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Applying Utility Theory to Cost Allocation of Pavement Maintenance and Repair

Kuo-Liang Lin[1+] and Chien-Liang Lin[2]

Abstract: Lacking a systematic and effective pavement maintenance strategy, Kaohsiung, the largest industrial city and second most populated metropolitan in Taiwan, struggles to manage its ever-growing urban road network. To help deliver a satisfactory infrastructure facility for public users, this research incorporates a modern pavement management system based on utility theory and integer programming to improve the overall efficiency of Kaohsiung's pavement maintenance practices. The current work establishes guidelines and requirements of a localized pavement management system of Kaohsiung by organizing an expert panel and conducting a series of seminars. This study develops an optimization model involving pavement quality index IRI and traffic volume as the main criteria to support the decision making process of allocating a pavement maintenance budget. Using Kaohsiung urban core roads as the test bed, this study delivers optimal maintenance programs with the greatest total utilities, which represents the maximum benefits to road users. The utility theory mechanism allows simple implementation and fast integration of other performance measures in the future. The utility conversion is a customized process meeting specific local regulations and requirements, making the optimization model more practical and easier to apply in the pavement maintenance program. This model provides a feasible and scientific solution for city officials to identify and prioritize pavement maintenance needs, as well as more effective budgeting.

Key words: *Optimization; Pavement maintenance; Utility theory.*

Introduction

The past few decades of rapid road infrastructure development have created a solid foundation for Taiwan's economic success. However, as road infrastructure development evolves from the construction stage to the operation stage, insufficient pavement maintenance and repair practice have gradually become a big concern of local road users. According to the Public Construction Commission statistics in 2007 [1], there were 3,615 complaint cases against public construction projects and 3,221 cases relating to unsatisfactory pavement quality, which accounts for more than 89% of all complaint cases. During the 2005 and 2007 periods, 211 state compensation cases involving flawed pavement maintenance accounted for 38% of total cases. Lacking a systematic pavement preservation strategy to maintain these infrastructures effectively, Taiwan's transportation agencies have had a difficult time delivering a satisfactory infrastructure facility for public users.

Kaohsiung, the largest industrial city and second most populated metropolitan in Taiwan, has trouble managing its ever-growing highway network. Relying heavily on its highway network for freight delivery between industrial districts within the area and the seaport, two agencies in Kaohsiung are responsible for network maintenance tasks, the Maintenance Office for pavement M&R and the Bureau of Transportation for signage, channelization, and traffic light control. Similar to many other highway agencies in the world, Kaohsiung agencies face a limited maintenance budget and often encounter delay in maintenance works. With such limited resources, local agencies have a hard time deciding how much funding to allocate to the transportation infrastructure and how to get the best value from the allocated money [2]. Since pavement maintenance efficiency has been difficult to achieve, top management officials of these agencies give high priority to renewing their management practice. Kaohsiung agencies mostly use the Worst First strategy, which treats pavements in the worst condition first and pavements in better condition in priority order [3]. Unfortunately, the Worst First strategy, which severely edges out preventive maintenance funds, does not meet the requirements of contemporary pavement management practice, as shown by its poor user-satisfaction records. Preventive maintenance should be the central focus in pavement network management since it helps prolong infrastructure life. [4].

Aiming to improve the overall efficiency of Kaohsiung's pavement maintenance practice, authors of this paper pioneered the applicability of the modern pavement management system. After organizing an expert panel and conducting a series of seminars, the authors established guidelines and requirements for a localized pavement management system in Kaohsiung. The result is an optimization model that supports the decision making process of allocating a pavement maintenance budget and to provide optimal maintenance programs, using Kaohsiung's urban core roads as the test bed. This model provides solutions to identify and prioritize pavement maintenance needs and assists justification for funding levels.

This paper first documents the status of pavement management related research and various related information, then goes on to describe key consensus from the expert panel study. Based on the findings, this article describes an optimization model that can achieve the best utility performance while allocating a budget. Finally, the paper presents a case study to demonstrate the proposed

[1] Assistant Professor, Dept. of Civil and Ecological Engineering, I-Shou University, No.1, Sec.1, Syuecheng Rd., Dashu Township, Kaohsiung County 840, Taiwan.
[2] Assistant Professor, Dept. of Construction Engineering, National Kaohsiung First University of Science and Technology.
[+] Corresponding Author: E-mail kllin@isu.edu.tw
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model's usability.

Pavement Management System

Pavement Management System (PMS) helps decision makers manage pavement maintenance and repairs in a cost-effective manner. Generally, a PMS assists decision makers at two levels of pavement management— the project level and the network level [5, 6]. The project level deals with engineering concerns for the actual implementation of an individual project and determines optimal techniques for repairing specific pavement segments. This level of management involves evaluating causes of pavement damage, identifying potential solutions, assessing the effectiveness of repair alternatives, and ultimately selecting a solution. Network level management supports upper-level management decision making by considering the whole pavement network. The main objectives of network level management are to establish network level repair policies, budget requirements, repair priorities and schedules, as well as account for pavement conditions and all necessary repair work for pavement segments managed by a transportation agency.

The network level management further divides into the programming level and the project selection level [7, 8, 9]. The programming level establishes maintenance budgets and allocates general resources over the entire network, according to many related research works [10, 11, 12, 13, 14]. The project selection level involves prioritization to identify which projects to carry out in what time frame.

Using network level management requires prioritization and optimization techniques. Prioritization involves generating indices for the ranking, scheduling, budgeting, and treatment selection of potential projects. Many indicators, such as the disaggregate index and the aggregate index, are useful to rank indices. Generating suitable indices for comparing or setting priority schemes should suit different local needs. Fwa et al. [15] identified the highway class and distress condition as reasonable priority indices. Bharn et al. [16] developed composite indices involving IRI benefit and Rutting Benefit with physical condition, smoothness, and safety as indicators. Planning and field maintenance personnel need to understand priority rating as a means of managing routine maintenance [17].

Optimization achieves the best performance of every pavement section within certain budget constraints or the lowest budget when all pavement sections are above a minimum acceptable performance level. To reach optimization, decision makers have to specify one ultimate objective or a number of objectives, such as maximizing network benefits subject to budget constraints and minimizing total expected costs subject to certain network performance levels [18].

Setting one ultimate objective is within the scope of a single objective problem. The single objective could be *agency cost*, *user cost*, or *network condition*. In addition to the objective, decision makers have to identify constraints that govern the objective. The constraints often include resource limitations of the agency, externally determined threshold conditions of a network, etc. Such problems are typically combinatorial in nature since the decision variables are often discrete. Single objective optimization techniques are adequate if one single objective can summarize the overall consideration of the pavement maintenance. Sometimes more than one objective needs optimizing. Then the optimization problem is in the scope of multiple objective programming and becomes very complex [19].

To relieve the burden of solving complex multiple objective problems, researchers have proposed two main approaches to simplify the problem [14]:

1. Optimize one objective and include the other objectives as constraints: This approach involves optimizing one objective, for example, minimize *user cost* and make other objectives as constraints, such as making the *agency cost* a budget constraint. The approach assumes that one already knows the optimal or desired levels of the objectives being put in the constraints.
2. Optimize the sum of all objectives: Cost is usually selected as the single unit for formulating the single composite objective from the set of competing objectives (e.g., *total cost* = *user cost* + *agency cost*). One problem with this approach is that it assumes that all competing objectives can be expressed in a single unit. For example, if the objectives are *agency cost*, *drivers/passengers comfort*, and *average pavement distress level*, one must quantify and convert all three objectives into a single unit for this approach to work.

Index for Pavement Quality

One of the most important aspects of pavement management is identifying the current pavement condition of the network. Decision makers require the information on current conditions to predict future conditions and to determine the required treatment and its priority. Many agencies rely on a composite index that incorporates both structural and functional components of a condition to determine treatment needs [20]. The Pavement Condition Index (PCI) developed by the Corps of Engineers is a popular composite index based on the type, severity, and extent of nineteen different distresses for hot mix asphalt (HMA) roads and streets. The overall index, a numerical rating between 0 and 100 (with 100 representing a pavement in excellent condition), provides an objective and repeatable method of reporting pavement conditions.

In addition to PCI, another pavement condition index concerns ride quality. Road roughness or smoothness is the most important factor to evaluate the ride quality of pavement. Many roughness indices derive from profile data and correlate with road users' perceptions of ride quality to indicate the level of pavement roughness. These include the Profile Index (PI), the International Roughness Index (IRI), the Ride Number (RN), the Michigan Ride Quality Index (RQI), and the Truck Ride Index (TRI) [21]. Among them, IRI is the index most widely used for representing pavement roughness and has become a worldwide standard for measuring pavement smoothness. A quarter-car vehicle math model calculates IRI with an accumulated response to yield a roughness index with units of slope (in/mi, m/km, etc.) [22]. The quarter-car moves along the longitudinal profile at a simulation speed of 80 km/h, and the measured profile displacement and standard car structure parameters calculate the suspension deflection. The accumulated, simulated suspension motion divided by the distance traveled obtains an index with a unit of slope (m/km), known as the IRI. Most highway agencies use the IRI to evaluate new and rehabilitated pavement conditions and for construction QC/QA purposes [23]. IRI (m/km)

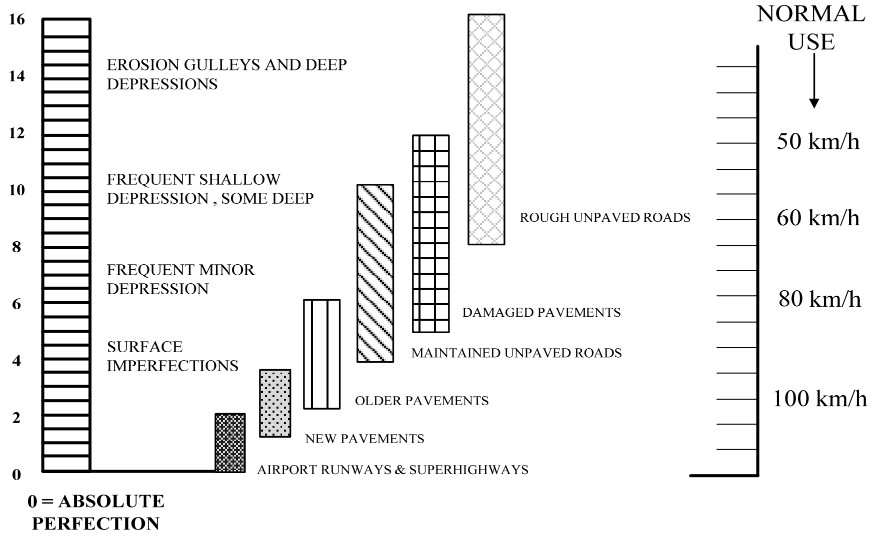

Fig. 1. IRI Roughness Scale [24].

is represented by the accumulated suspension motion of a vehicle (m) divided by the distance traveled by the vehicle (km). Fig. 1 shows the roughness scale, which describes the typical categories of road, surface shape defects, and typical travelling speed associated with each given roughness level.

Expert Panel Study

This research organizes an expert panel to guide the development of a pavement management system in Kaohsiung. The expert panel consists of ten pavement professionals, including four college professors specialized in civil engineering, four government officers, and two industrial representatives with at least ten years of field experience.

After two panel study sessions, the panelists set up current pavement management practices in Kaohsiung and established primary requirements for a new pavement management system. Currently, the Maintenance Office of the Public Works Bureau is the agency responsible for pavement maintenance in Kaohsiung. Maintenance jobs involve two types: repair tasks based on local complaint reports and preventive maintenance tasks based on subjective pavement condition judgments from pavement surveyors. PCI or IRI investigations are not regular practices but are performed as a reference through out-sourcing. Complaints, pavement conditions, and traffic volume are the main factors governing maintenance decisions, but no systematic approach has been implemented.

The expert panel reached the following consensus as guidelines for achieving effective pavement maintenance management:

1. Develop a systematic decision-making procedure for allocating annual maintenance budget.
2. Incorporate simple and flexible criteria into the procedure for prioritizing maintenance jobs.
3. Investigate IRI regularly as a pavement condition indicator since IRI has gradually become the world standard.
4. In addition to IRI, use traffic volume as the other index for prioritizing maintenance jobs.

Utility Theory Implementation

This study uses utility theory to set up an optimization model that considers both IRI and traffic volume based on guidelines from the expert panel study. In economics, utility is a measure of relative satisfaction. Given this measure, increasing or decreasing utility can explain economic behavior in terms of attempts to increase one's utility. Various goods and services, possession of wealth, and leisure time affect the utility model. In this paper, utility governs the allocation of M&R budgets.

Utility theory provides a methodological framework for evaluating alternatives made by individuals, firms, and organizations. Utility refers to the satisfaction that each choice provides to the decision maker [24]. Thus, utility theory assumes that decisions are made based on the utility maximization principle, where the best choice is the one that provides the highest utility (satisfaction) to the decision maker. Many studies have used utility theory in selecting investment strategies [25, 26, 27, 28, 30]. Other research uses utility theory to explain the behavior of individual consumers [24]. The consumer decides which of the many different goods and services to consume to secure the highest possible level of total utility subject to his/her available income and the prices of the goods/services.

In all cases, the utility that the decision maker gets from selecting a specific choice is measured by a utility function U, which is a mathematical representation of the decision maker's system of preferences such that: $U(x) > U(y)$, where choice x is preferred over choice y, or $U(x) = U(y)$, where choice x is indifferent from choice y, and both choices are equally preferred.

Utility functions can be either cardinal or ordinal. In the former case, a utility function is used to derive a numerical score for each choice that represents the utility of that choice. In this setting, the utilities (scores) assigned to different choices are directly comparable. For instance, a utility of 100 units towards a cup of tea is twice as desirable as a cup of coffee with a utility level of 50 units. In the ordinal case, the magnitude of the utilities (scores) are not important; only the ordering of the choices as implied by their utilities matters. For instance, a utility of 100 towards a cup of tea and a utility level of 50 units for a cup of coffee simply state that a cup of tea is preferred to a cup of coffee, but a cup of tea is not twice as desirable as a cup of coffee. Within this setting, it is important to note that an ordinal utility function is not unique, since any monotonic increasing transformation of an ordinal utility function will still provide the same ordering for the choices.

Irrespective of the type of utility function, utility theory assumes that preferences are complete, reflexive, and transitive. The preferences are complete if, for any pair of choices *x* and *y*, one and only one of the following is true: (1) *x* is preferred to *y*, (2) *y* is preferred to *x*, or (3) *x* and *y* are equally preferred. The preferences are reflexive when, for any pair of choices *x* and *y, x* is equally preferred to *y,* and thus *y* is also equally preferred to *x*. Finally, the preferences are transitive when, for any three choices *x*, *y*, and *z,* x is preferred over *y* and *y* is preferred over *z*, then *x* is preferred over *z*. The hypotheses on reflexivity and transitivity imply that the decision maker is consistent (rational).

In the field of pavement management research, the current study fits within the scope of network level optimization, which identifies optimal pavement M&R policies. The goal is to maximize some measure of benefit subject to meeting budgetary and other applicable policy constraints or to minimize the total cost subject to meeting specified performance goals and policy constraints. The first network level optimization model was employed in the PMS developed for Arizona Department of Transportation [31]. For this system, a decision process was used to model pavement decision making, and a large scale linear program algorithm was used to obtain the optimal pavement M&R policies. With the successful application of the Arizona system, several other systems were developed using the same or similar techniques of network optimization [32]. Still, the use of formal optimization models, particularly at the network level, is rather limited and is not very user-friendly [33].

Applying utility theory in an optimization model can have at least the following three benefits, which makes the model more useful.

1. Provide the flexibility for management to specify different objective functions and simplify the problem to single objective optimization, as long as all objectives be converted into reasonable utilities
2. Provide the flexibility for management to consider and accommodate localized constraints in the model
3. Provide capability to perform systematic and efficient “what if” analysis to address problems. For example, what if the budgets allocated to pavement M&R get reduced?

The current study defines two utilities for pavement M&R: U_{IRI} as the road condition index and $U_{traffic}$ as the traffic volume index. Both are normalized to have the maximum value of 1 so that they can be put on the same comparable basis. Assigning appropriate U_{IRI} and $U_{traffic}$ for decision making makes the pavement system simple and flexible. However, there should be a reasonable tactic to convert the original IRI and traffic volume data into U_{IRI} and $U_{traffic}$.

According to Sayers *et al*. (1986), at the roughness range of 3.5 to 4.5, the pavement is in good condition with only negligible depressions (e.g. < 5 mm/3 m) and no potholes, although drivers still have to be aware of gentle undulations or swaying,. At the roughness range of 7.5 to 9.5, pavement quality has deteriorated with frequent shallow, moderate depressions or shallow potholes (e.g. 6-30 mm/3 m with frequency 5-10 per 50 m) and some moderate corrugations (e.g. 6-20 mm/0.7-1.5 m). Drivers would experience sharp movements and some wheel bounce. To provide the best network surface, the pavement should be maintained to stay in the range of 3.5 to 4.5.

Based on past maintenance practices, the Kaohsiung Maintenance Office considers eight alternative treatment methods: (1) do nothing, (2) seal slurry, (3) patch, (4) mill and overlay 7.5 cm AC, (5) mill and overlay 10 cm AC, (6) mill and overlay 15 cm AC, (7) mill and overlay 20 cm AC, and (8) reconstruct. Table 1 shows the Treatment Matrix listing these M&R treatment methods, their treatment effects, and unit costs for implementing M&R actions based on past maintenance records.

Based on past M&R experiences, an IRI value of 5.3 is the point at which citizens start to complain about road quality, and the major treatment of milling and overlay is required. Considering Sayers’ IRI scale, as well as past practices, the expert panel suggested an IRI value of 5.3 as the maintenance threshold. $U_{IRI}(5.3)$ is set to be 0, which represents the point at which the pavement starts to be worthy of maintenance. When the IRI is below 5.3, the pavement quality is considered acceptable and should not undergo maintenance process and consequently results in negative utility. An IRI value of 12 has been the worst unrepaired pavement in the Kaohsiung municipal district, and thus $U_{IRI}(12)$ is set to be 1, meaning the agency will receive the greatest utility when a road section’s IRI is at 12,

According to past maintenance records in Kaohsiung, the maintenance budget allows the agent to treat approximately 50% of its important network sections. Sections with high traffic volume receive high maintenance priority. The expert panel suggests that the median of the traffic volumes of all sections be the threshold of $U_{traffic}$, and the section with the highest volume receives the greatest utility of 1. This mechanism allows road sections with low quality and high traffic volume to receive high priority in M&R. This

Table 1. Treatment Matrix for Kaohsiung Pavement M&R.

	Treatment Method	IRI(m/km) before Treatment	IRI(m/km) After Treatment	Treatment Cost NT$/m²/(USD/ m²)
I	Do nothing (Inspection only)	IRI＜2.4	—	—
II	Seal Slurry	2.4≦IRI＜3	2.2	460/15.3
III	Patching	3≦IRI＜5.3	2.8	560/18.7
IV	Mill and Overlay 7.5 cm AC	5.3≦IRI＜7	4	660/22.0
V	Mill and Overlay 10 cm AC	7≦IRI＜8	3.8	702/23.4
VI	Mill and Overlay 15 cm AC	8≦IRI＜9	3.5	1,010/33.7
VII	Mill and Overlay 20 cm AC	9≦IRI＜10	3	1,120/37.3
VIII	Reconstruction	10≦IRI	2	1,350/45.0

straightforward application of utility theory makes decision making for the Kaohsiung pavement M&R very flexible. If decision makers want to consider factors other than IRI and traffic volume, it will not be difficult to combine PI, PCI, or other factors into the utility function. The function processes the solution with minimal modifications to the constraints.

Cost Allocation Model for Kaohsiung Pavement M&R

Objective Function

Objective variables considered in this research are (1) IRI utility (U_{IRI}) maximization and (2) traffic volume utility ($U_{traffic}$) maximization. These two variables combine to obtain a single objective optimization model. The model considers maintaining serviceability of the entire road network, as well as receiving maximum satisfaction level from road users by treating the worst conditioned and highest-volume sections first. For comparison purposes, this work develops three objective functions with different U_{IRI} and $U_{traffic}$ combinations: one with equal weights on both U_{IRI} and $U_{traffic}$, the second where U_{IRI} weighs twice as much as $U_{traffic}$, and the third with $U_{traffic}$ weighing twice as much as U_{IRI}. The three objective functions are as follows:

$$\text{Maximize } U_1 = \sum_{i=1}^{m} x_i * (U_{IRI_i} + U_{traffic_i})$$

$$\text{Maximize } U_2 = \sum_{i=1}^{m} x_i * (2 * U_{IRI_i} + U_{traffic_i})$$

$$\text{Maximize } U_3 = \sum_{i=1}^{m} x_i * (U_{IRI_i} + 2 * U_{traffic_i})$$

where U_{IRIi} = IRI utility of section i

$U_{traffici}$ = Traffic volume utility of section i

m = number of road sections analyzed

x_i denotes whether section i receives treatment or not. When section i is treated, $x_i = 1$, and when section i is not treated, $x_i = 0$.

Budget Constraint

The proposed model considers budget in the constraints. The overall maintenance cost should not exceed the budget available. The constraint is as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij} \times A_i \times x_i \le B$$

where c_{ij} = the maintenance cost of section i receiving treatment method j

A_i = total maintenance area of section i

n = number of treatment methods

B = budget limit.

Solving the Model

The pavement M&R model can be categorized as a Binary Integer Programming problem (BIPs), since the solution set can only take the values of 1 and 0, representing whether the road is undergoing maintenance or not. Branch and bound approaches, such as the Balas Additive algorithm [34] or Dakin's algorithm [35], are used for solving BIPs. This research uses commercial optimization software to solve the BIPs [36]. The software is an add-in to Excel that allows users to build large-scale optimization models in a free form layout within a spreadsheet. Building the model requires assigning the following elements:

1. Adjustable Cells

Specify the cells in the Excel workbook that the solver can adjust to find the best solution. The adjustable cells are variables of the optimization problem that needs to be solved. Users can allow these cells to take any value or restrict them to whole numbers (i.e. integer values). In this case, we allowed the cell to take the value of 0 or 1.

2. Best Cell

Specify the best cell you wish to maximize or minimize, which is your objective function. In this research case, the objective function maximizes the sum of all utilities.

3. Constraints

Specify the restrictions or limitations on the problem. These are the relationships the solution must satisfy to be feasible. Constraints are expressed using standard Excel style equations, so they are easy to read, understand, and modify.

The integer solver works in conjunction with the linear and nonlinear solvers to solve general and binary integer models. For linear models, the integer solver does extensive preprocessing and adds constraint "cuts" of several different varieties to significantly improve solution times on large classes of integer models. Upon building the objective function and constraints in Excel, the optimal solution in the pavement M&R model derives within seconds.

Case Study

This research computerized and conducted all the developed procedures for a range of different planning scenarios to test the computational performance of the proposed model. To demonstrate the application of the proposed model to municipal pavement network, this study used typical data for Kaohsiung.

The Maintenance Office of the Public Works Bureau maintains a pavement network divided into a number of districts and allocates a certain fraction of the yearly municipal budget to each district, depending on its needs. The case study uses a subset of the district of Sung-Ming (city core) containing nineteen road sections (Fig. 2). Combining the Treatment Matrix in Table 1 and the IRI data of 2008, Table 2 summarizes the total cost of treatment, which considers the respective treatment area and the selected treatment method. As Calculated in Table 2, treatment of the entire network would require a funding of $21,345,200 NT ($711,507 USD). Past record has shown that the municipal government tends to allocate funding to meet approximately 50% of the requirement, and the Maintenance Office is then responsible for distribution of the money to different districts. City core districts usually receive more funding than other districts. The budget limit in the case study is set at $13,000,000 NT ($433,333 USD), which is about 60% of the requirement and is consistent with past records. IRI data of each section converted into U_{IRI} are shown in Fig. 3.

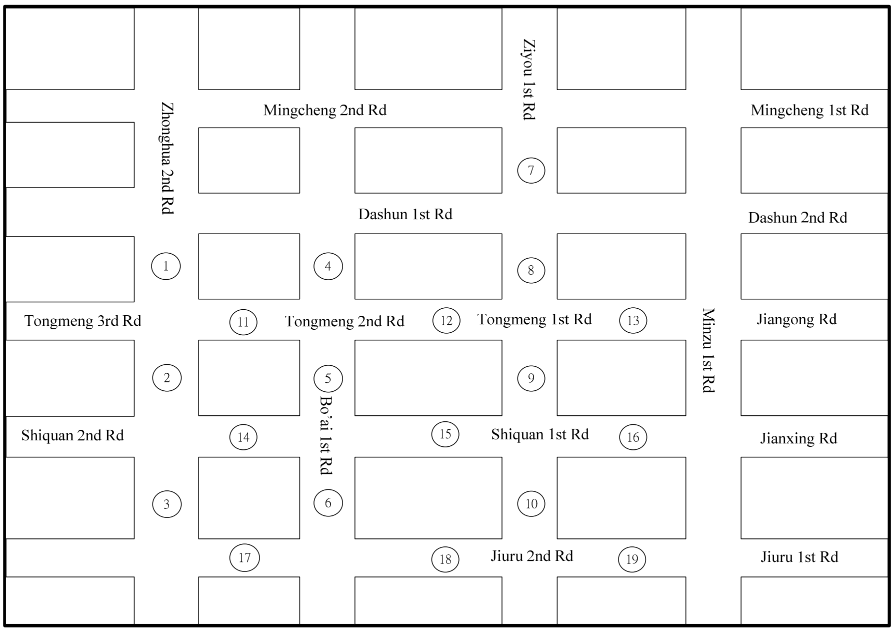

Fig. 2. Case Study Road Sections.

Traffic volume data converted into $U_{traffic}$, where the median of these 19 sections of $U_{traffic}$ (69,235) is set to 0, and the section with the highest volume $U_{traffic}$ (151,268) is set to 1, as shown in Fig. 4.

The U_{IRI} and $U_{traffic}$ conversions of all nineteen road sections are shown in Table 3 and Fig. 5. The use of the solver to derive the model results in the three sets of optimal solutions for U_1, U_2, and U_3, are shown in Tables 4, 5, and 6.

Different combinations of U_{IRI} and $U_{traffic}$ in U_1 (1:1), U_2 (2:1), and U_3 (1:2) yield intriguing results. Both Model U_1 and U_2 identify the same seven road sections (#1, #2, #4, #6, #10, #18, and #19) with an identical total maintenance cost of $12,622,000 NT ($420,733 USD), though the maintenance priority varies between models U_1 and U_2. However, in model U_3, where traffic volume utility obtains twice the weight of IRI, the optimal solution yields a maintenance program of nine road sections instead of seven, with a total cost of $12,905,500 NT ($430,183 USD). The road sections model U_3 picks sections #1, #2, #3, #4, #8, #9, #10, #17, and #18.

Comparing the solutions in models U_1, U_2, and U_3, models U_1 and U_2 pick sections #6 and #19, while model U_3 replaces them with sections #3, #8, #9, and #17. Sections #6 and #19 have relatively low $U_{traffic}$ at -0.255 and 0.000, which make their total utility lower than that of sections #3, #8, #9, and #17, when $U_{traffic}$ obtains a higher weight.

Table 7 shows the comparison of these two alternatives. In models U_1 and U_2, the total utility of sections #6 and #19 is still higher than that of sections #3, #8, #9, and #17. However, in model U_3, the total utility of sections #3, #8, #9, and #17 surpass that of sections #6, and #19.

In models U_1 and U_2, sections selected in the optimal solution happen to be the top seven prioritized sections. Results in model U3 reveal that the nine sections selected do not consist of the 8th and 9th ranked section (#6 and #19) but include the 10th and 11th sections (#8 and #9). The reason is that if either section #6 or #19 is selected in model U_3, then the total cost will exceed the budget constraint of $13,000,000 NT ($433,333 USD) and become infeasible. The optimization procedure is simple and straightforward but appears to be the solution sufficient for Kaohsiung's current practices.

Conclusions

This research develops a single objective optimization model by incorporating Utility theory and the Binary Integer Programming algorithm to determine optimal maintenance programs. The developed optimization model is applied to a real M&R case in Kaohsiung. The research considers two maintenance objectives of the road network condition (U_{IRI}) and traffic volume ($U_{traffic}$). The optimization model considers both objectives simultaneously with three different weighting combinations. Budget constraint ensures the feasibility of solutions. This work sets various treatment method levels to determine the proper time to implement the treatment when maximizing road users' benefit and overall road condition.

By applying different weights on U_{IRI} and $U_{traffic}$, the proposed model yields two sets of optimal solutions. When a higher weight is put on pavement quality (IRI), the model tends to select bad quality sections with small traffic volumes. On the other hand, when a higher weight is put on traffic volume, the model tends to select heavy traffic sections with fair road conditions. The current stage of the study does not intend to suggest an appropriate weight combination but provides a first step model and the necessary tools for maintenance officials to experiment with the combination. This flexible perspective also allows the officials to further address the trade-off between heavy M&R and preventive maintenance. That is, for a fixed budget, should one select a major M&R for a small number of segments/road users or preventive maintenance for a larger number of segments/road users?

As the pioneering study, the developed models consider only limited aspects of pavement performance measures. However, the

Table 2. Detailed Information – Road Sections.

No	Section	IRI (m/km)	Traffic Volume (pcu)	Treatment Area (m^2)	Treatment Method	Total Cost NT$/ USD
1	Zhonghua 2nd Rd (between Dashun and Tongmeng)	6.22	151,268	2,000	Milling and Overlay 7.5 cm AC	$1,320,000/ USD44,000
2	Zhonghua 2nd Rd (between Tongmeng and Shiquan)	7.63	134,199	2,000	Milling and Overlay 10 cm AC	$1,404,000/ USD46,800
3	Zhonghua 2nd Rd (between Shiquan and Jiuru)	4.82	111,159	2,000	Patching	$1,120,000/USD37,333
4	Bo'ai 1st Rd (between Dashun and Tongmeng)	10.42	122,223	2,000	Reconstruction	$2,700,000/USD90,000
5	Bo'ai 1st Rd (between Tongmeng and Shiquan)	5.27	57,274	1,050	Patching	$588,000/USD19,600
6	Bo'ai 1st Rd (between Shiquan and Jiuru)	11.82	48,325	1,050	Reconstruction	$1,417,500/USD47,250
7	Ziyou 1st Rd (between Mingchen and Dashun)	2.77	51,547	1,050	Slurry Seal	$483,000/USD16,100
8	Ziyou 1st Rd (between Dashun and Tongmeng)	5.61	76,857	1,050	Milling and Overlay 7.5 cm AC	$693,000/USD23,100
9	Ziyou 1st Rd (between Tongmeng and Shiquan)	4.96	75,319	1,050	Patching	$588,000/USD19,600
10	Ziyou 1st Rd (between Shiquan and Jiuru)	8.46	90,933	1,050	Milling and Overlay 15 cm AC	$1,060,500/USD35,300
11	Tongmeng 2nd Rd (between Zhonghua and Bo'ai)	5.87	41,657	1,050	Milling and Overlay 7.5 cm AC	$693,000/23,100
12	Tongmeng 1st Rd (between Bo'ai and Ziyou)	4.10	47,863	1,050	Patching	$588,000/USD19,600
13	Tongmeng 1st Rd (between Ziyou and Minzu)	2.61	50,547	1,050	Slurry Seal	$483,000/USD16,100
14	Shiquan 2nd Rd (between Zhonghua and Bo'ai)	6.43	65,267	1,050	Milling and Overlay 7.5 cm AC	$693,000/USD23,100
15	Shiquan 1st Rd (between Bo'ai and Ziyou)	7.54	51,268	1,050	Milling and Overlay 10 cm AC	$737,100/USD24,500
16	Shiquan 1st Rd(between Ziyou and Minzu)	7.24	57,157	1,050	Milling and Overlay 10 cm AC	$737,100/USD24,500
17	Jiuru 2nd Rd (between Zhonghua and Bo'ai)	6.59	81,306	2,000	Milling and Overlay 7.5 cm AC	$1,320,00/USD44,0000
18	Jiuru 2nd Rd (between Bo'ai and Ziyou)	11.37	75,878	2,000	Reconstruction	$2,700,000/USD90,000
19	Jiuru 1st Rd (between Ziyou and Minzu)	8.25	69,235	2,000	Milling and Overlay 15 cm AC	$2,020,000/USD67,333
	Total:			26,600 m^2		$21,345,200/USD711,507

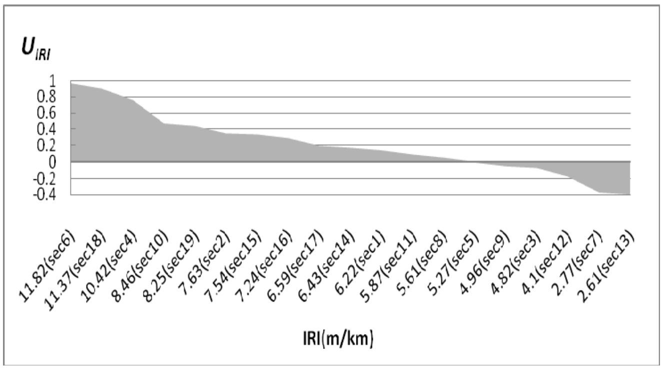

Fig. 3. IRI vs $U_{IRI.}$

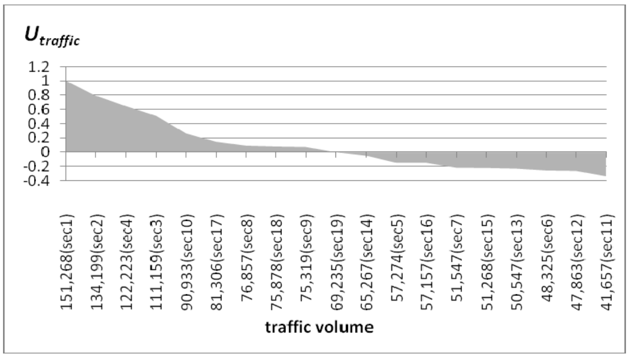

Fig. 4. Traffic Volume vs $U_{tra.}$

Table 3. Utility Conversions.

Section	IRI(m/km)	U_{IRI}	Traffic Volume	$U_{traffic}$
1	6.22	0.137	151,268	1
2	7.63	0.348	134,199	0.792
3	4.82	-0.072	111,159	0.511
4	10.42	0.764	122,223	0.646
5	5.27	-0.005	57,274	-0.146
6	11.82	0.973	48,325	-0.255
7	2.77	-0.378	51,547	-0.216
8	5.61	0.046	76,857	0.093
9	4.96	-0.051	75,319	0.074
10	8.46	0.472	90,933	0.265
11	5.87	0.085	41,657	-0.336
12	4.1	-0.179	47,863	-0.261
13	2.61	-0.402	50,547	-0.228
14	6.43	0.169	65,267	-0.048
15	7.54	0.335	51,268	-0.219
16	7.24	0.289	57,157	-0.147
17	6.59	0.193	81,306	0.147
18	11.37	0.907	75,878	0.081
19	8.25	0.44	69,235	0

Table 4. Optimal Solution U_1=6.569.

Section	U_1	Priority	Selected?	Cost(U_1)
1	1.137	3	Yes	NT$1,320,000/USD44,000
2	1.14	2	Yes	NT$1,404,000/USD46,800
3	0.44	8	No	0
4	1.41	1	Yes	NT$2,700,000/USD90,000
5	-0.15	15	No	0
6	0.718	6	Yes	NT$1,417,500/USD47,250
7	-0.593	18	No	0
8	0.139	11	No	0
9	0.024	14	No	0
10	0.736	5	Yes	NT$1,060,500/USD35,350
11	-0.252	16	No	0
12	-0.44	17	No	0
13	-0.63	19	No	0
14	0.12	12	No	0
15	0.116	13	No	0
16	0.142	10	No	0
17	0.34	9	No	0
18	0.988	4	Yes	NT$2,700,000/USD90,000
19	0.44	7	Yes	NT$2,020,000/USD67,333
Total M&R Cost(U_1)				NT$12,622,000/USD420,733

idea of converting IRI and traffic volume into utilities is unique in the field of pavement management research, and the utility theory mechanism allows simple implementation and fast integration of other performance measures in the future. The utility conversion is a customized process that meets specific local regulations and requirements, making the optimization model more practical and easier to apply in the pavement maintenance program. This study has provided a feasible and scientific solution for Kaohsiung city officials to identify and prioritize pavement maintenance needs while budgeting more effectively, which has been missing from past practices.

Table 5. Optimal Solution U2=10.609.

Section	U2	Priority	Selected?	Cost(U2)
1	1.275	5	Yes	NT$1,320,000/USD44,000
2	1.488	4	Yes	NT$1,404,000/USD46,800
3	0.368	11	No	0
4	2.174	1	Yes	NT$2,700,000/USD90,000
5	-0.155	15	No	0
6	1.691	3	Yes	NT$1,417,500/USD47,250
7	-0.971	18	No	0
8	0.186	13	No	0
9	-0.027	14	No	0
10	1.208	6	Yes	NT$1,060,500/USD35,350
11	-0.167	16	No	0
12	-0.619	17	No	0
13	-1.031	19	No	0
14	0.289	12	No	0
15	0.45	9	No	0
16	0.431	10	No	0
17	0.533	8	No	0
18	1.894	2	Yes	NT$2,700,000/USD90,000
19	0.88	7	Yes	NT$2,020,000/USD67,333
Total M&R Cost(U2)				NT$12,622,000/USD420,733

Table 6. Optimal Solution U_3=9.962.

Section	U_3	Priority	Selected?	Cost(U_3)
1	2.137	1	Yes	NT$1,320,000/USD44,000
2	1.932	3	Yes	NT$1,404,000/USD46,800
3	0.951	6	Yes	NT$1,120,000/USD37,333
4	2.056	2	Yes	NT$2,700,000/USD90,000
5	-0.296	15	No	0
6	0.463	8	No	0
7	-0.809	18	No	0
8	0.232	10	Yes	NT$693,000/USD23,100
9	0.098	11	Yes	NT$588,000/USD19,600
10	1.001	5	Yes	NT$1,060,500/USD35,350
11	-0.588	16	No	0
12	-0.7	17	No	0
13	-0.857	19	No	0
14	0.072	12	No	0
15	-0.104	14	No	0
16	-0.005	13	No	0
17	0.487	7	Yes	NT$1,320,000/USD44,000
18	1.069	4	Yes	NT$2,700,000/USD90,000
19	0.44	9	No	0
Total M&R Cost(U_3)				NT$12,905,500/USD430,183

Table 7. Comparison of Different Selections.

Section	U_{IRI}	$U_{traffic}$	U_1	U_2	U_3
6	0.973	-0.255	0.718	1.691	0.463
19	0.44	0	0.44	0.88	0.4398
		Total	1.158	2.571	0.9028
3	-0.072	0.511	0.44	0.368	0.9506
8	0.046	0.093	0.139	0.185	0.232
9	-0.051	0.074	0.023	-0.028	0.097
17	0.193	0.1471	0.34	0.533	0.4872
		Total	0.942	1.058	1.7668

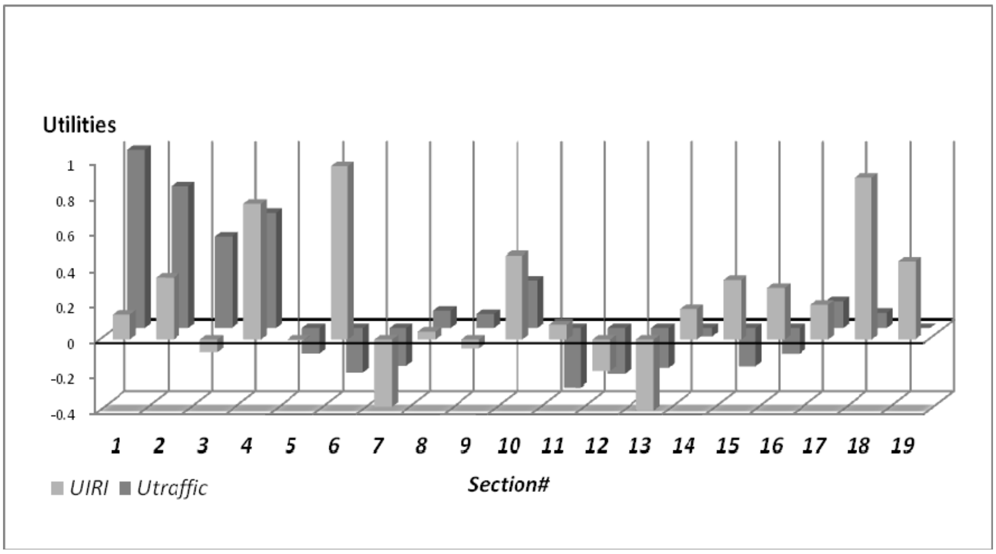

Fig. 5. Utility Conversions.

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References

1. Public Construction Council (2008), http://erp.pcc.gov.tw/pccap2/BIZSfront/NewsContent.do?site =002&bid=BIZS_C00007694, Taipei, Taiwan, Retrieved August 2008.
2. Chang, J.R., Hung, C.T., and Lin, J.D. (2005). Application of Advanced Computation on Flexible Pavement Maintenance Management System in Taiwan, *15th International Road Federation World Meeting*. Bangkok, Thailand.
3. Tserng, J.H. (2007). Modernization of Highway Facility Management, *Construction Info*, Vol. 292, pp. 11-13 (in Chinese).
4. Miller, T.D. and Bahia, H.U. (2010). Establishing a Framework for Analyzing Asphalt Pavement Sustainability. *International Journal of Pavement Research and Technology*, 3(3), pp. 149-155.
5. Haas, R., Hudson, W. R., and Zaniewski, J. (1994). *Modern Pavement Management*, Krieger Publishing Company, Malabar, Florida.
6. Zhang, Z. (1996). A GIS Based and Multimedia Integrated Infrastructure Management System, *PhD Dissertation*, University of Texas at Austin, Texas, USA.
7. Wang, F., Zhang, Z., and Machemehl, R.B. (2003). Decision Making Problem for Managing Pavement Maintenance and Rehabilitation Projects. *TRB 2003 Annual Meeting,* Washington, D.C., USA, CD-ROM TRB2003-002202.
8. Sharaf, E.A. (1993). Ranking vs. Simple Optimization in Setting Pavement Maintenance Priorities: A Case Study from Egypt, *Transportation Research Record,* No. 1397, pp. 34-38.
9. Zambrano, F., Scullion, T., and Smith, R.E. (1995). Comparing Ranking and Optimization Procedures for the Texas Pavement Management Information System, *TTI Research Report 1989-2F*, Texas A&M University, Texas, USA.
10. Abaza, K. A., and Ashur, S. A. (1999). Optimum Decision Policy for Management of Pavement Maintenance and Rehabilitation, *Transportation Research Record,* No. 1655, pp. 8-15.
11. Chen, X., Hudson, S., Pajoh, M., and Dickinson, W. (1997). Development of New Network Optimization Model for Oklahoma Department of Transportation, *Transportation Research Record,* No. 1524, pp. 103-108.
12. Grivas, D. A., Ravirala, V., and Schultz, B.C. (1993). State Increment Optimization Methodology for Network-level Pavement Management, *Transportation Research Record,* No. 1397, pp. 25-33.
13. Liu, F. and Wang, K.C.P. (1997). Pavement Performance-Oriented Network Optimization System, *Transportation Research Record,* No. 1524, pp. 86-93.
14. Mbwana, J. R. and Turnquist, M. A. (1997). Optimization Modeling for Enhanced Network-level Pavement Management Systems, *Transportation Research Record,* No. 1524, pp. 76-85.
15. Fwa, T.F., Sinha K.C., and Riverson, J.D.N. (1989). Priority Rating of Highway Routine Maintenance Activities, *Transportation Research Record,* No. 1246, pp. 54-64**.**
16. Bharn, G.H., Darter, M.I., and Gharaibeh, N.G. (2002). Consequence of Utilizing Alternative Pavement Ratings for Prioritizing Pavement Rehabilitations of Illinois's Interstate Highway Network. *Proceeding of the Seventh International Conference on Application of Advanced Technologies in Transportation*, pp. 956-971, Massachusetts, USA.
17. Kerali, H.R. and Mannisto, V. (1999). Prioritization Methods for Strategic Planning and Road Work Programming in a New Highway Development and Management Tool, *Transportation Research Record*, No. 1655, pp. 49-54.
18. Golabi, K. (2002). A Pavement Management System for Portugal. *Proceeding of the Seventh International Conference*

on Application of Advanced Technologies in Transportation*, pp. 561-567, Massachusetts, USA.
19. Wei, J., Kong Y., and Fu, Z. (2009). Multi-Objective Optimization for Pavement Maintenance and Rehabilitation Strategies, *International Conference on Transportation Engineering- Proceedings of the Second International Conference on Transportation Engineering* (ICTE), Chengdu, China.
20. Lee, J.S., Suh, Y.C., Kwon, S.A., Kim, G.Y., and Lim, K.S. (2009). Development of Pavement Condition Index for Korean Asphalt National Highway and Decision Criteria for Resurfacing, *International Journal of Pavement Research and Technology*, 2(3), pp. 106-114.
21. Sayers, M.W. and Karamihas, S.M. (1996). Interpretation of Road Roughness Profile Data, *FHWA/RD-96/101*, Federal Highway Administration, Washington D.C., USA.
22. Sayers, M.W. and Karamihas, S.M. (1998). *Little Book of Profiling*, University of Michigan Transportation Research Institute, Ann Arbor, Michigan, USA. http://www.umtri.umich.edu/content/LittleBook98R.pdf, Retrieved April 4, 2010.
23. Wang, H. (2006). Road Profiler Performance Evaluation and Accuracy Criteria Analysis, *Master Thesis*, Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.
24. Stigler, G..J. (1968). *The Development of Utility Theory*, John Wiley & Sons, New York, USA.
25. Booth, P.M. and Ong, A.S.K. (1994), A Simulation Based Approach to Asset Allocation, *Proceedings of the 4th AFIR International Colloquium*, Vol. 1, pp. 217-39, Orlando, FL, USA.
26. Khorasanee, M.Z. and Smith, D.A. (1997). A Utility Maximisation Approach to Individual Investment Choices in a Money Purchase Pension Scheme, *Proc. 1997 Investment Conference*, Vol. 2, pp. 261–289, London, England, UK.
27. Mitchell, O.S., Bodie, Z., Hammond, P.B., and Zeldes, S. (2001), *Innovations in Retirement Financing*, University of Pennsylvania Press, Philadelphia, Pennsylvania, USA.
28. Thomson, R.J. (2003). The Use of Utility Functions for Investment Channel Choice in Defined Contribution Retirement Funds II: A Proposed System, *British Actuarial Journal*, 9(4), pp. 903-958.
29. Sayers, M.W. (1986). *Guidelines for Conducting and Calibrating Road Roughness Measurements*, World Bank Technical Paper, No. 46.
30. Vigna, E. and Haberman, S. (2001). Optimal Investment Strategy for Defined Contribution Pension Schemes, *Insurance: Mathematics and Economics*, Vol. 28**,** pp. 233–262.
31. Kulkarni, R. B. (1984). Dynamic Decision Model for a Pavement Management System, *Transportation Research Record*, No. 997, pp. 11-18.
32. Kulkarni, R.B., Finn, F.N., Alviti, E., Chuang, J., and Rubinstein, J. (1983). Development of a Pavement Management System- Final Report, Woodward-Clyde Consultants for Kansas Department of Transportation, Topeka, Kansas, USA.
33. Kulkarni, R. and Miller, R. (2003). Pavement Management Systems: Past, Present, and Future, *CD-ROM*, TRB 2003 Annual Meeting, Washington, D.C., USA. 34. Balas, E. (1965). An Additive Algorithm for Solving Linear Programs with Zero-One Variables, *Operations Research*, Vol. 13, pp. 517-546.
34. Balas, E. (1965). An Additive Algorithm for Solving Linear Programs with Zero-One Variables, *Operations Research*, Vol. 13, pp. 517-546.
35. Dakin, R. J. (1965). A Tree Search Algorithm for Mixed Integer Programming Problems, *Computer Journal*, Vol. 8, pp. 250–255.
36. Lindo Systems (2010). http://www.lindo.com/index.php?option=com_content&view=article&id=3&Itemid=11, Accessed on April 2010.