

## OPTIMAL MAINTENANCE STRATEGIES FOR BITUMINOUS PAVEMENTS: A CASE STUDY IN VIETNAM USING HDM-4 WITH GRADIENT METHODS

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**Abstract:** The paper presents a systematic approach to find optimal maintenance strategies for pavement management systems by using the World Bank's Highway Development and Management System (HDM-4) combined with gradient methods proposed by Tsunokawa *et al* (2005). The optimal maintenance strategy is defined as the set of optimal maintenance options corresponding to different traffic levels and various initial pavement conditions, which minimizes the sum of agency costs and road user costs in present value or maximizes the net benefit to society over an analysis period. The basic data for the analysis was derived from the Vietnamese conditions and the most sensitive parameters in HDM-4 were calibrated into the local conditions for a basic application. The findings may help highway agencies in better applying the right maintenance work at the right time and thus result in savings with regard to the total transport costs to the society.

**Key Words:** PMS, Vietnam, HDM-4, pavement maintenance, optimal maintenance strategy

### 1. INTRODUCTION

The Highway Development and Management System (HDM-4, 2003), which was developed by the World Bank and other international organizations, has been widely used in over one hundred countries including developed countries. Also, it is recognized as a state-of-the-art system for the analysis of road management and investment alternatives because of the following advantages: (1) the incorporation of both agency costs and road user costs in a life-cycle cost analysis, (2) the use of calibration parameters for broad-based applicability in diverse climates and conditions, and (3) the use as an appropriate design tool for pavements, if properly calibrated, especially for developing countries, while borrowing design standards directly from the design specifications of industrialized countries (Tsunokawa and Ul-Islam, 2003). Recently, HDM-4 has been used in Vietnam for a pavement management system (PMS) by various major projects such as the highway management capacity improvement project (HMCP, 2002) and the road network improvement project (RNIP, 2003). These studies showed the potential and promise of using this advanced tool, incorporated with the existing tools in the PMS (such as ROSY Database), to establish the strategic management plan for the national road network.

In addition, a major emphasis has recently been placed on the maintenance of existing road pavement systems to preserve the huge investments in pavements. However, they are still lacking suitable strategies for the pavement maintenance of road systems in Vietnam. As a

consequence this leads to an increase in the total transport costs (the sum of highway agency costs and road user costs) and causes many problems to the society, such as traffic accidents, traffic congestion and environmental pollution. If innovative and effective strategies for maintenance are employed, the pavement system can provide higher levels of service for a longer period of time and thus result in savings with regard to the total transport costs to the society.

The HDM-4, as like other “what-if models” of pavement management analysis, predicts the consequences of the different maintenance options that are to be investigated and that are specified exogenously. Since there are usually an infinite number of options to be considered, it is impossible to exhaust all of them and only suboptimal optimizers are found among those tested. To overcome this deficiency, Tsunokawa *et al.* (2005) proposed a new approach to find the true optimal maintenance option which maximizes the net benefit over an analysis period for a given road section by using HDM-4 at the project level, combined with gradient methods. To obtain the optimal maintenance option, the approach shows the search direction for moving along, instead of testing all possible options.

Based on the core of the above-mentioned methodology, the objective of this paper is to investigate the optimal maintenance strategies which are defined as the set of optimal maintenance options corresponding to different traffic levels and various pavement conditions. The basic data for the analysis is derived from the Vietnamese conditions and the most sensitive parameters in HDM-4 are calibrated into the local conditions for a basic application. The findings may help highway agencies in better selecting the appropriate maintenance work at the right time based on condition surveys and to make the pavement system provide higher levels of service for longer periods of time and thus result in savings of the total transport costs to the society. In the following, we shall first present an overview of the adopted methodology and then follow it up with a discussion on the employed data. Finally, the analysis results will be presented and discussed.

## 2. METHODOLOGY

The HDM-4 models comprise relationships for predicting (1) pavement deterioration as a function of traffic loading, environmental effects, and maintenance impacts, and (2) user costs as a function of pavement conditions. Given all the necessary data, such as the physical and environmental characteristics of a road section, traffic loading, vehicle fleet characteristics, unit prices, etc., one can use HDM-4 to compute the net benefit to society based on a simulation of the history of pavement deterioration and a prediction of the stream of road user costs and maintenance costs during the analysis period. The net benefit is computed as the difference in the total transport costs in present value between each exogenously specified maintenance option and a do-minimum option as the base case. By combining HDM-4 runs at the project level with gradient methods, the optimal maintenance option, which maximizes the net benefit to society over the analysis period, is obtained from all possible options. In this study the Steepest Descend Method is used, since it is simple in manually computing the search direction and the performance of the two gradient methods (the Steepest Descend and Conjugate Gradient Methods) has no substantial difference as discussed by Tsunokawa *et al.* (2005). The analysis is repeated for different traffic levels and various initial pavement conditions, thereby identifying the optimal maintenance options corresponding to the levels of traffic and initial pavement conditions as shown in Figure 1. The traffic level is expressed in terms of the annual average daily traffic (AADT) and the composition of traffic. The

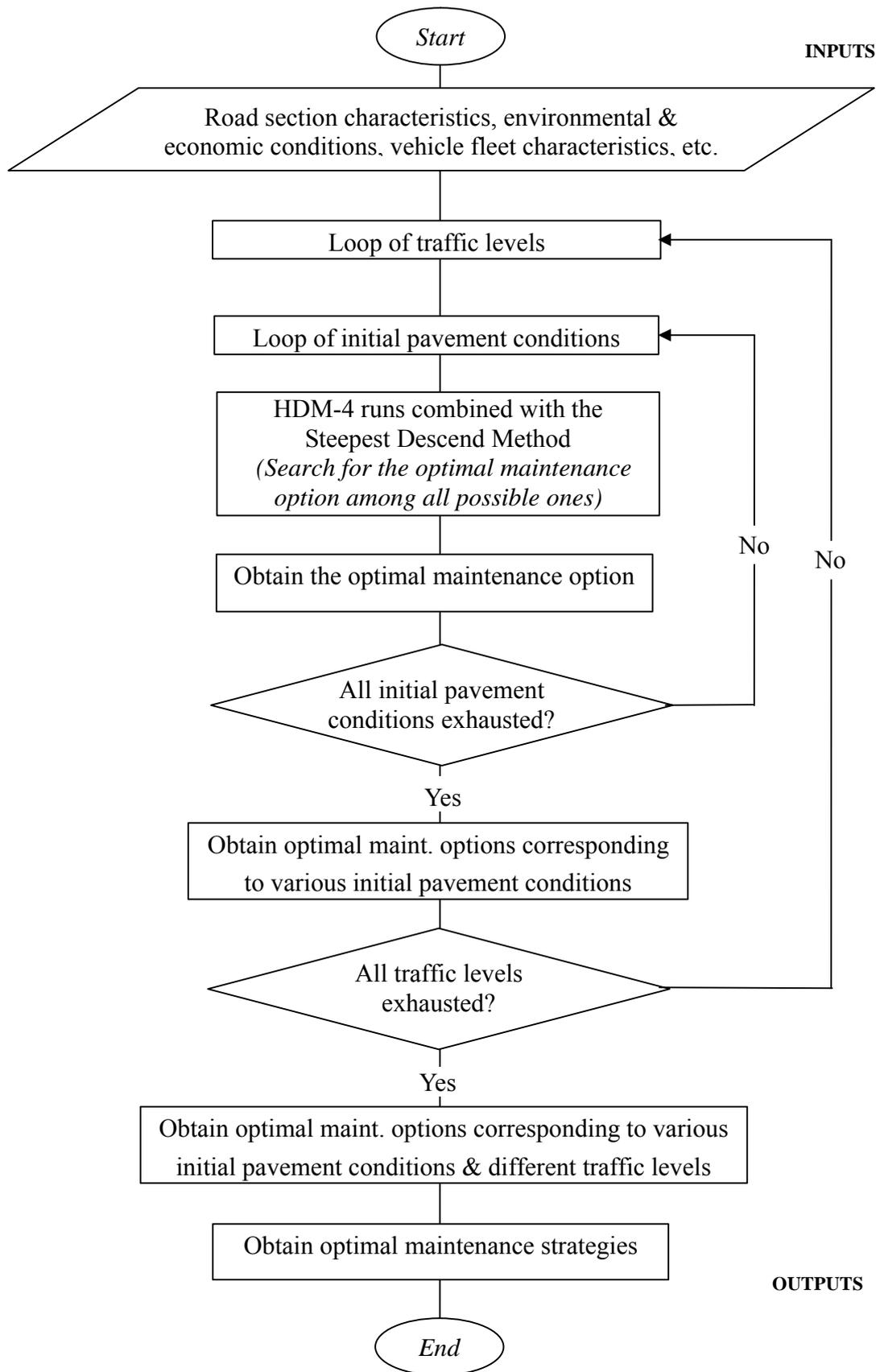


Figure 1. Search Algorithm for Investigating Suitable Maintenance Strategies

pavement condition is expressed in terms of the international roughness index (IRI), which reflects other pavement condition performance indicators (such as cracking area, number of potholes, edge break area, and mean rutting depth) based on the statistical relationships derived from the Vietnamese road network data.

### 3. INPUT DATA

A road section used in the analysis is defined by a unique set of geometric characteristics, environmental conditions, traffic loading, pavement conditions and pavement design. The parameters of the representative sections used in the analysis will be discussed as follows.

#### 3.1 Road Section Characteristics

A section of road with a length of 50 km in a sub-humid/tropical environment was considered in the present study. The basic design elements of the section were taken from the highway standard (TCVN 4054, 1998) for primary roads with two standard lanes in flat terrain, i.e. 7m-carriageway and 2.5 m-shoulder on each side (2.0 m paved and 0.5 m unpaved). The aggregate rise and fall, number of rise and fall, average horizontal curvature, and superelevation are 5 m/km, 4, 26 deg/km, and 2 %, respectively. These values were average ones in weights of the total paved road length in flat terrain of the 12,380 km-paved road network obtained from the Vietnamese road network improvement project (RNIP, 2003).

#### 3.2 Traffic, Analysis Period and Discount Rate

The annual average daily traffic (AADT) of 1000, 4000 and 10000 vpd in the year 2004 as representative for low, medium and high traffic volumes were considered in the analysis. Note that the traffic composition of the low traffic case is different from the high and medium traffic cases, and the dominant motorcycle percentage reflects the road transport condition in Vietnam as shown in Table 1. A twenty-year analysis period starting from 2004 and a 12% social discount rate (as suggested by the World Bank, 2003) were used in the study.

Table 1. Composition and Annual Growth Rate of Traffic

Traffic Case	Composition and Annual Growth Rate	Vehicle Type					Total
		Motorcycle	Passenger Car	Medium Truck	Large Bus	Heavy Truck	
High & Medium Traffic	<i>Composition (%)</i>	63	13	10	9	5	100
	<i>Annual growth rate (%)</i> *)	8/4	8/5	6/3	3/3	6/3	
Low Traffic	<i>Composition (%)</i>	63.3	12.5	24.2	n/a	n/a	100
	<i>Annual growth rate (%)</i> *)	8/4	8/5	6/3	n/a	n/a	

Source: (RNIP, 2003);

\*) Annual growth rate from 2003 to 2013 / 2013 onward; "n/a" denotes "not applicable".

### 3.3 Pavement Structural Characteristics

The study investigates for bituminous pavement with asphalt mix on granular base for all the traffic cases. For surface materials, Hot Rolled Asphalt (HRA) was used in the case of high traffic level, whereas Single Bituminous Surface Dressing (SBSD) was used for low and medium traffic levels given that these were the actual material types used for sections that have different levels of traffic.

Sub-grade strength was assumed at California Bearing Ratio (CBR) of 8 as the same as that reported in RNIP (2003). The pavement strength, measured in terms of the structural number, was calculated according to traffic loading by using AASHTO (1993), which has been primarily adjusted to be used broadly in Vietnam recently. Table 2 shows the values of structural number corresponding to traffic loadings.

Table 2. Annual Average Daily Traffic (AADT) Vs. Structural Number (SN)

	Traffic Case		
	Low Traffic	Medium Traffic	High Traffic
AADT (vpd)	1000	4000	10000
SN <sup>*)</sup>	2.60	3.38	3.80

<sup>\*)</sup> The structural number was calculated by using cumulative ESAL over a 10-year performance period converted from AADT, traffic composition, and ESAL factor (as indicated in Table 4). Typical values for calculating were used, i.e. CBR = 8;  $M_R = 1500 \times \text{CBR}$ ;  $R = 85\%$ ;  $S_o = 0.35$ ; initial serviceability  $p_i = 4.5$  PSI; and terminal serviceability  $p_t$  of 2.5, 2.25, and 2.0 PSI for high, medium, and low traffic respectively as suggested by AASHTO (1993).

### 3.4 Pavement Condition

The pavement condition is expressed in terms of roughness value and classified into four catalogues corresponding to the range of the IRI scale, i.e. good ( $\text{IRI} < 4$ ), fair ( $4 \leq \text{IRI} < 6$ ), poor ( $6 \leq \text{IRI} < 8$ ), and very poor ( $\text{IRI} \geq 8$ ) (HDM-4, 2003). Therefore, in order to incorporate other pavement condition performance indicators, the study carried out statistics analyses based on available data to find acceptable statistical relationships between these indicators and IRIs as shown in Table 3.

### 3.5 Vehicle Operating Costs

*Vehicle fleet characteristics:* Table 4 shows the characteristics of the Vietnamese vehicle fleet consisting of typical vehicles, average operating weight of a vehicle, number of wheels per vehicle, equivalent standard axle loads (ESAL), average number of kilometers driven per year, average total hours of making complete round trips per year, average vehicle service life, economic cost of new vehicle, and economic cost of one replacement tyre.

*Maintenance labour costs:* Vehicle workshop labour was estimated at US\$ 2.00 per person-hour for all the vehicle types. The labour rate includes a 150 percent mark-up for consumables such as grease and cleaning materials, and for other workshop overhead costs such as rental, power and water, and tools and equipment depreciation (RTP2, 2002).

*Operator overhead costs:* Overhead costs were included for those vehicle types operated

full-time on a commercial basis, i.e. medium and heavy trucks, and buses. The fixed cost element of running a transport business may represent a large part of the total expenses, but only directly allocable overheads (consisting of staff costs for customer contact and invoicing, and vehicle operations and loading) were included here in the study. These costs were estimated at US\$ 1,200 per vehicle-year.

Table 3. Statistical Relationships between Pavement Condition Performance Indicators and Roughness

Traffic Case & Pavement Type	Pavement Condition Performance Indicator	Statistical Relationship
Low Traffic & SBSD	Area of Cracking (%)	$IRI \geq 3; 0.31IRI^2 - 1.56IRI + 1.85, R^2 = 0.65,$ and $IRI < 3; 0$
	Raveled Area (%)	$0.13IRI^2 - 0.54IRI + 0.57; R^2 = 0.64$
	No. of Potholes (No./km)	$IRI \geq 4; 0.74IRI^2 - 4.28IRI + 5, R^2 = 0.46,$ and $IRI < 4; 0$
	Edge Break Area (m <sup>2</sup> /km)	$IRI \geq 3; 1.48IRI^2 - 8.96IRI + 13.56, R^2 = 0.65,$ and $IRI < 3; 0$
	Mean Rutting Depth (mm)	$IRI \geq 3; 8.37Ln(IRI) - 8.64, R^2 = 0.46,$ and $IRI < 3; 0$
Medium Traffic & SBSD	Area of Cracking (%)	$0.61IRI^2 - 2.96IRI + 3.50, R^2 = 0.74$
	Raveled Area (%)	$IRI \geq 3; 0.67IRI^2 - 4.54IRI + 7.55, R^2 = 0.71,$ and $IRI < 3; 0$
	No. of Potholes (No./km)	$IRI \geq 4; 1.15 IRI^2 - 7.42 IRI + 10, R^2 = 0.95,$ and $IRI < 4; 0$
	Edge Break Area (m <sup>2</sup> /km)	$IRI \geq 4; 2.06IRI^2 - 14.22IRI + 24.10, R^2 = 0.75,$ and $IRI < 4; 0$
	Mean Rutting Depth (mm)	$IRI \geq 4; 13.92Ln(IRI) - 16.05, R^2 = 0.50,$ and $IRI < 4; 0$
High Traffic & HRA	Area of Cracking (%)	$0.25IRI^2 - 1.06RI + 1.10, R^2 = 0.72$
	Raveled Area (%)	$0.1266IRI^2 - 0.4779IRI + 0.45, R^2 = 0.73$
	No. of Potholes (No./km)	$0.1148IRI^2 - 0.3824IRI + 0.30, R^2 = 0.45$
	Edge Break Area (m <sup>2</sup> /km)	$IRI \geq 4; 1.25IRI^2 - 7.53IRI + 10.50, R^2 = 0.38,$ and $IRI < 4; 0$
	Mean Rutting Depth (mm)	$4.99Ln(IRI) - 3.42, R^2 = 0.63$

Note: + The range of roughness values was considered from 2 to 10 IRI, according to the available data of the road network.

+ The pavement condition performance indicators were at the end of the year 2003.

Table 4. Vehicle Fleet Characteristics

Vehicle Type	Weight (tons)	Number of Wheels	ESAL	Annual Utilization		Average Life (Years)	Eco. Price (US\$)	Tyre Price (US\$)
				Driven Km	Working Hours			
Motor Bike	0.1	2	0.00	8000	320	8	926	18
Passenger Car	1.4	4	0.00	12000	400	10	14530	42
Medium Truck	7.5	6	0.50	40000	1600	12	28850	105
Heavy Truck	13.0	10	3.27	50000	1670	12	49300	145
Large Bus	11.5	6	0.89	60000	1500	12	52800	145

Source: (RNIP, 2003)

### 3.6 Maintenance Options

The maintenance options considered in this study consisted of scheduled periodic maintenance works associated with appropriate routine maintenance, except a do-minimum option as the base case adopts only the routine maintenance. As suggested by Ul-Islam and Tsunokawa (2004), the appropriate routine maintenance used in the study consists of (1) drainage works for every year, (2) pothole patching when number of potholes reaches 2, and (3) crack sealing when transverse thermal cracking<sup>1</sup> and wide structural cracking reach 10% and 5%, respectively. Periodic maintenance works includes a double bituminous surface treatment (DBST) of 25 mm thickness, asphalt concrete (AC) overlays with thickness ranging from 30 to 70 mm, and reconstructions used DBST or AC with thickness ranging from 50 to 70 mm. Table 5 lists the unit costs of maintenance works in both economic and financial terms used in the study. Table 6 shows the adjusted structural numbers (SNP) of the periodic maintenance and reconstruction options considered in this study. Note that the structural numbers of periodic maintenance options listed in the table are only those of the incremental contributions of the added layers, while those of the reconstruction options are those of the entire pavements after reconstruction. Precise pavement strengths after application of periodic maintenance options are computed in HDM-4 simulations by taking account of the contributions of previous surfacing layers, sub-bases and sub-grades (Rolt and Parkman, 1997).

High traffic roads considered only the periodic works with AC, while medium and low traffic roads considered all the periodic works, due to the existing pavement surface materials used for sections that have different levels of traffic. As the maintenance options used in this study consist of heterogeneous maintenance works, unit cost per kilometer of maintenance works was used as the denominator representing for maintenance intensities.

### 3.7 Calibration into Local Condition

The HDM-4 model should be calibrated according to the specific conditions of a country or region where it is to be used, due to the significant differences in traffic, economic, and environmental conditions between the specific regions (such as Kenya, the Caribbean, India,

<sup>1</sup> Not applicable in this study for Vietnam.

and Brazil) and the considered regions. In this study, the calibration was carried out at level I for basic application (Bennett and Paterson, 2002). According to the sub-humid/tropical environmental condition, the three most sensitive factors in road deterioration and works effects model, i.e. the roughness age-environment, cracking initiation, and cracking progression factors, were calibrated at 0.78, 1.10, and 0.90 respectively.

Table 5. Unit Cost of Maintenance Works

Maintenance Works	Unit	Cost (US\$/ Unit)	
		Economic (a) = 0.85*(b)	Financial (b)
I – Preparatory Works			
Patching	Sq-m	2.87	3.38
Edge repair	Sq-m	6.28	7.39
II - Routine Maintenance			
Drain works	Km length	1921	2260
Crack sealing	Sq-m	0.47	0.55
Pothole patching	Sq-m	2.87	3.38
III - Periodic Maintenance			
a) DBST 25 mm	Sq-m	1.88	2.21
b) Overlays without preparatory works			
30 mm	Sq-m	5.76	6.78
40 mm	Sq-m	6.95	8.18
50 mm	Sq-m	8.13	9.56
60 mm	Sq-m	9.30	10.94
70 mm	Sq-m	10.46	12.31
c – Reconstruction <sup>*)</sup> with:			
DBST 25 mm	Sq-m	7.88	9.27
Overlay 50 mm	Sq-m	12.55	14.76
Overlay 60 mm	Sq-m	12.99	15.28
Overlay 70 mm	Sq-m	13.42	15.79

Source: (RNIP, 2003)

<sup>\*)</sup> Reconstruction consists of 18 cm-aggregate sub-base, 12 cm-aggregate base and asphalt wearing courses.

Table 6. Adjusted Structural Number (SNP)

	DBST 25 (mm)	Overlay, mm					Reconstruction, mm			
		30	40	50	60	70	DBST 25	50	60	70
SNP	0.2	0.35	0.47	0.59	0.71	0.83	2.79	3.20	3.32	3.44

Note: Pavement layer strength coefficients of DBST and overlays are 0.2 and 0.3, respectively (Watanatada et al., 1987)

#### 4. ANALYSIS RESULTS

The number of HDM-4 runs required to obtain the optimal maintenance option was around 30 for a given pavement condition and traffic level using the Steepest Descent Method presented in Tsunokawa *et al.* (2005). Therefore, with three values of AADT and nine values of initial roughness (corresponding to 27 representative sections considered), the 810 (30 x 3 x 9) cases of HDM-4 runs were required to identify the optimal maintenance strategies. Table 7 lists the results of this effort, including the optimal maintenance option and its corresponding net benefit gained over 20-year analysis period. The suitable maintenance works applied in the first year of the analysis period are summarized in Table 8 for different traffic levels and initial pavement conditions. Figures 2 to 4 show the pavement conditions in terms of roughness over the analysis period for different traffic levels with various initial pavement conditions. Results of the analysis pertaining to the maintenance works applied in the first year of the analysis period are presented below.

- 1) Reconstruction (through scarifying deteriorated pavement and providing a new base course and a new asphalt wearing course) was much more effective when the pavement was badly deteriorated for all the traffic cases. Reconstruction with DBST was advisable for the pavement of low and medium traffic roads at a roughness of 8<sup>2</sup> and 7 IRI respectively, whereas reconstruction with 50 mm-asphalt concrete was suggested for high traffic roads at a roughness over 8 IRI.
- 2) Thick overlays of 60 and 70 mm were suggested for high traffic road in poor condition with a roughness of 6, and 7 or 8 IRI, whereas overlays of 50 mm were applied for high and medium traffic roads with a roughness of 5 and 6 IRI, respectively.
- 3) Thin overlays of 30 mm were advisable for high and medium traffic roads with a roughness of 4 IRI, and overlays of 40 mm were applied for medium traffic roads with a roughness of 5 IRI.
- 4) Routine maintenance was much more effective for high and medium traffic roads in good condition ( $IRI \leq 3$ ), whereas for low traffic roads routine maintenance was advisable even in relatively poor condition ( $IRI \leq 7$ ).
- 5) Overlays of 30 mm along with routine maintenance were much effective to maintain the pavement of high and medium traffic roads at a roughness under 4 IRI for long-term period performance, as a result of the dominant motorcycle percentage (63% of total) and the low percentage of heavy truck (only 5% of the total). Furthermore, the frequency of overlays of 30 mm for high traffic roads was found higher than for the medium traffic one, due to the influence of the high traffic loading on pavement deterioration. For low traffic roads, DBST along with routine maintenance are advisable before the pavement reaches a very poor condition ( $IRI \geq 8$ ). The results also showed that DBST did not improve the roughness condition, but it is effective in delaying the deterioration progress, as a result of obtaining the positive NB value in comparison with the base case (only routine maintenance).
- 6) As indicated in the last column of Table 7, the net benefit gained over a 20-year

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<sup>2</sup> Re-DBST is also suggested for pavements with lower initial roughness with low traffic but it was applied at later years when roughness was predicted to reach 8 IRI.

analysis period was much larger for high and medium traffic roads than for low traffic roads, especially for the roads in poor and very poor condition, because for the low traffic roads with the absence of large buses and heavy trucks (as commercial basis for operating cost), the vehicle operating cost savings as a result of road improvements are much smaller for two-wheelers and passenger cars, and so leading to low net benefit gained over the analysis period. This finding suggests that the priority should be given to the roads with high or medium traffic levels, if funds are not available to provide optimum maintenance to all the traffic levels.

Table 7. Optimum Maintenance Options

<b>High Traffic (AADT = 10000vpd) &amp; HRA</b>			
Initial IRI	<i>k</i> (1)	Optimum Maintenance Options (2)	NB (\$US mil) (3)
2	2	[2015, 2021; Ovl-30, Ovl-30]	25.08
3	2	[2008, 2016; Ovl-30, Ovl-30]	28.35
4	3	[2004, 2011, 2018; Ovl-30, Ovl-30, Ovl-30]	51.92
5	3	[2004, 2013, 2019; Ovl-50, Ovl-30, Ovl-30]	60.69
6	3	[2004, 2013, 2019; Ovl-60, Ovl-30, Ovl-30]	70.83
7	3	[2004, 2014, 2020; Ovl-70, Ovl-30, Ovl-30]	82.38
8	3	[2004, 2013, 2019; Ovl-70, Ovl-30, Ovl-30]	95.28
9	3	[2004, 2014, 2021; Re-50, Ovl-30, Ovl-30]	108.47
10	3	[2004, 2014, 2021; Re-50, Ovl-30, Ovl-30]	123.08
<b>Medium Traffic (AADT = 4000vpd) &amp; SBSB</b>			
	(1)	(2)	(3)
2	1	[2012; Ovl-30]	25.53
3	1	[2012; Ovl-30]	26.05
4	2	[2004, 2016; Ovl-30, Ovl-30]	34.96
5	2	[2004, 2014; Ovl-40, Ovl-30]	50.63
6	2	[2004, 2014; Ovl-50, Ovl-30]	53.67
7	2	[2004, 2012; Re-DBST, Ovl-30]	55.95
8	2	[2004, 2012; Re-DBST, Ovl-30]	59.48
9	2	[2004, 2012; Re-DBST, Ovl-30]	63.25
10	2	[2004, 2012; Re-DBST, Ovl-30]	65.90
<b>Low Traffic (AADT = 1000vpd) &amp; SBSB</b>			
	(1)	(2)	(3)
2	1	[2016; DBST]	0.62
3	1	[2016; DBST]	0.65
4	2	[2010, 2020; DBST, DBST]	5.71
5	1	[2009; Re-DBST]	6.02
6	1	[2009; Re-DBST]	6.19
7	1	[2007; Re-DBST]	6.75
8	1	[2004; Re-DBST]	7.11
9	1	[2004; Re-DBST]	7.70
10	1	[2004; Re-DBST]	8.39

Note: (1) "*k*" is the number of maintenance works applied over the analysis period  
 (2) Ovl-30, Ovl-40, Ovl-50, Ovl-60, and Ovl-70 denote overlays with thicknesses of 30, 40, 50, 60, and 70 mm, respectively; Re-DBST and Re-50 denote reconstruction with DBST of 25 mm thickness and with 50 mm- asphalt concrete, respectively.

(3) NB is the maximum net benefit over the analysis period of the optimal maintenance option, where net benefit being defined as the saving in total transport cost over the base case.

Table 8. Suitable Maintenance Works To Be Applied in the First Year for Pavements with Different Traffic Levels & Initial Conditions

Initial Pav. Condition		Traffic Level & Existing Pavement Type		
Condition	IRI	Low Traffic & SBSB (AADT = 1000 vpd)	Medium Traffic & SBSB (AADT = 4000 vpd)	High Traffic & HRA (AADT = 10000 vpd)
Good	2	Routine Maintenance Overlay 30 mm Overlay 40 mm      Overlay 50 mm Overlay 50 mm      Overlay 60 mm Overlay 70 mm Reconstruction with DBST Reconstruction with 50 mm-asphalt concrete		
	3			
Fair	4			
	5			
Poor	6			
	7			
Very poor	8			
	9			
	10			

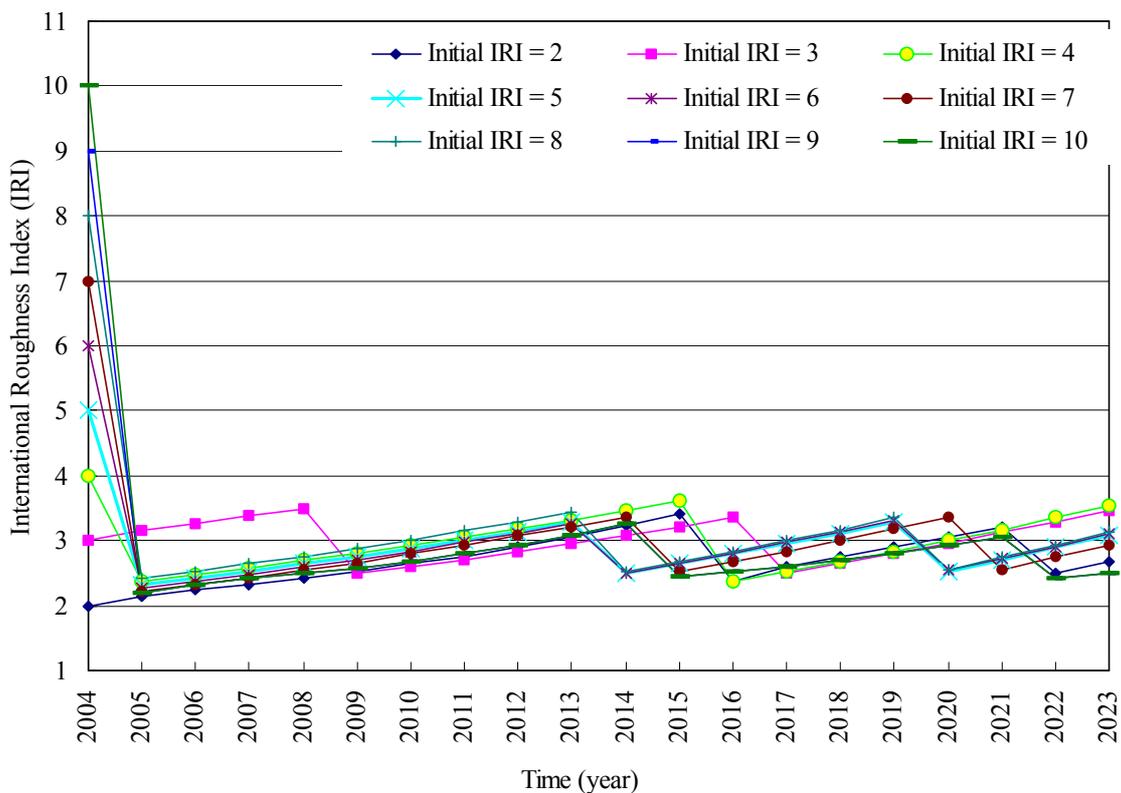


Figure 2. Predicted Roughness Progression under Optimal Maintenance Options High Traffic Case (AADT = 10 000 vpd)

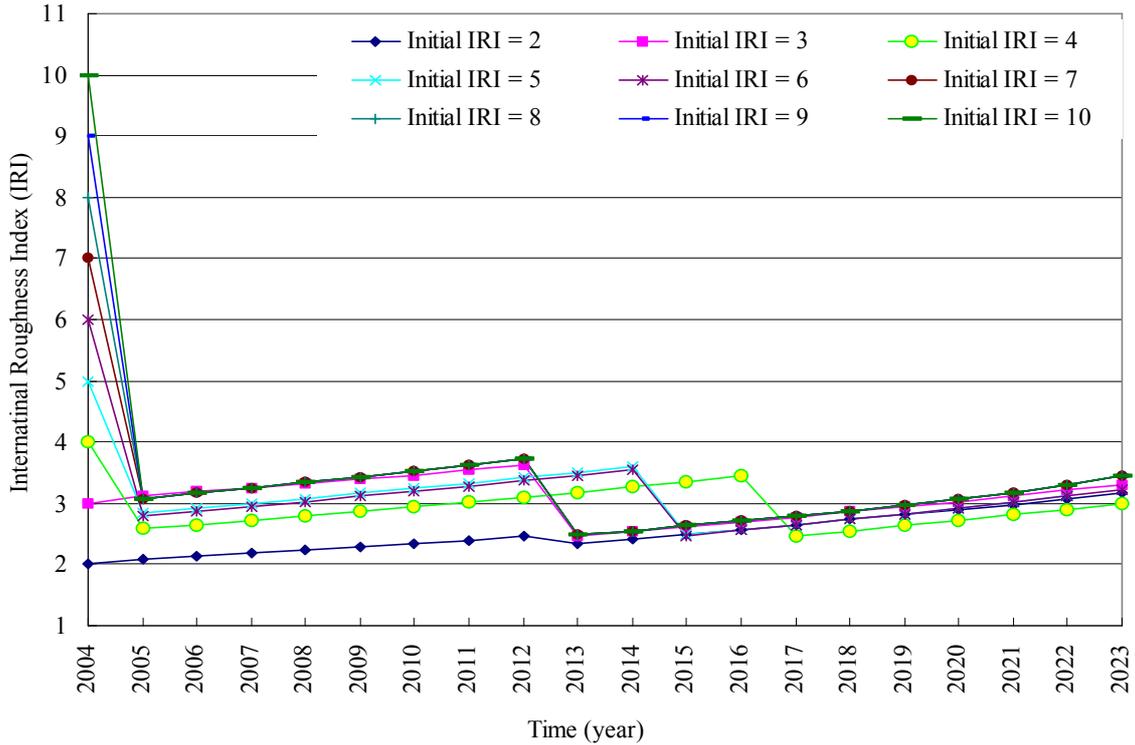


Figure 3. Predicted Roughness Progression under Optimal Maintenance Options Medium Traffic Case (AADT = 4000 vpd)

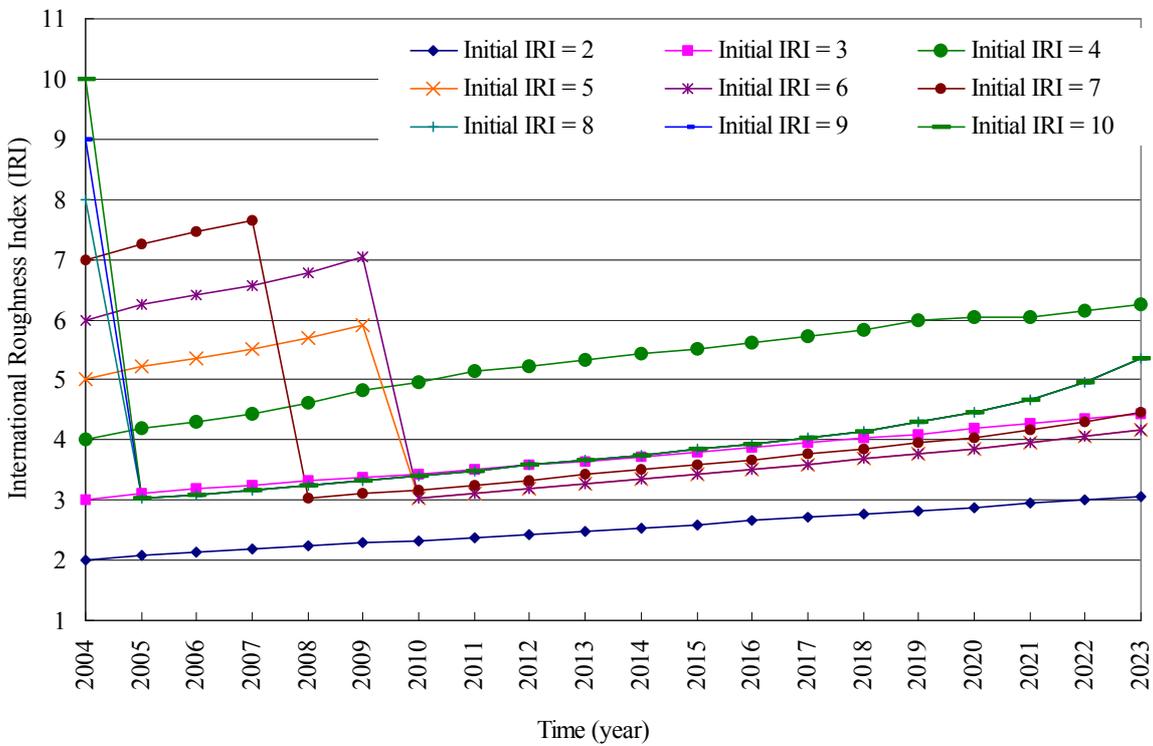


Figure 4. Predicted Roughness Progression under Optimal Maintenance Options Low Traffic Case (AADT = 1000 vpd)

## 5. CONCLUSIONS

The paper has presented a systematic approach to investigate the suitable maintenance strategy for the pavement management system by using HDM-4 with gradient methods corresponding to the traffic levels and initial pavement conditions of bituminous pavements in the flat terrain of Vietnam. From this study, it was found that reconstruction was much more effective for badly deteriorated pavements, while other maintenance works were advisable depending on the levels of traffic and initial pavement conditions. Also, thin overlays of 30 mm along with routine maintenance were much more effective to maintain the pavements of high and medium traffic roads in good condition ( $IRI \leq 3$ ), while the DBST along with routine maintenance were found to be the optimum for the pavements of low traffic roads in good or even in relatively poor condition ( $IRI \leq 7$ ). In addition, the findings showed that the priority should be given to the roads with high or medium traffic levels, if funds are not available to provide optimum maintenance to all the traffic levels. The investigated results, thus, may help road agencies in better selecting the right maintenance works based on condition surveys and to pay more attention to routine maintenance to preserve the road network in appropriate ways. If detailed data are available and all sensitive parameters are properly calibrated according to the specific conditions of the considered regions, further examinations should be carried out to obtain more appropriate results, including different types of pavements and terrain conditions.

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