintenance scenario, in which no treatments are applied until the condition goes below PCI 70 (IRI 1.4), results in 1.2% overall cost increase due to fuel consumption, emissions, and social costs when compared to the Optimal Needs scenario.

No preventive maintenance										
Year	Cost per Year		PCI	Asset Value	International Roughness Index [in/mi]	Fuel consumption [gallon per mile]	CO2 Emissions [kg per vehicle-mi]	Network fuel consumption per year [gal]	Emissions per year [kg CO2 per network]	Social cost of CO2 [USD] at 3% discount rate
	PM	Rehab								
2014	$ -	$ 109,901,000	84	$ 453,600,000	221.2	0.04604	0.391	315,893,337	2,681,290,247	$ 101,889,029
2015	$ -	$ -	81	$ 437,400,000	229.0	0.04604	0.391	315,893,337	2,681,290,247	$ 101,889,029
2016	$ -	$ -	79	$ 426,600,000	234.4	0.04613	0.392	316,522,606	2,686,631,463	$ 102,091,996
2017	$ -	$ -	77	$ 415,800,000	240.0	0.04613	0.392	316,522,606	2,686,631,463	$ 102,091,996
2018	$ -	$ -	75	$ 405,000,000	245.7	0.04613	0.392	316,522,606	2,686,631,463	$ 102,091,996
2019	$ -	$ -	73	$ 394,200,000	251.5	0.04622	0.392	317,151,876	2,691,972,678	$ 102,294,962
2020	$ -	$ -	71	$ 383,400,000	257.5	0.04622	0.392	317,151,876	2,691,972,678	$ 115,754,825
2021	$ -	$ -	69	$ 372,600,000	263.7	0.04622	0.392	317,151,876	2,691,972,678	$ 115,754,825
2022	$ -	$ 49,802,000	82	$ 442,800,000	226.4	0.04604	0.391	315,893,337	2,681,290,247	$ 115,295,481
2023	$ -	$ -	77	$ 415,800,000	240.0	0.04613	0.392	316,522,606	2,686,631,463	$ 115,525,153
2024	$ -	$ -	75	$ 405,000,000	245.7	0.04613	0.392	316,522,606	2,686,631,463	$ 115,525,153
2025	$ -	$ -	73	$ 394,200,000	251.5	0.04622	0.392	317,151,876	2,691,972,678	$ 129,214,689
2026	$ -	$ -	71	$ 383,400,000	257.5	0.04622	0.392	317,151,876	2,691,972,678	$ 129,214,689
2027	$ -	$ 7,778,000	74	$ 399,600,000	248.6	0.04622	0.392	317,151,876	2,691,972,678	$ 129,214,689
2028	$ -	$ -	70	$ 378,000,000	260.6	0.04622	0.392	317,151,876	2,691,972,678	$ 129,214,689
2029	$ -	$ -	68	$ 367,200,000	266.8	0.04631	0.393	317,781,145	2,697,313,894	$ 129,471,067
2030	$ -	$ -	66	$ 356,400,000	273.3	0.04631	0.393	317,781,145	2,697,313,894	$ 140,260,322
2031	$ -	$ 23,845,000	69	$ 372,600,000	263.7	0.04622	0.392	317,151,876	2,691,972,678	$ 139,982,579
2032	$ -	$ -	66	$ 356,400,000	273.3	0.04631	0.393	317,781,145	2,697,313,894	$ 140,260,322
2033	$ -	$ 23,845,000	70	$ 378,000,000	260.6	0.04622	0.392	317,151,876	2,691,972,678	$ 139,982,579
TOTAL	$ -	$ 215,171,000					7.840	**6,338,003,361**	**53,796,723,842**	**$2,397,020,069**
								0.4%	0.4%	0.4%

Figure 7. No Preventive Maintenance scenario.

On the case study results, it is observed that timely applied preservation treatments not only preserve the pavement condition and asset value but also leads to lower emissions and lower fuel consumption compared to Do-Nothing. The case study shows savings estimates of 662,310,738 kg CO2 over a 20 year period that are equivalent to $31 million in social costs. Hence, agencies should consider in their asset management decision-making process the impact of maintenance on gas emissions and social costs.

CONCLUDING REMARKS

An enhanced asset management decision making process that incorporates sustainability perfromance measures as target obejectives can lead to better balanced funding allocation decisions when developing maintenance and rehabiltation programs.

This paper shows an example based on reduced gas emissions but there are a number of other environmental and social sustainability targets that can be incorporated in the TAM.Transportation agencies can benefit from an enhanced TAM that considers the economic, enviromental, and social impacts in the following ways:

- Considering reduction of vehicle emissions due to pavement condition will lead to pavement maintenance plans that will have a positive impact on air quality and drivers will benefit with fuel savings.
- Sustainable multi-objective model can help to address the needs of not only motorized vehicles but also cyclists and pedestrians, contributing to a safer environment.
- Synchronization of asset maintenance schedule with on-road bikeway maintenance can help to support Complete Streets policies adopted by several cities in the U.S. It may also improve the funding allocation effectiveness while providing better bikeways condition.
- Synchronization of asset maintenance schedule with utility cuts can save funds for unnecessary treatment applications and improve treatment effectiveness and extend the asset life.

- Considering accident statistics and livability rating in a transportation asset management system can lead to funding allocation to streets that need an improvement in safety/livability, either by improving the asset condition or by performing synchronized activities for an optimal, cost-effective schedule.

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DISCLAIMER

The opinions and conclusions expressed or implied in the report are those of the authors. They are not necessarily those of the Metropolitan Transportation Commission in Oakland, California or the Tier I University Transportation Center Consortium led by Rutgers University.

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