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OPTIMIZING ENVIRONMENTAL SUSTAINABILITY AND PUBLIC BENEFITS OF TRANSPORTATION NETWORK PROGRAMS

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Abstract: Transportation is among the highest energy-consuming economy sectors. Therefore, new national priorities and laws passed in the United States in an effort to control the environmental impacts of highway rehabilitation efforts. This created new challenges to planners and decision makers in transportation agencies to optimize, under budget constraints, rehabilitation efforts of aging networks in order to maximize net public benefits while minimizing network energy consumption. This mandates a substantial change in existing ad-hoc and need-based decision-making practices in order to add new criteria to evaluate and measure network energy consumption. Accordingly, this paper presents a new model for planning highway rehabilitation efforts that is capable of identifying near optimal program(s) in terms of maximizing net public benefits while minimizing energy consumption of transportation networks. The new model is designed to: (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. An application example for a transportation network in South Florida is analyzed to demonstrate the model capabilities and examine the relationship between lifecycle net public benefits and total network energy consumption. The analysis of the application example showed that there is a trade-off between the expected net public benefits and network energy consumption. The new model should prove useful to transportation agencies in identifying rehabilitation program(s) that satisfy public expectations while minimizing energy consumption in transportation networks.

1 INTRODUCTION

Transportation agencies in charge of planning and programming highway repair and rehabilitation efforts face the challenging task of allocating limited funding to an increasing number of competing projects. The American Society of Civil Engineers is forecasting the funding gap is continuing to widen, which will have a direct and significant impact on surface transportation and therefore the United States' economy (ASCE 2013). Currently, the transportation agencies use ad-hoc and need based approaches to identify and implement their highway repair and rehabilitation programs. For example, rehabilitation programs can be programmed by selecting projects that address roads with the worst pavement conditions and/or highest traffic volume. This approach might not be optimal and leaves ample room for improvement in order to include other significant factors to maximize public benefits (Sharaf and Mandeel 1998; Sathaye and Madanat 2011). In addition, the United States government passed a new law, the Moving Ahead for Progress in the 21st Century Act (MAP-21) of 2012, requiring transportation agencies to integrate a number of national goals into highway construction planning efforts (FHWA 2012). Since transportation is among the highest energy-consuming economy sectors with the vast majority of this energy from fossil fuels (EIA 2014), one of the national goals considered in MAP-21 is related to environmental sustainability. This will bring about substantial change to the current ad-hoc and need-based decision making approaches adopted by transportation agencies.

Several research studies focused on planning and optimizing highway rehabilitation efforts. Many of these studies had a single optimization objective focusing on: minimizing construction costs (Chan et al. 1994; Ferreira et al. 2002); and maximizing overall network performance (Wang and Lui 1997). Other research efforts had multi-objective optimization models that focused on: integrating energy consumption, GHG emissions, and construction costs into a single optimization objective (Zhang et al. 2012); minimizing construction costs and maximizing pavement performance (Mathew and Issac 2013); maximizing net benefits while minimizing network service disruption (Orabi and El-Rayes 2011); and minimizing construction costs and GHG emissions (Lidicker et al. 2012). Despite the significant contributions of these research studies, no reported research focused on optimizing highway rehabilitation programs in order to maximize public benefits while minimizing network energy consumption under budget constraints.

In order to address this important research gap, this paper presents the development and implementation of a new model for optimizing highway rehabilitation programs. The model consists of five modules that are capable of (see Figure 1): (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. The following sections describe these five modules in detail.

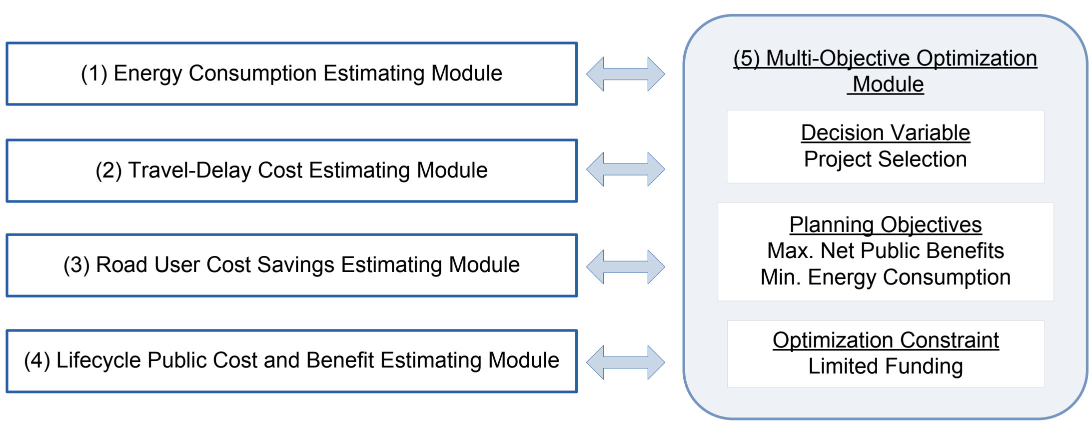

Figure 1: Highway rehabilitation programming and optimization model

2 ENERGY CONSUMPTION ESTIMATING MODULE

The main objective of this module is to evaluate and measure the impact of decision making in highway rehabilitation programs on network energy consumption. In order to achieve this objective, energy consumed in transportation networks is categorized into two main types: (1) energy consumed during highway construction operations; and (2) energy consumed during regular operation after the completion of highway rehabilitation works to improve pavement conditions.

First, network energy consumption during highway construction operation is expected to increase, compared to regular operation, due to the reduction in vehicle speed when travelling through construction zones. This reduction in vehicle speed can cause an increase in fuel consumption rate (NCHRP 2012). The change in vehicle speed can also cause the volume of traffic using the road under rehabilitation to change due to some travellers opting to use alternative routes. The total change in fuel consumption during the highway construction operations will also depend on the number of road sections in the network undergoing rehabilitation, road section lengths, and duration of construction operations. In this model, equations 1 and 2 are used to estimate the change in network total fuel consumption due to construction operations, as follows:

$$[1]\ \ \mathrm{TFC} = \sum_{r=1}^{R} \left(V_{W,r} - V_{F,r}\right) * L_r * D_r * \Delta FR_r$$

$$[2]\ \ \Delta FR_r = FR_{W,r} - FR_{F,r}$$

Where,
TFC = change in total network fuel consumption (in gallons) due to construction operations; R= number of road sections in the network; $V_{W,r}$ = traffic volume under work-zone conditions; $V_{F,r}$ = traffic volume under free-flow conditions; L_r = length of road section (r); D_r =construction duration that affects road section (r); ΔFR_r = change in fuel consumption rate due to construction; $FR_{W,r}$ = fuel consumption rate under work-zone conditions; and $FR_{F,r}$ = fuel consumption rate under free-flow conditions.

Second, the improvement in pavement conditions, as a result of the rehabilitation efforts, will also result in changes to the network energy consumption. In this model, the pavement roughness index (IRI) is used to represent pavement conditions. The IRI of road segments that undergo rehabilitation will decrease after rehabilitation and will therefore cause a significant reduction in energy consumption (Amos 2006) compared to pre-rehabilitation. Equation 3 is used to estimate lifecycle energy consumption in the transportation network over an analysis span of Y years after rehabilitation. This lifecycle energy consumption takes into consideration the gradual increase over time in IRI and therefore energy consumption. Therefore, network energy consumption is expected to be lowest directly after rehabilitation and gradually increases with time until the network is due for new rehabilitation, as shown in figure 2.

$$[3]\ \ \mathrm{TF} = \sum_{y=1}^{Y} \sum_{r=1}^{R} V_r * L_r * FRN_r^y * 365$$

Where,
TF = total fuel consumption (in gallons) during operation phase; Y = number of years to new rehabilitation effort; V_r = traffic volume (in terms of AADT) on road section (r); L_r = length of road section (r); and FRN_r^y = fuel consumption rate of road section (r) after year (y) of rehabilitation.

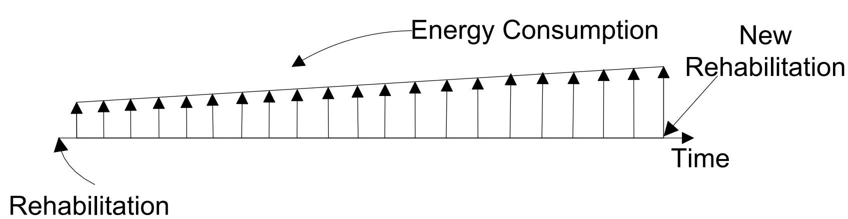

Figure 2: Impact of rehabilitation efforts on energy consumption

3 TRAVEL-DELAY COST ESTIMATING MODULE

The main objective of this module is to estimate the cost of travel delays increased from the expected traffic delay during the construction. Repairing a road can significantly affect traffic conditions on other roads in the highway network. For example, travelers tend to change to a faster route for driving to a destination in order to avoid the disruption that happens in the construction zone. However, this traffic diversion can increase volume in the alternated route and finally exceed the road capability. As a result, all vehicles on the road, including the routine travelers, will be affected from traffic congestion and a lower average travelling speed, which increase travel time. Additionally, travel delays can increase in the construction zone due to speed limit reduction. Therefore, construction is expected to change traffic patterns and increase travel time of all travelers on the highway network.

Equations 4 and 5 represent the estimation of entire travel-delay cost during the construction and change in travel time due to operating speed change, respectively. The cost of travel delays can be estimated from traffic volume, length of road, change in travel time, and unit time value. The last parameter, the predefined value from the user, will convert total travel delays (in hours) to monetary value (in dollars per hour). However, the cost of travel delays in this study was only estimated based on the effect of speed reduction.

$$[4]\ \ \mathrm{TTC} = \mathrm{UT} * \sum_{r=1}^{R} \mathrm{V}_{\mathrm{W,r}} * \mathrm{D}_{\mathrm{r}} * \Delta\mathrm{T}_{\mathrm{r}}$$

$$[5]\ \ \Delta\mathrm{T}_{\mathrm{r}} = \left(\frac{\mathrm{L}_{\mathrm{r}}}{\mathrm{S}_{\mathrm{W,r}}}\right) - \left(\frac{\mathrm{L}_{\mathrm{r}}}{\mathrm{S}_{\mathrm{F,r}}}\right)$$

Where,
TTC = total cost of travel delay (in dollars) during construction; UT = unit time value (in dollars per hour); ΔT_r = change in travel time; $S_{W,r}$ = average vehicle speed under work-zone conditions; and $S_{F,r}$ = average vehicle speed under free-flow conditions.

4 ROAD USER COST SAVINGS ESTIMATING MODULE

The main objective of this module is to estimate the expected savings in road user costs from the implementation of rehabilitation programs. This module accounts for the impacts of rehabilitation programs on the road operation phase. Two main components of road user costs are considered, which are: (1) tire depreciation cost, and (2) repair and maintenance costs (as shown in equation 6). However, the cost of fuel consumption is excluded from this module to avoid double counting of the planning objectives in the optimization module. Tire depreciation cost takes into consideration traffic volume, the length of the road section, and variation in tire depreciation rate as shown in equation 7. Tire depreciation rate can be calculated as a result of vehicle speed, vehicle type, and pavement conditions, which is an IRI in this study. The module also takes into account the effect of pavement deterioration over a lifecycle period. As deterioration has impact on pavement conditions, tire depreciation rate tends to increase over time until the next rehabilitation.

Similarly, repair and maintenance costs take into consideration traffic volume, length of road section, and changed rate in repair and maintenance costs as shown in equation 8. This cost rate depends on vehicle type and pavement conditions resulting from deterioration throughout lifecycle. Change in repair and maintenance cost rate can be calculated by comparing the pre-rehabilitation and post-rehabilitation stages.

$$[6]\ \mathrm{TRS}^{y} = \mathrm{DS}^{y} + \mathrm{MS}^{y}$$

$$[7]\ \mathrm{DS}^{y} = \sum_{p=1}^{P} \mathrm{V}_{p} * \mathrm{L}_{p} * (\mathrm{DRI}_{p} - \mathrm{DRN}_{p}^{y})$$

$$[8]\ \mathrm{MS}^{y} = \sum_{p=1}^{P} \mathrm{V}_{p} * \mathrm{L}_{p} * (\mathrm{MRI}_{p} - \mathrm{MRN}_{p}^{y})$$

Where,
TRS^y = total road user savings (in dollars) after year (y) of rehabilitation; DS^y = tire depreciation cost savings after year (y) of rehabilitation; MS^y = repair and maintenance cost savings after year (y) of rehabilitation; P = number of road projects undergoing rehabilitation; DRI_p = tire depreciation rate of road project (p) at pre-rehabilitation conditions; DRN_p^y = tire depreciation rate of road project (p) after year (y) of rehabilitation; MRI_p = repair and maintenance rate of road project (p) at pre-rehabilitation conditions; and MRN_p^y = repair and maintenance rate of road project (p) after year (y) of rehabilitation.

5 LIFECYCLE PUBLIC COST AND BENEFIT ESTIMATING MODULE

The main objective of this module is to evaluate the net expected benefits as a result of implementing rehabilitation programs. The calculation employs the concept of lifecycle since the costs and benefits can be found along the lifespan. Figure 3 presents the concept of lifecycle assessment and all related components that are used for calculating the net public benefits in this study, which include (1) cost of travel delays and (2) road user cost savings.

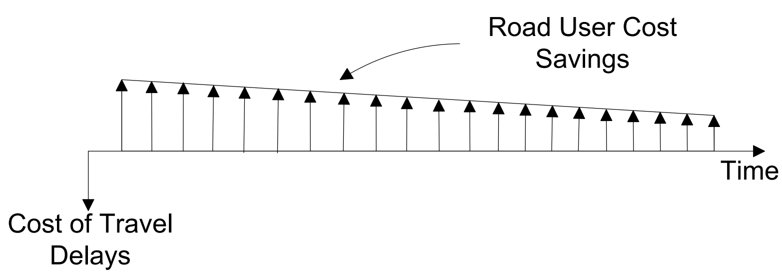

Figure 3: Expected public benefits of rehabilitation programs

First, the cost of travel delays is the cost incurred from increasing the total time of all travelers on the network. In this study, this cost is assigned by a single value at the beginning of the lifespan (year 0) of the lifespan (see figure 3), as it occurs during the construction stage. The second component is the savings in road user costs, which are the expected cost savings of traveling on the transportation network regarding the improvement of road conditions. It is calculated based on the savings in tire depreciation cost and the vehicle's repair and maintenance costs in this study. However, the savings are likely to decrease over the time after rehabilitation because the road tends to deteriorate regarding the traffic load and current road conditions. Until the pavement conditions reach an unacceptable threshold, the next rehabilitation is required to keep the road's better quality.

To evaluate the net public benefits of rehabilitation programs, the concept of net present worth is adopted to calculate the net present value of each component. The discount rate and number of lifecycle year are initially defined by the decision maker. Equation 9 presents how to calculate the net present value of total public benefits for a rehabilitation program.

$$[9]\ NPV\_B = \sum_{y=1}^{Y} TRS^{y}(P/F, ir, y) + TTC$$

Where,
NPV_B = net present value of total public benefits; ir = discount rate for the public benefit calculation (in percentage); TRS^{y} = total road user savings (in dollars) at year (y) after rehabilitation; and TTC = total cost of travel delays (in dollars) during construction.

6 MULTI-OBJECTIVE OPTIMIZATION MODULE

The main objective of this module is to optimize highway rehabilitation decisions in order to identify the program(s) that can maximize public benefits while minimizing network energy consumption under budget constraints. To this end, the decision considered in this the module is identifying which projects to select among the competing highway rehabilitation projects. This project selection is constrained by limited rehabilitation funding. In addition, the selection of rehabilitation projects will have a significant impact on the two optimization objectives of: (1) maximizing net public benefits; and (2) minimizing network energy consumption.

The impacts of decision variables on the planning objectives and constraints depend on decision making in project selection. Because of a limitation in financial resources, decision makers are restricted to select only some potential projects from the entire set of rehabilitation projects. In fact, decision making in project selection will have different effects on travelers and the economy since each project has its own characteristic, such as different pavement conditions, traffic volume, and speed limit. For instance, repairing the road with a high traffic volume can save a larger amount of road user costs and energy consumed compared to upgrading a low traffic-volume road. However, a high traffic volume usually requires a high capacity and the road is expected to be a large project. This also requires a higher construction budget. Similarly, improving a high-roughness pavement requires an intensive maintenance and rehabilitation method with a large expenditure. However, it can have a higher saving in road user costs and energy consumption than repairing a low-roughness road.

In this study, an evolutionary algorithm is utilized to solve the optimization problem. NSGA-II, which is the most superior multi-objective genetic algorithm nowadays (Deb et al. 2001), is used to generate the optimal rehabilitation programs to satisfy the planning objectives and constraints. It has proved that NSGA-II is capable of overcoming several challenges in the optimization problem: (1) the multi-objective nature, (2) the nonlinear and non-continuous objective functions, and (3) the large search space. To deal with the constraints, NGPM Version 1.4, which is the recent implementation code of NSGA-II in Matlab, is employed from Song (2011).

The genetic operations of this optimization module are given as shown in Figure 4. The process starts by generating an initial population of random solutions. The population is the set of decision variables that consists of the combination of project selections. In this study, project selection is coded as a binary variable by assigning 1 for selected and 0 for unselected projects, respectively. Then, the fitness functions of each population are evaluated in terms of public benefits and energy consumption. After that, the solutions are sorted based on the fitness values and the best solutions are selected. The genetic operators of crossover and mutation are then performed to generate a new population of better solutions. The steps are continuously repeated for a predefined number of generations or until the error between two successive generations is smaller than a predefined tolerance. The operations then can be stopped and the optimal/near optimal solutions are extracted from the final set of population.

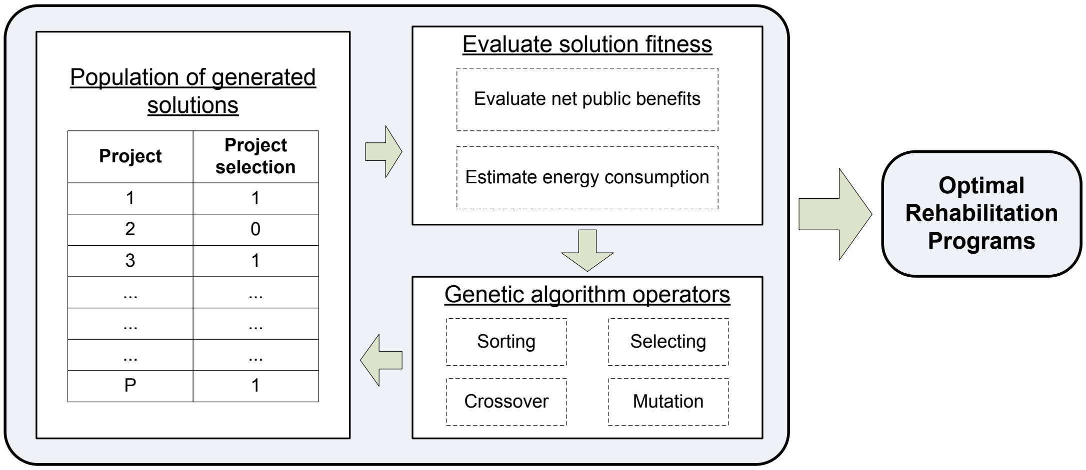

Figure 4: Multi-objective optimization module

7 APPLICATION EXAMPLE

An application example is analyzed to illustrate the model capabilities in optimizing the highway rehabilitation efforts. The example aims to search for the optimal rehabilitation program(s) that simultaneously maximize total net public benefits and minimize network energy consumption. In this section, the roads in the South Florida's transportation network are assumed to have rehabilitation needs due to pavement deterioration. The deteriorating roads at ten different locations are hypothetically selected under the limited funding in order to identify the optimal plan(s) that satisfy the planning objectives. Table 1 shows the data for all ten candidate rehabilitation projects. The data include: (1) current pavement conditions in terms of roughness index, (2) traffic volume in terms of annual average daily traffic (AADT), (3) section length, (4) free flow speed, (5) work zone speed, (6) rehabilitation cost, (7) rehabilitation duration, (8) number of lanes in each direction, and (9) total equivalent standard axle load for each project.

In this example, the available funding for the rehabilitation program is assumed to be 35 million dollars. The total benefits are calculated based on a 5% discount rate net present value over a 20-year lifecycle period. All candidate projects are assumed as a rural road with the rehabilitation cost $0.8 per lane-mile (CDTC 2003) for a simple calculation. The rehabilitation durations are estimated by using an average unit time per lane-mile (approximately 5 days per lane-mile) from OECD (2005). The unit cost of travel time ($23 per vehicle-hour) is adopted from Copeland (1998). All rehabilitation costs and the travel-delay costs are adjusted with the customer price index (U.S. Bureau of Labor Statistics 2014) for the analysis.

The result shows the model capabilities of generating a wide set of optimal solutions. These solutions illustrate the trade-off between the two planning objectives: (1) maximizing total net public benefits and (2) minimizing energy consumption. The thirty seven optimal programs were generated as shown in figure 5. The result presents that minimizing energy consumption of rehabilitation efforts can lead to a lowering in public benefits. The trade-off also contains the generated solution of one of the current ad-hoc planning models, which depends on a need-based criteria of pavement conditions, by selecting projects 1,5,6,7,8,9, and 10. This solution provides the highest energy consumption and net public benefits as 144 million gallons and 9.8 billion dollars, respectively (see solution 1). However, the rehabilitation program selected by a high traffic volume, which is another need-based criterion, is not contained in the optimal set. As projects 2,3,4,6,8,9 and 10 were selected, the total energy consumption and public benefits were able to be estimated as 162 million gallons and 6.5 billion dollars, respectively (see solution 2). It is shown that this alternative is dominated by the other optimal solutions. Therefore, selecting projects with a high traffic volume might not be an effective way for highway decision making.

Table 1: Candidate Rehabilitation Projects

Project	IRI (m/km)	Traffic volume (veh/day)	Length (mile)	Free-flow speed (mph)	Work zone speed (mph)	Construction cost (million dollars)	Construction duration (week)	Number of lane	Total ESAL (million ESAL/lane)
1	4.50	45,500	2.87	40	25	9.17	46	4	0.3546
2	3.20	55,000	2.11	40	25	5.07	26	3	0.5715
3	2.80	37,500	4.05	40	25	6.48	33	2	0.5845
4	3.00	50,500	2.00	45	30	4.8	25	3	0.5247
5	4.00	35,000	2.04	35	20	3.26	17	2	0.5455
6	4.00	48,500	1.62	40	25	3.88	20	3	0.5039
7	3.80	33,500	1.69	45	30	4.06	21	3	0.3481
8	5.00	63,000	2.66	45	30	6.38	32	3	0.6546
9	4.00	13,000	1.74	40	25	1.39	7	1	0.4052
10	3.80	71,000	2.24	45	30	5.37	27	3	0.7377

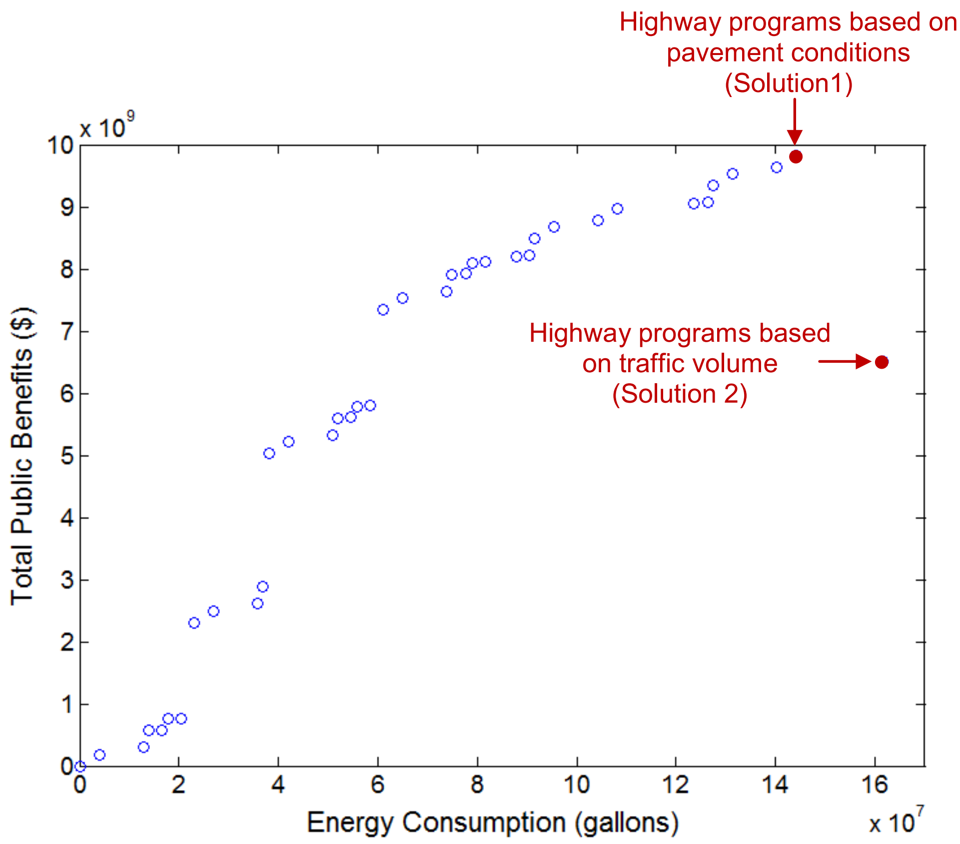

Figure 5: Trade-off between total public benefits and energy consumption

The result can be different from figure 5 if a minimum threshold for available budget is predetermined in the analysis. Under this condition, the optimal solutions will follow the same pattern of trade-off relationship. The number of optimal solutions, however, is smaller for the one with a minimum threshold. As a result, planners and decision makers can adjust their strategies to effectively select the most suitable rehabilitation programs and allocate the remaining funding for other purposes such as transportation safety improvement.

The analysis in this example presents the application and capabilities of the developed model in searching for and identifying the optimal rehabilitation programs under the trade-off between total net public benefits and environmental sustainability maximization. This contributes to provide planners and decision makers with a wide range of optimal trade-off solutions, which can be effectively selected to satisfy with transportation agencies' conditions and requirements.

8 CONCLUSIONS

In this study, a new model to support decision making in highway rehabilitation programming was developed in order to optimize the net public benefits and energy consumption in transportation networks. The model is capable of: (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. The application example was analyzed to demonstrate the performance and capabilities of the developed model. The optimization result generates the optimal trade-off between total public benefits and energy consumption for highway rehabilitation programs.

The developed model should prove useful to planners and decision makers in promoting the sustainability concept and simultaneously addressing a public perspective in the planning of highway rehabilitation efforts. However, some further improvements can be extended to advance the capabilities of the model. For example, the optimization decision variables can be expanded to include other types of decision. Not only the decision on project selection but it can also be made to prioritize the competent projects and identify the impacts of different rehabilitation methods on the projects. Future works are planned to expand the optimization scope of the developed model to be more practicable to transportation agencies' decision making processes.

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