Methodological Development of Strategy Analysis for a Nationwide Road Network: Option Evaluation Systems with Dynamic Sectioning

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Abstract: Option evaluation systems (OESs) have been extensively used as an effective means to support decision-making on investment and management of road asset in both developed and developing countries over the last four decades. When carrying out the strategy analysis using OESs with dynamic sectioning (called SDS), a nationwide network is typically subdivided into several sub-networks due to administrative or technical needs. However, techniques for doing SDS in such a case have not been well developed. Therefore, the objective of the paper is to present a comprehensive procedure to carry out the SDS for a nationwide road network including sound trade-off analyses of all constituent sub-networks. Although the Highway Development and Management System (HDM-4) is used as an OES in the case study in this paper, the proposed procedure is general enough to allow almost any OESs.

Key Words: *option evaluation systems, strategy analysis, pavement management, budget allocation*

1. INTRODUCTION

Option evaluation systems (OESs) have been widely used as a powerful tool for the analysis of road management and investment alternatives in both developed and developing countries over the last four decades. Examples of OESs include the Highway Design and Maintenance Standards Model, HDM-III (Watanatada *et al*. 1987); the Road Transport Investment Model, RTIM (Cundill, 1993); the Highway Development and Management System (HDM-4, 2002); the Highway Economic Requirements System, HERS-ST (FHWA, 2004); and the Deighton's Total Infrastructure Asset Management System, dTIMS-CT). Among these OESs, the HDM-4 system and its predecessor, HDM-III, have been recognized as state-of-the-art systems through many actual and research projects in more than one hundred countries over the last three decades (for example, Bhandari *et al.* 1987; The World Bank, 1988; Riley *at al*. 1994; Riley and Bennett, 1995; Mushule and Kerali, 2001; Veerargavan and Reddy, 2003; Tsunokawa and Ul-Islam, 2003; Hiep and Tsunokawa, 2005; and Jain *et al*. 2006). The use of OESs has shown a sign of successful application in managing road networks to maximize benefits to society (McPherson and Bennett, 2005). OESs are typically used for supporting decision-making on investments within a road agency at three levels, which are *(1)* strategy analysis involving the strategic planning for estimating medium- and long-term budget requirements for the development and preservation of a road network under various budgetary and economic scenarios; *(2)* program analysis dealing with the preparation of single or multiyear work programs for road network maintenance and development under budget constraints; and *(3)* project analysis concerned with the evaluation of one or more road projects through detailed life-cycle economic appraisal.

In strategy analysis using OESs, the concept of a road network matrix is usually applied which comprises categories of the road network defined according to the key attributes that most influence pavement performance and road user costs such as traffic volume or loading, pavement types, pavement condition, and environment or climatic zones (see for example, PIARC, 2002; Archondo-Callao, 2008). Although it is possible to model individual road sections in the strategy analysis, most road administrations will often be responsible for several thousand kilometres of roads divided into thousands of sections, thereby making it cumbersome to individually model each road segment. If good road inventory data are available, another approach for the strategy analysis which employs the dynamic sectioning may be conducted without resorting to a matrix concept. The strategy analysis with dynamic sectioning approach (called SDS) can increase the precision of an analysis by retaining section identities and section specific information while the matrix approach "averages" the values of the sections represented by each matrix element. It should be noted that there is no essential distinction between SDS and program analysis, and the SDS results may be used directly to identify single or rolling multiyear work programs.

To carry out SDS, OESs compute the net present values (NPVs) of all of maintenance policy alternatives for all sections and select those that maximize the total NPV among all combinations of policies while satisfying given budget constraints. As OESs are 'what-if' models, the generation of good policy alternatives for all links is crucially important. As the number of homogeneous sections can be as large as a few hundreds, however, it is a formidable task. As proposed by Tsunokawa *et al* (2007), an efficient way is to reduce the number of sections, for which policy alternatives are generated, by grouping homogeneous sections into a small number of representative sections in a similar manner to a matrix approach. A set of good policy alternatives for each representative section may be generated by firstly finding the optimal maintenance alternative by applying the Gradient Search with Option Evaluation Systems (GSOE) procedure presented by Tsunokawa *et al* (2006) and secondly, by generating good alternatives around it by applying the procedure presented by Tsunokawa *et al* (2008). The GSOE approach, as an efficient mean for finding optimal maintenance alternatives, overcomes the major weakness of OESs that they only find the mere best maintenance option among those exogenously specified by an analyst. It should be noted that practical constraints in terms of the number of policy alternatives that may be analyzed simultaneously by OESs must be observed. When using HDM-4 with Expenditure Budgeting Model (EBM-32) (Archondo-Callao, 1999), for example, the maximum number of maintenance alternatives is restricted up to 17 under the constrained budget mode.

Another major challenge when carrying out a strategy analysis of a nationwide network is the integration of the results from all sub-networks analyses. A nationwide road network may be subdivided by road class, administrative region, climatic zone, etc. which may be managed by different road agencies or different divisions of a road agency. The reason for subdividing a network may also be purely technical in that, explicitly or implicitly, there always exist certain limitations in the number of road sections that can be analyzed by most OESs. For example, the HDM-4/EBM-32 can handle only up to 400 sections with 17 project-alternatives for each section. Other similar pavement management tools such as HERS-ST, dTIMS CT, and RoSy PLAN have limitations in the size of the output files (mostly to be smaller than 2 GB). The SDS approach typically subdivides the network into several sub-networks according to certain characteristics such as traffic volume and surface conditions, so that each may be analyzed with OESs for finding optimal management strategies. Tsunokawa and Hiep (2008) presented an approach for finding optimal maintenance strategies of all sub-networks under a network-wide budget constraint that is based on the net present value functions of sub-networks (NPVF) for conducting sound trade-off analyses. Since their procedure considers only one budget constraint for the entire analysis period, it tends to produce uneven outlays of maintenance expenditures over time as discussed by Tsunokawa and Ul-Islam (2007). This is because, for example, if there is a backlog in maintenance investment, OESs predict larger expenditures at the early part of the analysis period as more beneficial. Since it is more desirable for any road agency to have more or less uniform outlay of maintenance expenditures over time, a procedure needs to be developed as part of SDS approach that can conduct sound trade-off analyses of constituent sub-networks under uniform annual budget constraints.

Given these observations, the objective of the paper is to present a comprehensive procedure for carrying out the strategy analysis of a nationwide road network using OESs with dynamic sectioning approach. The procedure includes a sound trade-off analysis procedure based on the NPVF approach that is necessary for taking account of uniform budget distribution over the planning period. The applicability of the proposed procedure is then demonstrated and evaluated through a case study using the data of Vietnamese road network. Although HDM-4 is used as an OES in the case study, the procedure is general enough to allow almost any OESs.

2. METHODOLOGY

The comprehensive procedure to carry out the strategy analysis for a nationwide road network comprises of two parts, the strategy analysis using OESs with dynamic sectioning approach (called SDS) for a road network or sub-networks, and a trade-off analysis of all constituent sub-networks.

2.1 Strategy Analysis with Dynamic Sectioning

The SDS approach for a road network or sub-networks is presented in Figure 1 and discussed as follows.

Step 1: Review and correction of network data

The length of a network for the strategy analysis usually consists of several thousand kilometers and a huge number of data items are required for each road segment. For example, 159 items of data are included in each road section in HDM–4 while 64 data items are required for a road segment when using HERS-ST. The data have to be reviewed and missing variables can be populated by using the results of correlation analysis of available data. In addition, The model of OESs needs to be calibrated into local conditions of the studied area.

Step 2: Dynamic sectioning approach

Determining the dynamic homogenous sections is one of the important tasks in SDS. Creating proper homogeneous sections is important for establishing the correct maintenance treatments or contract packages for individual sections. The dynamic sectioning is performed to produce sections which have homogeneous characteristics. The boundary between two consecutive homogeneous sections is defined when a predefined jump in one or more parameters is detected. Major attributes that are usually considered in dynamic sectioning include road name, road class, climate zone, speed-flow type, traffic flow pattern, surface class, surface materials, traffic volume, and roughness. Each homogeneous section is identified by a unique name and ID along with post marks. Short homogeneous sections may cause difficulties for implementing maintenance work in the field and they should be checked when carrying out the dynamic sectioning by the following condition.

$$l_j \geq l_{\min}, \quad j = 1, 2, ..., N \tag{1}$$

where l_j is the length of a homogeneous road section j, N is the total number of homogeneous road sections obtained after doing dynamic sectioning, and l_{min} is the minimum length of road section which is defined by the user for the sake of maintenance implementation in the field. If the requirement *(1)* is not satisfied, the dynamic sectioning will be repeated by changing the predefined jumps in one or more parameters, such as traffic volume or/and roughness. It is also noted that long sections can cause problems in strategy analysis as will be discussed in *Step 4*.

Step 3: Appropriate maintenance alternatives for strategy analysis

The generation of appropriate maintenance alternatives for all sections is a key task when carrying out SDS as discussed above. A routine for conducting this exercise task is presented as follows.

Step 3.1: Determination of representative sections

To reduce the number of road sections to a manageable size for generating alternative maintenance options, homogeneous sections are grouped into a smaller number of representative sections by considering the distribution of homogeneous sections with respect to key attributes such as traffic level and road conditions. The attributes of each representative section are derived from corresponding road section groups by using weighted means or dominant characteristics. The weighting factor can be the length of individual sections.

Step 3.2: Identification of optimal maintenance options for representative sections

The GSOE developed by Tsunokawa *et al* (2006) is suggested as an efficient means for finding optimal maintenance options for each representative section under the unconstrained budget circumstance at the project level over a predefined analysis period. If various maintenance treatments are considered in the analysis, the generalized GSOE presented by Tsunokawa and Hiep (*forthcoming*) may be used.

Step 3.3: Generation of appropriate maintenance alternatives for strategy analysis

Since the representative section is an “average” one for the corresponding road section group, the fundamental principle to define appropriate maintenance alternatives for each section group is to select alternatives that are cheaper or more expensive around the optimal one. This selection is a difficult task as there can be different ways of defining cheaper or more expensive alternatives based on timings, maintenance intensities (e.g. type of treatments or thickness of overlays) or by relaxing the threshold roughness for responsive type maintenance alternatives. This scheme, however, will lead to a large number of appropriate alternatives, which may be cumbersome because the number of sections can be huge. Tsunokawa *et al*. (2008) have recently presented a methodology for harmonizing the project and strategic levels which can be used in this exercise along with the results obtained from the GSOE optimization.

Step 4: Subdivision of long road sections

The length of a homogeneous section may affect the results of strategy analysis under constrained budgets. A long section which generates higher NPV but needs a bigger investment may be replaced by the shorter one which produce less NPV but satisfies a given budget constraint. In this case, the long road section with a big investment needs to be subdivided. The criteria proposed for checking long sections is as below.

$$\frac{b_j}{b} \le \gamma, \quad j = 1, 2, ..., N \tag{2}$$

where b_j is the total budget required for a road section j over the planning period T_p under the unconstrained budget circumstance, N is the total number of homogeneous road sections obtained after doing dynamic sectioning in *Step 2*, b is a given total budget for the considered network over the planning period, and γ *(%)* is the criteria defined by the analyst. The subdivided sections are also required to meet the condition *(2)*.

Step 5: Strategy analysis

Appropriate maintenance alternatives obtained in *Step 3* are assigned to corresponding sections for the strategy analysis using OESs. Tsunokawa and Ul-Islam (2007) suggested that the analysis period needs to be at least twice as long as the planning period to produce stable predictions when using OESs such as HDM-4. This remedy overcomes the deficiency that the OES models do not consider the condition of the network at the end of the analysis period and tend to produce expenditure patterns that have no or few investments towards the end of the analysis period. In addition, the strategic plan should be structured such that expenditure has a more or less uniform distribution in the planning period.

2.2 Trade-off Analysis of Sub-networks

In this section, the NPVF approach is modified to conduct a trade-off analysis of all constituent sub-networks under a uniform annual network-wide budget constraint over the planning period. The modified procedure is illustrated in Figure 2 and discussed in the following sections.

Step 1: Construct the *NPV* function for each sub-network as a function of its uniform annual budget, which may be written as $NPV_i = f_i(a_i)$, where i denotes the i-th sub-network and a_i is the uniform annual budget. Note that Tsunokawa and Hiep (2008) used NPV functions which are functions of total budget of an analysis period. The mathematical form of *NPV* function is similar to the one presented by Tsunokawa and Hiep (2008) and written as $NPV_i = \alpha_i(1 - e^{-\beta_i a_i})$, $0 \le a_i \le a_i^{MAX}$ (see Figure 3).

Reasonable values of the parameters α_i and β_i may be estimated with a non-linear regression analysis given s data points generated by an OES, (a_i^1, NPV_i^1), $(a_i^2, NPV_i^2), ..., (a_i^s, NPV_i^s)$. The value of a_i^{MAX} is defined as follows:

$$a_i^{MAX} = \max\{a_{i1}^0, a_{i2}^0, ..., a_{iT_p}^0\} \tag{3}$$

where a_{ik}^0, $k = 1,2,...,T_p$ is the annual maintenance expenditure of year k of the i-th sub-network under the unconstrained budget scenario (see Figure 4). The rationale of this expression is that no annual budget constraint larger than the maximum annual unconstrained optimal expenditure increases the NPV of a sub-network.

Step 2: Solve the following maximization problem under a budget constraint:

$$\textit{Maximize} \ \sum f_i(a_i) \quad s.t. \ \sum a_i \le A \ \text{ and } \ 0 \le a_i \le a_i^{MAX}, \ \forall i = 1, 2, ..., n \tag{4}$$

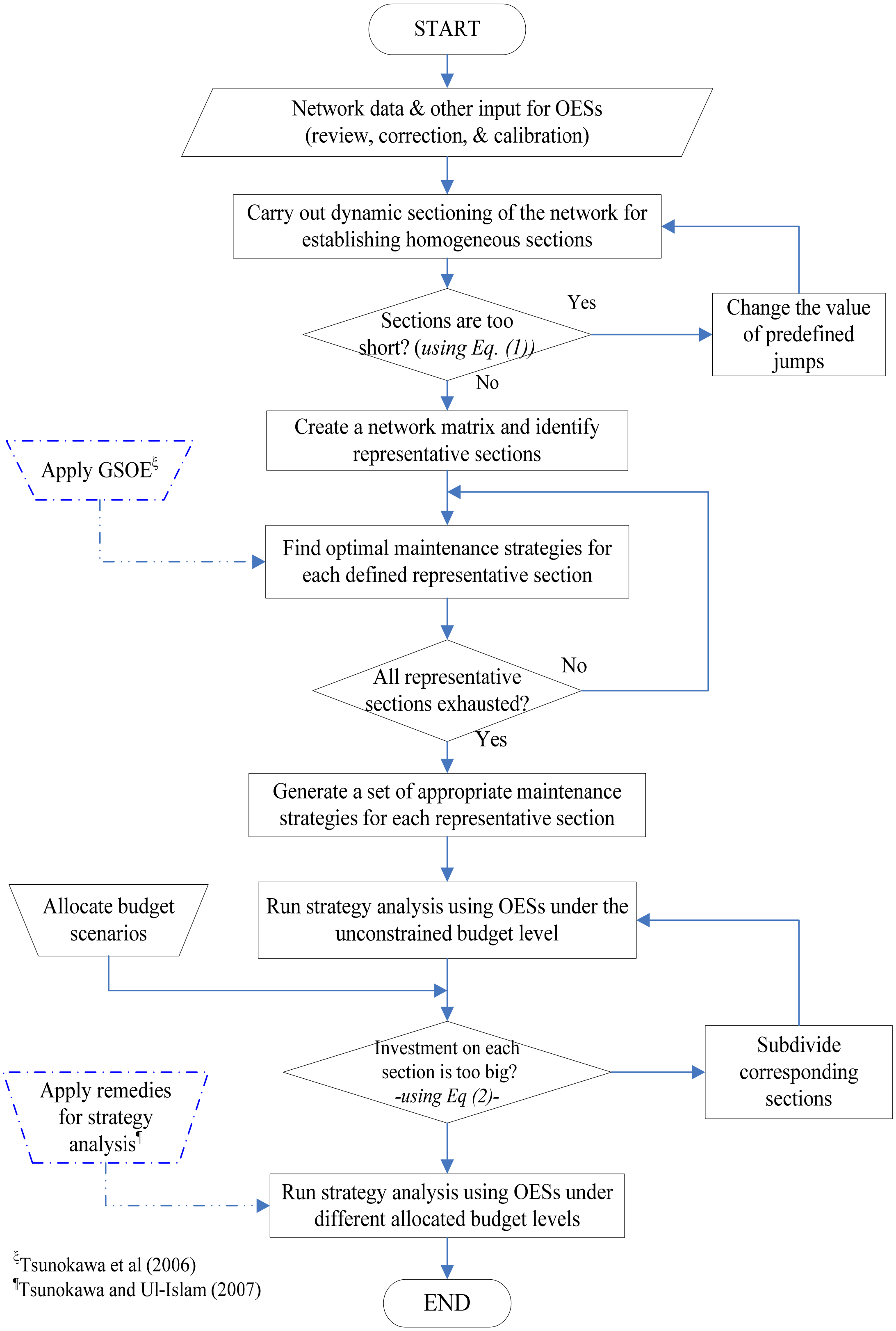

Figure 1. Strategy analysis using OESs with dynamic sectioning, called SDS

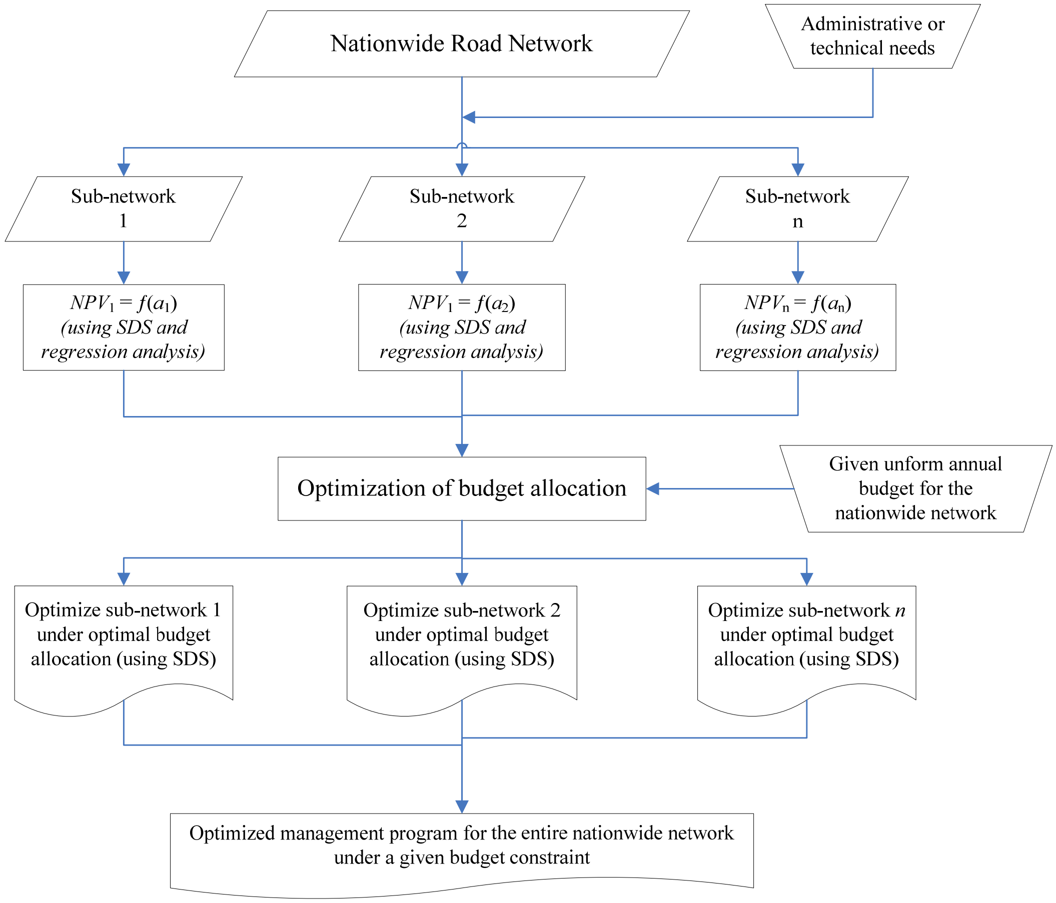

Figure 2. Optimization of budget allocation over sub-networks under uniform budget distribution

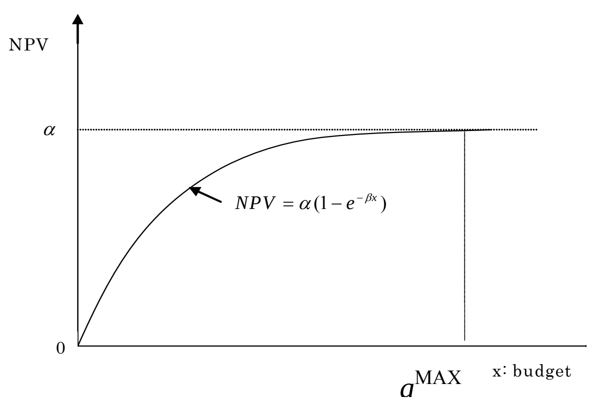

Figure 3: The shape and form of the *NPV* function

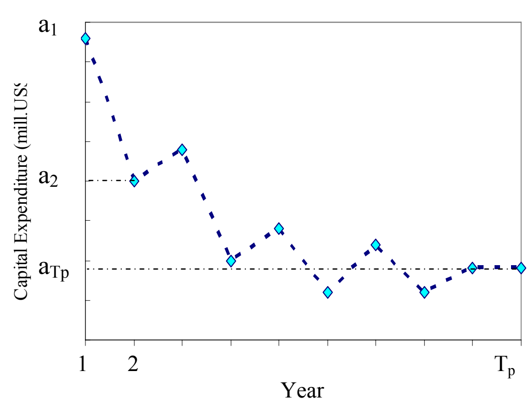

Figure 4. Annual investment pattern over T_p under the unconstrained budget mode

where A is a network-wide uniform annual budget. The maximization problem *(4)* can be simplified as the following system of equations:

$$\sum a_i \leq A, \quad \text{and}$$
$$\alpha_1\beta_1 e^{-\beta_1 a_1} = \alpha_2\beta_2 e^{-\beta_2 a_2} = ... = \alpha_n\beta_n e^{-\beta_n a_n}, \tag{5}$$

where n is the total number of sub-networks. The equations in the second line imply that the marginal *NPV*s of annual budget are all equal at the optimality. If the feasibility ranges of a_i, $0 \leq a_i \leq a_i^{MAX}$, $\forall i = 1,2,...,n$, are violated by any a_i's obtained as the solution to this system, their values are set as either 0 or a_i^{MAX} depending on the direction of the violation, and the above computation is repeated for all values of a_i's except for such a_i's until all feasibility conditions are satisfied. As indicated by the inequality of the first line of the above expression, the sum of the annual budgets of all sub-networks does not necessarily distribute the given entire network-wide annual budget, A, over the sub-networks. Rather, the sum of the distributed sub-networks annual budgets determines the necessary network-wide annual budget. Also, to be noted here is the fact that the above procedure can find only such distribution of sub-networks annual budgets that are sufficient and not necessary to achieve network-wide uniform annual budgets.

Step 3: Carry out the SDS analysis for each sub-network under the obtained optimal budget.

Step 4: Obtain the optimized management program for the entire network under a given nationwide budget constraint with uniform annual distribution over the planning period.

3. CASE STUDY

A national road network used in the case study was derived from the Road Network Improvement Project of Vietnam (RNIP, 2004). The HDM-4/EBM model is used as an OES to carry out the SDS for this nationwide road network in order to prepare for the ten-year planning strategy. A twenty-year analysis period starting from 2008 is suggested and a 12% social discount rate is used in the case study.

3.1 Network Definition and Data Correction

The length of the network consists of 9,201 km of paved national roads. The original data have been reviewed and corrected based on correlation and statistical analysis of available data. For instance, missing pavement condition variables were populated by using the results of correlation analysis with roughness values. Major analysis data will be discussed in the following sections, other data can be found in the RNIP report.

3.2 Traffic Data and Vehicle Operating Costs

The annual growth rate of each vehicle type was assumed the same for the whole network as shown in Table 1, while the traffic composition was derived for each road section based on available data.

Table 1. Annual traffic growth rates

Vehicle Type	Cars	Buses	Trucks, tractor	Motorcycles
Up to 2013	8%	5%	6%	8%
2014 onwards	5%	3%	3%	4%

Source: RNIP (2004)

Table 2 shows the characteristics of 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, economic cost of one replacement tyre, and passenger car single equivalent factors (PCSE) taken from TCVN 4054 (2005). Fuel and lubrication oil costs are 0.45$/lit and 2.500$/lit, respectively. Maintenance labour and operator overhead costs used are the same as in the report of RNIP (2004).

Table 2. Characteristics of vehicle fleet

Vehicle type	Vehicle Type	Weight (ton)	No. of wheels	ESAL	Distance km/yr	Work -ing (hrs)	Life (yrs)	Econ. Price ($US)	Tyre Price ($US)	PCSE
Passenger Car	2	1.20	4	0.00	12,000	400	10.0	19,350	56	1.00
Motorcycle	0	0.20	2	0.00	8,000	320	8.0	1,250	24	0.30
Minibus	11	2.20	4	0.01	25,000	1,000	10.0	23,780	73	2.00
Pickup/Light goods veh.	7	2.00	4	0.01	25,000	1,000	10.0	20,700	73	2.00
Medium Truck (2 axle)	8	7.50	6	0.50	40,000	1,600	12.0	38,370	140	2.00
Heavy Truck (3 axle)	9	13.00	10	3.27	50,000	1,667	12.0	86,800	195	2.50
Large Bus (46 seats)	14	10.00	6	0.89	60,000	1,500	12.0	70,200	193	2.50
Articulated Truck (4 axle)	10	28.00	14	2.79	60,000	2,000	12.0	117,000	220	3.00
Rural Tractor	-	4	4	0.80	25,000	1,700	10.0	1,700	86	2.00

3.3 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 in order to obtain more reliability. The model calibration is divided into three levels depending on the efforts and resources involved (Bennett and Paterson, 2002). In this study, the calibration was carried out at *Level I* for basic application in consideration of engineering data (i.e. the roughness – age – environment deterioration adjustment (K_{ge}), the cracking initiation adjustment (K_{ci}), and the cracking progression adjustment (K_{cp}) factors) as well as vehicle operating costs as above-mentioned. This is defined as the lowest level of effort and resources, using default values, best estimates and desk studies with minimal field surveys for the most sensitive parameters. The results of calibration according to the environmental and climate characteristics in Vietnam are summarized in Tables 3 and 4.

Table 3. Roughness environmental deterioration

Environmental factors	Tropical		Subtropical Hot		Subtropical Cool	
	m	K_{ge}	m	K_{ge}	m	K_{ge}
Semi-Arid	0.01	0.391	0.016	0.626	0.035	1.369
Sub-humid	0.02	0.782	0.025	0.978	0.06	2.347
Humid	0.025	0.978	0.03	1.173	1	39.130
Perhumid	0.03	1.173	0.04	1.565		

Note : $K_{ge} = m*K_m/0.023$, *where, m is environmental coefficient.* K_m *is the factor of construction and drainage effects with value of 0.9 which is an average for the condition of the Vietnamese road network.*

Table 4. Cracking initiation adjustment and cracking progression adjustment factors

Climate characteristics	Cracking initiation adjustment factor, K_{ci}	Cracking progression adjustment Factor, $K_{cp}=1/K_{ci}$
Medium oxidizing climate	1.0	1.0
Low oxidizing climate	1.1	0.9

3.4 Dynamic Sectioning

The sectioning and data transformation were done using the CUMSUM software available in the Viziroad toolbox (R&L, 1998). Uniform attributes considered in the sectioning include road name, road class, climate zone, speed-flow type, traffic flow pattern, surface class, surface materials, traffic volume, and roughness. Each homogeneous section was identified by a unique name and ID along with post marks. Then homogenous sections were compiled into the HDM input file using Microsoft Access for a total number of 414 sections over the network of 9,201 km.

3.5 Generation of Appropriate Maintenance Alternatives

3.5.1 Representative Sections

The number of representative sections was determined by examining the distribution of road networks with respect to traffic level and initial road condition. The network was divided into 16 groups corresponding to 4 levels of traffic (i.e. very high, high, medium, and low) in terms of annual average daily traffic (AADT) and 4 initial pavement conditions (i.e. good, fair, poor, and very poor) in terms of international roughness index (IRI) as the network matrix shown in Table 5. The values or parameters of each representative section were derived from the corresponding group of road sections by using weighted means or dominant characteristics. The weighting factor used was the length of individual sections. Basic characteristics of representative sections are presented in Table 6.

Table 5. Network distributions

Pavement Condition	Low traffic, AADT < 1000vpd		Medium traffic, 1000vpd ≤ AADT < 4000vpd		High traffic, 4000vpd ≤ AADT < 8000vpd		Very high Traffic, 8000vpd ≤ AADT	
	(Km)	(%)	(Km)	(%)	(Km)	(%)	(Km)	(%)
Good (IRI< 4.0)	156.24	1.70	906.45	9.85	1372.39	14.91	966.17	10.51
Fair (4.0≤IRI<6.0)	673.40	7.32	1163.34	12.64	446.13	4.85	265.12	2.88
Poor (6.0≤IRI<8.0)	709.01	7.70	774.21	8.42	213.95	2.33	106.44	1.16
Very poor (IRI≥8.0)	821.80	8.93	544.23	5.91	82.12	0.89	0.00	0.00
Sub-total	2360.45	25.65	3388.23	36.82	2114.59	22.98	1337.73	14.55
Total	9201.00(km) / 100 (%)							

Table 6. Basic characteristics of representative sections

Traffic category, AADT (vpd)	IRI category	Number of lanes	AADT (vpd)	2007 IRI (m/km)	Structural number, SN	CBR (%)
Low traffic, AADT < 1000	IRI< 4.0	2	662	2.90	2.85	7
	4.0≤IRI<6.0	2	490	4.81	2.74	7
	6.0≤IRI<8.0	2	393	7.47	2.82	7
	IRI≥8.0	2	456	9.99	2.65	7
Medium traffic, 1000≤AADT<4000	IRI< 4.0	2	2,791	3.21	3.65	8
	4.0≤IRI<6.0	2	2,115	4.92	3.48	8
	6.0≤IRI<8.0	2	2,286	7.21	3.45	8
	IRI≥8.0	2	2,104	9.09	3.34	8
High traffic, 4000≤AADT<8000	IRI< 4.0	2	6,924	2.82	3.75	8
	4.0≤IRI<6.0	2	5,918	4.63	3.54	8
	6.0≤IRI<8.0	2	5,433	7.64	3.67	8
	IRI≥8.0	2	6,267	9.10	3.55	8
Very high traffic, 8000≤ AADT	IRI< 4.0	2	14,531	3.01	3.82	8
	4.0≤IRI<6.0	2	13,883	4.76	3.95	8
	6.0≤IRI<8.0	2	11,695	6.63	3.73	8

3.5.2 Maintenance Alternatives

Maintenance works associated with routine maintenance were considered for maintenance options, except a do-minimum option as the base case adopts only the routine maintenance. The routine maintenance used in this study consists of drainage works for every year, pothole patching when number of potholes reaches 2 number/km, and crack sealing when wide structural cracking reaches 5%. Table 7 lists the unit costs of preparatory and routine maintenance works. For the simplification of calculation, maintenance works in the case study consist of only asphalt concrete overlays with different thicknesses as presented in Table 8. Note that the unit cost used in this study is represented in terms of economic cost in US$ and it was assumed as 85 % of financial cost.

Table 7. Unit costs of preparatory and routine maintenance

Preparatory and maintenance works	Preparatory works		Routine maintenance		
	Patching	Edge repair	Drain works	Crack sealing	Pothole patching
	($/m2)	($/m2)	($/km.length)	($/m2)	($/m2)
Unit cost	2.87	6.28	1921	0.47	2.87

Table 8. Unit costs of overlays

Thickness of overlays (mm)	30	40	50	60	70
Unit cost ($/m^2)	5.76	6.95	8.13	9.30	10.46

3.5.3 Optimum Alternatives for Representative Sections

The GSOE developed by Tsunokawa *et al* (2006) was used to find optimal maintenance strategies for each representative section under the unconstrained budget mode over 20-year analysis period at the project level. These optimal strategies are shown in Table 9.

Table 9. Optimum maintenance strategies for representative sections

Traffic category, AADT (vpd)	IRI category	Treatment 1			Treatment 2			Treatment 3		
		Year	IRI (m/km)	h_{ovl} (mm)	Year	IRI (m/km)	h_{ovl} (mm)	Year	IRI (m/km)	h_{ovl} (mm)
Low traffic, AADT < 1000	IRI< 4.0	2020	3.88	30	-	-	-	-	-	-
	4.0≤IRI<6.0	2009	4.97	30	-	-	-	-	-	-
	6.0≤IRI<8.0	2008	7.47	40	2019	5.42	30	-	-	-
	IRI≥8.0	2008	9.99	50	2019	5.51	30	-	-	-
Medium traffic, 1000≤AADT <4000	IRI< 4.0	2016	3.62	30	-	-	-	-	-	-
	4.0≤IRI<6.0	2008	4.92	40	2019	3.60	30	-	-	-
	6.0≤IRI<8.0	2008	7.21	70	2017	3.73	30	-	-	-
	IRI≥8.0	2008	9.09	70	2016	3.73	30	-	-	-
High traffic, 4000≤AADT <8000	IRI< 4.0	2013	3.52	30	2034	3.48	30	-	-	-
	4.0≤IRI<6.0	2008	4.63	50	2021	3.42	30	-	-	-
	6.0≤IRI<8.0	2008	7.64	70	2020	3.42	30	-	-	-
	IRI≥8.0	2008	9.10	70	2017	3.36	30	2025	3.48	30
Very high traffic, 8000≤AADT	IRI< 4.0	2012	3.50	30	2020	3.36	30	-	-	-
	4.0≤IRI<6.0	2008	4.76	50	2017	3.28	30	2023	3.38	30
	6.0≤IRI<8.0	2008	6.63	70	2018	3.36	30	2024	3.36	30

3.5.4 Appropriate Maintenance Alternatives for Strategy Analysis

Appropriate maintenance alternatives generated for strategy analysis for each representative section are shown in Tables 10a and 10b. Twelve to fifteen alternatives were generated for each section, since the number of alternatives that can be defined for each section is restricted to 17 in the HDM-4/EBM strategy analyses under budget constraints.

Table 10a. Appropriate maintenance alternatives generated for strategy analysis
(Low and medium traffic categories)

Traffic Category, AADT	IRI category	Appropriate maintenance alternatives
Low traffic, AADT < 1000	IRI< 4.0 4.0≤IRI<6.0	1. Base alternative 2. OVL30 when IRI ≥ 3.7 from 2008 3. OVL30 when IRI ≥ 3.8 from 2008 4. OVL30 when IRI ≥ 4.0 from 2008 5. OVL30 when IRI ≥ 4.2 from 2008 6. OVL30 when IRI ≥ 4.5 from 2008 7. OVL30 when IRI ≥ 4.8 from 2008 8. OVL30 when IRI ≥ 5.0 from 2008 9. OVL40 when IRI ≥ 7.0 from 2008 & OVL30 when IRI ≥ 5.0 from 2018 10. OVL40 when IRI ≥ 7.1 from 2008 & OVL30 when IRI ≥ 5.0 from 2018 11. OVL40 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 5.0 from 2018 12. OVL40 when IRI ≥ 7.3 from 2008 & OVL30 when IRI ≥ 5.0 from 2018
	6.0≤IRI<8.0 IRI≥8.0	1. Base alternative 2. OVL40 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 3. OVL40 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 5.5 from 2018 4. OVL40 when IRI ≥ 7.3 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 5. OVL40 when IRI ≥ 7.3 from 2008 & OVL30 when IRI ≥ 5.5 from 2018 6. OVL40 when IRI ≥ 7.4 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 7. OVL40 when IRI ≥ 7.4 from 2008 & OVL30 when IRI ≥ 5.5 from 2018 8. OVL50 when IRI ≥ 9.7 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 9. OVL50 when IRI ≥ 9.7 from 2008 & OVL30 when IRI ≥ 5.5 from 2018 10. OVL50 when IRI ≥ 9.8 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 11. OVL50 when IRI ≥ 9.8 from 2008 & OVL30 when IRI ≥ 5.5 from 2018 12. OVL50 when IRI ≥ 9.9 from 2008 & OVL30 when IRI ≥ 5.4 from 2018 13. OVL50 when IRI ≥ 9.9 from 2008 & OVL30 when IRI ≥ 5.5 from 2018
Medium traffic, 1000≤ AADT <4000	IRI< 4.0 4.0≤IRI<6.0	1. Base alternative 2. OVL30 when IRI ≥ 3.5 from 2008 3. OVL30 when IRI ≥ 3.6 from 2008 4. OVL30 when IRI ≥ 3.7 from 2008 5. OVL40 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.5 from 2018 6. OVL40 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.6 from 2018 7. OVL40 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.7 from 2018 8. OVL40 when IRI ≥ 4.8 from 2008 & OVL30 when IRI ≥ 3.5 from 2018 9. OVL40 when IRI ≥ 4.8 from 2008 & OVL30 when IRI ≥ 3.6 from 2018 10. OVL40 when IRI ≥ 4.8 from 2008 & OVL30 when IRI ≥ 3.7 from 2018 11. OVL40 when IRI ≥ 4.9 from 2008 & OVL30 when IRI ≥ 3.5 from 2018 12. OVL40 when IRI ≥ 4.9 from 2008 & OVL30 when IRI ≥ 3.6 from 2018 13. OVL40 when IRI ≥ 4.9 from 2008 & OVL30 when IRI ≥ 3.7 from 2018
	6.0≤IRI<8.0 IRI≥8.0	1. Base alternative 2. OVL60 when IRI ≥ 7.0 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 3. OVL60 when IRI ≥ 7.0 from 2008 & OVL30 when IRI ≥ 3.7 from 2016 4. OVL60 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 5. OVL60 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 3.7 from 2016 6. OVL70 when IRI ≥ 7.0 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 7. OVL70 when IRI ≥ 7.0 from 2008 & OVL30 when IRI ≥ 3.7 from 2016 8. OVL70 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 9. OVL70 when IRI ≥ 7.2 from 2008 & OVL30 when IRI ≥ 3.7 from 2016 10. OVL70 when IRI ≥ 8.8 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 11. OVL70 when IRI ≥ 8.8 from 2008 & OVL30 when IRI ≥ 3.7 from 2016 12. OVL70 when IRI ≥ 9.0 from 2008 & OVL30 when IRI ≥ 3.6 from 2016 13. OVL70 when IRI ≥ 9.0 from 2008 & OVL30 when IRI ≥ 3.7 from 2016

Note: OVL denotes overlay treatments along with their thicknesses in mm.

Table 10b. Appropriate maintenance alternatives generated for strategy analysis
(High and very high traffic categories)

Traffic category, AADT	IRI category	Appropriate maintenance alternatives
High traffic, 4000≤ AADT <8000	IRI< 4.0 4.0≤IRI<6.0	1. Base alternative 2. OVL30 when IRI ≥ 3.3 from 2008 3. OVL30 when IRI ≥ 3.4 from 2008 4. OVL30 when IRI ≥ 3.5 from 2008 5. OVL30 when IRI ≥ 3.6 from 2008 6. OVL40 when IRI ≥ 3.5 from 2008 & OVL30 when IRI ≥ 3.4 from 2033 7. OVL40 when IRI ≥ 3.5 from 2008 & OVL30 when IRI ≥ 3.5 from 2033 8. OVL40 when IRI ≥ 3.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2033 9. OVL40 when IRI ≥ 3.6 from 2008 & OVL30 when IRI ≥ 3.5 from 2033 10. OVL50 when IRI ≥ 4.4 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 11. OVL50 when IRI ≥ 4.4 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 12. OVL50 when IRI ≥ 4.5 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 13. OVL50 when IRI ≥ 4.5 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 14. OVL50 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 15. OVL50 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.5 from 2020
	6.0≤IRI<8.0 IRI≥8.0	1. Base alternative 2. OVL70 when IRI ≥ 7.5 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 3. OVL70 when IRI ≥ 7.5 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 4. OVL70 when IRI ≥ 7.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 5. OVL70 when IRI ≥ 7.6 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 6. OVL70 when IRI ≥ 7.7 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 7. OVL70 when IRI ≥ 7.7 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 8. OVL70 when IRI ≥ 8.8 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 9. OVL70 when IRI ≥ 8.8 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 10. OVL70 when IRI ≥ 8.9 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 11. OVL70 when IRI ≥ 8.9 from 2008 & OVL30 when IRI ≥ 3.5 from 2020 12. OVL70 when IRI ≥ 9.0 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 13. OVL70 when IRI ≥ 9.0 from 2008 & OVL30 when IRI ≥ 3.5 from 2020
Very high traffic, 8000≤ AADT	IRI< 4.0	1. Base alternative 2. OVL30 when IRI ≥ 3.3 from 2008 3. OVL30 when IRI ≥ 3.4 from 2008 4. OVL30 when IRI ≥ 3.5 from 2008 5. OVL30 when IRI ≥ 3.6 from 2008 6. OVL40 when IRI ≥ 4.0 from 2008 & OVL30 when IRI ≥ 3.3 from 2020 7. OVL40 when IRI ≥ 4.0 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 8. OVL40 when IRI ≥ 4.2 from 2008 & OVL30 when IRI ≥ 3.3 from 2020 9. OVL40 when IRI ≥ 4.2 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 10. OVL40 when IRI ≥ 4.3 from 2008 & OVL30 when IRI ≥ 3.3 from 2020 11. OVL40 when IRI ≥ 4.3 from 2008 & OVL30 when IRI ≥ 3.4 from 2020 12. OVL40 when IRI ≥ 4.5 from 2008 & OVL30 when IRI ≥ 3.3 from 2020 13. OVL40 when IRI ≥ 4.5 from 2008 & OVL30 when IRI ≥ 3.4 from 2020
	4.0≤IRI<6.0 6.0≤IRI<8.0	1. Base alternative 2. OVL50 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 3. OVL50 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 4. OVL50 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 5. OVL50 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 6. OVL60 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 7. OVL60 when IRI ≥ 4.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 8. OVL60 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 9. OVL60 when IRI ≥ 4.7 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 10. OVL70 when IRI ≥ 6.5 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 11. OVL70 when IRI ≥ 6.5 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 12. OVL70 when IRI ≥ 6.6 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 13. OVL70 when IRI ≥ 6.6 from 2008 & OVL30 when IRI ≥ 3.4 from 2016 14. OVL70 when IRI ≥ 6.7 from 2008 & OVL30 when IRI ≥ 3.3 from 2016 15. OVL70 when IRI ≥ 6.7 from 2008 & OVL30 when IRI ≥ 3.4 from 2016

Note: OVL denotes overlay treatments along with their thicknesses in mm.

Table 11: NPV functions of sub-networks

Sub-network	Length (km)	Number of Sections	NPV function	Feasibility range
High/very high traffic (AADT≥ 4000)	3452.32	166	$NPV_1 = 5023.43(1 - e^{-0.0962\,a_1})$ $R^2 = 0.984$	$0 \le a_1 \le 116.34$
Medium traffic (1000≤ AADT<4000)	3388.23	136	$NPV_2 = 421.08(1 - e^{-0.1381 a_2})$ $R^2 = 0.999$	$0 \le a_2 \le 117.40$
Low traffic (1000< AADT)	2360.45	112	$NPV_3 = 63.08(1 - e^{-0.1954\,a_3})$ $R^2 = 0.995$	$0 \le a_3 \le 45.77$
Total	9201.00	414		

Table 12: Solutions for different nationwide budgets

% of A^0 a)	(A)	Iter-ation	Allocated Budgets for Sub-networks ($mil.)				Net Present Value ($mil.)					Diff. b) (%)
							Sub-networks				Nation-wide network	
			a_1	a_2	a_3	Total $\sum a_i$	NPV_1	NPV_2	NPV_3	Total $\sum NPV_i$		
500%	341.30	1	171.50	104.14	65.66	341.30						
		2	116.34	186.46	38.50	341.30						
		3	116.34	117.40	107.56	341.30						
		4	116.34	117.40	45.77	279.51	5121.400	428.660	62.190	5612.250	5612.239	0.00
400%	273.04	1	140.32	82.41	50.31	273.04						
		2	116.34	118.20	38.50	273.04						
		3	116.34	117.40	39.30	273.04	5121.400	428.660	61.920	5611.980	5612.140	0.00
300%	204.78	1	109.14	60.69	34.95	204.78	5118.290	423.840	61.820	5603.950	5608.652	0.08
200%	136.52	1	77.95	38.97	19.60	136.52	5115.810	413.750	61.330	5590.890	5597.726	0.12
175%	119.46	1	70.16	33.54	15.76	119.46	5107.260	425.830	60.450	5593.540	5588.517	-0.09
150%	102.39	1	62.36	28.11	11.92	102.39	5092.520	406.690	59.300	5558.510	5579.002	0.37
125%	85.33	1	54.57	22.68	8.08	85.33	5073.130	401.700	55.000	5529.830	5557.688	0.50
100%	68.26	1	46.77	17.24	4.25	68.26	4995.710	379.470	32.780	5407.960	5500.331	1.68
75%	51.20	1	38.97	11.82	0.41	51.20	4884.990	336.030	2.500	5223.520	5353.738	2.43
50%	34.13	1	31.18	6.38	-3.43	34.13						
		2	29.15	4.98	0.00	34.13	4545.260	198.720	0	4743.980	4965.352	4.46
							AHMED/EBM c)				HDM-4 d)	

a) A^0 is calculated as $A^0 = B^0/T$, where B^0 is the total budget over T-year analysis period under unconstrained mode. b) "Diff." is calculated as $\frac{NPV(Network) - \sum NPV(Sub-network)_i}{NPV(Network)} x100\%$. c) AHMED is a "heuristic" optimization method used in EBM. d) HDM-4 uses a "heuristic" optimization method called NPV/Cost method when the number of road sections is larger than 400, which is the case with the present case study.

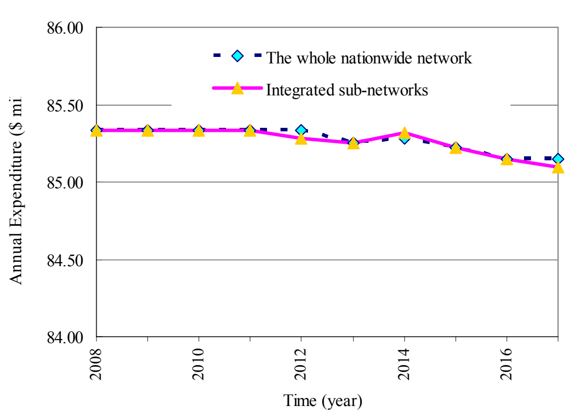

Figure 5. Comparison of annual capital expenditures between the nationwide network and integrated sub-networks ($A = 125\%A^0$)

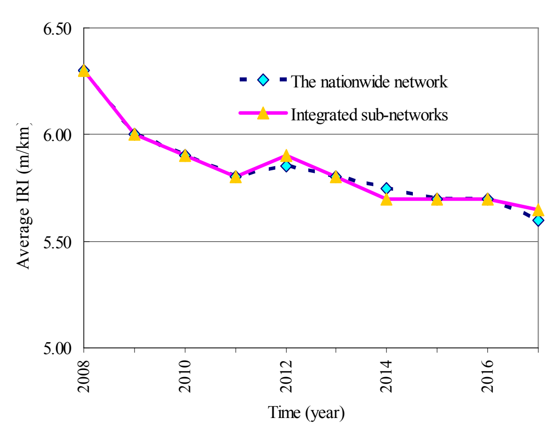

Figure 6. Comparison of network average IRI's between the nationwide network and integrated sub-networks ($A = 125\%A^0$)

4. ANALYSIS RESULTS

The road network was grouped in three sub-networks based on traffic loadings (i.e., high/very high, medium, and low traffic sub-networks). The HDM-4/EBM model is used as an OES for carrying out the SDS for these sub-networks. A twenty-year analysis period and a 12% social discount rate are used in the case study. The planning period is ten years. The NPV functions constructed for these sub-networks are shown in Table 11**.** It was found that the proposed specification of NPV function is reasonable in the modified NPVF as shown by the very high R-square values. Table 11 also shows the feasibility range of annual budget for each sub-network. The upper bounds of these ranges were found by running the HDM-4/EBM in the unconstrained budget mode and using Eq. *(3)*. Table 12 shows the results of the optimal budget allocation over these sub-networks for different nationwide budgets. Most budget levels required two to three iterations until all feasibility requirements were satisfied. To evaluate the accuracy of the NPVF modified for the uniform annual budget distribution, the HDM-4 with the incremental NPV/Cost method was run separately using the entire road network with the same nationwide budgets. The last column in Table 12 shows that the sum of the NPVs of three sub-networks under optimal budget allocations are very close to those obtained by running the whole network, indicating a very high accuracy of the modified NPVF.

Figures 4 and 5 present comparisons for annual capital expenditures and average network conditions (for the case with the total budget A equals to 125%A^0) between the analyses with the whole network and the integrated sub-networks applying the modified NPVF. These results are very similar and imply that the budget allocation methodology proposed is feasible and applicable when considering the case of uniform annual budget distribution over the planning period.

5. CONCLUSIONS

The paper has presented a comprehensive procedure to carry out the strategy analysis using OESs with dynamic sectioning (SDS) for a nationwide road network including the sound trade-off analysis of all road sub-networks. Generation of appropriate maintenance alternatives for the use of SDS was presented in a systematic manner along with the application of GSOE. The NPVF approach has been expanded to more general applications when considering uniform distribution of annual budgets over the planning period. The procedure can be used as a guideline to assist a road agency when conducting the strategy analysis, or program analysis, of a nationwide road network using OESs to prepare expenditures of the entire network or sub-networks under various budget policies and economic scenarios.

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