Development of A Practical Model for Pavement Management Systems

Hamzah Suharman

Development of A Practical Model for Pavement Management Systems

by

Hamzah Suharman

A dissertation submitted in partial satisfaction of

the requirement for the degree of

Doctor of Philosophy in Engineering

in the

Department of Urban Management

Graduate School of Engineering

Kyoto University

Acknowledgments

Research and scientific activity perhaps have a uniquely among other activities. What we did, why it was done, how it was done, and what was learned from it are common questions should be considered in doctoral research activity. To answer the questions and to accomplish doctoral research by writing this dissertation, as well as an individual effort, the support and help from colleagues is decisive. Apparently, my doctoral research and the people in Room 331/332/333/337 in C1-2 Cluster Katsura Campus Kyoto University is a pronounced example. With happiness, here I would like to acknowledge a number of special people that helped me make this research reach its goals.

I would like to express my deepest gratitude to my academic supervisor, Professor Kiyoshi Kobayashi for his endless encouragement and guidance throughout my research life in his laboratory in Kyoto University. His foresight, pithy comments and ultra smart way of thinking always make effort in a certain direction of my research to a clearly point. Furthermore, I would not have had the courage nor the strength to draw out the challenges he sent at me. For me, he is a role model and I owe profound to him.

My special thanks to the members of my research committee Professor Hiroyasu Ohtsu and Professor Hirotaka Kawano for their valuable suggestions, constructive comments and warmth discussion.

I am deeply indebted to Associate Professor Kakuya Matsushima for his mentoring and advising during my doctoral study. With his patient to support me both in seminar research and in daily life in Kyoto, many difficulties seemed like lighter after discuss and get feedback from him. I learned a lot from him, especially to manage many people come from any background. He is a great pathfinder.

My gratitude also goes to Assistant Professor Masamitsu Onishi and Assistant Professor Mamoru Yoshida for their support and encouragement during my study. Through an enjoyable discussion in the leisure time of our research that put me away from boredom. What a moment you have been to me.

My profound thanks to Associate Professor Kiyoyuki Kaito and Dr. Kazuya Aoki for their significant support, suggestion and feedback related to asset management research field. A combination of academic and industrial point of view helps this research being a valuable in the future.

My sincere thanks to Dr. Hayeong Jeong, for her support and friendship during my doctoral study. My special thanks to Ms. Aya Fujimoto for continuous support and kindness. My thankful and indebtedness also to all members of Planning and Management System Laboratory for their friendship, kindness and sharing in deepen our understandings and expand our knowledge together. Too many to name them here, and a great thank you to you, All.

I am especially grateful to the Hasanuddin University Faculty of Engineering Development Project in which I granted my scholarship under JBIC/JICA supporting to pursue this doctoral program. This dissertation would not have been complete without the scholarship I gained and of course the kindness of the people of Japan.

Finally, and most of all, my deepest sense of gratefulness goes to my beloved parents Sukma Hamzah and Harsiah Make, my beloved parents in law Andi Mohammad Syauki and Anna Rohana, my wonderful wife Andi Suheyra Syauki and my lovely son Muhammad Zayyan Abiyyi Shyrazi Syauki for all the love and support they have show me over the years.

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Chapter 1

Introduction

1.1 General Introduction

Increasing utilize of infrastructure to support society's activities creates a new research area that should be developed. As a nature of most infrastructures, continuous development becomes a vital part. To cope with demands of infrastructure, asset management have been introduced in recent years. Asset management as integrated approach may become disentangled conflicting of resource constraints, performance requirements and risk acceptances that always exist in the infrastructure system. Now, asset management is come in as efficient way to maintain civil infrastructures which has gradually deteriorated under a limited budget (Kobayashi and Ueda, 2003). This means that not only a wide-scale of research has been done well, but also applying research for asset management practices.

Infrastructure asset management is not generally fitted to be an engineering discipline, combining humanities and sciences (i.e. economics, accounting, business administration) are also invited. Therefore, a comprehensive understanding on asset management as a whole may not be reached by a single researcher or decision maker. Based on that, the entire infrastructure network has different systems and of course a definition developed in case by case approaches. Nevertheless, a broader perspective can be understood according to Kobayashi (2008), infrastructure asset management as "the optimal allocation of the scare budget between the new arrangement of infrastructure and rehabilitation/maintenance of the existing infrastructure to maximize the value of the stock of infrastructure and to realize the maximum outcomes for the citizens". On the one side, asset management as applied to the road and pavement sector can be considered to be "a systematic process of maintaining, upgrading, and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations" (OECD, 2001).

Underlining above definition, one important key in asset management is maintenance or repair strategy. Even though we have had many high technologies in design and construction infrastructure, however the maintenance is often excluded as a part of sustainable infrastructure. Infrastructure asset including road and bridge sector are highly and frequently maintained such as inspection and monitoring which are needed by decision makers in order to make a plan of maintenance and rehabilitation. To address infrastructure optimal maintenance, repair and rehabilitation, a variety of research have been accumulated (Madanat and Ben-Akiva, 1994; Guigner and Madanat, 1999; Swilowitz and Madanat, 2000). Regarding uncertainty measurement in conjunction with facility deterioration is mostly emphasized (Madanat, 1993a; Tamura and Kobayashi, 2001; Jido et al, 2008; Mishalani and Gong, 2009). With stochastic model using Markov decision process tries to serve optimal repairing policy that minimizes facilities life-cycle cost.

A large number of researches on pavement (including bridge) management system have been disseminated. Pavement management system is developed in order to reduce life-cycle cost of road pavement that is suitable with project level and or network level (Hass et al, 1994; Hudson et al, 1997; Herabat et al, 2002). Estimating the demand of pavement repair becomes challenge effort to road management agencies. On other side, there is a lack of deterioration data to use in deterioration estimation. Repair budget often unable to provide annually due to economic policy or public work budget changes. Whereas, ideally, road pavement repair should be done when the life-cycle cost is at a minimum. It is obligatory to manage the demand of repair and determining budget at a certain time in order to reach pavement long-lived.

1.2 Background of Study

A challenge in infrastructure asset management occurred in both developed countries and developing countries. The challenge is how to predict infrastructure performance with appropriate models regarding the ability of complete data in order to make optimal maintenance and repair strategies. A great attention focused in maintenance field has been run well. Carnahan et al (1987) and Harper et al (1990) proposed maintenance and repair under forecasting uncertainty of facility deterioration. In these studies, inspections with predetermined and fixed time intervals are incorporated.

Basically there are two dimensions of inspection decision. Firstly is when inspections will be doing to the facility. This decision is related to the presence of forecasting uncertainty. Secondly is how to inspect it (including which technology to use) that refers to measurement uncertainty. An improved model presented incorporating of both forecasting and measurement uncertainty. Madanat (1993b) tried to incorporating inspection decision of optimal timing problem of both inspections.

A great study on maintenance, repair and rehabilitation is generally in form of stochastic control models (Madanat et al, 1995; Mishalani and Madanat, 2002; Aoki et al, 2005a; Madanat et al, 2006; Aoki et al, 2006) with found on Markov decision process (MDP). Standard models of infrastructure management are based on the MDP which the condition state of facilities is defined in discrete states. The optimal maintenance models were documented using discrete time, state-based models (Durango and Madanat, 2002; Frozzi and Madanat, 2004; Aoki et al, 2007; Nakat and Madanat, 2008). However, increases the rank of transition probability matrix rapidly with small increments in the number of state variables and policies bring on difficulties for estimations using MDP (Guillamout et al, 2003; Khun and Madanat, 2005; Jido et al, 2008). Kobayashi and Kurino (2000) propose an optimal repairing strategy model for infrastructure facilities under a continuous-state-deterioration process and succeed in facing such difficulties. Others of continuous state solution approach were suggested by Tsunokawa and Schofer (1994) and using a steady state of continuous time and continuous state space and deterministic deterioration (Li and Madanat, 2002; Ouyang and Madanat, 2006)

Statistical estimation methods have been applied to overcome the problem of deterioration using econometric analysis approach (Lancaster, 1990; Gourieroux, 2000). Lancaster (1990) developed the multi stage model for the behavior of labor transition which using a rational approach to estimate transition probability from multiple condition states. This research tries to answer the problem of binary condition states as proposed by Shin and Madanat (2003) using Weibull deterioration hazard model to forecast the starting time crack on pavement structures or similar research by applying the Weibull distribution function in case of tunnel lightning facilities deterioration (Aoki et al, 2005b). To overcome the problem of deterioration prediction using Weibull Hazard model, profound research have been accumulated mostly to pavement management by Asset Management Group of Kyoto University (Aoki et al, 2005c; Kaito et al. 2008; Aoki et al, 2008; Kobayashi et al, 2010; Kobayashi et al, 2011).

As a part of statistical method, the Markov hazard model becomes a valuable research that is proved by a plentiful paper and research produced in this field referring to some foundation books (White, 1993; Puterman, 1994; Norris, 1997). Tsuda et al (2006) portrayed the vertical transitive relation between condition states and figured a method to estimate Markovian transition probabilities with multi-stage hazard model applied in bridge deterioration forecasting. Whilst, Kobayashi et al (2009) developed the model for pavement deterioration forecasting with the Korean case. This model is possible to apply in several of infrastructure asset management system. Application of hazard models in asphalt pavement (Hiroshi et al, 1990; Abaza et al, 2004; Kaito, et al, 2007), deck bridge and bridge networks (Golabi and Shepard, 1997; Morcous, 2005; Robelin and Madanat, 2007), and also for waste water systems (Baik et al, 2006) are obvious progress of long research related to Markov chain models.

Inspection data is an essential in Markov hazard models application. Accuracy of estimation occupied at least two inspection times which will be affected by quality of inspection data. A measurement error should be done due to errors occurred in inspection data as caused by measurement system or inspector (human or machine), inspected objects, or from data processing and data interpretation (Humplick, 1992). Methods with focused on formulating evaluation techniques for quantifying the error term have been posted (Cochoran and Cox, 1968; Grubbs, 1973). In addition, estimation methodologies using Bayesian estimation technique suggested in order to overcoming small sampling population of inspection data and measurement errors, (Ben-Akiva and Ramaswamy, 1993; Ibrahim et al, 2001; Hong and Frozzi, 2006; Kaito and Kobayashi, 2007).

To eliminate error term, bias or noise in inspection data, a Hidden Markov hazard model as a branch of Markov chain model is useful. Although, as for infrastructure system is still limitation in application, however in applied statistics can be shown more documented (MacDonald and Zucchini, 1997; Robert and Titterington, 2000; Kobayashi et al, 2009). On economic and financial side, researches invents by using non-stationary series of information. Using Markov chain theory is possible for the transition probability in non-linear regression approach (Hamilton, 1989; Kim and Nelson, 1999). Employ Bayesian estimation and Markov Chain Monte Carlo (MCMC) simulation is best way to estimate the Markov transition probability to overcome the limitation of hidden Markov chain models (Wago, 2005).

Estimation of heterogeneity factor of individual group using Mixture hazard model is being applicable. With mixture hazard model, estimating is accorded on inhomogeneous data and also in the same set of inspection data. Nevertheless, it is important to understand if we will estimate of heterogeneity factor in relation to different group of facilities (Nam et al, 2008). Following that, by mixture hazard model, it is considered model as an excellent technical tool for benchmarking study. Particularly in developing countries, benchmarking study is used to find the best practice in management and technology.

Recently, a variety of databases have been developed by road administrators. However, it is still measly database functions contributing to infrastructure asset management. This fact mentions that even if a database contains plentiful and detailed data, it is not a guarantee that it would definitely be used. Appropriate management suitable in developing countries depends on their needs and limitations. Poor systems of database or due to the database is seemed like just black boxes are kind of challenge in database application in infrastructure asset management. Thus, a comprehensive strategy to build a methodology of database application in infrastructure asset management should be considered. Understanding of basic knowledge of deterioration model in connecting with tools will be valuable in field of pavement database development.

1.3 Objectives of Study

The objectives of the present study are mainly reflected by current discourse of finding the answer of more practically of infrastructure asset management. In brief, it would be categorized in three solid items, that is:

- Understanding and elaborating deterioration prediction model by referring to application of Markovian deterioration hazard process and pavement maintenance policy and strategy for utilizing in benchmarking evaluation.

- Verifying and applying The Kyoto model pavement management systems as part of road pavement asset management systems with preferential on pavement database to support pavement maintenance work.

- Developing a practical approach of empirical studies of pavement maintenance management systems. The practical model is provided as open systems of database for practical orientation.

1.4 Scope of Study

This study is being figured in four main chapters. Outlines of scopes are stated as follows:

- Chapter 3 discusses the pavement maintenance management policies which provide a step of constructing maintenance management systems. Utilize of inspection method and repair method in relating with information systems in order to rationalize objective data acquisition and inspection work.

- In chapter 4, presents benchmarking evaluation of deterioration speed for long-lived pavement. A new maintenance management work that making pavement long-lived using logic model is evaluated neither in secularly or continually. Empirical study was implemented in usual maintenance work in Kyoto city.

- The chapter 5 scope is on development of Kyoto Model pavement management systems. Featuring international standards of pavement management systems which consist of information management functions, analysis-evaluation and planning for decision making support systems are predominantly.

- Development of practical systems is conducted on utilities of pavement asset management systems in the form of database functions. This study is written in chapter 6. Specifically, the model of chapter 6 is developed by in a close link with the content of chapter 5.

- Conclusions and recommendations on models and empirical studies are come up at each last section of respective chapters.

1.5 Expected Contribution

Through the research, it is expected that the knowledge of this research will contribute to:

- Maintenance management policies in chapter 3 are expected to be used for road manager or governments who is responsible to hold the maintenance systems in their city or local government. This chapter is also possible to be extended with other infrastructure systems.

- In chapter 4, a benchmarking evaluation for pavement deterioration process is proposed. As a benchmark, the result of this research is possibly to support a plan of maintenance of different section in the future. Moreover, pavement long-lived and cost reduction which is related to maintenance work poised to be applied in asset management.

- Inspection data and repair method should be considered when working on pavement database. Thus, chapter 5 promises a tool as a new contribution to pavement asset management that will overcome the problem of deterioration prediction. Other contribution may in form of framework to develop a deterioration model appropriate with road managers demands.

- A practical approach of pavement database which used in open systems as stated in chapter 6 might useful for developing countries. The difficulties by expensive cost for using sophisticated models are facing by developing countries. Come out with this, to alleviate development of pavement management systems in their countries based on a practical model.

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Chapter 2

Pavement Management Systems

2.1 General Introduction

The infrastructure asset management process refers to decision making of maintenance, repair and rehabilitation to minimize life-cycle cost. Deciding maintenance strategic, for example, come up with performance of facilities in the network. Performances of facilities usually divide in two forms. Firstly is information on current condition, which is obtained from inspection. Secondly, information on future condition is supported by predicting of performance models. Thus, accuracy of current performance and prediction of future performance of infrastructure such as: pavement, bridge, airport, tunnel, etc is crucial point for developing appropriate deterioration prediction models.

Deterioration prediction can be broadly divided into mechanical methods and statistical methods. In other ways, it also can be namely by deterministic models and stochastic models in chronological order. Mechanical methods prescribe a prediction model based on two ways, either by experience, or developing a model to derive the mechanisms of deterioration and damage by using logical deduction. Meanwhile, a huge amount of visual inspection data is used as a base to denote statistical likelihood in statistical methods. Accordingly, mechanical methods are useful in deterioration prediction for specific infrastructures or facilities in form of a microscopic view. Conversely, statistical methods are advantageous for macroscopic view of deterioration prediction of entire infrastructures.

Employed deterministic or stochastic models for the deterioration prediction in infrastructure management rely on intended goal. However, since deterministic models have varying information and predictions which hinge with deterioration occurred, and information necessary is excluded in visual inspections standard, it makes less in used. In reverse, stochastic models require visual inspections of entire infrastructures which is assumed as discrete state, then even if in the different deterioration prediction, it will be much prefer alternative for practical applicable to deterministic one.

Output of deterministic models can be called as performance curves, meanwhile in stochastic model; it can definitely not be expressed as performance. It means that visual inspections are not figuring physical attributes of facilities, but results of visual inspections based on information obtained are needed to define repair time and suitable repair methods. As consequence, it will be valuable in practical when using stochastic models in order to elucidate investment time of life-cycle cost by employing visual inspection results of deterioration predictions. Thus, as in compared with performance curves that stated in previous, output of stochastic models is called management curves as an appropriate name. Management curve is more valuable for deterioration process.

This chapter reviews in-depth research works in infrastructure asset management which was proposed by asset management group at Kyoto University lead by Professor Kiyoshi Kobayashi. Main reference are the paper on multi-stage exponential hazard model (Tsuda et al, 2006), paper on measuring deterioration risk of infrastructure (Aoki, 2007), and paper on local mixtures hazard model (Nam, 2008).

The following sections (2.2) expresses background literature on infrastructure asset management approach, where encompasses the concept and practical of infrastructure asset management, and also role of visual inspection data in supporting Markov chain models. Section 2.3 presents deterioration prediction model using deterministic method. Adversely, deterioration prediction model by stochastic approach is described in section 2.4. The subsequent of section 2.4, multi-stage Markov exponential hazard model is discussed in section 2.5. Whilst, section 2.6 explains the mixture Markov deterioration hazard model. The last section summarizes this chapter and recommendations related to expanding this chapter in future.

2.2 Infrastructure Asset Management Approach

2.2.1 Overview of Infrastructure Asset Management System

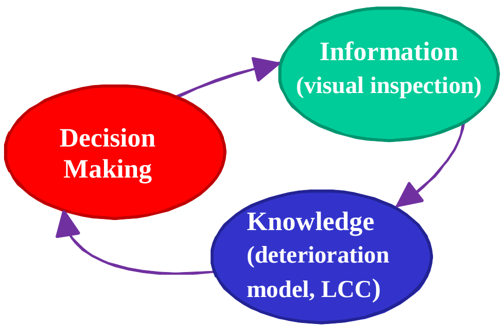


Figure 2.1 Concept of Management

As in line with the concept of management, infrastructure asset management encompassing a cycle of three processes as displayed in figure 2.1 (Kaito et al, 2010). Information deals with extracting a huge of information that is beneficial and applicable to gain knowledge. Information process is not only as the first step of management, but also to oversee the quality of decision making. Knowledge focuses on tools to support of decision making which cultivates information gained. Decision making pays attention to provide result of process as the end of this cycle. As noticed, in infrastructure asset management, a huge of information can be enlisted is narrow. Thus, it is important to realize information type that can be applied in practice.

Regarding the limitation, it is necessary to consider that some of limitations be in place with infrastructure applied. A number of structures to be managed, age, type, and state, as well as organizational limitations such as a number of employees, technical capability, and budget are possible. On other side, the characteristics, culture and history of the administrator, and also current social conditions may serve as limitations. These limitations are different in degree based on the specific administrator. By limitations existed, experience gained and know-how approach, the administrator carries out decision making processes.

Hereinafter, infrastructure asset management methodologies as stated above are likely rely on experience and hinge to the administrator. Hence, a shared framework of infrastructure asset management used jointly among the administrators is opened, but it is a narrow when ask how much a ready-made system could be practically used in infrastructure asset management. Other matter, systemization and a reliance on systems can induce misconceptions with respect to decision making. In other words, the “decision making” in figure 2.1 is related to assumption that administrator have to undertake by themselves. As explained in section 2.3-2.4, deterioration predictions and life cycle cost evaluations are commensurate to “knowledge”. These outputs (results analysis) are a tool to support the administrator’s decision making process.

2.2.2 Practical Infrastructure Asset Management

Infrastructure asset management tries to reduce costs in maintaining infrastructures or look for a method to increase infrastructure long-lived by repair activities. To achieve these conditions, figure 2.2 shows management structure that is hierarchical management system with emphasized on three differentiate managerial levels. The first top, strategic level, observes process of deterioration in a long-time planning of implementation. The second, tactical management level deals with plans and tactical activities in medium-term scenario. Whereas, the last level in the hierarchical management system focuses on a specific maintenance and repair works.

The three levels of management are integrated systems and working as a single functional entity for entire network structure. Even so, each level requires a specific analytical methodology and has its own missions or objectives.

In strategic level, in order to invent a long-term implementation, estimating the budget allocation as well as a method to allocate the budget by economics analysis such as life-cycle cost is one example of activities. To support budget plans and maintenance strategies, of course, deterioration prediction model is needed to estimate repair time and methods. The stochastic deterioration prediction model requires inspection data daily recorded at the maintenance and repair level. Adversely, as data input to strategic and tactical levels, the data should be reliable.

Further to tactical levels, the objective is following the basic policies or outputs as set at the strategic level, then in replying urgent activities such as citizen's requests and efficiently daily work procedures. Other activity is generating a list of candidate infrastructure component that should be maintained in near future. At this time, periodical inspection is carried out. Priority level of repair is adjusted by evaluating simultaneously various indicators.

In accordance with maintenance and repair level, the repair candidate components are processed within budget allocation in connection with priority level which decided at tactical levels. It is important notice here, record of actual performance of facilities is important to update status of facilities into inventory system.

Information recorded and learned from the project such as influence of maintenance performance to infrastructure long-lived, will be documented as knowledge data. This knowledge is considered as lesson-learned to other projects. Therefore, the Deming cycle (Plan-Do-Check-Act) (Deming, 1994) plays a positive role that connecting with management system to improve the system as whole.

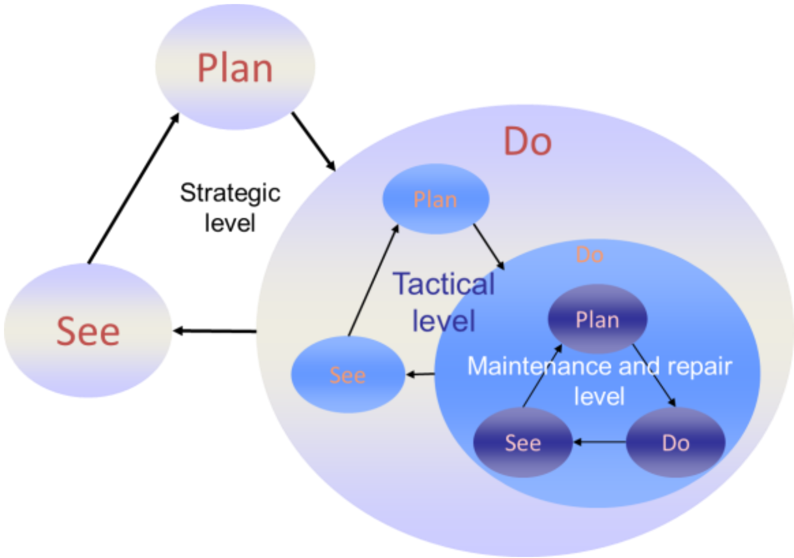


Figure 2.2 Management Flow by Level

2.2.3 The Role of Visual Inspection Data

As previously described, inspections are a source of information about condition of facilities. Nevertheless, it is not require for all decision-making methods. In case of deterministic decision-making models, it assumes that infrastructure performance can be predicted without error into any time in the future. Within this assumption, due to assume that the information provided is already known to the decision-maker, then it is not important to derive from performing inspections. In consequence, to being unrealistic in representing of pavement deterioration, deterministic models do not recognize the role of inspection (Madanat, 1993b).

On different way, employ of stochastic hazard model mainly based on Markov decision process means that asset management practices have to recognize the uncertainty and using information form inspection or monitoring to reduce uncertainty. Availability of historical information will support the better deterioration process result.

Visual inspection is a method to obtain the necessary information on deterioration progress. As a fact, using visual inspection as starting point to predict deterioration will be possible to reduce cost in life-cycle cost evaluation. A visual inspection records the status of facilities in the time of inspection; it is not define accurately at certain time changed in the future. Even if, just limited and uncertain information, utilizing probabilistic models to establish a model of deterioration processes and applying inspection data to develop stochastic predictions of deterioration are enable.

A large number of studies have been proposed on employing visual inspection data to deterioration prediction models. As in section 1.2, Markov chain model is a model for displaying transitions between discrete state variables such as visual inspection data. The Markov chain model relays probability of transiting one state to another specific state as Markov transition probability. The deterioration process is calculated in accord with Markov transition probability matrix. In case of transitions between ratings of facilities are fulfilled requirement of Markov transition probability, and then utilize visual inspection data to reveal deterioration process of infrastructures.

The concept of the Markov chain model is simple, and then the models have been widely implemented. However, it is necessary to tackle the problems of measurement error and bias, when estimating the Markov chain model based on visual inspection data. In fact, high accuracy of estimation is not a simple one. Several of Markov transition probability model proposes the subjective decision by the field engineer. Thus, why several of papers related Markov chain models may not be agreeable with actual data (visual inspection data). Consequently, estimation model are inappropriate to actual work. Therefore, there is a need to further develop a hazard model which considers the measurement errors and bias (Kobayashi et al, 2007). With these conditions, it would bring consistently comprehensive improvement in the field and deterioration prediction models in a logical way.

2.3 Deterministic Deterioration Prediction Model

2.3.1 The Simple Linear Regression Model

Regression analysis is one of the most generally used tools in many research fields. Regression analysis deals with measurement of a relationship between an independent or explanatory variable and a dependent variable. In specific way, regression analysis is used for predicting the value of y by given values of x. To examine of errors and evaluate the judging whether using the linear functional form is considered for applying the regression analysis.

In pavement application, we can employ this model to estimate road condition annually using function of elapsed time. This model can be applied as minimum requirement for all deterioration prediction models, so that will be suitable with countries which have minimum data of pavement (i.e. only pavement condition and maintenance history data). However, it is important to underline based on experience both from researchers and engineers that regression model have limitedness to overcame with uncertainties of pavement deterioration progress.

This section describes simple description of simple linear regression model. In term of the linear regression model, an important consideration should be noticed that whether we are obtaining prediction for particular value of y or for the average value of y. Another one is considering the conditions of Least Squares Estimators (LSE) that have desirable optimum properties which are called as linear unbiased estimator (Maddala, 2008).

The linear regression model essentially consists of following variables:

- The dependent variable, denoted as *"Y"*
- The independent or explanatory variable, denoted as *"X"*
- The regression parameter, denoted as *"β"*

Based on that variables, to estimate Y by a function of X and β using regression model can be defined as $Y \approx f(X, \beta)$. The formulation is usually formalized as:

$$E(Y|X) = f(X|\beta) = \beta_0 + \beta_1 \mathrm{X}_i + \varepsilon_i \ (i = 1, \dots, n) \tag{2.1}$$

In this case, the dependent variable Y is condition indices and meanwhile the time since last major rehabilitation or condition change between inspection points can be as the explanatory variable X. For adding several explanatory variables in terms of $X_i^2, \dots, X_i^n$, the regression is formulized in multiple linear regression as in below:

$$y_i = \beta_0 + \beta_1 X_i + \beta_2 X_i^2, \dots, \beta_n X_i^n + \varepsilon_i \ (i = 1, \dots, n) \tag{2.2}$$

As a note, equation (2.2) is still linear regression due to the parameters $\beta_{0,}\beta_1, \dots, \beta_n$ is linear even though in the explanatory variable on the right side is quadratic.

The ε_i in equation (2.1) and (2.2) is an error term. Given a random sample from the population, it can be estimated the population parameters and step into the sample linear regression model:

$$\widehat{y_i} = \hat{\beta}_0 + \hat{\beta}_1 x_i + e_i \tag{2.3}$$

The e_i is residual term, that is, $e_i = y_i - \hat{y}_i$. The method of least squares is required to estimate that choose $\hat{\beta}_0$ and $\hat{\beta}_1$ as estimates of β_0 and β_1 respectively. By this method, it generates parameter estimates that the Sum of Squared Errors (SSE) is a minimum:

$$\mathrm{SSE} = \sum_{i=1}^{N} \varepsilon_\mathrm{i}^2 = \sum_{i=1}^{N} (\mathrm{Y_i} - \beta_0 - \beta_1 x_i)^2 \tag{2.4}$$

To minimize SSE in equation (2.4) with respect to solve parameter estimators $\hat{\beta}_0, \hat{\beta}_1$, we equate its first derivatives with respect to $\hat{\beta}_0$ and $\hat{\beta}_1$ to zero. From those result (called normal equations) then substitutes each other, hence the formulas of least square estimates in the case of simple regression are:

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n} (x_i - \bar{x}_i)(y_i - \bar{y}_i)}{\sum_{i=1}^{n} (x_i - \bar{x}_i)^2} \text{ and } \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \tag{2.5}$$

Where $\bar{x}$ is average value of explanatory variable x and $\bar{y}$ is average value of dependent variable y.

From the graphical presentation of regression line, there is one important question, that is, dependability of relationship between dependent and explanatory variables. Standard error of estimate is generally used in that problem.

The Mean Squared Error (MSE) can be estimated by biased estimates of regression line refer to the variance σ^2:

$$\mathrm{MSE} = \frac{1}{n-2}\sum_{i=1}^{n} e_{\mathrm{i}}^2 = \frac{1}{n-2}\sum_{i=1}^{n}(\mathrm{y_i} - \hat{y}_i)^2 = \frac{1}{n-2}\sum_{i=1}^{n}(\mathrm{y_i} - \beta_0 - \beta_1 x_i)^2 \quad (2.6)$$

Then, the standard error of estimates, S_e are calculated by:

$$S_e = \sqrt{MSE} = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}(\mathrm{y_i} - \beta_0 - \beta_1 x_i)^2} \quad (2.7)$$

When the value of S_e is closer to zero, it explains that relationship between dependent variable y_i and explanatory variable x_i is well. Coefficient of determination R^2 should be used to check the goodness of fit of regression line. Regarding to differences between measurement y_i and $\bar{y}$, total deviation can be divided into SSE and SSR (Sum of Squares Regression):

$$(\mathrm{y}_i - \bar{\mathrm{y}}) = (\mathrm{y}_i - \hat{\mathrm{y}}_i) + (\hat{\mathrm{y}}_i - \bar{\mathrm{y}}) \quad (2.8)$$

$\sum_{i=1}^{n}(y_i - \bar{y})^2$ = total sum of squares (SST)

$\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$ = regression sum of squares (SSR)

$\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$ = error sum of squares (SSE)

The total deviation can be rewritten as:

$$\mathrm{SST} = \mathrm{SSE} + \mathrm{SSR} \quad (2.9)$$

Let divide equation (2.9) by SST, so the variation ratio of explained and unexplained variation, respectively:

$$\frac{\text{SST}}{\text{SST}} = \frac{\text{SSE}}{\text{SST}} + \frac{\text{SSR}}{\text{SST}} \text{ or } 1 = \frac{\text{SSE}}{\text{SST}} + \frac{\text{SSR}}{\text{SST}} \quad (2.10)$$

Here, the $\frac{SSR}{SST}$ is called as the sample of coefficient of determinant R^2. Then can also be written as:

$$R^2 = \frac{\text{SSR}}{\text{SST}} = 1 - \frac{\text{SSE}}{\text{SST}} = \frac{\sum_{i=1}^{n}(\hat{\mathrm{y}}_i - \bar{\mathrm{y}})^2}{\sum_{i-1}^{n}(\mathrm{y}_i - \bar{\mathrm{y}})^2}, \text{here}, 0 \leq R^2 \leq 1 \quad (2.11)$$

While all estimation well-off on the regression line,

$$\text{SSE} = \sum_{i=1}^{n}(\mathrm{y}_i - \hat{\mathrm{y}}_i)^2 = \sum_{i=1}^{n} e_i = 0 \; then \; R^2 = 1 \quad (2.12)$$

Values of R^2 will be in range 0 to 1. The higher R^2 indicates higher correlation coefficient. The R^2 1.0 stands for the regression line completely fit the data. However, it should be emphasized that the coefficient is a measure of relationship (not exactly a measure of correlation).

As stated before, engage of simple linear regression model respect to pavement management can be reached depends on data requirement. As a dependent variable, condition indices during the period of pavement life-cycle, otherwise elapsed time from last rehabilitation or construction, or interval time between two inspections will be an explanatory variable.

2.3.2 The Multiple Regression Model

As described in section 2.3.1, simple linear regression is configuring the relationship between an explained variable *y* and an explanatory variable *x*. In order to match the needs of research fields those require not only one explanatory variable, using multiple regression should be considered. The estimation of multiple regression has a similar way to that for simple linear regression. The most important difference that the multiple regression can surmount more than one explanatory variable. This model is often done to ascertain admit of additional explanatory variables impress to increased prediction of dependent variable. In pavement case, it is possible that too many explanatory variables affect to pavement deterioration process. Employ the multiple regression for pavement deterioration will more effective when understanding of effect of variables and their level contribution to deterioration rate due to that deterioration could be different in each section (in small scale) or among countries (in large scale).

The general form of the multiple regression equation with *n* variables, that is:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2, \ldots, \beta_n X_n + \varepsilon_i \tag{2.13}$$

In the similar way of simple linear model, the β_0 is the intercept of regression line in y-axis when the values of explanatory variables *x* are all zero. The $\beta_1, \ldots, \beta_n$ is partial regression line gradient to measure changing of estimate value per unit changing of each *x* variables $X_1, \ldots, X_n$. The rest, ε_i is a residual or errors due to measurement errors in *Y* and errors in the specification of the relationship between *Y* and the *X* variables.

Equation (2.13) can be written in vector form by:

$$Y_i = X_i \beta_i + \varepsilon_i \tag{2.14}$$

where:

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & X_{21} & X_{31} & \ldots & X_{n1} \\ 1 & X_{22} & X_{32} & \ldots & X_{n2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_{2n} & X_{3n} & \ldots & X_{nn} \end{pmatrix} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}$$

In other way, equation (2.14) also can be written as:

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} \beta_1 & \beta_2 X_{21} + & \beta_3 X_{31} + \cdots + & \beta_n X_{n1} & \varepsilon_1 \\ \beta_2 & \beta_2 X_{22} + & \beta_3 X_{32} + \cdots + & \beta_n X_{n2} & \varepsilon_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta_1 & \beta_2 X_{2n} + & \beta_3 X_{3n} + \cdots + & \beta_n X_{\mathrm{nn}} & \varepsilon_n \end{pmatrix} \tag{2.15}$$

The least square methods states that normal equation is needed to simplify the estimators "β"s.

$$\text{SSE} = e'e = (Y - X\beta)'(Y - X\beta) \tag{2.16}$$

The normal equation can be written in matrix form, that is:

$$(X'X)\beta = X'Y \tag{2.17}$$

To found the solution of estimators "β"s, multiply each side by the inverse of $(X'X)$.

$$(X'X)^{-1}(X'X)\beta = (X'X)^{-1}X'Y \tag{2.18}$$

Regarding the inverses properties, we get:

$$(X'X)^{-1}(X'X) = I \tag{2.19a}$$

$$I\beta = (X'X)^{-1}X'Y \tag{2.19b}$$

$$\beta = (X'X)^{-1}X'Y \tag{2.19c}$$

As same concepts refer to equation (2.9) and (2.10), the coefficient of determination can be estimated. Notice the SSE in equation (2.16), the R^2 can be written as:

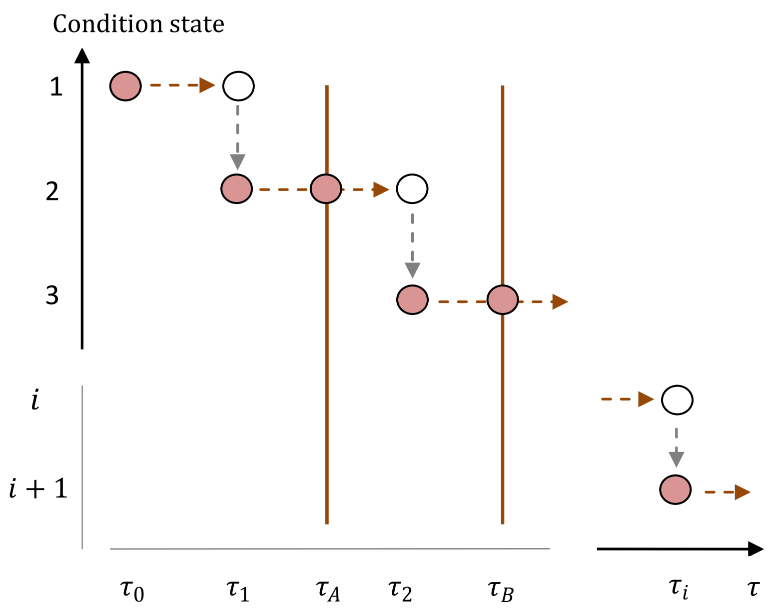
$$R^2 = \frac{\text{SSR}}{\text{SST}} = 1 - \frac{\text{SSE}^{\,2}}{\text{SST}} = 1 - \frac{(Y-\hat{Y})'(Y-\hat{Y})}{(Y-\bar{Y})'(Y-\bar{Y})} \tag{2.20}$$

The addition of variables always increases R^2. This does not mean that the regression equation is improving. The appropriate thing to look at is the estimate of the error variance. An equivalent measure is $\bar{R}^2$, the value of R^2 adjusted for the loss in degree of freedom due to addition of more explanatory variables. A procedure usually followed is to keep on adding variables until $\bar{R}^2$ stop increasing. The $\bar{R}^2$ might increase by addition (or deletion) of two or more variables even though it might not if one variable is added (or dropped) at a time (Maddala, 2008).

2.4 Stochastic Deterioration Hazard Model

2.4.1 Condition State and Periodical Inspection Scheme

In regard to deterioration prediction model using stochastic method, it is necessary to accumulate time series data on the condition states of the components. In reality, deterioration progress of pavement components has a serious problem of uncertainty. Furthermore, the condition state at each point in the time-axis carried out by visual inspection encounters a limitary of time. The concept of deterioration process of pavement component by periodical inspection scheme is presented in Figure 2.3.

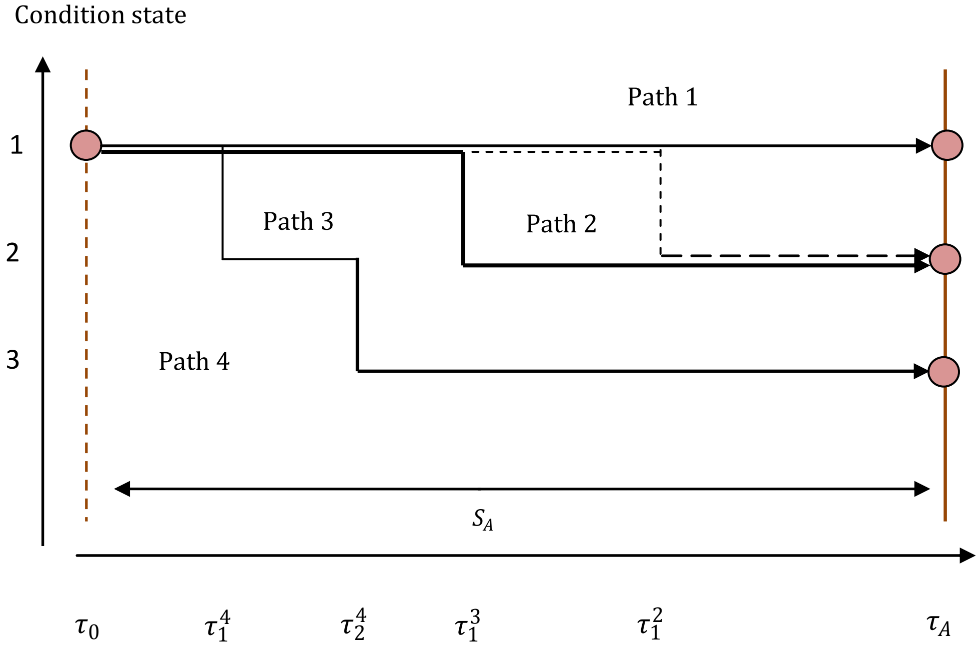


Note) In this example, the deterioration process of a pavement section if expressed in terms of calendar time $\tau_1, \tau_2, \ldots, \tau_i$, and condition state of the section is increased in unitary units.

Figure 2.3 Timely Transition of Condition States

In Figure 2.3, τ represents real calendar time (hereinafter will be used only by "time" expression). The deterioration of the pavement begins immediately after it is opened to the public at time τ_0. The condition state of a component is expressed by a rank J representing a state variable $(i = i, \ldots, J-1)$. For a component in the good or new situation, its condition state is given as $i = 1$, and increasing of condition state i expresses progressing deterioration. A value of $i = J$ indicates that a component has reached its service limit. In this figure, for each discrete time τ_i $(i = i, \ldots, J-1)$ on the time-axis, the corresponding condition state has increased from i to $i+1$. Hereinafter τ_i is referred to the time a transition from a condition state i to $i+1$ occur.

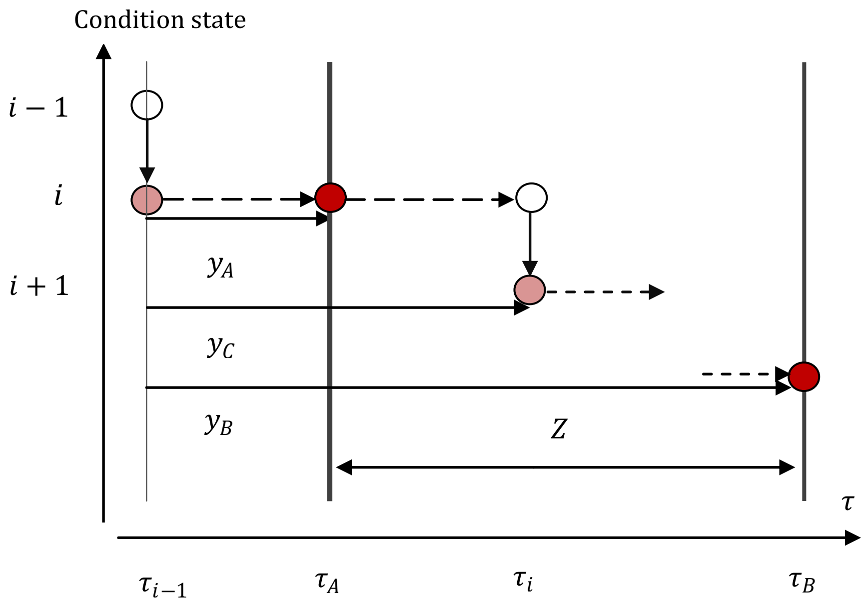
Information relating to the deterioration process of pavement can be obtained through periodical visual inspections. Nevertheless, information on the condition state based on continuous visual inspection is difficult to found. In this case, the initial inspections are carried out at times τ_{A} on the time-axis. It is supposed that at time τ_{A} the condition state observed by inspection is $(i = i, \ldots, J-1)$. The deterioration progress in future times is uncertain. Among the infinite set of possible scenarios describing the deterioration process only one path is finally realized.



Note) In this example, the deterioration process of pavement section is explained in terms of four different sample paths. In paths 2 and 3 the condition state has advanced to one upper state condition at the calendar times τ_1^2 and τ_1^3 respectively. In path 4, the condition state has increased one state at each time τ_1^4 and τ_2^4. Nevertheless, in the case of a periodical inspection carried out at times τ_A the condition state at any point in time between inspections cannot be observed.

Figure 2.4 Periodical Inspection Schemes of Condition States

Figure 2.4 displays four possible sample paths. Path 1 displays no transition in the condition state i during a periodical visual inspection interval. In paths 2 and 3, condition state has advanced to one upper state condition at the calendar times τ_i^2 and τ_i^3 respectively. The condition state of these two paths observed at time τ_B become $i+1$ are not determined. Moreover, path 4 displays transitions in the condition state at times τ_i^4 and τ_{i+1}^4 during the inspection interval. The condition state observed at time τ_B becomes $i+2$. That is, despite the transitions in the condition state are observable at the time of periodical inspection, it is not possible to gain information about the times in which those transitions occur.



Note)In the case the condition state changes from $i-1$ to i at the calendar time τ_{i-1} the inspections carried out at times τ_A and τ_B will also correspond to the points in time y_A and y_B when using τ_{i-1} as the time origin. The figure displays a sample deterioration path in which the condition state has advanced in one unit to y_C in the interval time $\tau_{i-1} - y_C$. Nevertheless, observations at time τ_{i-1} are not possible in a periodical inspection scheme, so there is no way to obtain observation at y_A ,y_B and y_C. Nevertheless, it is possible to use the information contained in $z = y_C - y_A \in [0, Z]$.

Figure 2.5 Model of Deterioration Process

2.4.2 Markov Transition Probability

The transition process of the condition states of pavement component is uncertain. Consequently, deterministic methods cannot be employed to predict future condition states. To address this situation, Markov transition probability is utilized to represent the uncertain transition pattern of the condition states of pavement section during two time points. Markov transition probabilities can be defined for arbitrary time intervals.

To simplify, Markov transition probabilities can be defined and utilized to predict the deterioration of pavement component in relating with the information from periodical inspection scheme shown in figure 2.4. The observed condition state of the component at time τ_{A} is expressed by using the state variable $h(\tau_{\mathrm{A}})$. If the condition state observed at time τ_{A} is i, then the state variable $h(\tau_{\mathrm{A}}) = i$. A Markov transition probability, given a condition state $h(\tau_{\mathrm{A}}) = i$ observed at time τ_{A}, defines the probability that the condition state at a future time (τ_B for example) will change to $h(\tau_B) = j$. That is:

$$\mathrm{Prob}[h(\tau_B) = j | h(\tau_A) = i] = \pi_{ij} \tag{2.21}$$

The Markov transition probability matrix can be defined by using the transition probabilities between each pair of condition states (i, j) as

$$\Pi = \begin{pmatrix} \pi_{11} & \cdots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{pmatrix} \tag{2.22}$$

The Markov transition probability (2.21) indicates the transition probability between the condition states at two given times τ_{A} and τ_B, accordingly, it is straightforward that the values of a transition probability will differ for different time intervals. Since deterioration continues as long as no repair is carried out $\pi_{ij} = 0 \ (i > j)$. From the definition of transition probability, $\sum_{j=1}^{J} \pi_{ij} = 1$. Afterwards, Markov transition probability must be satisfied succeeding conditions:

$$\left.\begin{array}{l} \pi_{ij} \geq 0 \\ \pi_{ij} = 0 \ (\text{when } i > j) \\ \sum_{j=1}^{J} \pi_{ij} = 1 \end{array}\right\} \tag{2.23}$$

The highest level of deterioration is expressed by the condition state J, which remains as an absorbing state in the Markov chain as long as no repair is carried out. In this case $\pi_{JJ} = 1$.

Markov transition probabilities are appointed independently from deterioration history. As shown in figure 2.5, the condition state at the inspection time τ_{A} is i, however, the time in which, condition state changed from $i - 1$ to i is unobservable. In a Markov chain model, it is assumed that the transition probability between the inspection times τ_{A} and τ_B is only dependent on the condition state at time τ_{A}.

The Markov chain model is largely implemented in infrastructure asset management strategies. In specific, in management of pavement macro level or network level, The Markov chain model is utilized in determining the average transition probability of the entire system, or a group of pavement sections which has two periodical inspection data.

2.4.3 Disaggregation of Markov Transition Probability

The Markov transition probability can be define by using hazard model in clarifying the deterioration process of an individual pavement component. In order to estimate Markov transition probabilities based on a variety of explanatory variables, it is desirable to develop an estimation methodology that considers specific characteristics of each pavement section. The purpose of hazard model is to determine the transition probabilities that characterize the deterioration process of each pavement section. Thus, Markov transition probabilities imposed by means of hazard model are referred as disaggregate Markov transition probabilities.

Figure 2.5 illustrates the deterioration process of a road pavement section. In this figure, it is assumed that the condition state at the calendar time τ_{i-1} has changed from $i - 1$ to i. The calendar time τ_{i-1} is assumed to be equal to $y_i = 0$, and known as the sample time-axis. The time represented by the sample time-axis is referred from now on as a "time point", and differs from "time" on the calendar time-axis. The times τ_{A} and τ_B correspond to the time points y_A and y_B on the sample axis. With these conditions, it can be seen that $y_A = \tau_A - \tau_{i-1}$, $y_B = \tau_B - \tau_{i-1}$.

Information on the condition state i at the beginning of the calendar time τ_{i-1} cannot be obtained in a periodical inspection scheme. Therefore, time points y_A and y_B on the sample time-axis cannot be obtained in a periodical inspection scheme. For clarity in description, it is assumed that the information at the time a point is known in order to develop the model, in spite of this assumption is not necessarily essential. The following paragraph discusses that even without information at time points y_A and y_B an exponential hazard model can be estimated.

In the case the condition state of a pavement sections at time τ_i (time point y_C) is assumed to change from i to $i+1$, the period length in which the condition state has remained at i (referred as the life expectancy of a condition state i) is represented by $\zeta_i = \tau_i - \tau_{i-1} = y_C$. The life expectancy of a condition state i is assumed to be a stochastic variable ζ_i with probability density function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$. Random variable ζ_i is defined in the domain $[0, \infty]$. The distribution function is defined as

$$F_i(y_i) = \int_0^{y_i} f_i(\zeta_i) d\zeta_i \qquad (2.24)$$

The distribution function $F_i(y_i)$ represents the cumulative probability of the transition in the condition state from i to $i+1$. Condition state i is arranged at initial time $y_i = 0$ (time τ_{A}). The time interval measured along the sample time-axis until the time point y_i is $\tau_{i-1} + y_i$. In consequence, using the cumulative probability $F_i(y_i)$, the probability $\tilde{F}_i(y_i)$ of a transition in the condition state i during the time points interval $y_i = 0$ to $\mathrm{y}_i \in [0, \infty]$ is defined by $\tilde{F}_i(y_i)$:

$$\mathrm{Prob}\{\zeta_i \geq y_i\} = \tilde{F}_i(y_i) = 1 - F_i(y_i) \qquad (2.25)$$

The conditional probability that the condition state of sections at time y_i leads from i to $i + 1$ during the time interval $[y_i, y_i + \Delta y_i]$ is defined as

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)\Delta y_i}{\tilde{F}_i(y_i)} \tag{2.26}$$

where the probability density $\lambda_i(y_i)$ is referred as the hazard function.

2.4.4 Exponential Hazard Model

In this section, it is assumed that the deterioration of a pavement section satisfies Markov property, and the hazard function is independent of the time y_i on the time-axis. That is, for a fixed value of $\theta_i > 0$,

$$\lambda_i(y_i) = \theta_i \tag{2.27}$$

By using the exponential hazard function (2.27), it is possible to represent a deterioration process of a pavement section that satisfies the Markov property (independence from the past history). In addition, it is assumed that $\theta_i \neq \theta_j \, (i \neq j)$. By differentiating both sides of equation (2.25) with respect to y_i,

$$\frac{d\tilde{F}_i(y_i)}{dy_i} = -f_i(y_i) \tag{2.28}$$

Equation (2.26) then becomes

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)}{\tilde{F}_i(y_i)} = -\frac{\frac{d\tilde{F}_i(y_i)}{dy_i}}{\tilde{F}_i(y_i)} = \frac{d}{dy_i}\left(-\log \tilde{F}_i(y_i)\right) \tag{2.29}$$

Take into consideration that $\tilde{F}_i(0) = 1 - F_i(0) = 1$ and by integrating equation (2.29):

$$\int_0^{y_i} \lambda_i(u)du = [-\log \tilde{F}_i(u)]_0^{y_i} = -\log \tilde{F}_i(y_i) \tag{2.30}$$

Utilizing the hazard function $\lambda_i(y_i) = \theta_i$, the probability $\tilde{F}_i(y_i)$ that the life expectancy of the condition state i becomes longer than y_i is expressed by

$$\tilde{F}_i(y_i) = \exp\left[-\int_0^{y_i} \lambda_i\,(u)du\right] = \exp(-\theta_i y_i) \tag{2.31}$$

Equation (2.31) is an exponential hazard model. Pursuant to equation (2.28), the probability density function $f_i(\zeta_i)$ of the life expectancy of the condition state i is

$$f_i(\zeta_i) = \theta_i \exp(-\theta_i \zeta_i) \tag{2.32}$$

Forth, considering that the condition state has changed to i at the time τ_{i-1}, and remains constant until the inspection time τ_A. Clearly to express, the condition state observed at inspection time τ_A is i. In term of duration, condition state i has actually stayed in the period y_A. The probability, to which the condition state i remains constant in a subsequent time $z_i(\geq 0)$ measured after the duration y_A, is then defined:

$$\tilde{F}_i(y_A + z_i|\zeta_i \geq y_A) = \mathrm{Prob}\{\zeta_i \geq y_A + z_i|\zeta_i \geq y_A\} \tag{2.33}$$

Dividing both sides of equation (2.33) by the probability $\tilde{F}_i(y_i)$ declared in equation (2.25) generates

$$\frac{\mathrm{Prob}\,\{\zeta_i \geq y_A + z_i\}}{\mathrm{Prob}\,\{\zeta_i \geq y_A\}} = \frac{\tilde{F}_i(y_A + z_i)}{\tilde{F}_i(y_A)} \tag{2.34}$$

By exercising to equation (2.31), the right side of equation (2.34) becomes:

$$\frac{\tilde{F}_i(y_A + z_i)}{\tilde{F}_i(y_A)} = \frac{\exp\,\{-\theta_i(y_A + z_i)\}}{\exp\,\{-\theta_i y_A\}} = \exp(-\theta_i z_i) \tag{2.35}$$

In regard to the same condition state, the probability, to which, the condition state i obtained at time τ_A keeps on to be observed at subsequent inspection time $y_B = y_A + Z$ is:

$$\mathrm{Prob}[h(y_B) = i|h(y_A) = i] = \exp(-\theta_i Z) \tag{2.36}$$

where Z denotes as the interval between two inspection times. The probability $\mathrm{Prob}[h(y_B) = i|h(y_A) = i]$ is nothing but the Markov transition probability π_{ii}.

Obviously, if the exponential hazard function is employed, the transition probability π_{ii} is dependent only on the hazard rate θ_{ii} and the inspection interval Z.

2.5 Multi-stage Markov Exponential Hazard Model

2.5.1 Determination of Markov Transition Probabilities

This section continues the formulation of hazard model with Markov transition probability as prior delivered in section (2.4.2 - 2.4.4) as for general case.

Engage with an exponential hazard function, the transition probability of the condition state at the inspection time points y_A and y_B form i to $i+1$ can be acquired. Firstly, with assumption that the condition state i remains during duration y_A and in subsequent increment of time $s_i = \mathrm{y_A} + z_i, (z_i \in [0, Z])$. Secondly, the condition state i changes into $i+1$ at $\mathrm{y_A} + z_i,$. Lastly, the condition state $i+1$ keeps constant during the interval $\mathrm{y_A} + z_i, y_B$.

Even though the exact time, at which the condition state transits from i to $i+1$ cannot be traced by periodical inspection, it can be temporarily assumed that the transition occurs at the time point $(\mathrm{y_A} + \bar{z}_i) \in [y_A, y_B]$. Given the condition state i immutable during y_A and until the time $y_A + \bar{z}_i$, the conditional probability density that at this time point the condition state changes to $i+1$ is

$$g_i(\bar{z}_i|\zeta_i \geq y_A) = \frac{f_i(\bar{z}_i + y_A)}{\tilde{F}_i(y_A)} = \frac{\theta_i \exp\{-\theta_i(\bar{z}_i + y_A)\}}{\exp\{-\theta_i y_A\}} = \theta_i \exp(-\theta_i \bar{z}_i) \tag{2.37}$$

In relating to satisfy the above condition, the conditional probability density that the condition state observed at the inspection time point y_B is $i+1$ becomes:

$$\begin{aligned} q_{i+1}(\bar{z}_i|\zeta_i \geq y_A) &= g_i(\bar{z}_i|\zeta_i \geq y_A).\tilde{F}_{i+1}(y_B - \bar{z}_i - y_A) \\ &= \theta_i \exp(-\theta_i \bar{z}_i)\exp\{-\theta_{i+1}(Z - z_i)\} \\ &= \theta_i \exp(-\theta_{i+1} Z)\exp\{-(\theta_i - \theta_{i+1})\bar{z}_i\} \end{aligned} \tag{2.38}$$

Regarding above explanation, then $\bar{s}_i = y_A + \bar{z}_i$ is assumed as fixed value. The elapsed time ζ_i of a condition state i is exactly a stochastic variable, thus, $\bar{z}_i$ may change in range $[0, Z]$. The Markov transition probability that the condition state change from i to $i+1$ during the time points y_A and y_B is accomplished by the law of integration:

$$\begin{aligned}\pi_{ii} &= \text{Prob}[h(y_B) = i+1 | h(y_A) = i] = \int_0^Z q_{i+1}\,(z_i | \zeta_i \geq y_A) dz_i \\ &= \int_0^Z \theta_i \exp\,(-\theta_{i+1} Z) \exp\{-(\theta_i - \theta_{i+1}) z_i\} dz_i \\ &= \frac{\theta_i}{\theta_i - \theta_{i+1}}\,\{-\exp\,(-\theta_i Z) + \exp(-\theta_{i+1} Z)\}\end{aligned} \tag{2.39}$$

where $\pi_{ii+1} > 0$ is indifferent to the relative size between θ_i and θ_j . The assumption $\theta_i \neq \theta_{i+1}$ implies 1 > $1 > \pi_{ii+1}$. As these characteristics are trivial in the derivation process of equation (2.39), the verification is omitted.

Moving to general case, when in a case of a condition state between two inspection time changes from i to two or more condition states $j (j \geq i+2)$. The distribution function and the probability density function of the duration condition state j immutable is denoted as $F_i(y_j)$ and $f_i(y_j)$. The hazard function linked to the condition state j is identified by $\lambda_j(y_j) = \theta_j$.

The process of transition at condition state from i to $i+1$ during interval $[y_A, y_B]$ takes a place if conform to following conditions. Firstly, the condition state i remains during the elapsed time y_A and in a subsequent time $\bar{s}_i = y_A + \bar{z}_i \in [y_A, y_B]$. Secondly, precisely at time $\bar{s}_i = y_A + \bar{z}_i$, condition state i changes into $i+1$. Thirdly, condition state $i+1$ remains in the duration $[\bar{s}_i = y_A + \bar{z}_i, \bar{s}_{i+1} = \bar{s}_i + \bar{z}_{i+1} (\leq y_B)]$ before changing to condition state $i+2$ at $\bar{s}_{i+1} = \bar{s}_i + \bar{z}_{i+1}$. Fourthly, after repeating the same transition process, condition state changes into j at time $\bar{s}_{j-1} (\leq y_B)$, and keep constantly until inspection time y_B. If the entire process of transition is examined, a conditional probability density function simultaneously is denoted by:

$$
\begin{aligned}
&q_j\left(\bar{z}_i, \bar{z}_{i+1}, \ldots, \bar{z}_{j-1} \middle| \zeta_i \geq y_A\right) \\
&\quad = g_i(\bar{z}_i|\zeta_i \geq y_A) \prod_{m=i+1}^{j-1} f_m(\bar{z}_m) \tilde{F}_j\left(Z - \sum_{m=i}^{j-1} \bar{z}_m\right) \\
&\quad = \prod_{m=i}^{j-1} \theta_m . \exp\left\{-\sum_{m=i}^{j-1} \theta_m \bar{z}_m - \theta_j\left(Z - \sum_{m=i}^{j-1} \bar{z}_m\right)\right\} \\
&\quad = \prod_{m=i}^{j-1} \theta_m . \exp\left\{-\theta_j Z - \sum_{m=i}^{j-1} (\theta_m - \theta_j) \bar{z}_m\right\},
\end{aligned} \tag{2.40}
$$

where $\bar{z}_i, \ldots, \bar{z}_{j-1}$ are called as fixed values. Since the elapsed time ζ_i of condition states $i (i = 1, \ldots, J-1)$ is a stochastic variable, the values of $z_i \geq 0, \ldots, z_{j-1} \geq 0$ are variable to satisfy the following condition:

$$
0 \leq z_i + z_{i+1} + \cdots + z_{j-1} \leq Z. \tag{2.41}
$$

Therefore, the Markov transition probabilities π_{ij} that a transition in the condition state from i to $j (j \geq i+2)$ occur between the inspections time y_A and y_B is expressed in equation 2.42, that is:

$$
\begin{aligned}
\pi_{ij} &= \mathrm{Prob}[h(y_A) = j | h(y_B) = i] \\
&= \int_0^Z \int_0^{Z - z_i} \ldots \int_0^{Z - \sum_0^{j-2} z_m} q_j\left(z_i, \ldots, z_{j-1} \middle| \zeta_i \geq y_A\right) dz_i \ldots dz_j \\
&= \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z)
\end{aligned} \tag{2.42}
$$

A detail of explanation for getting into equation (2.42) is given in the paper of Tsuda et al (2006). As a summary, general forms of Markov transition probabilities based on exponential hazard model are given as:

$$
\pi_{ii} = \exp(-\theta_i Z), \tag{2.43a}
$$

$$
\pi_{ii+1} = \frac{\theta_i}{\theta_i - \theta_{i+1}} \{-\exp(-\theta_i Z) + \exp(-\theta_{i+1} Z)\}, \tag{2.43b}
$$

$$
\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z), \tag{2.43c}
$$

$$
\pi_{iJ} = 1 - \sum_{j=i}^{J-1} \pi_{ij}, \tag{2.43d}
$$

$$
(i = 1, \ldots, J-1)\ (j = i, \ldots, J).
$$

2.5.2 Time Adjustment of Markov Transition Probability

As conceived in equations (2.43a - 2.43d), the Markov transition probabilities rely on the inspection interval Z. For convenience in understanding, the Markov transition probability is denoted as $\pi_{ij}(Z)$, then the Markov transition probabilities matrix respect to the inspection time interval Z becomes:

$$\Pi(Z) = \begin{pmatrix} \pi_{11}(Z) & \cdots & \pi_{1J}(Z) \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ}(Z) \end{pmatrix} \tag{2.44}$$

An integer number n of inspection is formed in a regular based time. If two inspection interval Z and nZ are considered, the Markov transition probability matrices $\Pi(Z)$ and $\Pi(nZ)$ also can be utilized expressing the dependency on inspection interval. Based on the law of matrix multiplication, the relation between $\Pi(Z)$ and $\Pi(nZ)$ is clearly defined:

$$\Pi(nZ) = \{\Pi(Z)\}^n \tag{2.45}$$

Equation (2.45) is called as the time adjustment condition of the Markov transition probability matrix. In order to satisfy above conditions, a fixed mathematical structure between the Markov transitions probabilities π_{ij} must be held. A brief summary here that in respect to different time interval Z, adjusted the properties of Markov transition probability can be reflected the actual inspection schedule in pavement section practices.

2.5.3 Estimation of Markov Transition Probability

2.5.3.1 Contents of Periodical Inspection Data

Suppose periodical inspection data on the same kind of K road pavement sections is available. An inspection sample $k(k = 1, \ldots, K)$ describes two continuous periodical inspections carried out at times τ_A^k and τ_B^k and the respective condition states ratings

$h(\tau_A^k)$ and $h(\tau_B^k)$ measured at those times. Differences in the inspection intervals of the samples are inconvenient. In regard to the above inspection data, the inspection interval of a sample k is defined as $Z^k = \tau_A^k - \tau_B^k$. In addition, a dummy variable $\delta_{ij}^k\,(i,j = 1, \dots, J; k = 1, \dots, K)$ respect to the deterioration progress patterns between two inspections times is defined as

$$\delta_{ij}^k = \begin{cases} 1 & \text{when } h(\tau_A^k) = i \text{ and } h(\tau_B^k) = j \\ 0 & \text{otherwise} \end{cases} \tag{2.46}$$

Furthermore, the structural characteristics and usage conditions that affect the deterioration of road pavement sections are represented by the vector $\boldsymbol{x}^k = x_1^k, \dots, x_M^k$. The $x_m^k\,(m = 1, \dots, M)$ expresses the value of a characteristic variable m observed in the sample data k. The information contained in the inspection sample data k can be rearranged as $\Xi^k = (\delta_{ij}^k, Z^k, \boldsymbol{x}^k)$. On the other hand, the exponential hazard function of the deterioration process for a sample data $k(k = 1, \dots, K)$ is

$$\lambda_i^k(y_i^k) = \theta_i^k\,(i = 1, \dots, J - 1) \tag{2.47}$$

The hazard rate for condition state J is not defined due to the condition state J is absorption state of Markov chain and $\pi_{JJ} = 1$. The hazard rate $\theta_i^k\,(i = 1, \dots, J; k = 1, \dots, K)$ characterizing the deterioration process of road section is advised to change in relation to the vector $\boldsymbol{x}^k$ as follow:

$$\theta_i^k = \boldsymbol{x}^k \boldsymbol{\beta}_i' \tag{2.48}$$

where $\boldsymbol{\beta}_i = (\boldsymbol{\beta}_{i,1}, \dots, \boldsymbol{\beta}_{i,M})$ is a row vector of unknown parameters $\boldsymbol{\beta}_{im}\,(m = 1, \dots, M)$ and the symbol $[']$ indicates the vector is transposed. In order to acquire Markov transition probabilities, firstly, the exponential hazard function $\lambda_i^k(y_i^k) = \theta_i^k$ is estimated subject to the observed sampling information $\Xi^k\,(k = 1, \dots, K)$. Secondly, Markov transition probabilities can be estimated by employing exponential hazard function as a result of previous one. This methodology permits estimating of Markov transition probabilities in every individual section.

Nevertheless, it is beneficially estimating of the average transition probability for the entire group of road pavement instead of estimating for individual section.

2.5.3.2 Risk Management Indicators

By applying exponential hazard model, a risk management indicator of pavement management can also be enlisted. The indicator is the remaining duration RMD_i of condition state i. This indicator reflects the expected elapsed time of condition state i can be reached until the following inspection as a result of deterioration progress. RMD_i is actually analogous to survival function $\tilde{F}_i(y_i^k)$ in infinite domain (Lancaster, 1990):

$$RMD_i^k = \int_0^\infty \tilde{F}_i\left(y_i^k\right) dy_i^k \tag{2.49}$$

With employing the survival function as in equation (2.49), the remaining duration RMD_i^k of section k in exponential form becomes:

$$RMD_i^k = \int_0^\infty \exp\left(-\theta_i^k y_i^k\right) dy_i^k = \frac{1}{\theta_i^k} \tag{2.50}$$

By assuming the condition state after the road opened to the public is i. The expected value $ET_j\,(j = 2, \dots, J)$ called as average life expectancy of condition state j, is a summation of all transition duration from each condition state i :

$$ET_j = \sum_{i=1}^{j} \frac{1}{\lambda} \tag{2.51}$$

Rating $j(j = 1, \dots, J)$ and average relation of elapsed time $ET_j\,(\boldsymbol{x})$ are used to portray the expectation deterioration curve.

2.5.3.3 Estimation of the Hazard Model

Information $\boldsymbol{\Xi}^k = \left(\bar{\delta}_{ij}^k, \bar{Z}^k, \bar{\boldsymbol{x}}^k\right)$ can be obtained in relation to the inspection sample k, where the symbol [$\bar{}$] indicates an actual measurement. The Markov transition probabilities can be described in terms of the hazard functions as expressed in equations (2.43a - 2.43d). The relationship between hazard rate $\theta_i^k (i = 1, \dots, J-1; k = 1, \dots, K)$ that is contained in the Markov transition probabilities and the characteristic variables $\bar{\boldsymbol{x}}^k$ of pavement section is explained in equation (2.48). In addition, the transition probability also depends on inspection interval $\bar{Z}^k$.

In regard to clarity of explanation, the transition probability π_{ij} is expressed as a function of the measured data $(\bar{Z}^k, \bar{\boldsymbol{x}}^k)$ obtained from visual inspection and the unknown parameters $\boldsymbol{\beta}_i$ as $\pi_{ij} = (\bar{Z}^k, \bar{\boldsymbol{x}}^k : \boldsymbol{\beta}_i)$. If the deterioration progress of the pavement section in a sample K are assumed to be mutually independent, the log-likelihood function expressing the simultaneous probability density of the deterioration transition pattern for all inspection samples is (Tobin, 1958; Amemiya and Boskin, 1974)

$$\begin{aligned} \ln[\boldsymbol{\mathcal{L}}(\boldsymbol{\beta})] &= \ln\left[\prod_{i=1}^{J-1} \prod_{j=i}^{J} \prod_{k=1}^{K} \left\{\pi_{ij}\left(\bar{Z}^k, \bar{\boldsymbol{x}}^k : \boldsymbol{\beta}\right)\right\}^{\bar{\delta}_{ij}^k}\right] \\ &= \sum_{i=1}^{J-1} \sum_{j=i}^{J} \sum_{k=1}^{K} \bar{\delta}_{ij}^k \ln\left[\pi_{ij}\left(\bar{Z}^k, \bar{\boldsymbol{x}}^k : \boldsymbol{\beta}\right)\right] \end{aligned} \tag{2.52}$$

where $\bar{\delta}_{ij}^k, \bar{Z}^k$ and $\bar{\boldsymbol{x}}^k$ are all determined through inspections, and $\boldsymbol{\beta}_i (i = 1, \dots, J-1)$ are parameters to be estimated. Estimations of the parameters $\boldsymbol{\beta}$ can be obtained by solving the optimality condition:

$$\frac{\partial \ln[\boldsymbol{\mathcal{L}}(\widehat{\boldsymbol{\beta}})]}{\partial \boldsymbol{\beta}_{i,m}} = 0 \qquad (i = 1, \dots, J-1; m = 1, \dots, M) \tag{2.53}$$

that result from maximizing the log-likelihood function (2.52). The optimal values $\widehat{\boldsymbol{\beta}} = (\boldsymbol{\beta}_{1,1}, \dots, \boldsymbol{\beta}_{J,M})$ are then estimated by applying a numerical iterative procedure such as the Newton Method for the $(J-1)M$ order nonlinear simultaneous equations (Isoda and Ohno, 1990). Furthermore, estimator for the asymptotic covariance matrix of the parameters is given by

$$\widehat{\boldsymbol{\Sigma}}(\widehat{\boldsymbol{\beta}}) = \left[\frac{\partial^2 \ln\{\boldsymbol{\mathcal{L}}(\widehat{\boldsymbol{\beta}})\}}{\partial \boldsymbol{\beta} \partial \boldsymbol{\beta}'}\right]^{-1} \tag{2.54}$$

The $(J-1)M \times (J-1)M$ order inverse matrix of the right-hand side of the above formula, composed by the elements $\partial^2 \ln\{\boldsymbol{\mathcal{L}}(\widehat{\boldsymbol{\beta}})\}/\partial\boldsymbol{\beta}_{i,m}\partial\boldsymbol{\beta}_{i',m'}$ results to be the inverse matrix of the Fisher information matrix.

2.5.3.4 Average Markov Transition Probability

Given the vector $\boldsymbol{x}^k$ and the inspection interval Z^k, the Markov transition probabilities of a pavement section can be estimated by using equations (2.43a - 2.43d). Markov transition probabilities to satisfy time adjustment conditions can be estimated for arbitrary inspection intervals by changing the value Z^k.

Depart from the experiences, and due to there is a necessary of consuming time and resources, if predicting the deterioration pattern of road pavement as a whole, it would be better to determine the average transition probability rather than a transition probability for each section.

In referring to above conditions, developing a method to estimate the average transition probability, which also satisfies the time adjustment condition is considered. The hazard rate $\theta_i^k (k = 1, \dots, K)$ is utilized and related to the distribution of characteristic variable $\boldsymbol{x}$. The distribution function for the population sample of pavement sections is denoted as $\Gamma(\boldsymbol{x})$.

Then, the expected value of hazard rate $E[\theta_i]$ subject to the entire population sample can be defined as:

$$E[\theta_i] = \int_{\Theta} \boldsymbol{x}\boldsymbol{\beta}_i' d\,\Gamma(\boldsymbol{x}) \quad (2.55)$$

where Θ subjects to the entire population sample. The Markov transition probability matrix is realized to satisfy the time adjustment conditions if it ties up in two conditions. First condition is employing exponential hazard equations (2.43a - 2.43d) to estimate it. Second condition obligates the matrix properties for each sample k to be defined based on individual hazard rate $\theta_i^k (i = 1, \ldots, J-1; k = 1, \ldots, K)$. Accordingly, the Markov transition probability matrix estimated by using equation (2.55) is also satisfying the time adjustment condition.

2.6 Mixture Markov Deterioration Hazard Model

2.6.1 Deterioration Process Heterogeneity

In previous section (2.4 - 2.5), a comprehensive explanation of the Markov deterioration hazard model as a stochastic deterioration prediction method based on visual inspection data has been documented. Nevertheless, as indicated earlier, in regard to the incompleteness of visual inspection data and records, and also considering in more practically, the Markov deterioration hazard model should be expanded.

As a fact, the Markov deterioration hazard model can predict deterioration for individual section under the same characteristic and environmental conditions as a characteristic variables (or explanatory variables). Even though, the deterioration process of pavement section employed same methods and materials, and also under the same conditions, the result will differ depend on the environmental conditions and quality of construction. Therefore, it is admitted to consider the heterogeneity of deterioration process. If considering in representing the heterogeneity of the deterioration process of pavement sections as characteristic variables, increasing the number of characteristic variables and adversely decreasing the explanatory power of individual characteristic variables are unavoidable in occur. Further, there are some factors cannot be estimated within the heterogeneity of deterioration processes. Thus, a Mixture Markov deterioration hazard model is formulated to describe the heterogeneity of hazard rates with a probabilistic distribution as an advanced Markov deterioration hazard model. In Figure 2.6, overall procedures of mixture hazard model developed by Nam (2009).

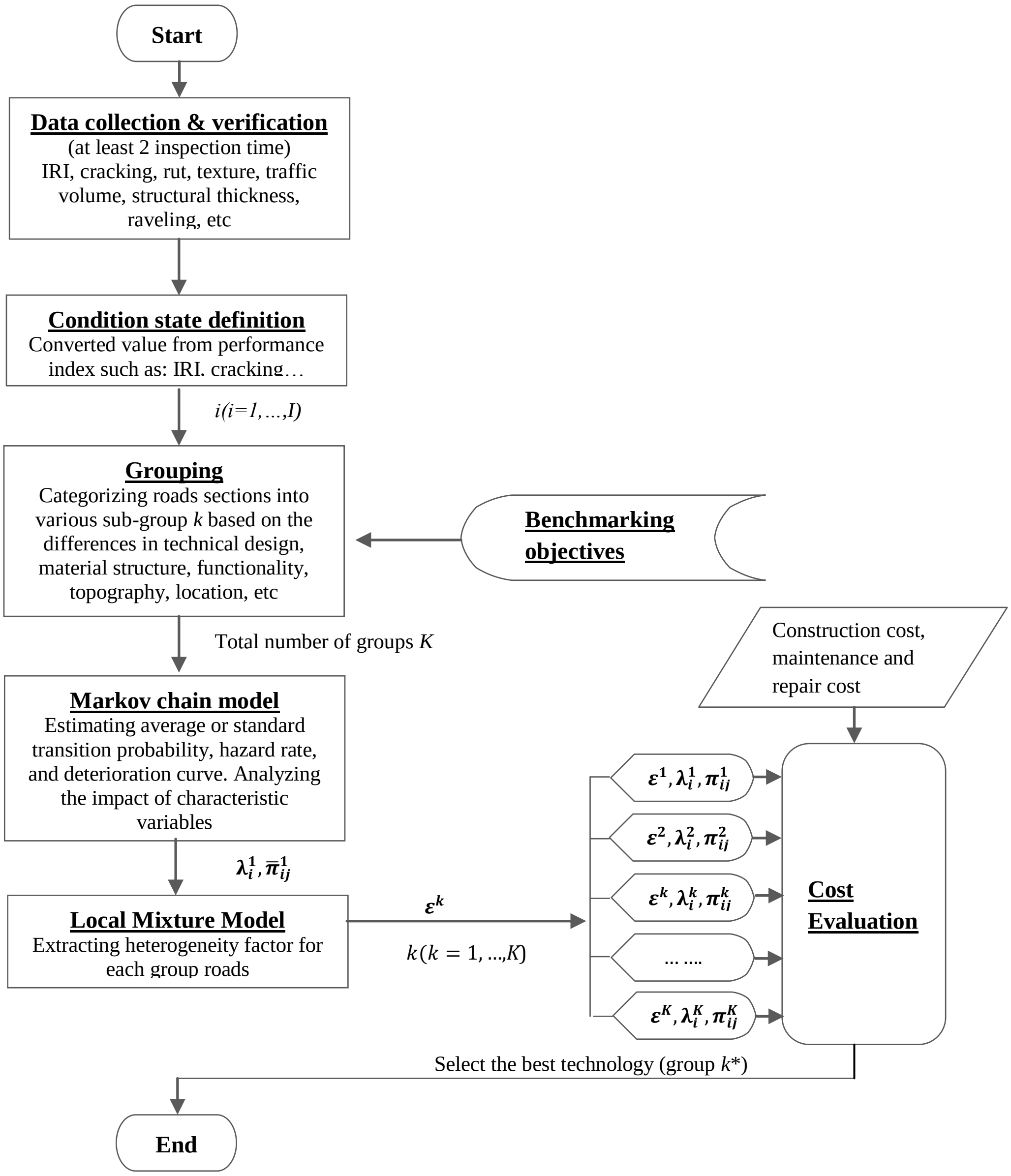


Figure 2.6 Benchmarking Flowchart by the Mixture Hazard Model

2.6.2 Markov Transition Probability and Heterogeneity Factor

As realized in term of deterioration process, similar group of individual infrastructure components can be produced a different in deterioration speed. In other way, due to dynamic factor, a different of deterioration speed among pavement sections is possibly occurred. Thus, to remark these differences, employ the term "heterogeneity factor" is truly assisting. In pavement system, the entire road system is assumed in comprising of K group of road pavement according to their technological difference. In each group $k(k = 1, \dots, K)$, total road pavement section is S_k, and ε^k is called as the heterogeneity factor, which infers the change of characteristic of a peculiar hazard rate $i(i = 1, \dots, I-1)$ to a pavement section $s_k(s_k = 1, \dots, S_k)$. Thus, the mixture index hazard function can be expressed as:

$$\lambda_i^{sk} = \tilde{\lambda}_i^{sk}\varepsilon^k \quad (i = 1, \dots, I-1; k = 1, \dots, K; s_k = 1, \dots, S_k) \tag{2.56}$$

where $\tilde{\lambda}_i^{sk}$ is average hazard rate and ε^k always non-negative. It is important here to notice, the higher value of ε^k means the faster deterioration speed of road section s^k. Within the one group of road sections (or one technology), the hazard index of all ratings holds the same value of the heterogeneity factor ε^k. Counting all the road sections as a whole, the distribution of ε^k is exactly representing the influence of individual group of road sections on the overall deterioration process. By rely on structural characteristic of each system; heterogeneity factor ε^k can be in form of a function or stochastic distribution.

For measurable representation, a set of value of $\varepsilon^k(k = 1, \dots, K)$ is denoted as a vector $\bar{\varepsilon}^k$. The bar [¯] indicates measurable value. As a result, the survival probability in equation (2.31) by means of mixed hazard rate in equation (2.56) for pavement group k can be further expressed:

$$\tilde{F}_i(y_i^k) = \exp(-\tilde{\lambda}_i\bar{\varepsilon}^k y_i^k) \tag{2.57}$$

In similar way, Markov transition probability expressed in equations (2.43a - 2.43d) are derived as follows:

$$\pi_{ii}^k(z^k : \bar{\varepsilon}^k) = \exp(-\tilde{\lambda}_i^k \bar{\varepsilon}^k z^k), \tag{2.58}$$

$$\begin{aligned} \pi_{ii}^k(z^k : \bar{\varepsilon}^k) &= \sum_{l=i}^{j} \prod_{m=i,\neq l}^{j-1} \frac{\tilde{\lambda}_m^k}{\tilde{\lambda}_m^k - \tilde{\lambda}_l^k} \exp(-\tilde{\lambda}_l^k \varepsilon^k z^k) \\ &= \sum_{l=i}^{j} \psi_{ij}^l(\tilde{\boldsymbol{\lambda}}^k) \exp(-\tilde{\lambda}_l^k \varepsilon^k z^k) \\ &(i = 1, \dots, I-1; j = i+1, \dots, I; k = 1, \dots, K), \end{aligned} \tag{2.59}$$

where

$$\psi_{ij}^{l}\left(\tilde{\boldsymbol{\lambda}}^{k}\right) = \prod_{m=i,\neq l}^{j-1} \frac{\tilde{\lambda}_{m}^{k}}{\tilde{\lambda}_{m}^{k} - \tilde{\lambda}_{l}^{k}} \ . \quad (2.60)$$

2.6.3 Local Mixing Mechanism

Regarding the difficulties in determining the heterogeneity factor ε^{k} follows in a particular function. The assumption of the heterogeneity factor to be in the form of a function or a stochastic variable crucially depends on the characteristics of the system itself and the availability of inspection data (Lancaster, 1990; Anaya-Izquierdo and Marriot, 2007). This section concerns on utilizing mixture model in the case that the value distribution of heterogeneity factor ε^{k} has a small dispersion. It is similar to say that it departures from homogeneity in a small scale. This type of mixture model is namely as the local mixture model. In exponential family form $f(x;\epsilon)$ (where x and ϵ are the variable and heterogeneity respectively), local mixing mechanism is defined via its mean parameterization δ^{k}:

$$g(x;\mu) := f(x;\epsilon) + \sum_{i=2}^{r} f^{k}(x;\epsilon), \quad (2.61)$$

where

$$f^{k}(x;\epsilon) = \frac{\delta^{k}}{\delta\epsilon^{k}} f(x;\epsilon).$$

Another class of the local mixture model that captures the behavior of scale dispersion in mixture value of $f(x;\epsilon)$ particularly if the dispersion parameter ϵ is small, is defined as the local scale mixture model, that is:

$$g(x;\epsilon) := f(x;\epsilon) + \sum_{i=2}^{r} \frac{\epsilon^{k}}{k!} f^{k}(x;\epsilon). \quad (2.62)$$

It can be noticed here that equations (2.62) and (2.63) can be expand to follow the Taylor series. Since the likelihood function of Markov transition probability in equations (2.62) and (2.63) belongs to the exponential family. It is possible to approximate the transition probability as in the form of the local mixture distribution.

$$\tilde{\pi}_{ij}(z) = \int_0^{\infty} \pi_{ij}\ (z{:}\,\varepsilon) f(\varepsilon) d\varepsilon (i = 1, \dots, I-1). \tag{2.63}$$

For comfortable of mathematical expression, the local mixture transition probability is assumed as an exponential function $f_{mix}(\epsilon, z, \lambda)$ with mix indicates the abbreviation of mixture. As in series, the mixture function $f_{mix}(\epsilon, z, \lambda)$ can be explained by means of standard function $f(\epsilon, z, \lambda)$ and distribution $H(\varepsilon)$. Equation (2.63) can be simplified as:

$$f_{mix}(\varepsilon, z, \lambda) = \int f(\varepsilon, z, \lambda)\, dH(\varepsilon), \tag{2.64}$$

where $dH(\varepsilon)$ is arbitrary distribution around the mean of 1 and $f(\varepsilon, z, \lambda) = \exp(-\varepsilon\lambda z)$. In addition, function $f(\varepsilon, z, \lambda)$ is exponential family and likely a function of ε about its mean. Without any loss of generality, and as long as the mean exist, equation (2.61) can be parsed as:

$$exp(-\varepsilon\lambda z) = e^{-\lambda z}(1 + (\epsilon - 1)(-\lambda z) + \frac{(\epsilon-1)^2}{2!}(-\lambda z)^2 + \cdots\ . \tag{2.65}$$

This is the Taylor series. And thus, the quadratic form (when r = 2) is acceptable for an accurate approximation. Thus, an explicit form of approximation can be obtained for the Markov transition probability:

$$E(e^{-\varepsilon\lambda z}) \approx e^{-\lambda z}\{1 + \frac{(\sigma\lambda z)^2}{2}\} \tag{2.66}$$

and

$$\tilde{\pi}_{ii}(z) = e^{-\tilde{\lambda}_i z}\{1 + \frac{(\sigma\tilde{\lambda}_i z)^2}{2!}\}, \tag{2.67a}$$

$$\tilde{\pi}_{ij}(z) = \sum_{l=i}^{j} \psi_{ij}^{l}\ (\tilde{\boldsymbol{\lambda}}) e^{-\tilde{\lambda}_l z}\left\{1 + \frac{(\sigma\tilde{\lambda}_l z)^2}{2!}\right\} \tag{2.67b}$$
$$(i = 1, \dots, I-1; j = i+1, \dots, I)$$

2.6.4 Likelihood Estimation Approach

2.6.4.1 Estimation Assumption

The estimation of Markov transition probability and heterogeneity factor requires at least two visual inspections data. Suppose that the periodical inspection data of S_k road sections is on hand. An inspection sample s_k (a road section) has two consecutive discrete periodical inspections at times $\bar{\tau}_A^{s_k}$ and $\bar{\tau}_B^{s_k} = \bar{\tau}_A^{s_k} + \bar{z}^{s_k}$, with its respective of condition states $h(\bar{\tau}_A^{s_k}) = i$ and $h(\bar{\tau}_B^{s_k}) = j$. By linked to inspection data of $\sum_{k=1}^{K} S_k$ samples, dummy variable $\bar{\delta}_{ij}^{s_k}(i = 1, \dots, I-1, j = i, \dots, I; s_k = 1, \dots, S_K; k = 1, \dots, K)$ is defined to satisfy the following conditions:

$$\bar{\delta}_{ij}^{s_k} = \begin{cases} 1 & h(\bar{\tau}_A^{s_k}) = i\,, h(\bar{\tau}_B^{s_k}) = j \\ 0 & \text{otherwise} \end{cases} \tag{2.68}$$

The range of dummy variable $(\bar{\delta}_{11}^{s_k}, \dots, \bar{\delta}_{I-1,I}^{s_k})$ is denoted by using the dummy variable vector $\bar{\boldsymbol{\delta}}^{s_k}$. Furthermore, structural characteristics and environment conditions of the road are presented by means of characteristic variable vector $\bar{\boldsymbol{x}}^{s_k} = (\bar{x}_1^{s_k}, \dots, \bar{x}_M^{s_k})$, with $\bar{x}_m^{s_k}(m = 1, \dots, M)$ referring the observed value of variable m for sample s_k. The first variable $x_1^{s_k} = 1$ is a constant term. Thus, the information concerning inspection data of sample m can be described as $\boldsymbol{\Xi}^{s_k} = (\bar{\boldsymbol{\delta}}^{s_k}, \bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k})$.

The hazard rate of condition state i of sample s_k can be expressed by using mixture hazard function $\lambda_i^{s_k}(y_i^{s_k}) = \tilde{\lambda}_i^{s_k} \varepsilon^k (i = 1, \dots, I-1$, with I as the absorption condition state in regard to satisfy the conditions $\pi_{II}^{s_k} = 1$ and $\tilde{\lambda}_I^{s_k} = 0$. The hazard rate $\tilde{\lambda}_i^{s_k}(i = 1, \dots, I-1; s_k = 1, \dots, L_k$) depends on the characteristic vector of pavement section, and is expressed as follows:

$$\tilde{\lambda}_i^{s_k} = \boldsymbol{x}^{s_k} \boldsymbol{\beta}_i^{'}, \tag{2.69}$$

where $\boldsymbol{\beta}_i = (\beta_{i,1}, \ldots, \beta_{i,M})$ is a row vector of unknown parameters $\beta_{i,m} = (m = 1, \ldots, M)$, and the symbol $[']$ indicates the vector is transposed. Deriving equations (2.67a) and (2.67b), the standard hazard rate of respective condition states can be expressed by means of hazard rate $\tilde{\lambda}_i^{s_k}(i = 1, \ldots, I-1; s_k = 1, \ldots, L_k$ and heterogeneity parameter ε^k. By considering characteristic variable $\bar{\boldsymbol{x}}^{s_k}$, the average Markov transition probability can be represented in equation (2.67b). Moreover, the transition probability depends on inspection interval $\bar{z}^{s_k}$.

For clearly explanation, transition probability π_{ij} can be denoted as a function of measurable monitoring data $(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k})$ and unknown parameter $\boldsymbol{\theta} = (\boldsymbol{\beta}_1, \ldots, \boldsymbol{\beta}_{I-1}\sigma)$ as $\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \boldsymbol{\theta})$. If assuming the deterioration of road sections l_k in the entire L_K samples to be mutually independent, the likelihood function expressing the simultaneous probability density of the deterioration transition pattern for all inspection samples is defined (Tobin, 1958; Amemiya and Boskin, 1974):

$$\boldsymbol{\mathcal{L}}(\boldsymbol{\theta}, \Xi) = \prod_{i=1}^{I-1} \prod_{j=i}^{I} \prod_{k=1}^{K} \prod_{s_k=1}^{S_k} \{\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \boldsymbol{\theta})\}^{\bar{\delta}_{ij}^{s_k}}. \tag{2.70}$$

By means of local mixture distribution with Taylor series, the explicit form of the Markov transition probability can be expressed as follows:

$$\tilde{\pi}_{ii}^{s_k}(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \boldsymbol{\theta}) = e^{-\bar{\boldsymbol{x}}^{s_k}\boldsymbol{\beta}_i' \bar{z}^{s_k}}\{1 + \frac{(\sigma \bar{\boldsymbol{x}}^{s_k}\boldsymbol{\beta}_i' \bar{z}^{s_k})^2}{2!}\}, \tag{2.71a}$$

$$\tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \boldsymbol{\theta}) = \sum_{i=i}^{j} \psi_{ij}^{l}(\tilde{\boldsymbol{\lambda}}) e^{-\bar{\boldsymbol{x}}^{s_k}\boldsymbol{\beta}_l' \bar{z}^{s_k}}\{1 + \frac{(\sigma \bar{\boldsymbol{x}}^{s_k}\boldsymbol{\beta}_l' \bar{z}^{s_k})^2}{2!}\}, \quad (i = 1, \ldots, I-1; j = i+1, \ldots, I). \tag{2.71b}$$

where $\psi_{ij}^{s}(\tilde{\boldsymbol{\lambda}}^{l_k})$ is referred to equation (2.60). Since $\tilde{\delta}_{ij}^{s_k}, \bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}$ are known from inspection, then $\widehat{\boldsymbol{\theta}} = (\widehat{\boldsymbol{\beta}}, \hat{\sigma})$ can be estimated by utilize maximum likelihood approach. Likelihood function in equation (2.70) can be rewritten by means of logarithm as follows:

$$\ln \boldsymbol{\mathcal{L}}(\boldsymbol{\theta}, \Xi) = \sum_{i=1}^{I-1} \sum_{j=1}^{I} \sum_{k=1}^{K} \sum_{s_k=1}^{S_k} \tilde{\delta}_{ij}^{s_k} \tilde{\pi}_{ij}^{s_k}(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \boldsymbol{\theta}) \tag{2.72}$$

The estimation of $\boldsymbol{\theta}$ can be obtained by solving the optimality condition:

$$\frac{\partial \ln \boldsymbol{\mathcal{L}}(\boldsymbol{\theta},\Xi)}{\partial \theta_i} = 0, \quad (i = 1, \dots, (I-1)M+1) \tag{2.73}$$

The, the optimal value of $\widehat{\boldsymbol{\theta}} = \left(\hat{\theta}_{\mathbf{1}}, \dots, \hat{\theta}_{(I-1)M+1}\right)$ are estimated by applying a numerical iterative procedure such as Newton Method for the $(I-1)M+1$ order nonlinear simultaneous equations (Isoda and Ohno, 1990). Furthermore, estimator for the asymptotical covariance matrix $\widehat{\boldsymbol{\Sigma}}(\widehat{\boldsymbol{\theta}})$ of the parameters is given by

$$\widehat{\boldsymbol{\Sigma}}(\widehat{\boldsymbol{\theta}}) = \left[\frac{\partial^2 \ln \boldsymbol{\mathcal{L}}(\widehat{\boldsymbol{\theta}},\Xi)}{\partial \boldsymbol{\theta} \partial \boldsymbol{\theta}'}\right]^{-1} \tag{2.74}$$

The $\left((I-1)M+1\right) \times ((I-1)M+1)$ order inverse matrix of the right-hand side of the formula, composed by the elements $\partial^2 \boldsymbol{\mathcal{L}}(\boldsymbol{\theta}, \Xi)/\boldsymbol{\partial}\theta_i \boldsymbol{\partial}\theta_j$ results to be the inverse matrix of the Fisher information matrix.

2.6.4.2 Heterogeneity Factor Estimation

Information concerning inspection sample s_k of pavement group k is denoted as $\boldsymbol{\xi}^{s_k}(s_k = 1, \dots, S^k)$. In order to explain the condition states of individual sample, the first and second condition states of sample s_k are assumed as $i(s_k)$ and $j(s_k)$. It is supposed that the parameter set $\widehat{\boldsymbol{\theta}} = \left(\widehat{\boldsymbol{\beta}}_1, \dots, \widehat{\boldsymbol{\beta}}_{\boldsymbol{I}-1}\hat{\sigma}\right)$ is available. If the distribution of heterogeneity factor ε^k expressed by function $\bar{f}(\varepsilon: \hat{\sigma})$ is reviewed, the probability density accounting for the transition pattern of each inspection sample $\boldsymbol{\xi}^{s_k}$ can be attained by:

$$\rho^{s_k}\left(\varepsilon^k: \widehat{\boldsymbol{\theta}}, \boldsymbol{\xi}^k\right) = \left\{\pi^{s_k}_{i(s_k)j(s_k)}\left(\bar{z}^{s_k}, \bar{\boldsymbol{x}}^{s_k}: \widehat{\boldsymbol{\beta}}, \varepsilon^k\right)\right\}^{\bar{\delta}^{s_k}_{i(s_k)j(s_k)}} \bar{f}(\varepsilon^k, \hat{\sigma}) \tag{2.75}$$

where function $\bar{f}(\varepsilon^k: \hat{\sigma})$ follows local mixing mechanism as previously discussed. As consideration sampling population in pavement group k as a whole, consideration for the entire sampling population in pavement group, it is a possibility in expressing the simultaneous occurrence probability density function refers to heterogeneity factor ε^k as shown in following formula:

$$\rho^k\left(\varepsilon^k : \widehat{\boldsymbol{\theta}}, \boldsymbol{\xi}^k\right) = \prod_{s_k=1}^{S^k} \rho^k\left(\varepsilon^k : \widehat{\boldsymbol{\theta}}, \boldsymbol{\xi}^k\right) \propto \prod_{s_k=1}^{S_k} \left\{\sum_{l=i(s_k)}^{j(s_k)} \psi_{i(s_k)j(s_k)}^{l} \left(\tilde{\boldsymbol{\lambda}}^{s_k}(\widehat{\boldsymbol{\theta}})\right) \exp\left(-\tilde{\lambda}_l^{s_k}(\widehat{\boldsymbol{\theta}})\varepsilon^k\right) \bar{z}^{s_k}\right\}^{\bar{\delta}_{i(s_k)j(s_k)}^{s_k}} \left\{1 + \frac{\left(\sigma \tilde{\lambda}_l^{s_k} z^{s_k}\right)^2}{2!}\right\}^{S_k} \tag{2.76}$$

The standard or average hazard rate is explainable by means of vector $\tilde{\boldsymbol{\lambda}}^{s_k}(\widehat{\boldsymbol{\theta}}) = \left(\tilde{\lambda}_1^{s_k}(\widehat{\boldsymbol{\theta}}), \dots, \tilde{\lambda}_{I-1}^{s_k}(\widehat{\boldsymbol{\theta}})\right)$. Thus, average hazard rate $\tilde{\lambda}_1^{s_k}$ is perceived to correspond on the parameter $\widehat{\boldsymbol{\theta}}$. Overtaking by an explicit form of probability density function, equation (2.76) is solved in partial logarithm:

$$\ln \rho^k\left(\varepsilon^k : \widehat{\boldsymbol{\theta}}, \boldsymbol{\xi}^k\right) \propto \sum_{s_k=1}^{S^k} \bar{\delta}_{i(s_k)j(s_k)}^{s_k} \ln\left\{\sum_{m=i(s_k)}^{j(s_k)} \psi_{i(s_k)j(s_k)}^{l} \left(\tilde{\boldsymbol{\lambda}}^{s_k}(\widehat{\boldsymbol{\theta}})\right) \exp\left(-\tilde{\lambda}_l^{s_k}(\widehat{\boldsymbol{\theta}})\varepsilon^k\right) \bar{z}^{s_k}\right\} + S_k \ln\left\{1 + \frac{\left(\sigma \tilde{\lambda}_l^{s_k} z^{s_k}\right)^2}{2!}\right\} \tag{2.77}$$

The last, optimal value of heterogeneity factor $\varepsilon^k (k = 1, \dots, K)$ can be reached through maximizing equation (2.77) with respect to ε^k as variable and $\widehat{\boldsymbol{\theta}} = (\widehat{\boldsymbol{\beta}}_1, \dots, \widehat{\boldsymbol{\beta}}_{I-1}, \widehat{\boldsymbol{\sigma}})$:

$$max_{e^k}\left\{\ln \rho^k\left(\varepsilon^k : \widehat{\boldsymbol{\theta}}, \boldsymbol{\xi}^k\right)\right\} \tag{2.78}$$

2.7 Summary and Recommendations

This chapter has discussed an in-depth literature review on hazard model practice in infrastructure asset management typically in field of pavement asset management. In regard to the importance of infrastructure to support society activities, formulation a methodology to overtake the problem of deterioration process should get attention in more. By utilizing deterministic and stochastic model to determine the deterioration process, it can be seen that stochastic model is more applicable and close to reality in asking the problem of deterioration as many paper that has been disseminated. Markov chain model with role of visual inspection data proposes the answer of deterioration problem exhaustively.

Besides, this chapter is emphasized to solve the heterogeneity factor that exists in pavement group. Thus, the mixture model is presented for benchmarking study which is determined by means of heterogeneity factor ε. This model is utilizing semi parametric approach with following the function of Taylor series. Two estimation approaches with maximum likelihood estimation method is applied to estimate the heterogeneity factor. From the advantageous of the mixture hazard model, it is supposed to be an excellent tool for benchmarking study, which is employed to found the best technology in pavement management systems.

Depart from the theory and model presented in this chapter, the following chapter of this dissertation is going to compose deterioration models to apply in pavement management systems in various objectives.

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Chapter 3

Pavement Maintenance Management Policy

3.1 General Introduction

Road has a significant function in supporting citizen's life and serving economic activities. Look carefully on that situation, maintenance has been surely advanced up to now while attempting harmonize among the uniqueness, the history and the future plan of the city or region. Pavement maintenance undertakes to be an integrated part of city or region planning. As a result, in many countries, a large of budget has been allocated in maintenance of infrastructure including pavement. However, there are original challenges of economic condition such as slowly economic growth, severe financial situation, thus pavement maintenance and repair cost is decreased. Within this context, it is a substantial to perform an approach that decreases life-cycle cost by reasonably allocating of limited resource, and by implementing an efficient management of pavement maintenance. In briefly words, that is maintenance management policy.

Regarding the potential value of road asset, by making pavement long-lived, and by applying an appropriate maintenance, reduction maintenance cost can be expected consequentially. Therefore, in pavement maintenance works, a first step of reform understands management situation of pavement objectively, grasps pavement inspection by operation automatic car measuring pavement road properties, carries out input of geographical information systems (GIS), and accumulates necessary data related to pavement inspection and maintenance history information.

A positive policy approach for implementing rational pavement maintenance will be promoted based on those accumulated data, especially a plan of maintenance management strategy respect to road pavement characteristic. In addition as a long-term vision, stated as a goal, optimal maintenance management to attempt the minimization of life-cycle cost, and leveling of maintenance cost by carried out of an appropriate maintenance policy and in order to long-lived pavement is promoted.

This chapter proposes a new policy approach in pavement maintenance management with deeply and comprehensively empirical application. The following sections presents maintenance management function using main four management functions. Section 3.3 deals the mid/long-term maintenance management policy. A main road maintenance management policy is discussed in section 3.4. Meanwhile, section 3.5 details comprehensively maintenance management policy in empirical study using data of Kyoto City Bureau of Construction Engineering Works (2008). The last summarizes contribution of this chapter and discussion for future research.

3.2 Maintenance Management Function

Defining maintenance works and activities is build upon its objective. In linked with these tasks, management function is suggested that the requisites of policy framework are met.

To derive maintenance management function, maintenance management integrates four main functions of management, namely: planning, programming, preparation and operations. These are described in the following sections.

3.2.1 Planning

Planning tries to determine road pavement standards with minimizing cost and also to determine the budget required in order to fulfill the standards determined. This function covers the entire network as a whole analysis in time of long term or strategic level. Senior managers and policy makers are responsible to handle within this function. Example of systems descriptions in planning function is strategic analysis system, network planning system and pavement management systems.

3.2.2 Programming

Programming aims to determine the works or activities that can be undertaken within the budgetary period. This function is preparing to cover the sections in the network likely need to maintain, repair and rehabilitate or should be making in a new construction. The programming activity is prepared in a medium term, and then will be a tactical analysis. Management staff concerned is managers and budget holders. Program analysis system, pavement management system, and budgeting system are example of systems description in programming function.

3.2.3 Preparation

This function is working to design the works or activities and also preparing and issuing the contract or activities instruction. Contract or activities packages should be covered in preparation function. Preparation will be appropriate in budget year of time horizon which is held by engineers, technical and contract or procurement staff of management. The project analysis system, pavement management system, bridge management system, overlay design system and contract procurement system are systems description in line with preparation function.

3.2.4 Operations

Operations function has to undertaking tasks as part of works activity within on-going operations. This function is preparing for sub-sections where works are taking place. Works supervisors are responsible for running activities. Examples systems description respects to operations function are project management system, maintenance management system, equipment management system and also financial management or accounting system.

A brief summary of pavement management function can be seen in table 3.1 as follows:

Table 3.1 Pavement Management Function

Function	Typical aims	Network coverage	Time horizon	Management staff	Typical system
Planning	• Determining pavement standards with minimizing cost • Determining the budget required to support the standards	Entire network	Long-term (strategic)	Senior managers and policy makers	• Strategic analysis system • Network planning system • Pavement management systems
Programming	Determining the work activities that can be undertaken within the budgetary period	Sections likely need MRR activities	Mid-term (tactical)	Managers and budget holders	• Program analysis system • Pavement management system • Budgeting system
Preparation	• Designing works activities • Preparing and issuing contract or activity instruction	Contract or work packages	Budget year	Engineers, technical and contract or procurement staff	• Project analysis system • Pavement analysis system • Bridge management system • Overlay design system • Contract procurement system
Operations	Undertaking tasks as part of works activity	Sub-sections where works are taking place	On-going	Works supervisors	• Project management system • Maintenance management system • Equipment management systems • Financial management /accounting system

Source: Developed from TRL (1998) and Kerali (2000)

3.3 Mid/Long-term Maintenance Management Policy

3.3.1 Overview of Mid/Long-term Maintenance

Figure 3.1 displays three terms of management flow, which are mid/long-term maintenance plan, short-term maintenance plan and single-term maintenance plan.

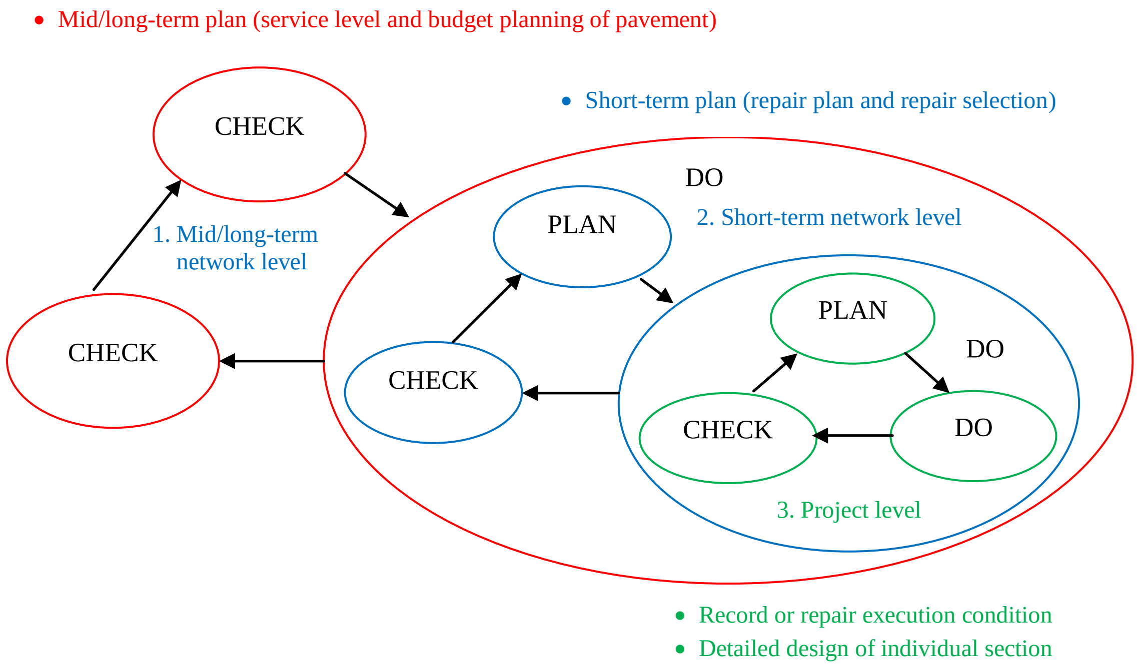

Figure 3.1 Hierarchical Management Flow

Each term of maintenance level has its own objectives and duties as well as calls for comprehensive technology. The first term focuses on service level and budget planning of pavement. The short-term deals with monitoring of repair plan and repair selection. Meanwhile, the last term refers to detailed or specific work of repair execution. However, the three terms are integrated into a single entity function for entire pavement network. Furthermore, this chapter discusses more in mid/long-term maintenance level.

3.3.2 Classification of Pavement Section (grouping)

In order to determine a plan of repair priority, a different repair policy, and a plan of budget, pavement section is classified according to the deterioration characteristic and importance of pavement section.

To achieve those goals, the purpose of groupings can be detailed into:

- Setting of phased management standard value
- Putting priority level of repair under budget constraint

Whilst, the basic idea of groupings is referring to:

- It greatly classifies into highways (main road), life road (residential road) and a peculiar route.
- A peculiar route shows concept to extract the section that should make a special remark by the management in the future.

The detail of basic concept in relation to type and variable of grouping can be seen in table 3.2 as follows:

Table 3.2 Basic Concept of Grouping

Pavement Group	Type of grouping	Variable of grouping
Highway/main road	Main section road	Traffic, urgent transportation road (by transportation demand, route characteristic, and priority level)
	Special section road	Special purpose
Life/residential road	Important section road	Road around sightseeing, bus road
	Other section road	Other sections (the rest of important road)
Peculiar route	Peculiar section	A section where deterioration is remarkably early

As for this study, it emphasizes on highway or main road. The total traffic, the urgent transportation road, the cultural heritage, and the long distance sections were adopted as an index of grouping. The detail of variable condition is showing in table 3.3.

Another consideration of variable that can be examined to be an index of grouping is disaster prevention facilities and also bus road route. However, it depends on how strong the correlation among the index. If the correlation was strong, the two rest of index can be excluded.

Table 3.3 Detail of Variable Condition

Group	Detail of variable condition
Group 1	Section that corresponds to: • The first urgent transportation road • Road around the cultural heritage • 30,000 total traffic
Group 2	Sections other than group 1 and it corresponds to: • The second urgent transportation roads • Long distance section • 10,000 total traffic
Group 3	• Other section
Group 4	• For annual event or festival route (special section)

3.4 Highway Maintenance Management Policy

3.4.1 Management by Objectives Level and Budget Planning

The objective level of maintenance is essential to arrange the plan of budgeting. With defining the objective level, the problem of budget constraint becomes easier to handle. In accordance with that, it is important to propose a scenario of repair plan.

A scenario of repair plan is composed with regarding of repair criteria, priority level concept, budget planning, and management by objective level. This scenario will be a guidance of maintenance management that is suitable to condition of respective city or region.

The criteria of repair as one of variable defined are structured by grouping of rutting and cracking occurred in pavement section. The number of group (e.g. G1-G4) depends on needs for grouping of rutting depth (mm) or cracking size (%). Following the criteria, a budget plan is proposed with respective group of repair criteria (G1-G4).

In the same way, priority level concept is arranged for each scenario. This priority refers to the section in which has a state of pavement (e.g. bad or good). Meanwhile, the management by objective levels subjects to the value of Maintenance Control Index (MCI) or more for each group.

3.4.2 Pavement Service Level

The road pavement service level is described as a Maintenance Control Index (MCI) value formulated by the Ministry of Construction of Japan. This section (3.4.2) refers to Kobayashi et al (2008).

3.4.2.1 MCI Management Level

Theoretically, there is a possibility to estimate pavement deterioration process by examining the MCI inspection records of the past. In the existing inspection data, however there are no data such as different measuring points by year. Therefore, deterioration process should be described with a simple deterioration model, which is supposed that the measuring MCI value for a road section in year t is $z(t)$. The estimated value of MCI in year $t+r$ may be expressed as follows:

$$z(t+r) = z(t) - \phi r \tag{3.1}$$

where ϕ is the average falling-off amount of MCI in the corresponding road section for one year. The real deterioration process is uncertain, and it is impossible to estimate the deterioration process that actually comes about. Equation (3.1) represents an expected value pass that is expressed by the expected value of MCI at each point in time. In many cases, ϕ in every road section was presented with reference to the MCI value at the point of past repair and at the point of inspection immediately prior to repair.

Expected life-cycle costs can be minimized by executing repair work at the point in time when the MCI value reaches some critical level (referred to as the MCI management level). Suppose that pavement is repaired at the initial point in time, $t = 0$ and MCI value is returned to Z. Then, suppose also a rule stipulating that repair work is performed again when the MCI value of pavement reaches $z(\theta) = z^o$ after θ years have passed from the initial year. The repair cost which is required to recover MCI from z^o to Z is denoted by $F(z^o)$. Suppose the expected life-cycle cost in the case the initial MCI value is Z is defined as $J(Z; z^o)$, then the expected life-cycle cost $J(Z; z^o)$ may be conveyed as follows using recursive property:

$$J(Z; z^o) = \sum_{t=0}^{\theta(z^o)} \frac{c(z(t))\beta}{(1+\alpha)^t} + \frac{F(z^o)}{(1+\alpha)^{\theta(z^o)}} + \frac{J(Z; z^o)}{(1+\alpha)^{\theta(z^o)}} \tag{3.2}$$

where $c(z(t))$ is user cost when MCI value is $z(t)$, β is annual average traffic volume, $\theta(z^o)$ is time interval (year) from the corresponding year to the year when the first repair is conducted. That is, the first term on the right side expresses the present value of total user cost that is generated up to the repair point of the next time, the second term deals the present value of repair costs at the next point in time, and the third term describes the present value of expected life-cycle costing that is generated by executing optimal repair the next time. By arranging the above equation for $J(Z; z^o)$, then next equation becomes:

$$J(Z; z^o) = \left\{1 - \frac{1}{(1+\alpha)^{\theta(z^o)}}\right\}^{-1} \text{x} \left\{\sum_{t=0}^{\theta(z^o)} \frac{c(z(t))\beta}{(1+\alpha)^t} + \frac{F(z^o)}{(1+\alpha)^{\theta(z^o)}}\right\} \tag{3.3}$$

In equation (3.3), expected life-cycle cost changes according to MCI value z^o at the time when repair is carried out. Using a one-dimensional direct searching method allows calculation of MCI management level z^o that renders $J(Z; z^o)$ as the minimum. Suppose that z^o, creating the minimal expected life-cycle costing, is considered the MCI management level, and is expressed as z^*. The MCI value measured at the present point in time $t = 0$ is z, and the expected life-cycle costing that is achieved in a case where the repair of pavement is performed at optimal timing referenced at MCI management level z^* hereafter may be declared as follows:

$$J(z;z^*) = \sum_{t=0}^{\hat{\theta}(z^*,z)} \frac{c(z(t))\beta}{(1+\alpha)^t} + \frac{F(z^*)}{(1+\alpha)^{\hat{\theta}(z^*,z)}} + \frac{J(Z;z^*)}{(1+\alpha)^{\hat{\theta}(z^*,z)}} \tag{3.4}$$

where $\hat{\theta}(z^*, z)$ is average number of elapsed years from the year when MCI value z is measured until MCI value obtains management level z^*.

3.4.2.2 Cost-Benefit Rule

The benefit of repair work on a certain road section is defined as the difference between expected life-cycle costs in the case of repairs deferred until the following year, and expected life-cycle costs acquired in case which optimal repair is performed using the MCI management level. Let us denote the expected life cycle cost in a case where repair is deferred for one year by $\tilde{J}(z)$, and the expected life-cycle cost in a case where repair occurs at optimal timing year by $J(Z; z^*)$. Then, the benefit of repair work is defined as $\tilde{J}(z) - J(Z; z^*)$. But life-cycle costing assumes that all repairs after next time are executed using the MCI management level z^*. The cost-benefit ratio (B/C) of repair work on pavement in the corresponding year t can be expressed as follows:

$$(B/C) = \frac{\tilde{J}(z) - J(Z;z^*)}{F(z)} \tag{3.5}$$

$$\tilde{J}(z) = c(z)\beta + \frac{F(z(t+1))}{(1+\alpha)} + \frac{J(Z;z^*)}{(1+\alpha)} \tag{3.6}$$

Using the cost-benefit ratio formulated above may determine the order in which maintenance should be carried out under a limited budget with the practical method outlined in the following sequence:

1. Determine the lowest MCI level $\underline{z}$ to repair.
2. Extract the section that reaches $\underline{z}$ as the highest priority section.
3. After calculating cost-benefit ratio (B/C) for all road sections, select the section of the highest (B/C) among sections where cost-benefit ratio is (B/C) > 1.

4. Determine the section where repair should be performed within the scope of budget constraints, referring to the priority decided by the steps listed above.

Thus, a desirable repair order of pavement may be calculated approximately in cases where budget constraint exists.

3.4.3 Priority Level of Repair

Due to limitation of budget, the repair plan that has been set up by management objectives level and budget planning in previous activity is considered to carry out. In this regards, it is necessary to deal with pavement section in which the repair is enforced by priority in the range of the budget.

The score of each pavement section is calculated by evaluation item shown in table 3.4 and evaluates of importance degree. Furthermore, by imposing evaluation point of each repair necessary section, the pavement section is distributed to a section in which has highly evaluation point. Highly evaluation point implies the section should be carried out in repair priority.

Table 3.4 Evaluation Item of Route

Evaluation item	Content
Total traffic	By 5 ranking section in total traffic 5 point : 20000 or more 4 point: 10000 to less than 20000 3 point: 2500 to less than 10000 2 point: 500 to less than 2500 1 point: less than 500
Long distance section	Long distance section (considering of high school student, administrative division’s, city event, and wheel chair or disabilities) 1 point: Pertinent either of above-mentioned section
Surrounding of sightseeing facilities	High-ranking visit ground by cultural heritage 1 point: Section from facilities for tourist within 1000m in radius
Urgent transportation road and shelter road specification	Urgent transportation road (the 1st and the 2nd) and shelter road 1 point: Section that corresponds to the above-mentioned route

The evaluation point in each pavement section i is calculated by the following expressions:

$$ep(i) = \frac{\sum_{ep} each\ item\ point\ in\ section\ (i) x\ weight\ of\ item}{Total\ point} x100 \quad (3.7)$$

where $ep(i)$ is evaluation point of pavement section i.

3.4.4 Examination Method of Repair Update.

As a member of maintenance activities, updating of repair should take into consideration by examination of method. Examination method of repair update aims at making pavement long-lived with cost reduction in the way of repair method selection and also as a benchmarking for application in new methods or new materials. Section 3.4.4.1 and 3.4.4.2 explains the 2 ways in respectively.

3.4.4.1Repair Method Selection

A repair method selection is a process of selection that is divided into 2 forms of evaluation, by function evaluation and structural evaluation. The selection process involved can be described as follows:

- Repair candidate section is selected from road characteristics investigation based on criteria of repair by the result of function evaluation.
- Pavement section structure investigation of selected repair candidate section is extracted by section in which damage shape, repair history, and deterioration progress are relatively early.
- Investigation by Falling Weight Deflectometer (FWD) of pavement section structure investigation is carried out as pavement structural evaluation.

- Pavement that does not necessary to repair and range of repair execution are assessed based on a structural evaluation result by FWD investigation, and then repair method is selected.
- Maintenance and repair are assessed based on both a function evaluation and a structural evaluation, and then repair method is selected.

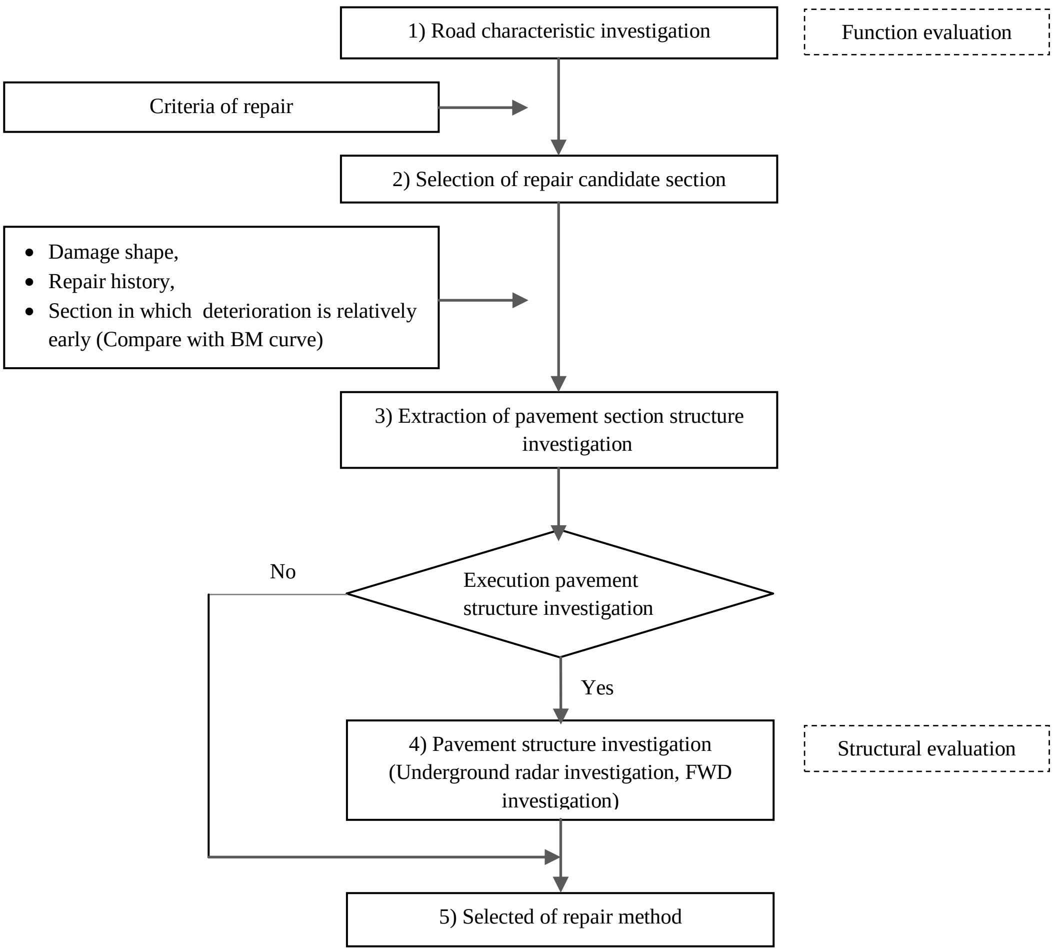

Figure 3.2 Repair Selection Implementation Flow

As a summary of repair selection method process, figure 3.2 shows flow of repair selection implementation in pavement.

a. Selection method by function evaluation

In selection of repair method using function evaluation, repair method is selected from condition state of cracking and rutting.

While repair method is selected, a different result may occur according to management by objectives level and budget planning. One example of basis selection is matrix of cracking and rutting (explained in detail by empirical application in section 3.5)

b. Selection method by structural evaluation

In selection of repair method using structural evaluation, there are three flow of selection. Firstly is evaluation of pavement soundness. Secondly, assessed based on following results obtained according to amount of deflection measured by FWD. Lastly, repair method is selected.

The following result obtained according to amount of deflection measured by FWD (figure 3.3) is defined by:

- Soundness of the entire pavement including sub-grade
- Sub-grade bearing capacity (CBR)
- Soundness of pavement (thickness rate equals the current state)
- Strength of asphalt layer (modulus of asphalt mixture layer)

3.4.4.2 Benchmarking for Application in New Methods or New Materials

It is preferable to adopt new methods and new materials positively to achieve pavement long-lived with cost reduction. However, it is difficult in disseminating a new technology as long as neither the performance nor the effect becomes clear. Then, to evaluate and analyze acquired data by examination constructed, and also considering the adequacy of such as effect and coverage, a benchmarking evaluation of pavement deterioration curve is introduced. Figure 3.4 shows the general procedure of benchmarking evaluation.

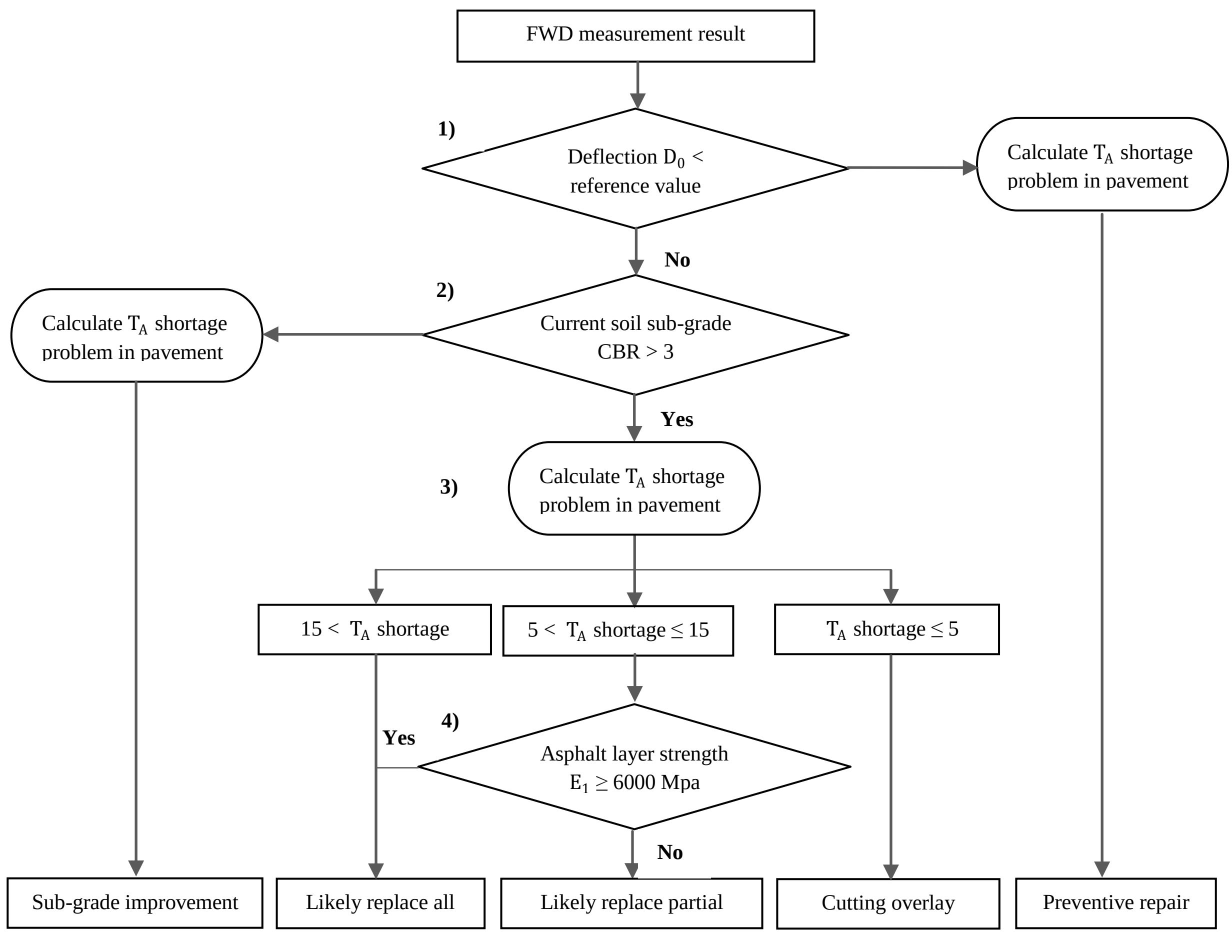

Figure 3.3 Repair Methods Selection by FWD

In benchmarking evaluation, extracting section in which deterioration progress is remarkable as a peculiar section by evaluating the transition of deterioration prediction model using inspection data of road characteristics, and then comparing with benchmarking curve. Examination construction is executed by considering measures and scrutinizes condition states of section. The effect of new materials in order to making pavement long-lived can be verified by follow-up survey afterwards. Furthermore, benchmarking curve shifts to making long-lived, if deterioration progress can be dulled by adopting and spreading a new technology

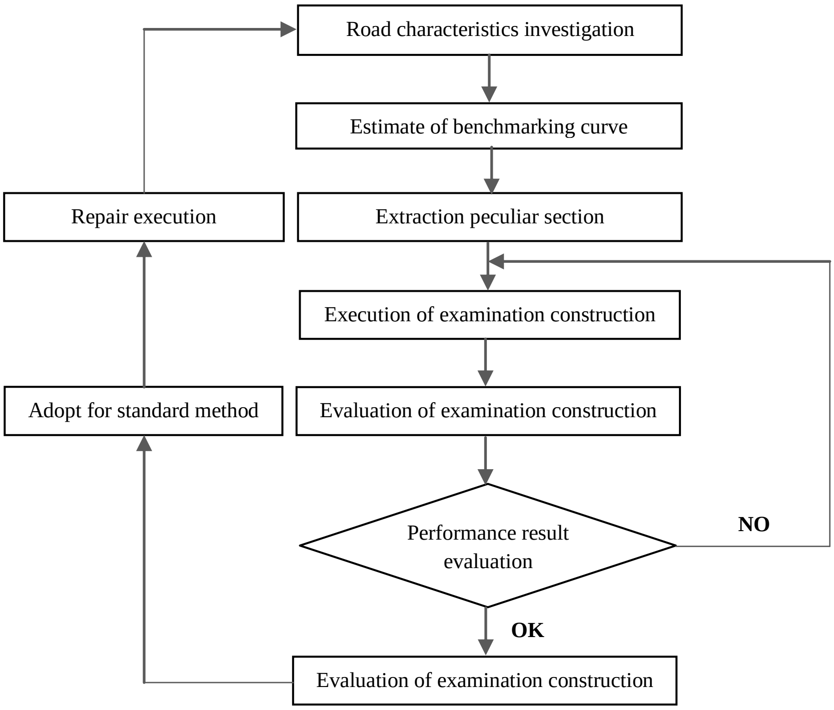

Figure 3.4 General Procedure of Benchmarking Evaluation

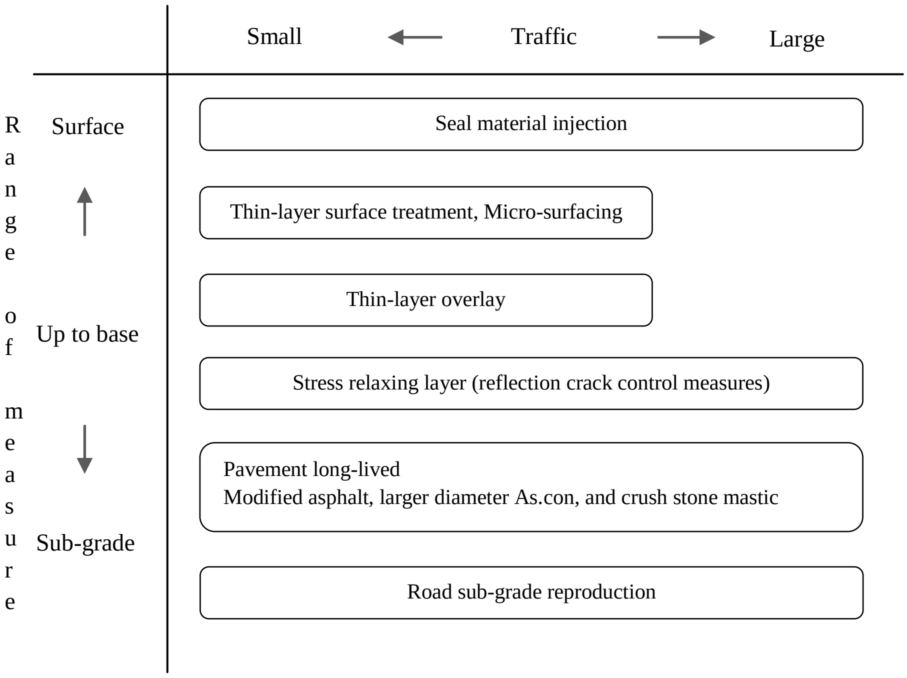

Figure 3.5 Range of Measures and Traffic Condition

The repair method is also possible conducted in accordance with range of measures and traffic condition. Figure 3.5 displays in detail relation between range of measures and traffic condition. Moreover, function requirement for each repair method is shown in table 3.5, and types of damage and preventive maintenance method that can be applied are shown in table 3.6.

Table 3.5 Function Requirement of Each Repair Method

Function requirement / Repair method	Abrasion resistance	Liquidity	Crack character	Drain	Slipping resistance
Macadam mastic asphalt pavement	✓	✓	✓		✓
Large diameter asphalt pavement	✓	✓			
Use of modified asphalt	✓	✓			
Stress relaxing layer			✓		
Drained pavement				✓	✓
Water penetration pavement				✓	
Composite pavement (high durable)	✓	✓	✓		
Semi-flexible pavement		✓			

Table 3.6 Preventive Maintenance Method and Damage Type

Damage type / Repair method	Crack	Rut	Flatness	Decrease of Slipping resistance
Thin-layer overlay	✓	△※	✓	✓
Thin-layer surface treatment	✓	△※	✓	✓
Micro-surfacing	✓			✓
Seal material injection	✓			

Note) Preventive maintenance: executed to recover road function before pavement is structurally deteriorated.

※ Execute cutting as prior processing before constructs it, and remove the convex part on the road.

3.4.5 Periodic Inspection Plan

Periodic inspection plan is conducted as process to investigate periodic maintenance and surface damage degree that will be utilized later in calculation of repair level and budget allocation. Periodic inspection is classified in visual inspection and machine inspection. In highways, both of these inspections are employed. Mean while, in life or residential road, only visual inspection is commonly used.

In order to make periodic inspection plan, there are two considerations should be prioritized, that is:

- A number of total traffic and special section that should investigate by machine inspection.
- An investigation frequency and a cycle in year.

3.4.6 Method of Selecting Construction Section (horizontal synchronization)

Considering preserving minimum load in traffic as well as does not cause deterioration given to congestion and route environment by pavement construction work, construction method is examined in highways of urban areas that has heavy traffic number.

The following concepts are introduced aims at decrease frequency of pavement construction work by doing a preventive repair of pavement section around the repair necessary section.

By doing preventive repair of pavement section, some of considerations in selection of repair section are pointed in below:

- A maximum section extension including preventive repair section is assumed to be about 500m.
- In regards to preventive repair section, repair method is selected besides repair necessary section, and repair method that becomes best and a minimum cost is adopted.

- Construction of an upper and lower section simultaneously is examined according to condition state of other side lane. However, it is necessary to carefully consider influence on a traffic network by closure of traffic.

Regarding notes about consideration in selection above, conditions in repair section (preventive repair) selection can be classified in two terms as follows:

a. Conditions 1

When deterioration in the section placed between repairs necessary section progresses to some degree (Do not select when it is not deteriorated at all)

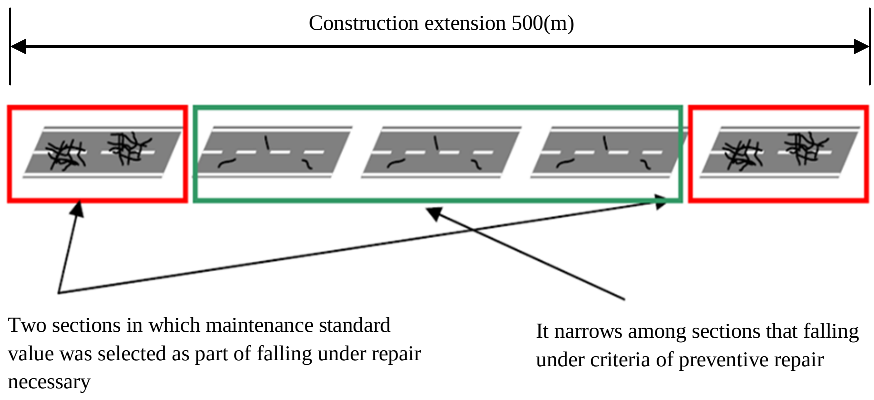

Figure 3.6 Deterioration Conditions 1

b. Conditions 2

When deterioration in the section progresses before and behind repair necessary section to some degree

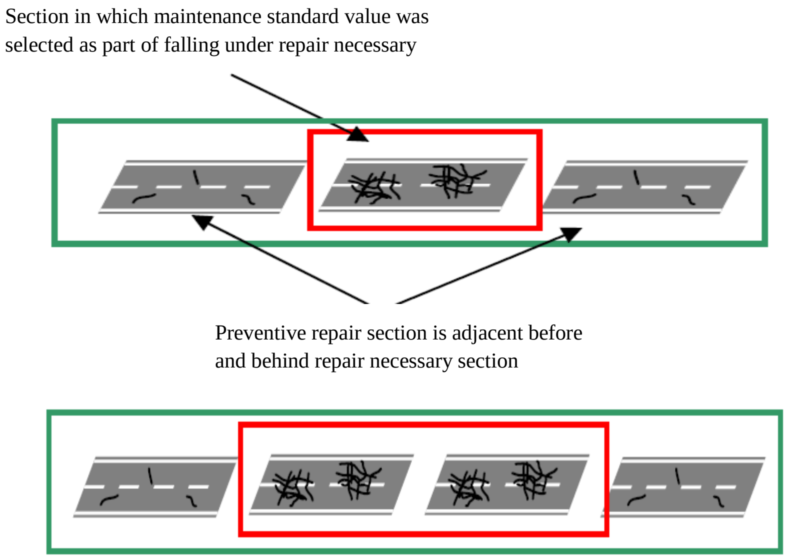

Figure 3.7 Deterioration Conditions 2

3.5 Empirical Application

3.5.1. Overview of Empirical Application

In this section, we present an empirical application of maintenance management policy to further review the applicability of this maintenance policy in pavement section. This empirical study refers to the Kyoto City Pavement Maintenance Management Policy (2008). This policy has been implemented since 2008 and widely further in a maintenance management policy plan until 2037.

3.5.2 Scenario of Repair Plan

The following three scenarios are set as a management by objectives level and a budget plan.

- *Scenario 1:* A current management standard value (average MCI 6.5) is maintained.
- *Scenario 2:* A current budget level is maintained and average MCI 6.5 of group 1 and group 4 is maintained.

- *Scenario 3:* Average MCI 6.0 or more of group 1, 2, and 4 is maintained.

According to the three scenarios above and to allocate a budget plan, table 3.7 shows the criteria of repair, the idea of priority level, and the management by objectives level.

Table 3.7 Repair Plan Scenarios

Scenario	Criteria of repair	Priority level idea	Management by objective levels
1) A current management standard value (average MCI 6.5) is maintained.	Rut 25 mm and more or crack 15% and more	It gives priority to section in which condition states is poor.	Average MCI 6.5 or more
2) A current budget level is maintained and average MCI 5.0 of group 1 and group 4 is maintained.	G1: Rut 20 mm and more or crack 10% and more G2: Rut 30 mm and more or crack 20% and more G3: Rut 30 mm and more or crack 30% and more G4: Rut 15 mm and more or crack 5% and more	It gives priority to section in which condition states is poor in each group.	Average MCI 5.0 or more of G1 and G4
3) Average MCI 6.0 or more of group 1, 2, and 4 is maintained.	G1: Rut 20 mm and more or crack 10% and more G2: Rut 25 mm and more or crack 15% and more G3: Rut 30 mm and more or crack 20% and more G4: Rut 15 mm and more or crack 5% and more	It gives priority to section in which evaluation point of repair necessary section is high in each group.	Average MCI 6.0 or more of G1, G2, and G4

As noted from table 3.7, criteria of repair for each scenario depends on the condition states of cracking and rutting occurred in respective section. Based on each group for each scenario, a budget plan is allocated. For scenario 1, a budget in total will be allocated. Meanwhile, in scenario 2 and 3, a breakdown of the total budget allocated is required.

In different way, priority level idea gives priority to section in two types. Firstly is given based on the poor of condition states (as in scenario 1 and 2). Other is delivered by highly evaluation point as for scenario 3.

3.5.3 Repair Method Selection by Function Evaluation

3.5.3.1 Standard of Repair Method Selection

The standard of repair method is established according to Maintenance Control Index (MCI) value. A value of MCI implies to action will be executed. This standard is corresponding to four groups of pavement section and two types of action, cutting overlay and replacement.

Table 3.8 presents the content of each respective group that describes consideration maintenance and actions suitable to each value of MCI.

Table 3.8 Repair Method Selection Standard

Group	Content of standard
Group 1,4	Consider to preventive maintenance, the value of MCI 5.0 or less should be repaired, the value of MCI is greater than 4.0 and less than 5.0 corresponding to cutting overlay, the value of MCI with less than 4.0 should be replacement
Group 2	The value of MCI 4.5 or less should be repaired, the value of MCI is greater than 3.5 and less than 4.5 corresponding to cutting overlay, the value of MCI 3.5 or less should be replacement
Group 3	Consider to a symptomatic response, the value MCI 4.0 or less should be repaired, the value MCI is greater than 3.0 and less than 4.0 corresponding to cutting overlay, the value MCI 3.0 or less should be replacement

3.5.3.2 Matrix of Cracking and Rutting

Matrix of cracking and rutting portrays classification value of each cracking rate (C1 until C10) and rutting depth rate (R1 until R7). In detail, this matrix provides information of MCI value that indicates appropriate action as illustrating in content of standard in table 3.8.

Group 1,4

Amount rut \ Crack rate		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
		C=0	0<C<5	5≦C<10	10≦C<15	15≦C<20	20≦C<25	25≦C<30	30≦C<35	35≦C<40	40≦C
R1	R≦3	9.1	7.1	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R2	4≦R<10	7.9	6.8	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R3	10≦R<15	6.8	6.3	5.5	5.0	4.7	4.3	4.0	3.7	3.4	3.0
R4	15≦R<20	6.0	5.8	5.0	4.6	4.2	3.9	3.7	3.5	3.3	3.0
R5	20≦R<25	5.2	5.2	4.6	4.1	3.8	3.5	3.3	3.1	2.9	2.6
R6	25≦R<30	4.5	4.5	4.2	3.7	3.4	3.1	2.9	2.7	2.5	2.2
R7	30≦R	3.5	3.5	3.5	3.2	2.8	2.5	2.3	2.1	1.9	1.7

Group 2

Amount rut \ Crack rate		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
		C=0	0<C<5	5≦C<10	10≦C<15	15≦C<20	20≦C<25	25≦C<30	30≦C<35	35≦C<40	40≦C
R1	R≦3	9.1	7.1	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R2	4≦R<10	7.9	6.8	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R3	10≦R<15	6.8	6.3	5.5	5.0	4.7	4.3	4.0	3.7	3.4	3.0
R4	15≦R<20	6.0	5.8	5.0	4.6	4.2	3.9	3.7	3.5	3.3	3.0
R5	20≦R<25	5.2	5.2	4.6	4.1	3.8	3.5	3.3	3.1	2.9	2.6
R6	25≦R<30	4.5	4.5	4.2	3.7	3.4	3.1	2.9	2.7	2.5	2.2
R7	30≦R	3.5	3.5	3.5	3.2	2.8	2.5	2.3	2.1	1.9	1.7

Group 3

Amount rut \ Crack rate		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
		C=0	0<C<5	5≦C<10	10≦C<15	15≦C<20	20≦C<25	25≦C<30	30≦C<35	35≦C<40	40≦C
R1	R≦3	9.1	7.1	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R2	4≦R<10	7.9	6.8	5.9	5.2	4.7	4.3	4.0	3.7	3.4	3.0
R3	10≦R<15	6.8	6.3	5.5	5.0	4.7	4.3	4.0	3.7	3.4	3.0
R4	15≦R<20	6.0	5.8	5.0	4.6	4.2	3.9	3.7	3.5	3.3	3.0
R5	20≦R<25	5.2	5.2	4.6	4.1	3.8	3.5	3.3	3.1	2.9	2.6
R6	25≦R<30	4.5	4.5	4.2	3.7	3.4	3.1	2.9	2.7	2.5	2.2
R7	30≦R	3.5	3.5	3.5	3.2	2.8	2.5	2.3	2.1	1.9	1.7

Yellow: cutting **Blue: replacement**

Figure 3.8 The MCI Value and Appropriate Actions

Figure 3.8 is clearly representing appropriate action regarding to the MCI value in different colors. Cutting overlay is indicated by yellow colors, on the contrary blue colors refers to replacement action.

As noticed here, from section 3.4.4.1 and 3.4.4.2, repair method is determined into two actions (cutting overlay and replacement). However, it is noteworthy to enforce verification of preventive maintenance and application of new methods repeatedly. In addition, to enhance conformity repair method by adopting new methods and new materials as a basis of selection in relation to be an effective repair method and an efficient way updating in the future.

3.5.4 Preferable Repair Method

As for pavement long-lived, by reducing content and frequency of repairs, it does not only offer an advantage for road administrator, but also confer a benefit for road user and people surrounding the road according to such as reducing traffic congestion because of reduction in construction indirectly. In addition, to contribute in the viewpoint such as conservation of energy and saving resource to global environment widely furthermore.

In consequence, repair method should have preferable target and condition criteria for implementing in each group. The target and condition criteria are detailed as follows:

- First, repair method is introduced as about group 1 and group 4 as a special section in maintenance route which have highly importance degree. Moreover, it is preferable to extend period until replacing all by implementing preventive maintenance in which deterioration state is remarkably early.
- Next, without considering of pavement long-lived, basically corresponds to level of damage, cutting overlay and replace out is performed in group 2 which have highly importance degree. Moreover, if measures are implemented, it is preferable to carry out measures together (both rutting and cracking measures) corresponding to damage level.
- In group 3, because it is comparatively slower than other group, a symptomatic response is considered. Thus, it refers to cutting overlay and replacement according to damage level.

Table 3.9 presents preferable repair method as a summary of target and condition criteria as deliver in previous.

Table 3.9 Preferable Repair Method

Group	Condition	Preferable repair method
Group 1	• The first urgent transportation roads • Road around cultural heritage • Section that corresponds to either of 30,000 total traffic or more	• The repair method in which expected to reduce frequency and content of repair is introduced. • Extending period until replacing all by executing preventive maintenance in which deterioration states is remarkably early.
Group 2	• The second urgent transportation roads, or • Long distance section, or • It corresponds to either of 10,000 total traffic or more, and sections other than group 1	• Measures are carried out by using method and material corresponding to pavement damage level (measures of rutting and crack)
Group 3	Other sections	• Considered a symptomatic response, and to apply cutting overlay and replacement
Group 4	For annual event or festival (special section)	• Preventive maintenance are implemented as well as group 1

As supplementary, it is superiorly applying pavement surface reproduction method and pavement sub grade reproduction method that recycles existing pavement section from viewpoint of cost reduction by conservation of energy and saving resource. Moreover, for group 2 and 3, in which, a little of large-sized vehicle traffic (below N5 traffic), route where deterioration pavement and respective roughness are in progress but the pavement structure is soundness, it is desirable to apply only thin-layer overlay.

3.5.5 Periodic Inspection Plan

Periodic inspection plan is documented and implemented in two steps, as follows:

- Each 10,000 total traffic or more and mountainous area (section in which operating inspection directly is though in danger) are executed by machine investigation.
- Investigation frequency organizes inspection frequency of each route by traffic and grouping based on three cycles of year.

3.6 Summary and Recommendations

This chapter has discussed a methodology of maintenance management with strategy and policy approach. The maintenance management strategy is represented by integrating of management functions appropriate in pavement maintenance. Based on these function, change in maintenance management processes are structured being a pavement management function.

The maintenance management policy is developed from viewpoint of mid/long-term maintenance plan. This policy is working with pavement main road maintenance. In order to verify the applicability of this policy, an empirical study was conducted on maintenance management in Kyoto City road pavement. This study has made a contribution to the field by comparison and benchmarking repair using maintenance policy approach. The maintenance policy approach represented can be extended to apply not only for main road pavement but to various other kinds of road facilities as well.

However, more discussions are still called in several points for considered later in broaden this study:

- A positive introduction of new methods is necessary to make pavement long-lived and reduction of life-cycle cost. However, acquired data should be evaluated; validity and impact of new methods should be analyzed.
- In order to benchmarking evaluation, using logic model to pavement maintenance is considered in the future.
- Regarding future management, the empirical application is implemented only on the pavement systems. However, this approach can be applied for various types of infrastructure. Understanding of structural characteristic and appropriate methodology is prominent in widely application of maintenance management policy approach.

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Chapter 4

A Benchmarking Evaluation using Logic Model with Pavement Application

4.1 General Introduction

In infrastructure asset management, rationalization of maintenance and inspection time can reduce total cost, and using a preventive maintenance may achieve long-lived facilities. Take example in bridge, it has been empirically shown that more proactive implementing a preventive maintenance at the early damage states will bring a great effect in reduction life-cycle cost compared with implementing maintenance after the fact that damage is progressed. However, there is a limitation of cost decreased by rationalizing the timing of maintenance and inspection. Particularly in case of road pavement, repair method depends on damage level of pavement structure and it is difficult to apply a preventive maintenance. Furthermore, deterioration processes of road pavement containing various uncertainties and being not able to specify deterioration mechanism are difficulties factor of pavement asset management. Maintenance cost in the future depends on deterioration speed of targeted pavement section. In road pavement, deterioration speed is greatly influenced not only by observable factor such as traffic and pavement structure, but also by unobservable factor such as construction conditions and weather conditions. In a sentence, divergence of deterioration speed of individual pavement section is extremely large. Therefore, understanding characteristic of pavement deterioration of all roads managed is impossible, and becomes important to extract peculiar pavement section which has divergence in deterioration speed to evaluate deterioration speed.

By arranging of making long-lived pavement as final outcome of road pavement maintenance work, it is necessary to evaluate achievement level of making long-lived quantitatively. Average long-lived pavement can be expressed in deterioration performance, and deterioration performance curve can be calculated by using statistical deterioration prediction model based on historical inspection data. Thus, the average performance curve estimated can be modulated as a standard (benchmark) to evaluate the relative deterioration speed in an individual pavement section. As a result, it is possible to extract the point which deterioration speed is remarkably fast as an important section to be managed compared with benchmarking curve. Thus, it is necessary to examine the measure to making long-lived for extracted important section. If deterioration speed in relevant section is improved, both of deterioration performances on entire network and deterioration performance curve of benchmark case are also improved. As a result, reduction of total cost is achieved. As for given influence at deterioration speed, multiple factors relates, and application result evaluation is requested to conduct a detailed investigation for each section of extracted important section, to try in applying such as a new method and new material. Continuously these practices can be called as a major issue which should addressed in the next generation of asset management. In this chapter, decision making issue in asset management that pays attention to deterioration speed of individual pavement section is defined as benchmarking evaluation.

In this chapter, by referring to paper of Aoki et al (2010), a new management system to monitor accomplishment of pavement maintenance work objective is developed. Accuracy of management system is continuously improved by using monitoring data acquired each year according to PDCA cycle of pavement maintenance work. Concretely, this chapter proposes a mechanism of evaluation long-lived pavement quantitatively in a long-term perspective using estimation result of pavement deterioration prediction model. Specifically, In order to develop the logic model for road pavement maintenance works in local government.

This chapter also introduces a practical case of a new pavement management system for pavement maintenance work in Kyoto City, Japan. This kind of effort can succeed the boundary of industry-government-academic in making a scheme of new approach of asset management.

Hereinafter, section 4.2 describes a pre-condition of logic model. Section 4.3 presents formulation of logic model in pavement field. Estimation method of deterioration hazard rate is explained in section 4.4. A practical case of benchmarking evaluation using logic model intended for pavement maintenance work in Kyoto City is discussed in section 4.5. The last section summarizes contributions of logic model and discussion for future study.

4.2 Pre-condition of Logic Model

4.2.1 Pavement Maintenance Work Issues

The road administrator of such municipalities manages road network in which reaches an enormous lengths, and has obligation to provide sustainable high service for the citizen's satisfaction in form of ensuring safety-security and comfort ability without decreasing function of these roads. On the contrary, in severe fiscal situation recent years, a sufficient maintenance management budget is not necessarily approved. Regarding the study on asset management so far, formulating a budget plan to rationalize pavement life-cycle cost is possibly arranged. However, a large discrepancy between the realistic budget constraints and the ideal budget plan was derived as a result of macro-management in asset management, may few significant barriers on running optimum maintenance strategy. If sufficient maintenance repair cost cannot be secured in the short-sighted even if the life-cycle cost can be decreased in a long-term, the optimum maintenance strategy was derived by life-cycle cost analysis progresses deterioration of pavement section and loses the timing of optimum maintenance. Thus, as well as a budget necessary to execute optimum maintenance scenario is procured, a rational maintenance plan is asked to be planned within a limited budget at the project level in macro-level of asset management.

Routine maintenance of pavement section due to differences in time of decision making is classified into three hierarchies. In addition, management tasks will be forwarded by management flow of Plan-Do-Check-Action (PDCA) in each hierarchy. These routine management tasks are arranged within the limited resources such as budgets and technologies. The "Plan" derives optimum maintenance strategies that aims at cost reduction and maximize service effort to the citizens. The "Do" activities perform maintenance works in consonance with optimum strategy. Whilst, a review of budget plan by updating deterioration prediction models and grasp left-off freight in maintenance are conducted in the "Check and Action". By post-evaluation carried out, continuing operational at management cycle contributes for system improvement strategy in routine management tasks.

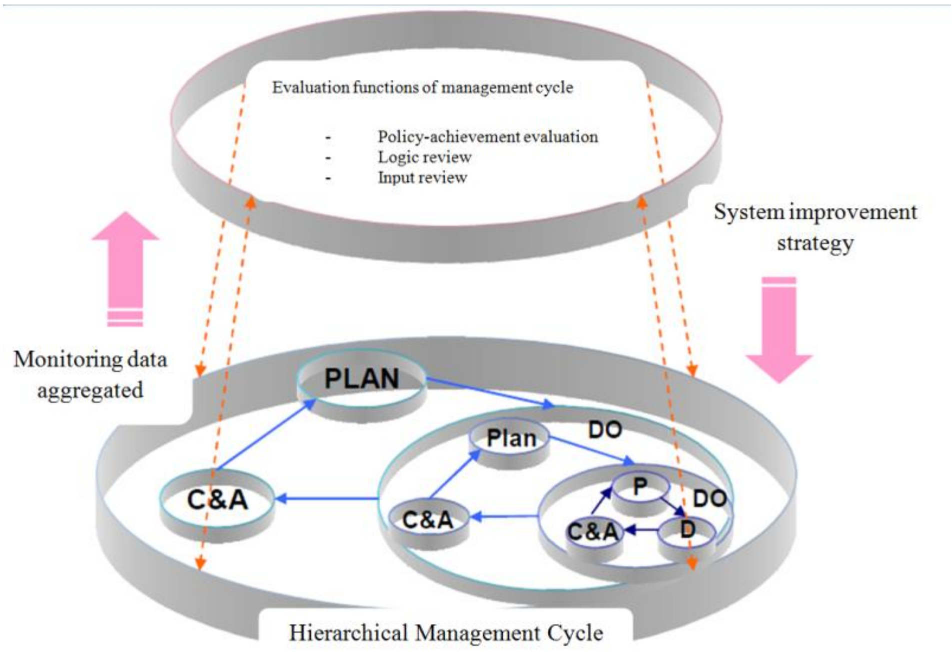

Figure 4.1 Management Systems with Evaluation Function

However, it has focused on the rationalization of maintenance work in the frame of policy objective and technological standard decided beforehand in manage routine maintenance. It is necessary to review validity and a technological standard of those policy objectives in order to reduce cost and long-lived of respective pavement. It is impossible, and needs the management function of the meta-level to aim at generalize the management tasks in routine maintenance work. The management system that provides learning function is constructed by serving a new hierarchy evaluation function in addition to the hierarchical management cycle that supports the routine maintenance management (figure 4.1). Monitoring data generated in hierarchical management cycle of daily management is consolidated, then evaluation of policy-target based on the monitoring data generated. Furthermore, the logic and the inputs are verified. The result is assumed to be a plan for improving system, and involved in making a feedback for routine management.

4.2.2 Benchmarking Evaluation and Logic Model

In order to shift deterioration performance curve of entire pavement section with long-lived condition of pavement, subdividing scope of pavement sections targeted by carried out unit of maintenance work is required to evaluate the heterogeneity of pavement deterioration speed in which belongs to individual sections. Then, by evaluating the relative deterioration speed, if deterioration speed is remarkably fast, it should be extracted as sections that need to improve of work processes. Improvement of pavement section using benchmarking evaluation aims to elevate the entire deterioration performance, and the improvement should be made by introducing new maintenance techniques such as maintenance methods. In addition, carried out inspection investigation to measure the work results introduced a new method, to obtain data for new maintenance, to estimate deterioration performance, and to evaluate heterogeneity of deterioration speed. The relative evaluation of deterioration performance curve extracts section subjected to a new target section of improvement work for benchmarking evaluation. Thus, continuing in inspection the result of maintenance works and functioning operational cycle to successively perform benchmarking evaluation in order to achieve entire pavement target and making long-lived pavement.

The principle of benchmarking evaluation is not performed pavement on routine maintenance; it is desirable that agencies or offices representative have ability to evaluate performance of pavement maintenance. Pavement logic model is an evaluation tool for a better measurement of pavement performance by routine maintenance work. With regards to derive each evaluation index by accumulating data concerning the performance of routine maintenance, and utilizing the logic model, consider improving the input is substantially. The improved inputs subjects to organize techniques and guidelines for practice routine maintenance work.

4.3 Formulation of Logic Model

4.3.1 Outline of Logic Model

As mention before, there are many activities related to pavement maintenance, for example, inspection (periodic inspections and routine patrols), maintenance works and budget planning. To tackle the problem of these activities, there is always a hypothetical logic that explains what outcomes are intended by conducting the pavement activities. As consequently, those individual activities can logically describe a causal relationship leading up to maintenance targets and outcomes due to executing those activities (Sakai et al, 2007).

Basically, a logic model is a tool with combining of planned activities and intended result. A logic model is systematic and visual way to integrates the relationship among the resources/inputs, activities, outputs, outcomes, and impact. The logic model is a beneficial evaluation tool that facilities effective program planning, implementation and evaluation (W.K Kellog, 1998).

A pavement logic model is a tool for activities of maintenance works such as maintenance implementation, budget, and inspection (inputs) to measure influence of achieving final target of pavement management as indicated in safety's and securing comfort ability. Furthermore, it is a tool to monitor achievement situation of the result (outcomes) regularly, and reviews the inputs in relating with improving the entire system.

The object that is evaluated and improved according to the pavement logic model shows a technical indicator such as patrol frequency, characteristics to be inspected, and introduction new methods of maintenance for instance. These objects comes in analyzes various data generated by continuing implementing the process of routine pavement management work, arranges the review of the inputs as an indicator, and disseminates to maintenance field.

The logic model has a role to observe the management flow of Plan-Do-Check-Action in routine maintenance. The logic model evaluation function located in upper level at the hierarchical management cycle shown in figure 4.1

4.3.2 Development of Pavement Logic Model

A pavement logic model is a model of causal relationship among all of work activities related to pavement management. The pavement logic model tries to define and display the action involved in achieving the outcomes, the intermediate outcomes in supporting of final outcomes, and final outcomes as a target of pavement service related to user's need.

Road pavement network using in this logic model is classified into two types, the highways and the residential road which provides movement space of citizen's daily life. The highways and the residential roads have different approach in pavement maintenance. In highways, in order to ensure safety and comfort ability of vehicle traffic, a large of repair with cutting overlay and replacement is applying for road damage occurred overall time (cracking, rutting, flatness index) due to deterioration of structure. Meanwhile, in residential road, to ensure safety of residential road users including pedestrians, a treatment in quickly identify road accident due to failures as well as potholes in order to preventing injury in incidence is required.

The logic model of the highway, as well as final outcomes of safety and comfort, has addressed rationalization of pavement maintenance work. Rationalization pavement maintenance work, in long-term perspective of pavement maintenance, as well as implementation of maintenance plan in order to contribute for long-lived pavement, discovering an early deterioration in specific locations, application new methods-new materials, which is the final outcome can be obtained in improving benchmarking curve.

Whilst, the logic model of residential road stated to ensure the safety of pedestrians and road users as a final target, assumes the number road damage handling such as potholes to be an output index, numbers of accidents defects management by damaged roads as an indicator to evaluate the final outcome. A review of inputs such as the frequency of reconfiguring routine patrols should be conduct to reduce the risk of accidents due to road damaged. In addition, a section where road damage occurs easily is possibly in structurally weak, submit a detailed investigation and repair respective pavement in priority location to reduce the risk of accidents.

By using a logic model in this way, regularly monitoring maintenance work are carried out on routine pavement, it is possible to consider sequentially improving the input for accomplishment of the target. To do this, quantitatively evaluating indicators of each output and outcome of the logic model becomes important. The maintenance management work of the pavement includes many things, and a lot of generated information and the derived index exist, too. In particular, this study focuses on the logic model to monitor in making long-lived pavement of the highway.

To indicate the degree of change or improvement in the policy or project, outcomes are implemented in multiple steps (for instance, intermediate and final outcomes) as illustrated in table 4.1 (Sakai et al, 2007).

Table 4.1 Elements of Logic Model

Element	Description
Input (resources and activities)	Resources and activities (such as budget and manpower) used to perform the operation
Output (results)	Results obtained by personnel activities
Intermediate outcomes (short-term results)	Short-term outcomes that may result from activities and outputs
Final outcomes (management objectives)	Final objective of the operation. It generally takes a long term to achieve and may be affected by an external factor to the operation

The logic model has features, in the following:

- The process between activities (input resources) and final outcomes is described by connecting the elements with single line or multiple lines.
- Outcomes are presented in multiple steps.
- The process of deriving outcomes of a policy or project is shown plainly and objectively, otherwise the process tends to be a black box.

4.3.3 Pavement Logic Model and Indicator Setting

As for reconsidered, pavement routine maintenance is implemented in order to ensure safety of road users. Causal relationship in pavement routine maintenance has been recognized but understanding in systematically way has in low progress. As a result, it is important to arrange the objective and measures of entire pavement maintenance work systematically. In this pavement logic model, the inputs include pavement routine maintenance and periodic inspection etc., and the outcomes include safety of road users, ensuring comfort ability and rational pavement maintenance works. Causal relationships in the intermediate processes are systematically described by using intermediate outcome and output indicators, as of enable of quantitative evaluation as much as possible. A policy evaluation model is established to evaluate the relationship between inputs and outcomes. Pavement logic model is a large-scale model. Figure 4.2 illustrates an example of a part of pavement logic model.

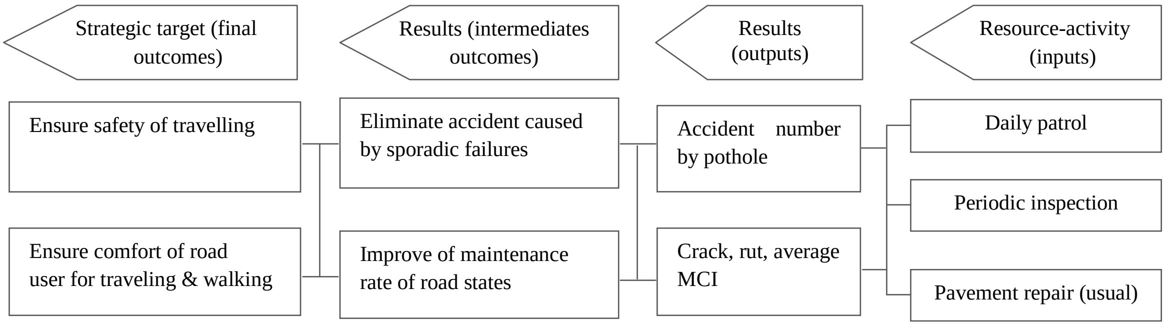

Figure 4.2 Example of Logic Model

The entire of pavement logic model used in this study is attached in appendix A of this paper.

4.3.4 PDCA Cycle in Pavement Maintenance Work Flow

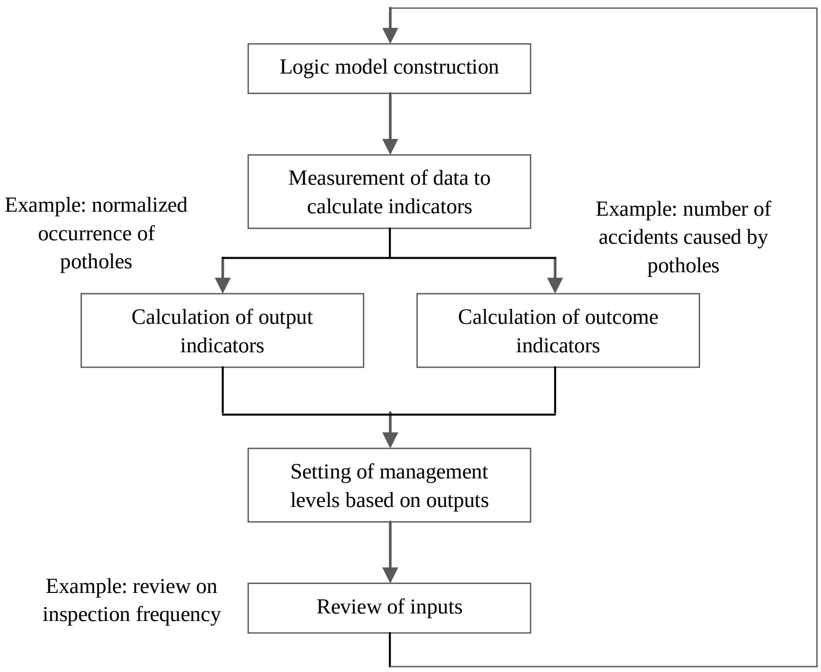

Figure 4.3 Pavement Maintenance Flow based on Logic Model

Figure 4.3 shows pavement maintenance work flow incorporating by PDCA cycle concerning on logic model approach. This flow includes logic model development, calculation of indicators and review of input. The PDCA cycle departs from constructing of logic model. During this cycle, measurements of data to calculate indicators, calculation of output indicators (for instance, occurrence of potholes), calculation of outcome indicators (for example, number of accidents caused by potholes) are conducted. To arrange management levels based on outputs before moving to review of inputs (such as review on inspection frequency) as final of PDCA cycle of this flow. If any indicator changes concerning benchmarking values, the causal relationship among input, output, and outcome indicators should be reevaluated. In addition, the relationship should be revised and inputs selected again if it is necessary. Through the PDCA cycle, pavement maintenance work can be improved continuously, and accountability to road users and the public can be strengthened (Sakai et al, 2007).

The whole of PDCA cycle in pavement maintenance work utilized in this chapter is enclosed in appendix B of this paper.

4.3.5 Post-Evaluation Method

Post-evaluation assess efficiency and effectiveness of pavement maintenance work and seeks to facilitate sustainability of improvement. Based on logic model, post-evaluation method for pavement maintenance is implemented in three kinds of activities as in the following:

- Updating of deterioration prediction model
  Deterioration prediction model is updated by using the latest data such as periodic inspection data and maintenance history data

- Extracting of deterioration characteristic with different peculiar sections

Deterioration characteristic of different peculiar section such as section in which deterioration speed is remarkably faster are extracted according to analysis of periodic inspection data and maintenance history data.

- Measuring current state of maintenance and accomplishing the objective.
  Current state of maintenance and accomplishment the objective are measured as an execution condition in each fiscal year and arranges it in time-series data.

4.3.6 Work Flow in Routine Maintenance

Routine work flow illustrates pavement maintenance work in daily of operation on-site maintenance. Work flow is arranged in accordance with the role of three relations. Firstly is a relation to management and maintenance service. Secondly is in relation to construction and lastly is correspondence to adjustment management division.

In relation to management and maintenance services, pavement damage states are obtained from routine patrol and request or complaint accepted. From discovering of pavement damage, repair or treatment is conducted and finally recorded results of treatment. Visual inspection activities are incorporated in construction relations; otherwise machine inspection is worked with adjustment management division.

The aggregate of work flow in routine maintenance applied in this chapter is included in appendix C of this paper.

4.3.7 Method of Deriving Evaluation Indicators

Deriving evaluation indicators is important in making correlation among indicators, contents, necessary data and problem of pavement maintenance work. Method of deriving evaluation indicators is established in relating with element of logic model.

In this case, output indicators, intermediate indicators and final outcome indicators are made in separately.

As one example, by indicators of pavement soundness, the content is road states (cracking, rutting and flatness) with states of pavement in each evaluation section as necessary data and possible problem is arranging rational maintenance at inspection cycle.

For completely understanding, overall of deriving evaluation indicators method can be seen in appendix D of this paper.

About benchmarking evaluation and finding out specific locations of heterogeneity of deterioration speed is described in following section. Estimation methods of benchmarking curve for pavement deterioration performance that describes benchmarking evaluation method for deterioration hazard rate is also carried out in section 4.4

4.4 Estimation Method of Deterioration Hazard Rate.

4.4.1 Data Management for Estimation Deterioration Hazard Rate

In this study, the target of benchmarking evaluation is pavement damage which is addressed into two condition states of pavement damage. Firstly is cracking and the second is rutting. In order to estimate deterioration hazard rate, it is necessary to maintain time-series data concerning on pavement deterioration. A several data and information are required in estimating deterioration hazard rate. At first, pavement properties investigation data were observed damage states of pavement. Secondly is maintenance history information, and the last is related to observable characteristics variables affect to pavement deterioration speed (traffic, etc.).

Regarding the first data needed, the pavement characteristics investigation data is acquired by investigation conducted periodically by using automatic car measurement, and the data were quantitatively evaluated damage states such as rutting and cracking in each pavement sections. Unit evaluation of pavement properties investigation should be based on 100m. However, in order to subdivide the point where exists a structure such as tunnels, intersections, and bridges, interval of unit could be shorter than 100m. When investigation data serves a time-series, it is important to create a standard to the identical investigation data by evaluation unit during pavement characteristics investigation were conducted in the past.

Meanwhile, maintenance history information as secondly data needed accumulates information such construction condition, repair methods and repair of section that was carried out. In maintenance history information, it is necessary to record each case linked to evaluation section of pavement properties investigation at point to which repair was carried out.

Thus, in estimating of deterioration hazard rate, create a data base made in one sample combination of interval time and properties variables of investigation and damage states at time of latest investigation from point which repair was executed or point which two or more investigation was carried out, for the same pavement condition, maintain a time-series data for each evaluation unit on various data concerning on pavement.

4.4.2 Estimation Deterioration Hazard Rate according to Pavement Section

This section briefly describes estimation methods of deterioration hazard rate obtained by relative evaluation of deterioration prediction models as well as pavement deterioration prediction models as explained in chapter 2. Details of estimation methods are given in the paper of Tsuda et al (2006) and Obama et al (2008).

Deterioration hazard rate is represented as parameters of statistical deterioration prediction models of road pavement. The statistical deterioration prediction model is formulated by using a Markov transition probability matrix, and Markov transition probabilities can be estimated using Markov deterioration model. Firstly, focuses on one of multiple pavement distress, and damage level is defined in discrete time of soundness rating. Now, at any time given, rating $i\ (i = 1, \dots, J-1)$ was observed for the pavement section, the probability density function changes to rating $(i+1)$ at time that has elapsed time y_i could be expressed using hazard function $(\lambda_i)y_i$. The hazard function independent on the elapsed time y_i, take in constantly $\theta_i > 0\ (i = 1, \dots, J-1)$, exponential hazard function is established.

$$\lambda_i(y_i) = \theta_i \tag{4.1}$$

By using exponential hazard function (equation 4.1), it is possible to express a deterioration process that satisfy the Markov property (independent from the past history). Furthermore, the Markov transition probability can be defined by using this hazard function.

Using the exponential hazard function $(\lambda_i)y_i = \theta_i$ the Markov transition probabilities $\pi_{ij}(z)\ (i = 1, \dots, J-1; j = i, \dots, J)$ when transitioning time interval z between rating i to $j(> 1)$ is

$$\pi_{ij}(z) = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z) \tag{4.2}$$

$$(i = 1, \dots, J-1; j = i; 1, \dots, J)$$

However, the following notation rule is given:

$$\begin{cases} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} - 1 & (when\ \ k = i) \\ \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} & (when\ k = j) \end{cases}$$

Unknown parameter θ_i on exponential hazard function, a combination of unknown parameter and observable variable, is represented as:

$$\theta_i = \boldsymbol{x}\,\boldsymbol{\beta}_i^{'} \tag{4.3}$$

Here, $\boldsymbol{x} = (\boldsymbol{x}_i, \dots, \boldsymbol{x}_M)$ is a characteristic vector of variables, $\boldsymbol{\beta}_i = (\boldsymbol{\beta}_{i,1}, \dots, \boldsymbol{\beta}_{i,M})$ is a row vector of unknown parameter $\boldsymbol{\beta}_{im}\,(m = 1, \dots, M)$. As a result, it is possible to represent the different rating of deterioration speed.

Next, expresses deterioration hazard rate for each pavement section by relative evaluation of deterioration speed, and describes deterioration hazard rate by relative evaluation of deterioration speed derived by estimation of Mixture Markov deterioration model. The pavement section that will be analyzed is divided into individual group of K as the basic unit for relative evaluation of deterioration speed. In addition, in the group $k\ (k = 1, \dots, K)$ is assumed that there is a total pavement section S_k. In group $k\ (k = 1, \dots, K)$ change of characteristics peculiar hazard rate (hereinafter referred to as the heterogeneity parameter) ε^k is introduced. At this time, a pavement section $s_k\ (s_k = 1, \dots, S_k)$and peculiar hazard rate $i\ (i = 1, \dots, J - 1)$ represented using a mixture exponential hazard function:

$$\lambda_i^{sk} = \tilde{\lambda}_i^{sk}\,\varepsilon^k \tag{4.4}$$

Here, $\tilde{\lambda}_i^{sk}$ is average hazard rate of rating i of section s_k in group k (hereinafter referred to as the standard hazard rate). Heterogeneity parameter ε^k is a random variable representing the influence of the standard hazard rate $\tilde{\lambda}_i^{sk}$ on the group k, that is assumed to satisfy $\varepsilon^k \geq 0$. The higher value of parameter heterogeneity ε^k is the faster deterioration speed of all facilities included in group k comparing to standard hazard rate.

In the hazard function θ_i, it is possible to represent average deterioration rate by observable factors of deterioration such as road characteristics and road traffic. Meanwhile, pavement deterioration process involves many uncertainties due to unobservable factors. The heterogeneity of these deterioration processes can be expressed in ε^k parameters derived by mixture Markov deterioration model.

4.4.3 Interpreting Deterioration Hazard Rate

As described in models above (section 4.4.2), it is possible to estimate deterioration hazard rate of each pavement section. This section discusses concept for interpretation of the deterioration hazard rate estimated.

Stochastic deterioration prediction model considers uncertainties of deterioration process which represents the uncertainty of deterioration processes in probability. In other words, rather than deterministic prediction of deterioration state of a certain time, at any given time, the probability represents possibility transition of soundness rank. This deterioration transition probability, in considering uncertainty of deterioration process, represents a variation in deterioration state at a certain time. In the macro analysis such as budget planning, if targeted in more facilities, there is a possibility to estimate maintenance demand in the future. The macro-analysis does not necessarily require information about deterioration speed of individual facilities.

On the other hand, deterioration hazard rate shown by equation (4.4) is an expression of the heterogeneity of deterioration speed of individual facilities according to deviation level from an average deterioration speed of the entire facility. Estimating the deterioration speed of individual facilities respect to assumption of transition in pursuance of probability distribution with heterogeneity parameter, the differences deterioration speed of individual facilities is formulated in accordance with heterogeneity parameter after an average deterioration speed of the entire facilities is estimated.

Even though, the hazard deterioration rate has been estimated in this way, it is important to notice here, a representation of average deterioration speed of peculiar individual section does not give information about deterministic deterioration prediction for each section. A high value of heterogeneity parameter ε^k shows deterioration speed in the pavement section is relatively faster compared with other pavement sections due to historical deterioration performance data. If deterioration performance is relatively faster in the past, it can assume that there is some factors influence deterioration speed. Using this information, preferentially repaired in sections that have high probability in deteriorated, reducing risk of future deterioration can be acquired. Furthermore, sections at which deterioration performance is extremely poor can be expected to achieve pavement long-lived by doing the examination construction such as application of new methods and new materials.

4.5 Practice of Benchmarking Evaluation

4.5.1 Summary of Practice

This section discusses application of benchmarking evaluation for pavement maintenance work of highways in Kyoto City. The Kyoto City manages 3.100km road pavement which reaches about 680km in total length of highways pavement. The country's leading sightseeing spot from the northern part to the center part in the city exists, the southern part has a prosperous region characteristic with industry and distribution activity, furthermore, a variety of different road network which characterized by traffic and urgent transportation road are formed.

The road characteristics investigation is implemented in highways from 2006 and the result has accumulated in data base. Also, repair history of pavement maintenance work constructed in the past as well as road damage information has documented. As for target, to implement benchmarking evaluation, to estimate deterioration hazard rate by evaluation heterogeneity of deterioration speed along the route as well as to create deterioration prediction model using data accumulated. Moreover, undertaking operational improvement of pavement maintenance work based on the logic model is considered.

4.5.2 Issues of Pavement Maintenance Work

Kyoto City has managed an enormous of road lengths that obviously has deterioration in the pavement. Each engineering works office which in charge of road maintenance has selected route for repair based on routine patrol and demands from the citizen, and also has determined the necessity of maintenance. However, in current severe financial situation, it is difficult to increase maintenance budget dramatically. In such situation, an understanding objectively damage states of road and importance level of route, selects route candidate for repair, and requires effective repair to be carried out by priority level from among of an enormous length of pavement.

Firstly, road characteristic investigation of highway in 2006 tries to understand damage states quantitatively in road flatness, rutting and cracking. The evaluation result of each 20m is managed at the same time to aim at understanding damage of targeted road such as potholes and pavement detached with 100m as basis of unit evaluation of investigation result in order to adjust with evaluation section of road characteristic investigation executed in the past. By understanding road damage states quantitatively, objective indicators while selecting candidate repair section is possible.

Meanwhile, determining optimal maintenance method in only by road deterioration states is difficult, it is obligatory to evaluate soundness of structure under road pavement. The FWD (Falling Weight Deflection) investigation can evaluate non-destructive structural strength and pavement materials strength by measuring amount of deflection as a method of investigating soundness of pavement structure. Implementing the FWD investigation at all enormous length is unrealistic but appointing optimum maintenance repair method and a repair plan with very high accuracy becomes possible, due to that can evaluate comprehensively from both sides of road damage and pavement structure if the FWD investigation is enforceable in all routes in the city. Therefore, effectively used of existing data such as maintenance history information and road characteristics investigation that has already implemented requires a method to conclude priority of structural investigation section and repair section.

The benchmarking evaluation proposed in this study was applied to pavement maintenance management work issues under such a situation, and a new management system that improves pavement maintenance management work was established

4.5.3 Benchmarking Evaluation using Logic Model

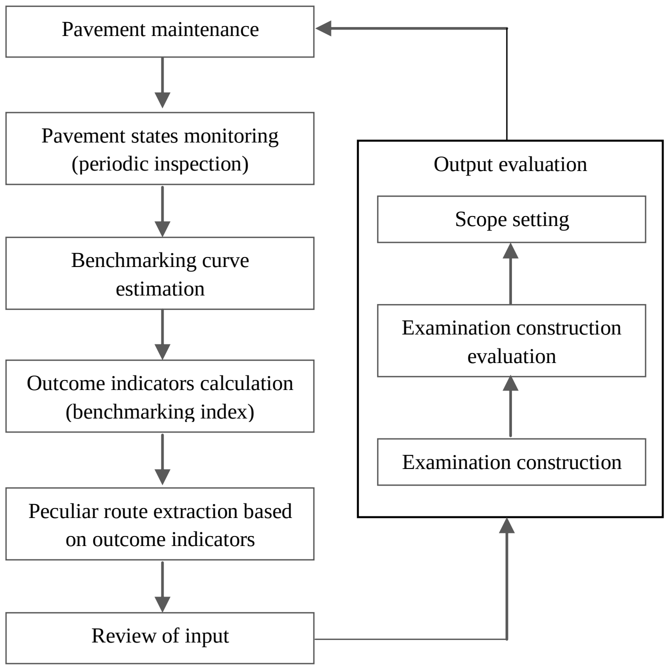

Figure 4.4 Benchmarking Evaluation Procedures

The benchmarking evaluation is performed by deriving deterioration hazard rate in pavement section, and as a result, review of input such as maintenance strategy improvement is carried out pursuant to the logic model. By evaluating heterogeneity deterioration speed in highway, classifies an early pavement section as a peculiar route in relatively deterioration speed, performs an experimental application of such new building methods and new materials, and verifies an effective maintenance method in making long-lived pavement.

The scope of an effective maintenance method is organized in making long-lived pavement as a result of examination construction, spreads as a standard method, and updates the benchmarking curve. By repeatedly performing these in sequential, rationalization of pavement maintenance work and making long-lived pavement and also cost reduction can be realized. A benchmarking evaluation procedure can be seen in figure 4.4.

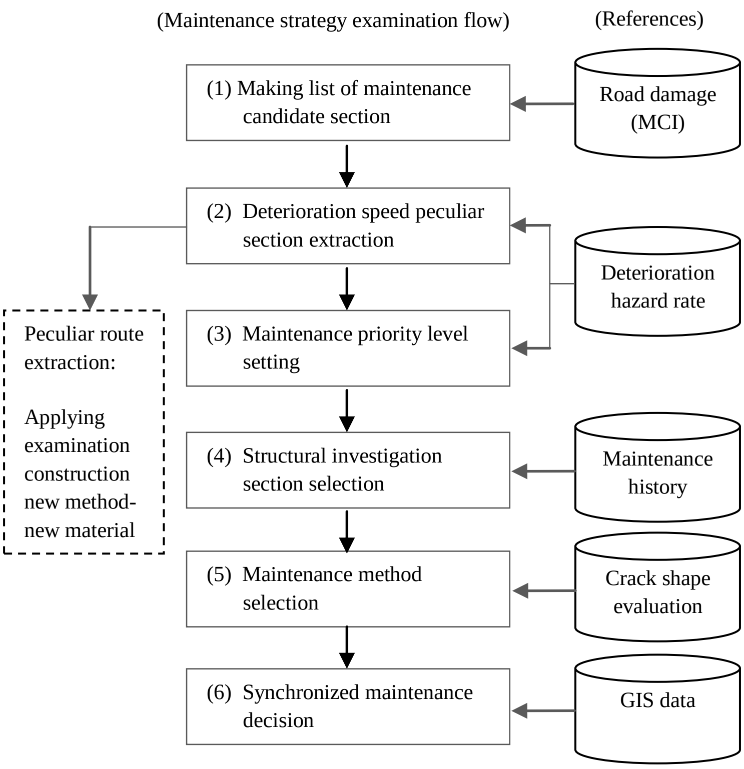

Figure 4.5 Maintenance Strategy Examination Flow using Deterioration Hazard Rate

The estimation result of deterioration hazard rate can be referred in decision making for planning of maintenance strategic plan. Figure 4.5 demonstrates a flow maintenance strategy review that employs deterioration hazard rate. A high deterioration hazard rate of pavement section indicates a high deteriorated risk in respective pavement section in the future.

4.5.4 Analysis of Benchmarking Evaluation

Here, let's acquire new inspection data, and assume deterioration prediction model is updated. The road characteristic investigation is executed after deterioration prediction model is estimated, and a certain time passes and inspection data is acquired. An existing deterioration prediction model is updated by using acquired inspection data. In that case, an existing deterioration prediction model before updating is defined as the benchmarking curve. If updated deterioration prediction model shifts from the benchmarking curve to the right side of figure 4.6, it is meant that an average deterioration speed slowed by carried out maintenance from that time to update that constructs benchmarking curve. During this time, a number that shifts from bench marking curve to the right side can be evaluated as an effect of making to long-lived if measure of making to long-lived of some pavements was applied.

In addition, deterioration hazard rate was calculated to estimate heterogeneity at deterioration speed for each route.

In order to create deterioration prediction models, several investigation results related to same investigations unit in road characteristic investigation are needed. Several data cannot be obtained in same unit investigation of road characteristic investigation that has begun since 2006 in Kyoto City. However, maintenance construction information executed in the past was accumulated, data base for estimating deterioration progress and elapsed time from repair time to road characteristic investigation which summed up as one sample was constructed, and about 2,300 samples were acquired.

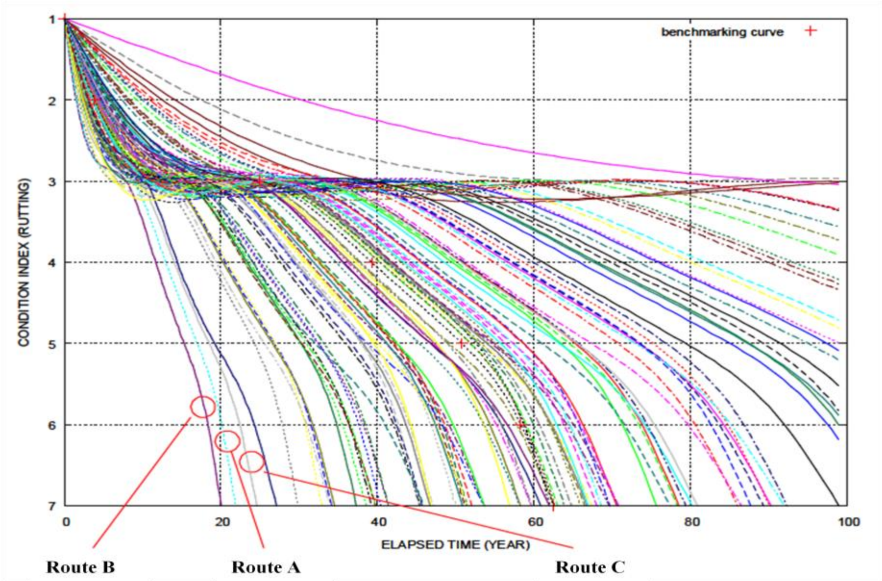

Figure 4.6 Deterioration Curve of Rutting along Route

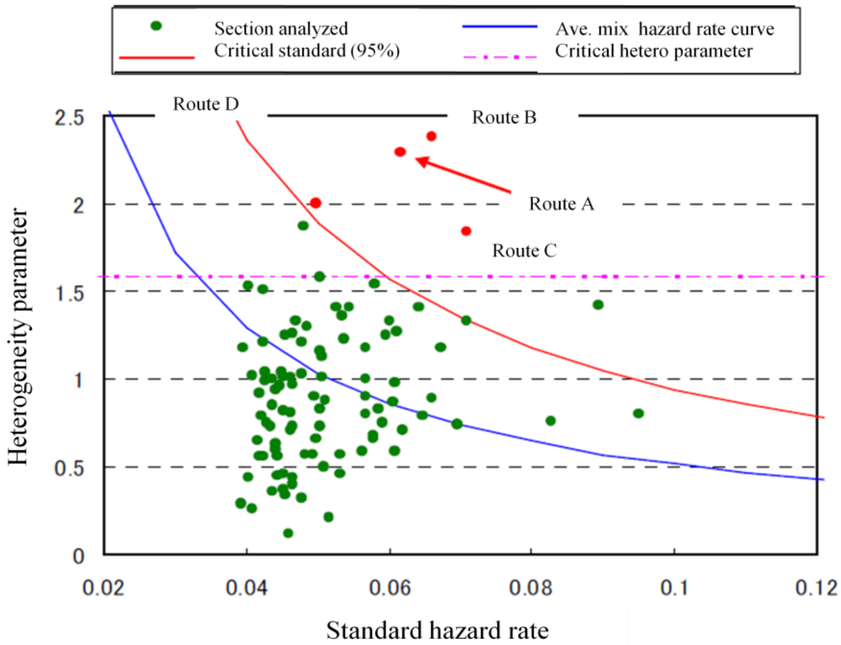

Figure 4.7 Relation of Standard Hazard Rate and Heterogeneity Parameter (rutting: rank 2)

Next, by using mixture Markov hazard deterioration model, deterioration hazard rate was estimated based on evaluation of heterogeneity of deterioration speed. The unit evaluation of heterogeneity parameter was established by a group into each route. If one route consists of two or more management office, it was concluded by jurisdiction of the office area.

Figure 4.6 shows deterioration performance curve is drawn according to the life expectancy and deterioration hazard rate along the route is estimated for rutting states. Deterioration hazard rate evaluates deterioration risk in each pavement section, and deterioration hazard rate of a large pavement section can be determined that a deteriorated possibility is high in the future independent from damage states of current pavement. Figure 4.7 is plotted relation between heterogeneity parameter and standard hazard rate (rank 2) related to each evaluation section using estimate result of deterioration hazard rate by similar rutting. The horizontal axis of standard hazard rate expresses variation of large-sized vehicle traffic. Meanwhile, the vertical axis of heterogeneity parameter expresses difference of deterioration speed according to factors other than large-sized vehicle traffic. The average mixture hazard rate curve shown by the blue line in figure 4.7 illustrates the average hazard rate of the entire route, and the red line that shows critical standard (95%) indicates critical level extracted of top 5% as a product of hazard rate. Meanwhile, the critical heterogeneity parameter shown by dashed line is a critical level extracted of top 5% of large evaluation section of heterogeneity parameter excluding the influence of standard hazard rate. Similarly, figure 4.8 and figure 4.9 show estimation result of cracking.

As a result of figure 4.6 and figure 4.7, we further classified the group of route into three routes (route A, route B, and route C) which deterioration is remarkably fast in rutting. On these three routes, Maintenance Control Index (MCI) calculated from three indices of cracking, rutting, and flatness is 4-5, and damage level at the current state does not progress remarkably in compare with other routes. Three routes of these are major highways in the southern part of Kyoto City, and it is conceivable one of the causes of fast progress in rutting that many routes has significantly large-sized vehicle traffic.

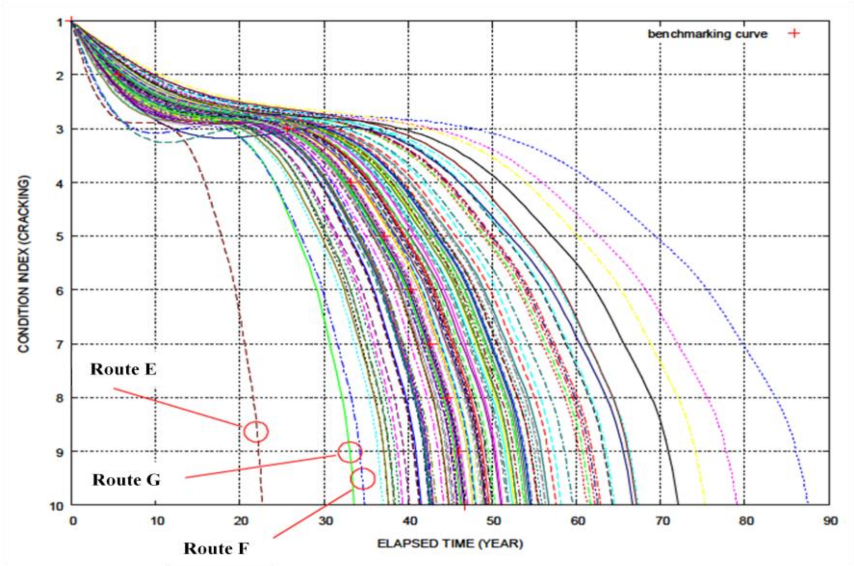

Figure 4.8 Deterioration Curve of Cracking along Route

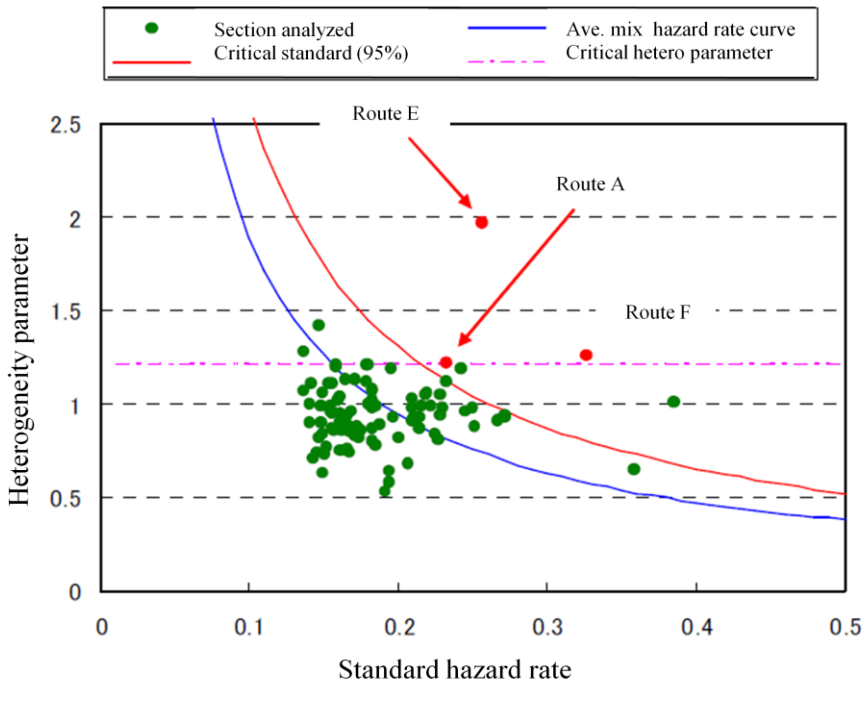

Figure 4.9 Relation of Standard Hazard Rate and Heterogeneity Parameter (cracking: rank 1)

Moreover, it is also considered due to construction quality at this time and unobservable factor. Until now, these routes was set high priority level of repair and demanded repair cost by engineering works office which is in charge of repair construction on-site did not become necessarily target of repair by MCI evaluation. However, estimation deterioration hazard rate as a result of benchmarking evaluation on road pavement coincide with repair demand section based on empirical finding by engineer on-site, a result considering influence deterioration risk not appreciable only by damage level of road section is obtained.

In other words, there is a case that proper empirical perspective was clarified by analysis of technological finding on-site based on benchmarking evaluation and the engineer who in charge on-site understands route which is high deterioration risk empirically by routine maintenance. Meanwhile, in section which is high risk in deterioration extracted by benchmarking evaluation is also possible to find a new section issues not always only by empirical finding by the engineer on-site. For this case, verifying validity of benchmarking evaluation by executing a detailed investigation to analyze mechanism of deterioration in extracted section issues becomes important.

4.5.5 Issues and Effect by Applying to Pavement Maintenance Work

In order to practice pavement maintenance work using benchmarking evaluation, it is necessary to understand purpose and content of operational model improved by each person in charge in pavement maintenance work, and to play each role. Therefore, dissemination activities such as training concerning to asset management and training of system operation to input repair history information to the database were executed. Moreover, collects information of introduction new methods and new materials that able to expect the effect on making long-lived pavement and cost reduction together, as adjustment control division checks adaptability to a technical standard and validity, for the content of the design of repair construction executed with the engineering works office, and the dissemination to the engineering works office was done. By employing such as training and information sharing, the effort to work improvement in the organizations is infiltrating steadily.

During execution of repair construction, Adjustment Management Division consolidates information on the engineering works office in line with creating repair candidate section list, and selects the priority level of repair by benchmarking evaluation. The engineering works office carry out detail investigation in the site based on information offered by Adjustment Management Division, decides the repair method, and creates the budget request document. If the best repair method is decided, the execution section of FWD investigation is selected by using benchmarking evaluation. Thus, the approach of maintenance work to a new pavement by using benchmarking evaluation is begun. Related to the route in which remarkably the deterioration speed of rutting shown by benchmarking evaluation, some sections that has excellent drain ability by pavement combination material is adopted as strengthening rutting measures and to aim at making long-lived. The consensus of stakeholders concerned to the strategy of making long-lived in rutting to consider the deterioration risk in the future by using benchmarking evaluation was obtained and will be referred to other routes to be given priority in the repair plan as before to use only MCI value by the road characteristic investigation.

On the other hand, in maintenance work intended for mountainous area, up to now, since that not necessary to consider higher road when repairing pavement section which house does not stand by road side, using overlay is a general approach in this case. However, a policy for adopting the road sub-grade reproduction method was taken in condition both route which current MCI value was low and deterioration risk in the future was high. The road sub-grade reproduction method was evaluated to be able to expect in reducing life-cycle cost and making pavement long-lived even though rises in initial cost compared with the method as before. In the road sub-grade reproduction method, it is newly to implement sub-grade stabilization treatment by doing mixture-compaction of stability material such as bitumen material and cement at the same time and crushing in-situ existing asphalt in the road. This method has advantage such as attempting the cost reduction compared with replace method, a few of scrap and fast in works. Thus, by understanding of asset management infiltrates the engineers who in charge of maintenance works in the site, and recognizing again importance of the pavement design that considers cost reduction and making long-lived, a maintenance strategy using benchmarking evaluation is being practiced.

In Kyoto, the practice of maintenance strategy using benchmarking evaluation based on the logic model has just started. Thus, it requires certain time to appear actually effect of cost reduction and making long-lived by these approaches. The logic model functions as a tool in monitoring effect of these approaches. It is important to do regularly review of the input such as maintenance strategy in order to improve benchmarking curve and evaluates the outcome achievement in the logic model regularly. Moreover, it is significant to accumulate continuously road characteristics and maintenance history information for benchmarking evaluation. It is prominent to analyze the factor with fast deterioration speed in detail to give effective measures to those pavements which possible extract fast section in relatively deterioration speed according to deterioration hazard rate. Furthermore, it must be verify the changing of benchmarking curve and accumulate more detailed data while the examination work is done to the section in which deterioration is remarkably fast. And, it is substantial to evaluate the effectiveness to reduction maintenance cost and making long-lived in the entire pavement management by expanding coverage to other routes as an effective repair method. Take time to this, continuously accumulate and verify various data in order to achieve rational pavement maintenance, also clarify specific effect of reduction cost related to pavement maintenance work as an outcome indicators using logic model, continues improvement work by continuous operation of logic model, and is a major issue in the future.

4.6 Summary and Recommendations

In this study, deterioration risk in pavement section was evaluated by paying attention to road pavement maintenance issues, generates routine maintenance work using statistical data, and proposes concept of asset management system that continuously decreased deterioration risk. In addition, a methodology that requests maintenance strategy to aim at achieving reduction cost and making long-lived pavement was developed, and an approach that attempts in applying to actual maintenance work was considered. In that case, focuses on maintenance of road pavement that local government managed, constructs pavement logic model for highway, and proposes operation method. In addition, management system to perform steadily such as repair method selection and updating necessary data in order to propose benchmarking evaluation method at deterioration speed using statistical deterioration prediction model as a quantitative evaluation method to achieve cost reduction and pavement long-lived.

Furthermore, concept of a new management system of road pavement proposed by this research was applied to maintenance work of highway in Kyoto City, and a practical example which aims at rationalization pavement maintenance work was presented. Deterioration hazard rate was estimated using road characteristics investigation result and maintenance history information that has accumulated in Kyoto city in actual and also benchmarking evaluation of deterioration process of road pavement was applied. As a result, benchmarking evaluation empirically describes that it was an effective method in consensus forms between the person in charge who executed maintenance work at the project level and the decision makers who managed the network level. Additionally, this method is an efficient way to grasp not only damage state of road pavement but also developing of repair plan using deterioration risk in each pavement section in the future. Moreover, it is considered that concept in achieving cost reduction and making pavement long-lived is infiltrating in the organization regarded to maintenance of pavement because applied benchmarking evaluation based on logic model in practice of maintenance work, and the system to work on asset management was in order.

However, in regard to improve practical use of this study, several points should be emphasized as topic for extending in the future:

- Mid/long-term practice is a necessary, for this relation, an important issue to accumulate and to update various data by executing evaluation based on logic model surely in order to achieve final outcomes such as cost reductions and making long-lived.

- Due to that estimation result of deterioration hazard rate comes to influence maintenance strategy strongly, pavement maintenance strategy used benchmarking evaluation as presented by this study should construct a mechanism to update sequentially deterioration hazard rate from accumulated enormous data.

- Establishing a methodology to operate logic model in pavement maintenance work arranged systematically in widely is the greatest issues in the future to achieve rationalization of pavement maintenance work.

- It is important to continue activity to construct management system that can achieve a high result while repeating by trial and error and doing a discussion among parties concerning in practice established methodology proposed by this study.

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Chapter 5

Kyoto Model Pavement Management System as International Standard

5.1 General Introduction

Globalization of economic activity advances, various failures to international market reduces, and market borderless has progressed. Global markets are flattened, and "technically excellent product" became an age that was able not to be necessarily captured market. In a word, it is the necessary condition for not stay only in development of a technically excellent product, recognition of product as the world standard, and adjustment to the world standard in order to secure the merchantability. Furthermore, agreement of WTO/TBT (agreement relating to Technical Barrier to Trade) was obligated to ratification of many countries, and adjustment to domestic technical regulations system and to an international standard.

Here, the standard is classified by several level depends on its scope. For instance, an enterprises standard and an industry standard are created for enterprise and industry as small scope. A national standard organization should provide generalization of national standard in each country. In others, an international standard is the widest scope of standard. These are approved by mechanism of a priori market standardized by being registered such as to the organization of standardization, and generally called an industrial standard. ITU (International Telecommunications Union), ISO (International Organization for Standardization), and IEC (International Electro-technical Commission) are typical organizations that promotes standardization internationally and mostly for industrial standardization.

Furthermore, recently, an industrial standard that settles on standardization of management systems such as the ISO 9000 series (quality control system standard) and the ISO 14000 series standard (environmental protection system standard has spread rapidly. Those industrial (engineering and production standard) are de-jure standards which will be formulated by the standardization organization.

In contrast, product and standard that had come to be used widely by the user as a result of market competition became a posteriori standards (eventually) is a de-facto standard. Standardization of the ubiquitous type (system that can use by everyone without a barrier in anytime and anywhere) shown in the change of a social infrastructure recently such as internet, line network, and transportation network has progressed rapidly. These are de-facto standard that is formed on business field, and is called business standard.

In many developing countries, a little discussion of sufficiently and necessity an international standard despite of approach of a national standard had been done from such as geographic condition so far. In addition, correspondence to de-jure standard such as ISO has been captured if anything passive (increase in amount of work) in the business. On the other hand, developed countries has been implementing generally a strategy to use this standardization positively in forms of incorporating standardization into business model as tool of business. Now, facing of change in international market from approach to standardization by incorporating concept of business standards so far, developing a new business standard has become the most pressing issues in order to survive in the global market.

A discussion concerning international standardization of infrastructure asset management is encouraged. In de-jure standard of asset management, what should be done for rationalization of maintenance of infrastructure asset *(What)* are targeted. De-jure standard are intended to be one of sharing attempted and can called as hardware standard. Meanwhile, in technical perspective of asset management, a discussion of method for deriving rationalization of maintenance *(How)* is arranged. As for management methodologies, technological systems that should be applied by some situations of maintenance field are different. For instance, there is an assumption that setting a strategic objective of asset management is obligated. However, content and standard of objective setting are different depends on the managers. Moreover, acquired data items, contents of monitoring, and methods for achieving the objective are entrusted by the manager. Therefore, the possibility of excellent method in more technically becomes a de-facto standard is high. In standardization of asset management, software standard is required at the same time.

Hardware standard as de-jure standard and software standard as de-facto standard are not completely conflicting in the context of standardization strategy that aims at making of oligopoly market though standardization approach is various. It is necessary to establish business model that simultaneously achieves software standardization and hardware standard. In the field of pavement asset management as targeted in this study, a lot of studies that have progressed to technological developments, available knowledge and technology that can be put in practical use have been accumulated not only in Japan but also in international way. Referring to paper of Aoki (2011), the objective of this study is to propose pavement asset management system based on standardization strategy for diffusion and to consolidate those new technologies and accumulated knowledge. Service and innovation of pavement asset management occurs because of diffusion element technology.

Pavement Asset management system proposed in this study is an integrative system that aims at global platform standard in pavement management that provides a standardization of element technology in accordance with international standard and independent to conventional PMS, and flexible in corresponding to pavement management field furthermore.

In this chapter, following section presents the basic concept of Kyoto model. Section 5.3 describes the whole structure of Kyoto model. Relation between Kyoto model and international standard of asset management is discussed in section 5.4. Meanwhile, section 5.5 deals with logic model evaluation and pavement maintenance work. Section 5.6 provides benchmarking evaluation of road pavement. The last section summarizes contributions of Kyoto model as de-facto international standard and recommendations for future study.

5.2 The Basic Concept of Kyoto Model

As previously mentions, since 1970, a variety of studies on the pavement management systems (PMS) have been conducted. These studies are designed to reduce the life-cycle cost of road pavement at the project level and or network level (Hass et al, 1994; Hudson et al, 1997; Herabat et al, 2002). Take example in United States, PMS developed is configured as a system of centering and uniting in data banks for all action related to pavement organically (Kasahara, 2005). As in Japan, the studies on PMS have been positively executed in regard to pavement management systems. For instance, Jido et al (2004) present a pavement management accounting system (PMAS) for the road managers of local governments to execute rational repair referring to asset management information regarding road pavement.

Now, HDM (Highway Design and Maintenance Standards Model) developed by the World Bank is recognized as the de-facto standard of pavement management system that widely open to public user in the world (PIRAC, 2006). The latest version (HDM-4) has been used as a support system for road development and maintenance plan mainly in the developing country. This HDM-4 has a role as an analytical tool of PMS which supports economic analysis such as study on budget allocation, financial condition evaluation and road investment evaluation.

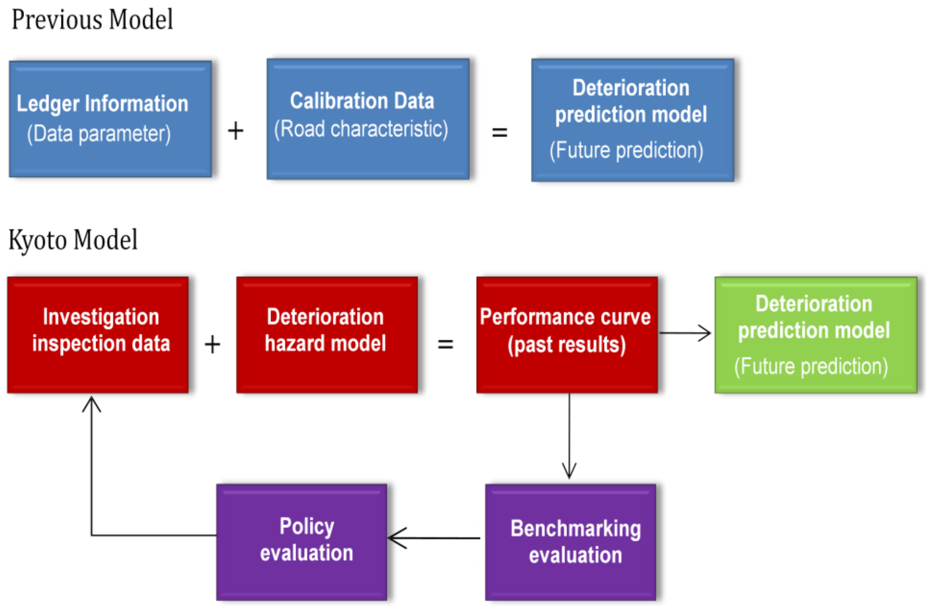

Figure 5.1 Kyoto Model Feature (compared with previous model)

However, using HDM-4 for analysis, calibration of deterioration prediction model by using an enormous amount of data input concerning a variety of data related such as regional characteristic, weather, and traffic data should be conducted (Aoki, 2011). In fact, it is impossible to collect input information of those related data to operate PMS which aims at rationalization of pavement maintenance work. Therefore, the HDM-4 cannot be operated in optimal way due to that collecting enormous input information is facing problem especially in some developing countries. The deterioration prediction model installed in HDM-4 predicts deterioration speed by adding road characteristic data (calibration data) as standard for deterioration prediction model and without using the archive data of actual investigation of road pavement maintenance targets. However, deterioration process of road pavement is complex, and various factors relate mutually, a certain specific pavement section is deteriorated. A difficult factor to observe such as material characteristics, condition during construction besides observational factors such as traffic and meteorological conditions might rule greatly. Moreover, different conditions of pavement section, different performance afterwards according to the constructed age. Therefore, it is difficult to specify deterioration factor and also there is diversity in the factor in deterioration in the road pavement. Even if enormous input information for deterioration prediction is collected so that HDM-4 may demand, it is impossible to express deterioration performance in pavement section concerned.

The Kyoto model proposed in this study adopts methodology that estimates deterioration prediction model (deterioration hazard model) by using repair history data, and history data of investigation inspection executed in actual pavement section of maintenance targets. The deterioration performance curve estimated by using data of repair and actual investigation inspection has just modeled the rule of past deterioration performance concerned to road pavement. In PMS, improvement and evaluation based on past performance (Check and Action) play an important role (Details are discussed in section 5.6). An actual performance of road pavement is expressed in the archive data such as repair history data and result of periodic inspection of pavement. In using deterioration prediction model that modeled rule of this archive data, the deterioration process in the future is assumed equal to past performance of concerned road pavement. As for the Kyoto model, a basic concept of the deterioration prediction model is different with conventional model of HDM-4. In addition, in Kyoto Model, by doing evaluation using past deterioration performance can give a feedback to the next plan.

Thus, the Kyoto model supports decision making of PMS based on an actual investigation inspection, repair data, and performance, is "Performance base" management systems (Figure 5.1).

5.3 The Whole Structure of Kyoto Model

In this paper, the “Kyoto model” pavement asset management system proposes regularly monitors by comprehensive perspective of routine works at management cycle of maintenance state and budget execution intended for routine works, and has hierarchical structure by strategic management cycle to point out improvement to routine works by policy evaluation. The pavement maintenance work is expressed by hierarchical management cycle, and the entire of work process is modeled by using logic model. Meanwhile, various data groups necessary for pavement maintenance work are used as an evaluation index of logic model for policy evaluation as well as being reference for decision making of routine works and being as archive of pavement data base.

5.3.1 Budget Execution-Maintenance State Management Cycle

In budget execution-maintenance state management cycle, routine pavement maintenance work is accomplished according to a unified technological standard in order to achieve the target that previously fixed. Range of influence in decision making is divided into three hierarchies with differences of project target: 1) budget plan level, 2) network level, and 3) project level. In the budget plan level (1), budget planning is settled on, and repair and update cost required to carry out long-term maintenance of road pavement managed are calculated. The budget approximation for repair and update of pavement is determined relies on situation of investment allocation to asset other than pavement, technological standard, targets and a new policy in accordance with policy evaluation. In the budget planning intended for pavement, deterioration states in the future is predicted by deterioration prediction model and current states of pavement and setting budget allocation in time axis and allocation of budget for road pavement targeted.

At the network level (2), section that requires repair and update is extracted from entire road pavement, and repair plan according to urgency level of repair and update is created. In addition, at the project level (3), repair and update of an individual section are executed according to repair plan. Information acquired in routine maintenance inputs to the pavement data base at any time, is kept and is recycled as reference data.

Post-evaluation of hierarchical management cycle formulates a new plan according to improvement content of input in policy evaluation of strategic management cycle in order to execute preferably each 3-5 years in general.

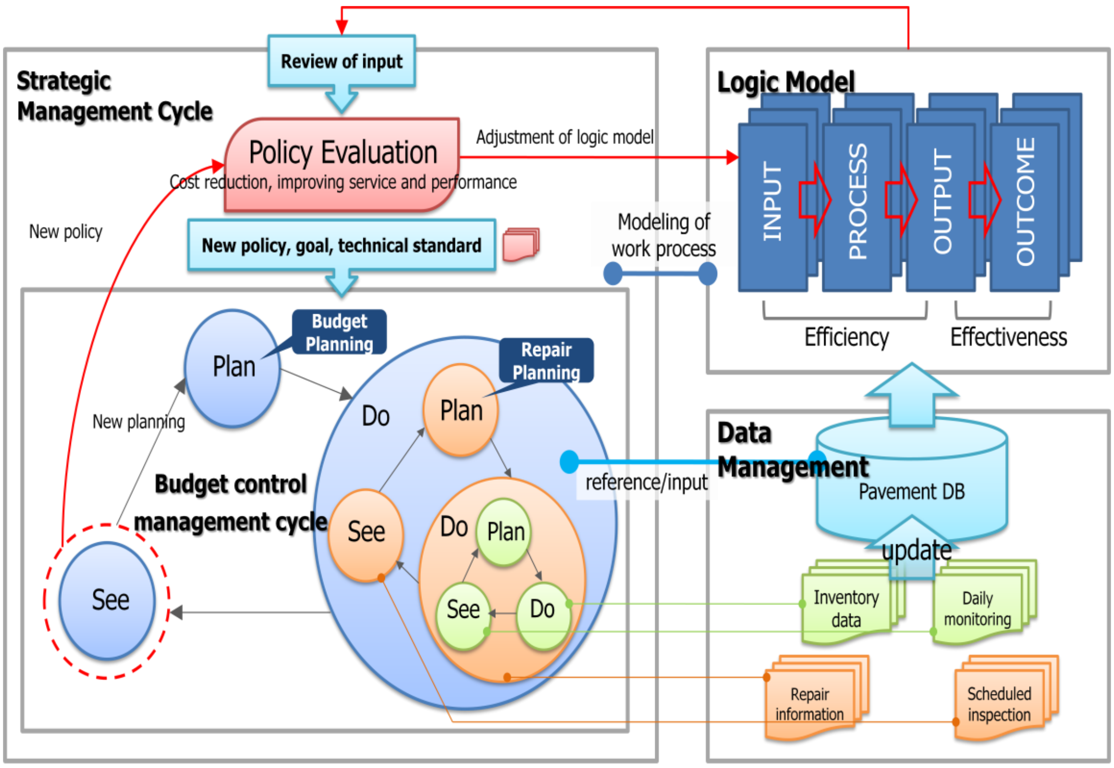

Figure 5.2 The Whole Structure of Kyoto Model

5.3.2 Strategic Management Cycle

The roles at the strategic management cycle is to review routine maintenance method regularly, to set such as technological standard, target and new policies to achieve improvement of performance (making long-lived) and improvement of service and cost reduction, and to apply in routine works. First of all, result at the budget execution-state maintenance management cycle is reviewed, and setting the following target from such achievement situation of target. Next, review of input required for target setting, arrange the result as a new technological standard, and making improvement in routine work. Further, policy evaluation is carried out based on the logic model, and restructures the logic model with review of work process.

5.3.3 Logic Model

The logic model is represented as result (outcome) of service aspect for objectives of maintenance works linked logically to relation between the result and the work in order to achieve the objectives, and expresses the entire work in an orderly sequence.

The result that executes the work based on the logic model is quantitatively evaluated as an output index and an outcome index, and as a result, target of input improvement is clarified by analyzing contribution level of individual work and routine work to the entire work, and extracting the work (activity) with low contribution level. Moreover, the factors are analyzed by logic model if failure to achieve the objectives and combination of ways to achieve the objectives (input) is reexamined during review time of a new plan.

Thus, the logic model is a tool in improving and monitoring accomplishment of the work and modeling the entire of pavement maintenance work. Method of pavement maintenance work and setting objectives are different in regard to management subject, and customizing management system is compiled in developing logic model.

Policy evaluation based on the logic model requires regularly monitoring, and maintenance information is required in evaluation and calculation output indicators and outcome indicators. Information that should be acquired in routine maintenance work is decided by evaluation item of the logic model. Example of important monitoring information when considering evaluation based on the logic model of PMS is arranged as follows.

5.3.3.1 Complaint

A complaint comes from citizens and road user concerning road pavement states. Information on complaint should be utilized as an important source to evaluate output and outcome indicators by aspect of service delivery and user satisfaction rating. It might be found a failure of road does not evaluated in road deterioration index (such as rutting and cracking rate) but evaluated by road characteristic investigation.

- In which part of road those complaints refer?
- In what failure of pavement those complaints refer?
- Which is attributes of complaint source (road user, pedestrian, and residential road)?

5.3.3.2 Factor of Repair

If pavement section repaired which is caused by trouble and deterioration of pavement, it is needless to say that accumulation of repair history data that describes content and location of repair are important. However, recording of repair factors during repaired is not so much. Repair of road pavement does not limited to road deterioration but is performed by various factors such as decrease in drainage function, noise, and vibration. Repair factor data becomes valuable monitoring data to evaluate service level, performance of pavement in similar data complaint.

- In what deterioration factor and damage repaired caused?

5.3.3.3 History for Maintenance Support

An emergency action is subjected to damage that has a risk compromising with user safety suddenly occurred such as pothole by routine maintenance (maintenance support). History information for maintenance support can be used as an indicator of such as setting of repair priority level, evaluating vulnerability of pavement structure, and examining of rationalization of execution frequency of routine patrol.

- What kinds of damage were treated (content and location of damage)?

5.3.3.4 Pavement Database

As for the Kyoto model PMS "performance base", accumulation of pavement data base in order to evaluate the performance becomes important. The logic model is intended to model entire pavement management cycle as shown in entire structure of Kyoto model in figure 5.2. The pavement data base is generated form pavement management cycle, and can be defined as knowledge data to evaluate the logic model. Therefore, definition of pavement data base is defined when the logic model is made.

5.3.3.5 Evaluation of Road and Role of Pavement Database

In pavement maintenance work, handled information reaches an enormous amount due to covering all pavement sections in the route. Arranging enormous information, considering influence to safety and comfort of road user, selecting repair candidate section efficiently become important.

Section deterioration states contain a large variation (uncertainty) from complexity deterioration progresses by various factors though road pavement deterioration progresses with the passage of time.

Therefore, it is impossible to push down possibility in zero (zero risk) that pavement section necessary repair which damage progresses cannot be discovered (overlook) even if a variety of investigation inspection (such as routine patrol, road characteristic investigation, complaint and demand) to discover damaged section of pavement are executed. However, the risk can be indefinitely reduced by examining evaluation and method used of information obtained by a variety of investigation inspection.

In pavement maintenance investigation inspection, the final objective understands influence damage states to road user's safety and comfort. Simply, the objective does not represent the road state numerically. Further, catching process of a variety of investigation inspection and information overall, and understanding the meaning of the information accurately become important.

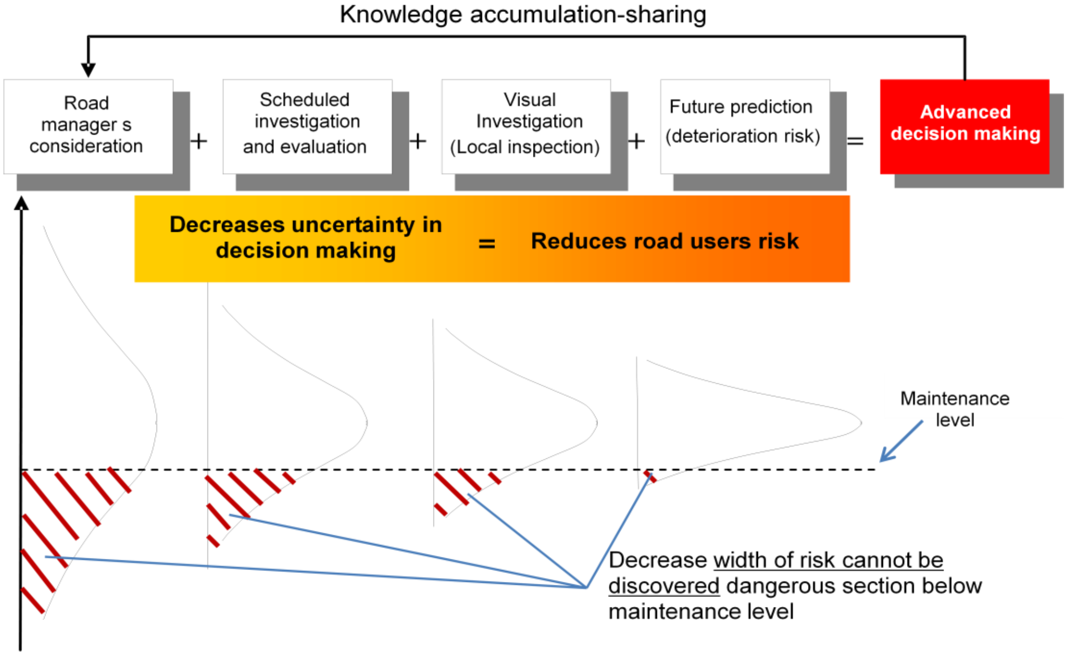

Figure 5.3 Uncertainties of Pavement Investigation and Decision Making

Figure 5.3 illustrates concept of reduction uncertainty process in pavement investigation inspection and decision making for selection process of repair candidate section. Decision making process of reduction uncertainty is shown based on acquired data on investigation inspection. The road manager observes pavement states by routine patrol in every day. Deterioration in road pavement progresses gradually excluding such as pothole occurred suddenly at long time.

It is possible to understand level of severe damage of pavement section that influences user's safety and comfort by routine patrol.

Furthermore, necessary measures due to such as road drainage, noise, vibration, and other road states by demand from citizen are implemented. Within consideration of such road manager has information of pavement states. A regular investigation of pavement is executed at intervals 3-5 year generally. In regular investigation, damage pavement states can be understood quantitatively using evaluation result and evalutes road states according to indicator such as 1) cracking rate, 2) rutting depth, and 3) flatness, using automatic measurement car (Aoki, 2011). However, a regular investigation of pavement generally divides pavement into evaluation section of 100m, and is presented as a damage value to evaluation section. Moreover, in section that has multiple lanes, all lanes are not necessarily investigated. Damage value is represented by investigation of representative lane. Thus, a regular pavement investigation by automatic measurement car remains uncertainty in a regular investigation result and catches as a sampling investigation by investigation frequency of investigation and evaluation method is a strong technique in order to evaluate damaged section. Therefore, repair methods and repair section are decided after confirming visual inspection on-site based result of a regular investigation when identifying repaired actual pavement section.

If past deterioration process is different, method and priority of measures are different even if deterioration state in current pavement is an equal section. Deterioration in pavement section depends on deterioration of entire pavement structure. Deterioration progresses in sub-grade will influences at deterioration speed of road. Deterioration process of pavement contains a large uncertainty, and deterioration speed varies widely in individual pavement section. Section which faster in deterioration speed as section which is high risk in deterioration, if section can be identified even if the factors cannot be specified can utilize as useful information for decision making of next measures.

Thus, process and information for the engineers who especially manages on-site in order to make decision in decrease uncertainty of decision making by fusing evaluation result of by machine and human decision, and support an advanced decision making in pavement maintenance work. It is important to understand the role (merit) and the limit (demerit) in each information. The limit (demerit) of single evaluation exists in each role respectively.

In other words, decreasing uncertainty of decision making due to constructing the logic model of complementary decision making for each evaluation independently to technique of each investigation inspection, and using an overall information and evaluation result each other, and consequently effect of reducing road user's risk is achieved.

5.3.3.6 Deterioration Performance Evaluation of Road Pavement

In PMS, constructing deterioration prediction model is indispensable in order to estimate pavement repair demand in the future and to evaluate life-cycle cost. The method of estimating regularity of deterioration process statistically based on recorded data of past deterioration is called as statistical deterioration prediction model which varies properties depend on objective of use of deterioration prediction model. Statistical deterioration prediction model is estimated using performance data of an actual maintenance object, and there is a merit of attempting easily in adjustment of empirical findings in maintenance on-site as a result of condition in order to utilize in accumulating some data. A large of uncertainties interposes in deterioration process of pavement, and a significant difference in performance deterioration is occurred if service and construction environment are different even if the pavement has same environment.

Meanwhile, another characteristic of statistical deterioration prediction model is possible to express performance of past deterioration. In routine maintenance, deterioration and repair demand in the future for facilities are estimated based on this statistical deterioration prediction model. Deterioration prediction model is invariable as long as new data is acquired and the deterioration forecasting model is not updated.

Here, let's assume a case which new inspection data is acquired and deterioration prediction model is updated. Road characteristics investigation is executed after acquired inspection data and passes a certain period to estimate deterioration prediction model. An existing deterioration prediction model is updated by using inspection data acquired. In that case, an existing deterioration forecasting model before updating is defined as benchmarking curve (Obama et al, 2008). If updated deterioration prediction model shifts from benchmarking curve to direction of making to long-lived, it is meant that an average deterioration speed slowed by maintenance done for the period from point to update that constructs benchmarking curve. Meanwhile, it is possible to evaluate influences of making to long-lived by amount of changes from benchmarking curve if it is assumed that measure of making to long-lived of some pavements was applied.

In asset management of road pavement, it is necessary to develop deterioration prediction model in order to analyze life-cycle cost for predicting of repair demand in the future. However, it is impossible to predict damage of individual pavement section in the future determinately as mentioned above. By constructing pavement database, investigation result and maintenance history data according to pavement section can be are stored. Then, there is a concept to modify present damage value by adding investigation result of damage value that will progress by passage of time from the latest investigation result to present investigation result. In this case, estimating deterioration prediction type according to deterioration factor of pavement, and amount of average deterioration progress in pavement section that has same characteristic is predicted by adding to investigation result. However, due to such as location which deterioration does not progress completely and location which deterioration progress rapidly in realistically by uncertainty of deterioration process in pavement section, prediction result by amount of average deterioration progress is actuality in different state.

Moreover, the road administrator does not determine necessity of repair only from database, but also can be able to confirm the state by visual inspection on-site. Pavement road has different feature with other major infrastructures that is easily to verify road deterioration states visually while has complex deterioration process and varies characteristic widely. Deterioration performance evaluation using statistical data has an important role at PDCA cycle of pavement management by post-evaluation (Check and Action) instead of planning (Plan). Pavement deterioration prediction model is requested to be utilized after pavement deterioration characteristic and objective of use of deterioration prediction model are discussed sufficiently.

5.4 Kyoto Model and International Standard of Asset Management

5.4.1 Relation between Kyoto Model and ISO

The Kyoto model is a pavement management system that supports pavement decision making with performance base and features evaluation function at PDCA management cycle. Meanwhile, in advance discussion related to international standardization of asset management is expected to be standardized as a requirement of asset management. The Kyoto model provides a standard platform corresponding to an international standard as well as PMS that supports overall pavement asset management.

This section discusses relation between Kyoto model and ISO. The Kyoto model is composed by accumulation of routine maintenance work both circles at strategic (growth) management cycle with a focus on policy evaluation and management cycle of budget execution and maintenance state as shown entire structure on figure 5.2. Meanwhile, ISO is in a position to evaluate the plan and implementation result of asset management, monitoring of entire pavement management and has a different position from target of overview with pavement management.

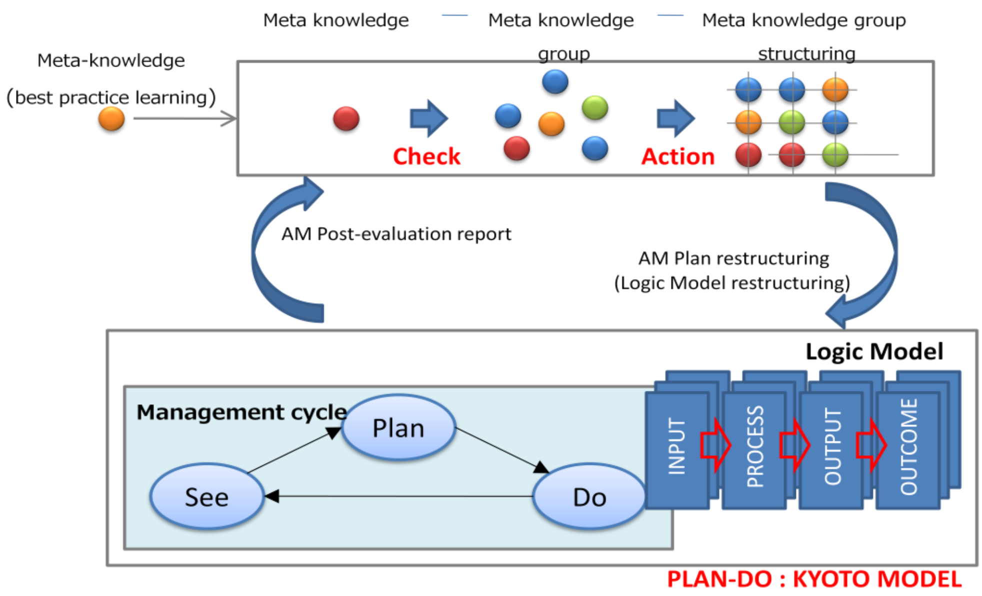

Figure 5.4 Relation between meta-knowledge of ISO and Kyoto model

The relation between Kyoto model and ISO is shown in figure 5.4. A schematic illustration of entire structure of Kyoto model as in figure 5.2 is shown in the bottom of figure 5.4 and the flow of ISO rule is displayed in upper row of figure 5.4. The relation between the Kyoto model and ISO composes PDCA cycle besides PMS. The entire Kyoto model subjects to Plan-Do, and ISO plays the role of Check and Action. In a word, it can be understood that ISO standardizes system of evaluation and improvement, and monitors entire pavement maintenance work in routine that PMS composes. Requirement to execute Check and Action system is provided by ISO. Pavement maintenance work is executed according to the logic model, and, as a result, Kyoto model generates the result of executed pavement maintenance work (post-evaluation report of asset management). ISO converts from post-evaluation report to meta-knowledge (method for acquisition of knowledge concerning Asset management). In order to restructure of asset management plan, meta-knowledge group is structured by adding past meta-knowledge and the best practice. Restructuring asset management plan in PMS is based on meta-knowledge, while Kyoto model is restructured by logic model. Customization ability and improvement of management system corresponding to standardization of ISO can be maintained by reviewing structure of logic model.

5.4.2 Correspondence of Kyoto Model and Asset Management Plan.

Next, correspondence between each module of Kyoto model and requirement of ISO in PMS is arranged. Process of asset management plan is composed by 10 steps. First of all, requirement to PMS is arranged if applies a general 10 step process of asset management to pavement asset management. In addition, relation of each module corresponding to Kyoto model for each requirement is shown in figure 5.5. Noticed here, Kyoto model module is an individual subsystem that forms PMS platform and should be understood that mechanism and concept configuring input of logic model not an application of management system.

5.4.2.1 Pavement Maintenance Condition

Maintenance state of road pavement that should be managed is verified in road length, area, and position (road network). It is a property ledger of pavement and possibly to show in relation to GIS data and pavement database.

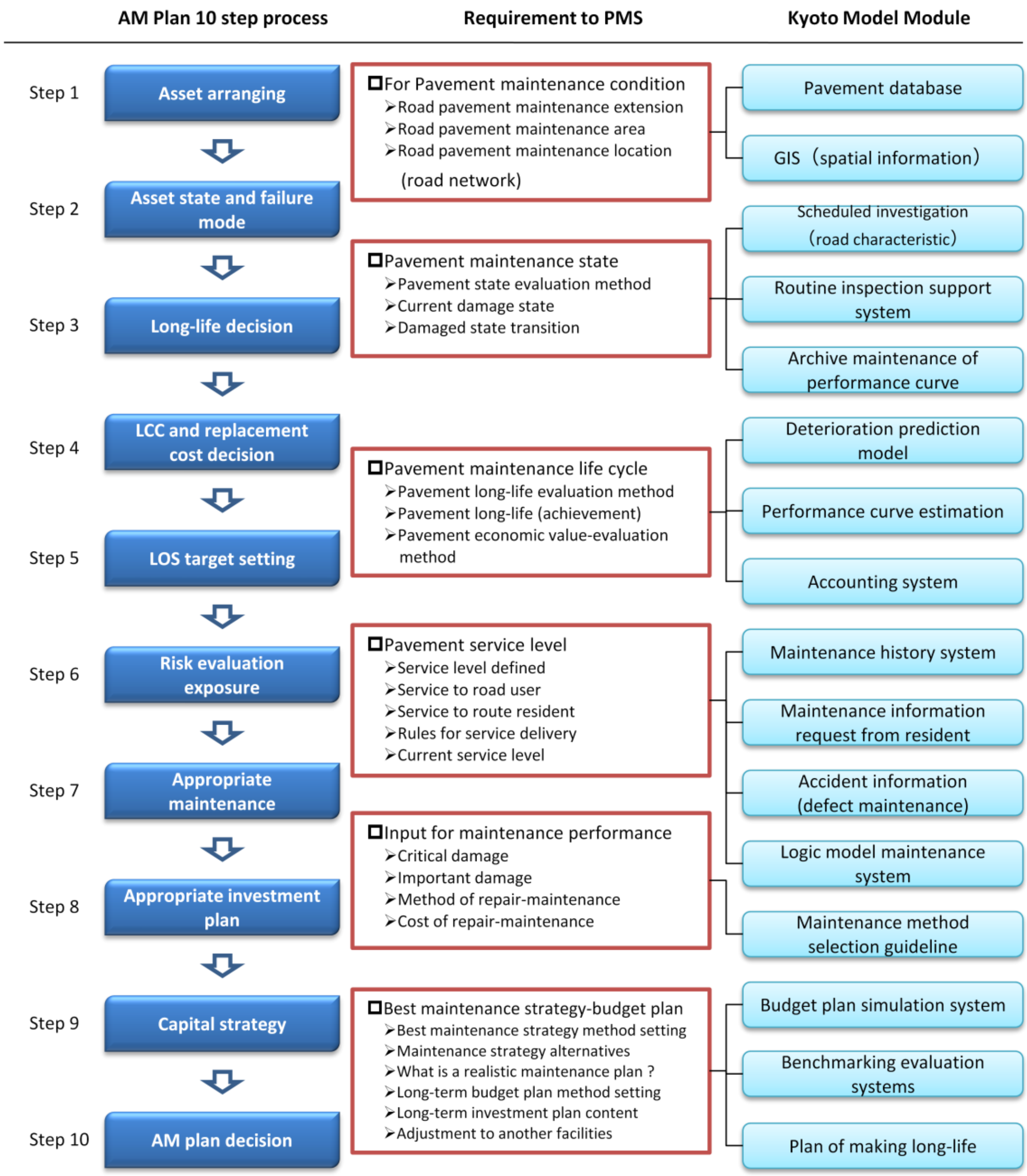

Figure 5.5 Relation among AM Plan Process, Requirement to PMS and Kyoto Model

5.4.2.2 Pavement Maintenance States

Next, it is necessary to show current damage states objectively and define method of evaluating the states in demands concerning maintenance states of road pavement managed. In addition, to evaluate process from transition condition of damaged states to current states. Pavement states can show quantitatively by accumulating states of result of routine inspection and regular investigation of road. Moreover, the transition of damage states by evaluating transition of deterioration performance curve using the time-series data.

5.4.2.3 Pavement Maintenance Life-Cycle

Define method of evaluating long-lived pavement is defined, and show result evaluating of long-lived pavement to be actually managed. Long-lived pavement can be shown as a result value of long-lived and performance curve is estimated by using deterioration prediction model. Moreover, it is possible to arrange evaluation method and extent of economic value of pavement as accounting information.

5.4.2.4 Pavement Service Level

Pavement service level requires decision whether to have obligation to provide kind of services for various service target provided after clarifying role of pavement. If thinking about service level of pavement, working in linked to damage factor and content of failure feel by resident and road user is needed (for instance, driver's handle operability, such as water splash to pedestrian user at rain, a lot of cases causes rutting, meanwhile, noise and vibration feel by resident around the route is highly influence to cracking progress). Logic model is a tool to show relation of maintenance state of pavement and to define demanded service content of each target that receives service such as route resident and road users (drivers and pedestrian user). The input for setting service level that aims by using logic model is examined in considering on demand level and rule relating to service offer. Furthermore, service level target reviews input as benchmark of current service level.

5.4.2.5 Input for Service (performance maintenance)

Aspect and method of measures to execute an appropriate maintenance are defined as an input for service (performance maintenance). If pavement deteriorated by various type of damage, the most important (critical) damage is defined by comparing it with service level based on logic model. Moreover, it is necessary to arrange standard concerning to such as recovery level, method of maintenance and repair, and levels of cost. In that case, it is important to record factor led to repair by arrange archive data of repair information in maintenance history.

5.4.2.6 The Best Maintenance Strategy and Budget Planning

Finally, is performing post-evaluation and setting method of optimum maintenance strategy and budget planning. Pavement maintenance strategy derives minimum work cost necessary to maintain target service level from relation of the trade-off of work cost and service level, and sets such as repair standard, repair method, investigation inspection frequency in order to achieve it. In that case, objective setting corresponding in actual is needed and consider not only an ideal maintenance strategy and budget planning but also alternatives such as a realistic maintenance plan. In budget planning, a long-term plan is necessary in accordance with life-cycle of pavement. Moreover, optimization of maintenance plan is aimed at arrange relation-dependency of repair and such occupancy and underground such as sewerage pipeline and collateral facilities that does not limited to road pavement. Plan of making to long-lived pavement can decide supporting policies and achievement situation to target progressively depend on benchmarking evaluation system based on comparative evaluation of deterioration performance.

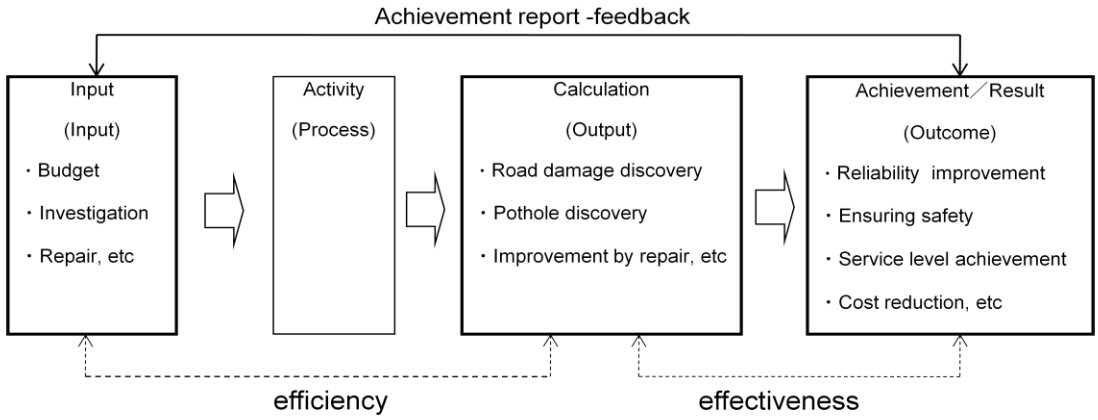

Figure 5.6 Service Production Process (logic model)

5.5 Logic Model Evaluation and Pavement Maintenance Work

An entire structure of Kyoto model is systematically arranged using the logic model, and comes to restructure logic model during reviews it. Here, a basic concept to evaluate logic model and pavement maintenance work is arranged.

Based on clearly discussion so far, road pavement maintenance work is not only all of strategic maintenance of intentional inspection-repair-update plan contributes in reduction life-cycle cost. Outline of service production process in pavement maintenance is shown in figure 5.6. Process in the left side of figure 5.6 switches on budget, executes of investigation and repair of pavement. As a result, damage such as pothole and road damage is found, and then, those failures are improved by repair. Here, each input and output indicators are measured, and evaluation of efficiency from that relation is executed. On the other hand, right process shows process to generate achievement/result (outcome) from calculated output, and executes evaluation of effectiveness from relation and performance indicator corresponding to output and outcome indicators (Yoshikawa, 2007). In addition, achievement result is reported based on result of effectiveness evaluation in accordance with performance/result indicators and it will be a feedback for improvement of input. In this way, logic model shows relation linked in logically of such as budget and work-various measures in actual and target of maintenance strategy.

Some cases of constructing and operating logic model intended for maintenance of infrastructure asset has been reported (Aoki et al, 2010; Sakai et al, 2007; Sakai et al, 2009).

Logic model is a logical model with systematically express logically contribute in relating with output such as works, services, policies and method of utilize maintenance resources for outcome as maintenance objectives of maintenance work system. Logic model functions as a tool of performance evaluation, achievement level evaluation for maintenance objectives of maintenance systems that can show relation between qualitative target and quantitative target at the same time. The logic model becomes a tool that operates achievement measurement of strategic maintenance and supports the management cycle of Plan-Do-Check-Action.

Target that should be improved as a result of evaluate based on logic model is reconsidered configuration of unit input and reviews of target setting and might be considered for further review of logic model. As for maintenance of infrastructure asset, logic model has an active role in technical guidelines to observe in standpoint view of routine maintenance. Maintenance of infrastructure asset requires monitoring in under long-term environment and assumes in case that management system does not appropriately operate as originally designs, change occurs in social environment and the citizens needs. Furthermore, change in technological level which influences to maintenance work on-site cannot be disregarded. A minor change is required in entire system by changing of investigation inspection and repair standard. A continuous monitor is required by benchmarking in achievement measurement for change in these technological levels.

In this way, effectively function of logic model as tool that supports the evaluation according to evaluation flow based on achievement measurement, and standard of review and evaluation according to logic model and benchmarking to the execution of strategic maintenance work.

The machine that is operated from early time to measure while running in road damage of pavement can be utilized as means of achievement measurement. The output indicator that relates to damage of road can be calculated by executing regular road characteristic investigation. Historically, road characteristic investigation discovers damage section of pavement, specifies repair location, understands entire damage in the macro, and has been operated as objectives of maintenance level evaluation. As for the Kyoto model, it is necessary to redefine role of road characteristic investigation. Achievement measurement requires regular monitoring of results value in order to understand achievement situation of outcome indicator, requires review of execution frequency and method of road characteristics investigation with adaptive to logic model.

5.6 Benchmarking Evaluation of Road Pavement

The Kyoto model is PMS performance base, and has a learning ability in providing information for decision making and actions for improving evaluation of maintenance work based on actual monitoring data. This section shows a basic concept of benchmarking evaluation that is major evaluation function of the Kyoto model, and introduces a case of benchmarking evaluation.

5.6.1 Benchmarking Evaluation using Logic Model

There is a technique of benchmarking in single maintenance techniques of the enterprise. The process is 1) to evaluate quantitatively their own works, 2) to explore other enterprises work with excellent in maintenance work process (best practice), and evaluates it similarly, 3) to understand deviation with their enterprises, to bury the deviation, and continuously improve of work contents. Benchmarking has intended to attempt and introduce exploring of best practice continuously and systematically, clarifies the work objective, and shows not just comparison of work results but by a quantitative indicator. Concept of the best practice in is not new, since 1990, a measure has been incorporated to paradigm shift of enterprises rapidly.

On the other hand, benchmarking in public sector is utilized in 3 forms in the following, 1) First, applies directly a concept of private enterprises as mentioned above, 2) views as wider concept, setting targets for achieving entire vision such as local government, measuring target level achievement, 3) a concept of comparing the target that is achievement of owned organization with appropriate reference value (Osumi, 2003). In the public-sector, many cases which benchmarking is only used in forms of "measureable objective" (Yoshikawa, 2007). It closes to (3). Actually, it can be said that starting from approach of finding realistic problem, exploring for the best practice that private enterprises executes many difficult case’s there, setting measureable target at first, doing a relative comparison with benchmark set in an organization concerned. Gradually, by stepping on similar process and approach of benchmarking by private enterprises as of 1), connecting to a positive improvement work by comparing performances with foreign counterpart, and discovering the best practice furthermore.

A matter of fact, this benchmarking concept comes to accomplish important role in setting target value and comparison analysis in achievement measurement. Benchmarking evaluation is a concept that can be implemented at each stage of theory of evaluation by input - process - output - outcome. Outcome indicator and target value set at work level are strongly character of instrument for internal management, and will lead to work improvement from result of the relative comparison by benchmarking evaluation of efficiency and effectiveness of work management on-site.

Effectiveness of maintenance work in order to maintain a certain service level, performing relative comparison of road deterioration speed, priority maintenance section can be extracted for pavement maintenance in a more microscopic point of view (Aoki et al, 2010). This is based on concept of improving deterioration speed leads to reduction of pavement maintenance cost. On the other hand, outcome indicator and strategic target at policy level is not an indicator generated from internal management but an indicator that should be extracted from potential issues and needs of the citizens and road user as customers. From this, indicator set at policy level may face issues of causal relation and work level that is not always in actually. However, for operational management by management objectives type, a concept of benchmarking to support necessary of organically link to target at site level and objective of policy level and securing validity of indicator. Furthermore, logic model is utilized to clarify evaluation process ties organically causal relation of activity in each stage of input-process-output-outcome.

In addition, during benchmarking evaluation, processing might be required and standardization of indicator with relative comparison among indicators becomes possible in order to compare each standard by using indicator derived from achievement measurement. For instance, as simple measure standard, the standard of 3E is introduced: 1) Economy: minimize of input, 2) Efficiency: maximize of output, 3) Effectiveness: improve outcomes through outputs (Osumi, 2003).

5.6.2 Benchmarking Evaluation Case Studies

Benchmarking evaluation is performed by deriving deterioration hazard rate in pavement section, and, as a result, review of input such as improvement of repair strategy is executed according to logic model. Deterioration speed relatively classifies faster pavement section as a peculiar route by evaluating heterogeneity of deterioration speed, conducts application of such as new methods and new materials experimentally, and examines an effective repair method in making to long-lived. A scope of an effective repair method is set in making to long-lived pavement as a result of examination construction, spreads as a standard technology, and updates benchmarking curve. By repeatedly executing these in sequent, making to long-lived and cost reduction of pavement, and also rationalization of pavement maintenance work is achieved.

Estimation result of deterioration hazard rate can be referred to in decision making for the plan of more strategic repair plan. In the future, pavement section which is high in deterioration hazard rate indicates a high risk in deterioration of relevant pavement section.

As for local government manages highways, process of cracking rate and rutting depth are estimated by creating deterioration prediction model using Markov deterioration hazard model and benchmarking curve (performance curve that is shown an average deterioration speed) is arranged. In addition, heterogeneity of deterioration speed from benchmarking curve according to pavement section is evaluated (Aoki et al, 2010).

Figure 5.7 shows that deterioration performance curve is drawn according to life expectancy, and deterioration hazard rate along the route is estimated for rutting states. Deterioration hazard rate evaluates deterioration risk in each pavement section, and deterioration hazard rate of a large pavement section can be determined that a deteriorated possibility is high in the future independent from damage states of current pavement. Figure 5.8 is plotted relation between heterogeneity parameter and standard hazard rate (rank 2) related to each evaluation section using estimation result of deterioration hazard rate of rutting similarly. The horizontal axis of standard hazard rate expresses variation of large-sized vehicle traffic. Meanwhile, the vertical axis of heterogeneity parameter expresses difference of deterioration differences of deterioration speed according to factors other than large-sized vehicle traffic.

The average mixture hazard rate curve shown by the blue line in figure 8 illustrate the average hazard rate of entire route for analysis, and the red line that shows critical standard (95%) indicates critical level extracted of top 5% as a product of hazard rate. On the other hand, the critical heterogeneity parameter shown by dashed line is a critical level extracted of top 5% of large evaluation section of heterogeneity parameter excluding influence of standard hazard rate. Similarly, figure 5.9 and figure 5.10 show the estimate result of cracking.

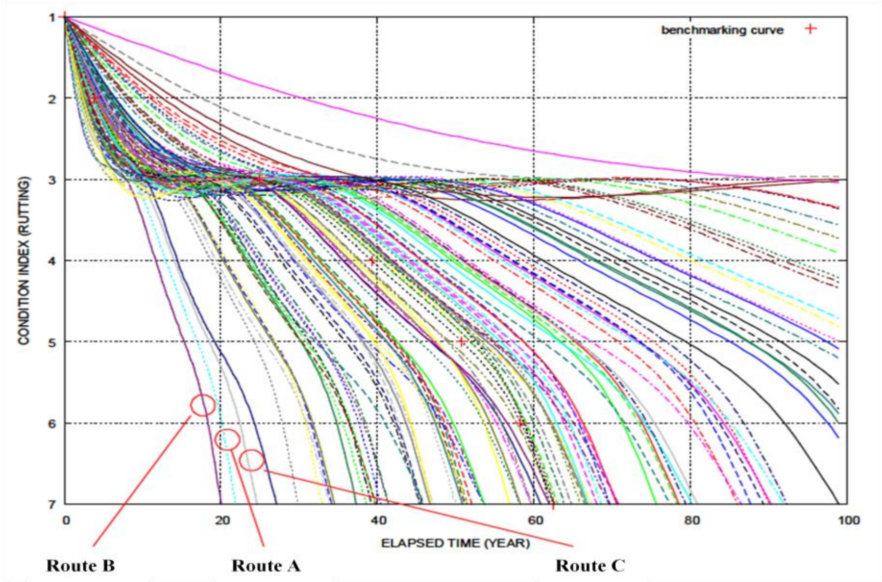

Figure 5.7 Deterioration Curve of Rutting along Route

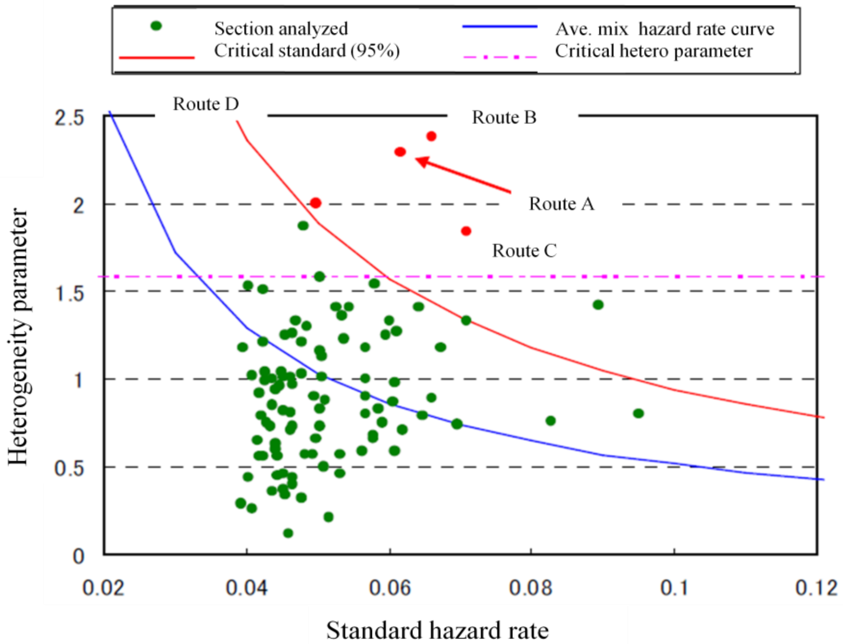

Figure 5.8 Relation of Standard Hazard Rate and Heterogeneity Parameter (rutting: rank 2)

From above-mentioned analysis result, route which deterioration speed was remarkably faster can be identified, and deterioration speed of each damage of cracking and rutting was evaluated according to each pavement section. These evaluation results can be utilized for decision making of such as priority level of a detailed investigation in order to select repair method and priority level setting maintenance. In a word, route which deterioration speed is early shows that deterioration risk in the future is relatively high, and entire deterioration risk can be decreased by executing repair priority in compare with pavement section that has same level of damage.

On the other hand, in figure 5.7 and figure 5.9, the vertical axis displays relative evaluation result of differences in deterioration speed according to other uncertainties factors excluding influence at deterioration speed by large-sized vehicle traffic as mentioned above. Understanding deterioration situation of entire structure pavement from road damage data by road characteristic investigation that progresses to deteriorate in passing age during construction is not able in road pavement. As for road damage, might be that factor in quicken deterioration speed of road and encourage road deterioration by decreasing load bearing ability/ultimate strength to below the base-course even if the state is allowed to recover damage of road by cutting overlay.

Such in pavement section, there is a rational case to select recovering ultimate strength of entire structure of pavement, for instance, carry out replacement and not by cutting overlay in evaluation states of entire pavement structure by executing detailed investigation such as FWD investigation. A standard for optimum repair method selection is installed by expressing difference of performance curve after repairs according to elapsed year and repair method of entire structure pavement in life-cycle cost analysis.

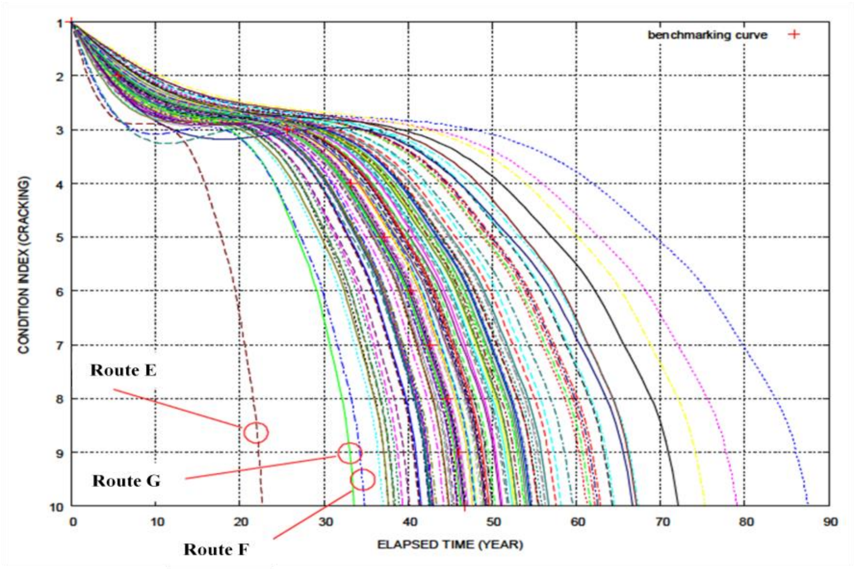

Figure 5.9 Deterioration Curve of Cracking along Route

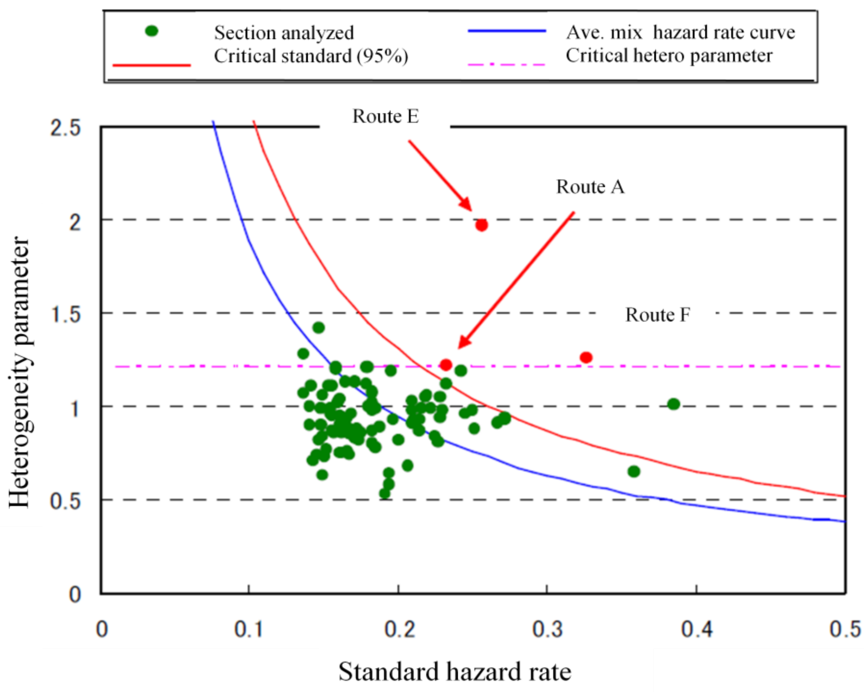

Figure 5.10 Relation of Standard Hazard Rate and Heterogeneity Parameter (cracking: rank 1)

In benchmarking evaluation presented here, there is a perspective to review method of future corresponding to section which deterioration speed is remarkably early, and review standard of applied repair method to improve logic model's input.

5.7 Summary and Recommendations

This chapter has explained logic model and benchmarking evaluation that forms as basis of the Kyoto model more in detail, has discussed a basic concept of Kyoto model pavement management system that has evaluation function and customization which enabled to overseas de-facto standardization, and has satisfied requirement of ISO for road pavement based on trend concerning international standardization of asset management. Furthermore, example of benchmarking evaluation was shown, and evaluation method that synchronized with logic model was confirmed. The Kyoto model wish to emphasize overall platform of PMS composed by logic model in more with database, application and evaluation system, mechanism, standard, in order to construct mechanism of PMS in average not merely aimed at standard application of PMS as pointed out but also while corresponding to each module and AM plan process as in figure 5.5. In addition, to form the strategic pavement management system in a long-term perspective, to construct PDCA cycle, and to synchronize with inspection function of ISO. When restructure asset management plan through Check and Action by ISO, the logic model is redefined. As a result, customization of asset management system is ensured, and standardization of PMS that has diversity is achieved.

Nevertheless, as a model that still requires an improvement, several points should be learned deeply as considering topics in the future:

- It is necessary to practice in advance of pavement asset management that applies the Kyoto model within proceed discussion concerning international standardization of asset management in the future.

- Accumulation of knowledge related to pavement asset management has achieved. In order to restructuring asset management plan, acquires strong meta-knowledge is expected.

- The Kyoto model has learning function in actual, so that, achieving PMS as a de-facto standard model in the future can be supported by accumulation of several requirements especially mechanism of adjustment with other features.

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Chapter 6

A Practical Model for Pavement Management Systems

6.1 General Introduction

Recently, a variety of studies were carried out on the pavement management system (PMS). An objective of pavement management system is to calculate optimal maintenance policy which is desired in making pavement long-lived and reduction of life-cycle cost. In relating with pavement deterioration, there are many uncertainties should be considered to predict when a next repair would become necessary accurately. Under such conditions, making observations at the service level of road pavement is looking for.

Moving toward in management approach with pavement in the core, PMS model has noteworthy support for pavement maintenance and management. Some of issues should be regarded in order to develop PMS model such as management cycle, inspection, data and database, deterioration prediction model, life-cycle cost, optimum accounting process, and additional matter like social and political issues. As for importance of PMS, development of decision support system is a must.

Continuously, a PMS tries a combination of pavement conditions in the past, present, and future. By accumulating of maintenance history of pavement in the past, then implementing management cycle in present, an optimum maintenance strategy is going to establish for the future. In regard to this kind of tasks, road agencies have to secure well-to-do effort and time in determining the optimum PMS in the first application. As well as effort and time, annual budget is also in order to carry out optimum repair strategy which usually has constraint in budget. Furthermore the optimum PMS does not means that has super function or one for all, but the system can fulfill road agencies PMS objectives and conditions.

Under these situations, self-development of PMS will square up with current states and future demand which is more considering in flexibility use of the systems. While developing their PMS, a road agency sometimes has facing a problem of strategy that usually proposes in long-term perspective. In consequently, a simple solution for them is using ready-made software which is not always appropriate with their needs. More in case, not only a wrong decision they did, but also spend gratuitous cost. This condition make a fuss with stated before that road agencies should secure budget within limitation of budget.

Learning from here, sustainable development of PMS could not be guaranteed by using ready-made software. Although ready-made software supports a size for modification by allocating calibration factors and coefficient change in model, to satisfy detail situation of their needs still in adequate. As a suggestion, moving to customized PMS is the best way to implement PMS successfully.

Along with customized PMS, accumulating of pavement data to support PMS implementation has an essential role. Comprehensive technology is required to provide sufficient pavement data. A comprehensive technology devotes component technology selected tune in with existing systems improved or newly developed in case by case approach (Kaito et al, 2010). From this comprehensive technology, a final objective of pavement data accumulating in special term and a final objective of pavement maintenance and management in general term could be reached.

Pavement data acquired during actual inspection sometimes different with data that needed to analysis by road managers or researchers. This is an example of divergence information that can be called as a lack of communication between component technologies of data acquisition and data analysis. It is also can express in general as comprehensive technology not being implemented.

In general, pavement data is closed to the public. In some countries, particularly in the developing countries, public (researchers, lecturers, student and people in general) have not able to access the data including for academic reasons. This condition affected by difficulties of collecting pavement data. To collect data pavement in example, of course, required amount of time, man-power, equipment and also cost.

Actually, there are many databases developed by road agencies. Nevertheless, there are still a few cases that these databases functions to pavement asset management and PMS implementation. This is evidence that develops a database with excessively and detailed data would inevitably be used in pavement maintenance is incorrect perspective. Put on data that can currently be acquired through visual inspection is a focus of pavement maintenance proposed in this study.

Pavement database has a different property with general database system. In pavement database just showing previous data, otherwise in the general one has all previous data. Other important is pavement database does not want to modulate function inside of database. According to experience of some countries, they did not do more action after collecting data by inspection. Other ways, some restricted regulation to share data about pavement condition making these problems being important matter.

To solve of problem related to lack of information of pavement condition due to minimum action of maintenance and inspection is a purpose of this study. With this problem in mind, change in approach from restricted to open database of pavement as a background for internationalization. Integrated database as a unification of several otherwise distinct files was an approach to sharing data and also enforcing standards to reach that goal. Other objectives of this study are to store information and to allow users to retrieve and update that information on demand.

In this chapter, following section (6.2) presents the importance of developing a practical model. Section 6.3 describes the roles and methodologies of practical model. Database system development in practical model PMS is discussed in section 6.4. Meanwhile, section 6.5 deals with a practical model structure and module support. Section 6.6 provides benchmarking evaluation in practical model with case study. The last section (6.7) gives summary and recommendations for future study.

6.2 Importance of Developing Practical Model PMS

A great optimal repair models using Markovian decision model has been proposed and applied in practical of PMS (Kobayashi and Ueda, 2003; Otazawa et al, 2004; Jido et al, 2004a; Aoki et al, 2006). Those optimal repair aiming at repair selection method, judgment of condition rate or inspection results, and optimal repair strategy planning. In regard with maintenance of road pavement, it is necessary to simultaneously deal with problems of managing two different levels, i.e. the project level for each pavement sections and system level for entire of road pavement.

As many result of recent studies on road pavement maintenance by PMS application, it could be emphasized that some problems related to reducing life-cycle cost has already developed. In summary, road pavement maintenance should implement when expected of life-cycle cost is at a minimum. As a consequent, securing a sufficient annual budget to execute optimum maintenance planning for all road pavement as well as limiting repair work within a certain year to only those road sections of the highest priority, postponing other necessary repairs until a later time are kinds of problem facing by road manager. As is the case with most infrastructures, in the case of road pavement, when a necessary repair is deferred temporarily, the effects do not immediately appear (Jido et al, 2004b).

Many road agencies have tried to estimate road pavement repair demand, in case that there is a lack of data relating for pavement deterioration prediction model estimation or has owned poor data. In order to grasp of repair demand in the future, a method by using time series data from the results of past repair history of pavement while making assumptions of life expectancy of road pavement with referring to repair information has been derived from 3 decades ago. However, there is disadvantage of using past history information of repair is that the budget level for repair does not figure out the entire life-cycle cost on road pavement. In addition, it cannot be predicted clearly at what degree the service level of road pavement will be degraded in the future if repair resources are inadequate (Kobayashi et al, 2008).

As for consideration, various pavement management systems implementation widely is more preferred to use ready-made software. For example, the micro PAVER, a ready-made software analysis which proposes pavement management implementation steps divided into 13 steps, as follows: 1) obtain map, 2) define network(s), 3) collect inventory data, 4) create database including shape file, 5) collect condition data, at a minimum, 6) develop condition deterioration models, 7) verify data, 8) obtain localized maintenance and rehabilitation unit costs, 9) obtain global maintenance and rehabilitation unit costs and frequency of applications, 10) develop pavement condition index (PCI) versus cost models, 11) perform condition analysis, 12) perform work planning analysis, and 13) formulate maintenance and rehabilitation projects and establish priorities (Shahin, 2005). Those steps are sufficient to cover basic procedures PMS analysis by road agency, but still insufficient to cover various object that will be extended for such as road user cost and environmental issues. This is only suitable for agency-oriented of PMS analysis (Shahin, 2005).

Similarly, as mentioned in chapter 5.2, HDM-4 (Highway Design and Maintenance Standards Model-the last version) developed by the World Bank is recognized as a support system for road development and maintenance plan mainly in developing country. This HDM-4 has a role as an analytical tool of PMS which supports economic analysis such as study on budget allocation, financial condition evaluation and road investment evaluation (PIRAC, 2006). There are some limitations in expressing deterioration performance in pavement section. Another important consideration from 2 kinds of ready-made software above is needs more budget in order to using the software.

In different perspective, Jido et al (2004b) and Kobayashi et al (2008) develops a pavement management accounting systems (PMAS) which is presented for road managers of local governments who wish to execute rational repair by referring to asset management information regarding road pavement. The PMAS is comprised of the following: 1) a Pavement Management Accounting (PMA) that is to record changes in asset prices (or debts) during the fiscal year and the changes in asset prices of road pavement; and 2) a Maintenance Management System (MMS) that is to determine repair strategies of road pavement with regard to the execution budget during the fiscal year. The results of repairs in a certain fiscal year are counted as increases in assets (or decreases in debt) in the corresponding year, and such information is used as a basic tool in managing the budget for repairs of road pavement in the following fiscal year.

As in different with conventional model, Kyoto model which is discussed in chapter 5, provides decision making of PMS based on investigation inspection, repair data and performance, that is called as performance base management systems. This Kyoto model is completed by benchmarking evaluation and logic model that can be utilized as feed-back for the next plan. As for result, ensuring customization of pavement asset management and achieving standardization of PMS.

The practical model of PMS proposed in this study adopts methodology that estimates deterioration prediction models using deterioration hazard model by employing repair history data and inspection data investigation as well as presented in the Kyoto Model. This practical model is recognized as “pedagogical model” of Kyoto Model.

This practical model tries to develop open-source pavement management system for constructing of a pedagogical standard of heterogeneity of PMS situations that support sustainable development of PMS models in practical way. A basic motivation of this study is that every researchers, lecturers and students can customized the PMS and develop and improved their own model concurrently with long-term PMS strategy.

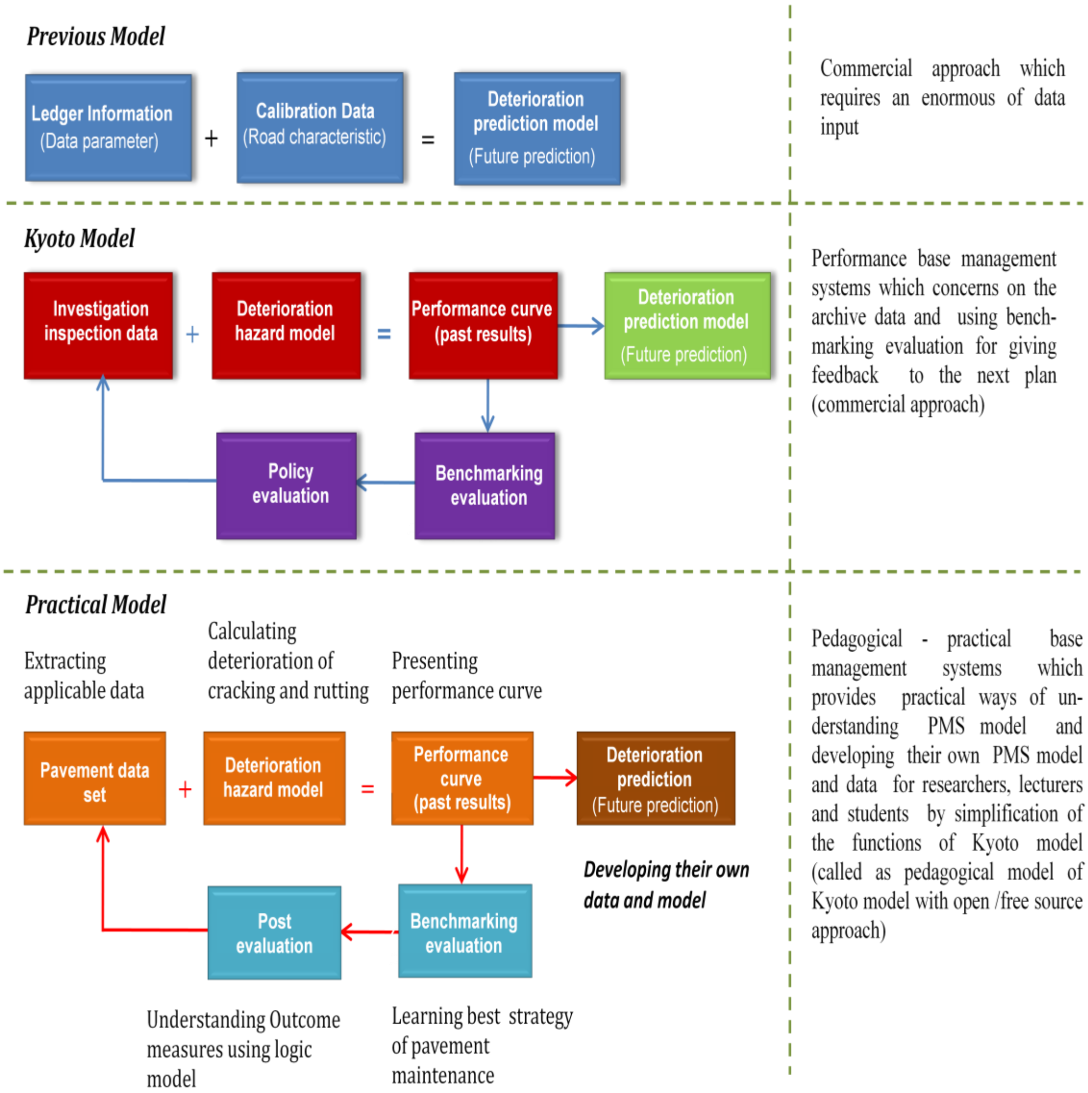

Figure 6.1 Practical Model Features

Within this practical model, the considerations are toward contributing for infrastructure asset management sector, practically for academic view of point (as for key element in developing infrastructure asset management):

- Deeply introduction of PMS model
- Sustainable improvement of PMS model
- Confidently development and improvement of PMS model (by their own model)

Regarding these considerations above, this study defined the Practical model as follows:
"An open-source pavement management system which is introducing PMS functions to support understanding the PMS model and developing customized PMS model for pedagogical orientation (as for researchers, lecturers and students)".

A new methodology using in this study is open-source of practical use of PMS model in term of pedagogical and non-commercial orientation by employing hypothetical and virtual-imaginary (but closes-in-reality) approach in supporting responsibility of academic (in collaboration of academic-governmental-industry) for providing pavement maintenance work.

6.3 The Roles and Methodologies of Practical Model PMS

6.3.1 The Roles and Purposes

A practical model PMS is a virtual or an artificial city with real pavement data which is used for open-source approach of database systems of road pavement management system. Since road pavement data is usually blocked up to the public, researchers or other parties related to academic activities will envisage some constraint in their research-academic work. Having common open-source data is prominent effort in providing beneficial work purposes, for instance, in research, in academic, and in non-commercial works.

Regarding those consideration, development a practical model of PMS is the way of handling problem of open-source pavement inventory data. In this works, hypothetical approach is utilized. Virtual or imaginary but closes-in-reality as a point of view with the target of highway network in form of city (municipalities) or province (prefecture) level target. Following integrated pavement database forms as customized database by flexible structure in regard to user's options, and compatibility with external and internal models.

As a model approach, this practical model has long-term roles and purposes expected to be achieved. The roles and purposes are, as follows:

- Practical and educational approach for researchers, lecturers, and students
  The concept of this model mainly is in agreement with practical approach and should be educational or academic oriented. The main objective will serve demand of researchers, lecturers, and students.

- Collaboration in consortium with several university and public institution
  As practical and educational approach, university and public institution are expected to join in consortium that has just developed to share information and knowledge and a possibility to joint in research concerning to pavement maintenance work.

- Virtual institute collaboration
  Collaboration in consortium is based on virtual institute. Within virtual institute, some rules are prepared in using information and knowledge available by the consortium.

- Platform for international research
  This model is planned to be an international platform for research collaborative and also as a communication platform to develop and extend knowledge about asset management especially in road infrastructure asset management.

6.3.2 Classification of Users and Demands Works

As a platform for international approach with main target to university consortium, the practical model is designed to encompass three types of important users expected. User type, user subject, and description of work concerning to the users can be noticed in table 6.1, as following:

Table 6.1 User Type and Works Description

User type	Works description
Lecturers and students of international consortium	Learning, sharing and discussing subject to road pavement asset management especially in predicting deterioration rate, i.e. Markovian model and software application
Researchers of international institution or public official	Getting supply material to develop the model for more practical approach of deterioration prediction model
Students for all university	Using small size of data to understand the concept of asset management mainly on road deterioration prediction model

Furthermore, regarding to the level of user, the users is divided into three levels, as can be seen in table 6.2.

Table 6.2 User Level and Demand Works

User level	User subject	Demand works
First level	All types of users (top user)	Preparing all data based on users may selecting data from entire data and also may extracting for all highway route data
Second level	Researchers and lecturers (middle user)	Preparing some "pedagogical data" file, for instance pavement design database, traffic database, and so on.
Third level	Students (basic user)	Preparing small size of data which they can calculate hazard model by example of data provided.

6.3.3 Expected Benefits

By using practical model of PMS, users may take advantages in term of "easier and cheaper" effort on some of contents as classified in the following:

- Eliciting data and data set from pavement database
  Lack of data is one of classic problem in research field. With this, users can elicit data from pavement database content, for example, selecting data to help users understood and apply kind of data which want to use in advance.

- Obtaining some of raw material of pavement modeling
  Some of raw materials for pavement modeling are provided in this model. The users can download and may use it in advance for pavement modeling.

- Comparing model and developing methodologies.
  As same as eliciting data and obtaining raw materials, users also can compare several models. It is also very likely to develop methodologies with referring to the guidance (may acquire a new idea from comparing models).

- Understanding in-depth knowledge related to pavement asset management
  In pavement asset management field, this model provides current and new research, which will become important matter, for instance, monitoring and inspection work and how to implement in practice.

6.4 Database System Development in Practical Model PMS

6.4.1 Database Development Procedures

As in line with other infrastructure management, PMS development embracing a cycle of three processes as illustrated in figure 6.2. The role of PMS focuses on satisfying requirement of pavement maintenance works and user's expectation. Road agencies should prepare long-term roles of PMS as target achievement for measurement the result of pavement maintenance. The roles are not only as the first cycle, but also will keeping in track the PMS quality. PMS functions deals with supporting of the roles of PMS. Data conditions are supporting the PMS functions. As noticed here, data condition disposes entire development scheme. In addition, in PMS database, a system of development should refers to entire the cycle in order to provide flexible and user-friendly system.

Regarding the concept of PMS development as declared in figure 6.1, the following table (table 6.3) summarizes procedures of database system development. It could be in different order but this is most typical (Stephens, 2009).

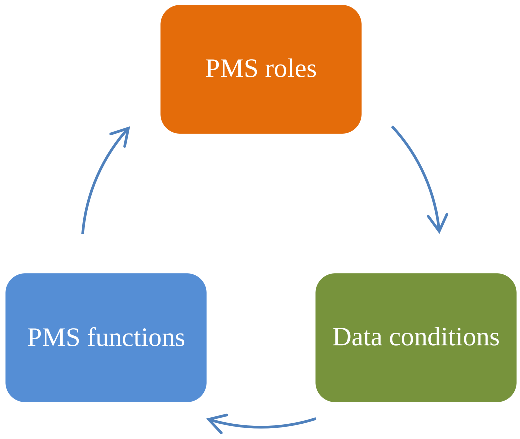

Figure 6.2 Concept of PMS Development

6.4.2 Consideration in Database System Development Plan

Database system should be served on searching data based on users need. In case of road pavement database, developing database system has to consider some of general question in which are mainly subjected to functionality, data needs, data integrity, and environment system (Stephens, 2009).

Table 6.3 Development Procedures

Procedures step	Description of activities
Devise a list of question	Listing of questions to ask users in obtaining better idea of database objective and scope
Identify users and main players	Getting to know them, what they do and figuring out who is who (user and or players)
Understands users need and their works	Picking users brains, grasp what is involved and how they did their works
Learn current operations	Looking around for any existing database that users use, figuring out information and how it relates to other pieces of information.
Hold brainstorming	Sitting together with users to be sure that everything is relevant
Look to the future	During brainstorming process, asking users what they might like to have in future releases explicitly
See through users reasoning	Digging deeper to find out why users reason and thinks for their obscure request
Take up what users really need	Observing real causes of users' problems and think ways to keep in track of their need
Review by prioritize	Prioritizing of desired functions and data content should include
Create use cases	Detailing by driven of function required within database system environment
Confirm feasibility	Reexamining possibility of database works and decide whether is possible

Note: customized from Stephens (2009)

However, developing of this practical model is departed from some of questions which are mainly divided into *what question approach* and *how/who question approach* as illustrated in table 6.4 as follows:

Table 6.4 Main Consideration in Planning Database

What question approach	How/who question approach
- What should the system do?	- Who are the users?
- What is purpose of building this system?	- How to define the level of user?
- What kinds of functions are necessary?	- How it will be used by users?
- What should user interface look like?	- How are those pieces of data related?
- What results are expected?	- How to modify the data?
- What data should be included?	- How to evaluate by criteria?
- What kinds of strategy for priority are planned?	

6.4.3 Main Database Functions

A basic function of database is searching data. The general information and corresponding of database function in pavement management of this model can be listed as in below:

- ***Searching by basic information**:* This searching is fundamental function of database. It is going to show the identity (name) of the road sections by level of administration, agency, and section unit. Examples of main data are such as name or identity of roads (identification number/ID, agency name, agency code, route name)

- ***Searching physical characteristics**:* This searching provides information of physical characteristics of road section that will be used for maintenance work. Others are showing properties of road such as road class, traffic flow, and road type. Examples of main data are section length, carriageway width, number of lane, slope, curvature, type of road (e.g. bridge, tunnel).

- ***Searching pavement design**:* This type exhibits information detail of pavement design (related to pavement structure and strength). This kind of data information should used for maintenance work. Examples of main data are pavement materials and thickness value.

- ***Searching pavement condition**:* This function will show deterioration indices as the character of pavement conditions. This data should be compatible with pavement maintenance criteria and for deterioration prediction estimation. Examples of main data are cracking, rutting, MCI and potholes (minimum) and type of cracking, patching, type of sealing (option).

- ***Searching maintenance and inspection history**:* This is a function of conducted maintenance histories from first construction until current work. From this data, elapsed time from last maintenance will be useful for deterioration modeling. Examples of main data are year of reconstructions, rehabilitation repair, routine maintenance, and inspection year.

- ***Searching traffic information**:* This function is an external data which is not directly respect to road pavement characteristic. This is going to reveal the traffic condition and vehicle types in use. Examples of main data are composition of vehicle type, total transportation volume, heavy vehicle load and also day-time rate.

- ***Searching subsidiary information**:* This searching function supports information additional of road which just showing an important thing about road to get information completely.

- ***Exporting files:*** This function will provide data for additional application of pavement management. The functions could be modified by users plan and needs.

6.4.4 Data Contents and Attribute Information

A database is a tool to store the data, which can provide sharing data in order to stick up pavement maintenance by PMS application. Without a data, a database will be meaningless. Road agency should understand data capacities to promote maintenance work and decision making by PMS. Each road agency may grasp about this, however, definition of data requirements in regard to the fact that data requirements are often renewed by changing or improving the PMS is still in a problem.

In many cases, much more data may guarantee efficiently maintenance work. Even so, during budget limitation, extending content of data has an obstacle. Simplified, road agencies have to consider in running of PMS management and budget simultaneously. In other words, extending data requirement is a consequence of improvement current PMS capabilities.

To arrange data is not complicated tasks. Nevertheless, finding the optimal data set among enormous of data contents in order to execute both of minimizing budgets for PMS operation and supporting desired level of PMS efficiently is not easy works. Briefly, data attribute needed for pavement database depends on road agencies approaches and details, types of deterioration models, and estimation methods of life-cycle cost and customization.

In relating with this practical method, data attribute information is arranged from 8 categories of data attribute. Each of data attribute is completed with item data with a basis of 100m evaluation (some cases using both 100m and also 20m evaluation for clearly explanation).

6.4.4.1 Road Characteristics

Road characteristics provide history of the road based on 100m evaluation. In this attribute, current state and 5 investigations history (the latest, twice ahead, 3 times ahead, 4 times ahead, and 5 times ahead investigation) is available. As for attribute item can be seen in table 6.5 as follows:

Table 6.5 Road Characteristics Attributes

Attribute	Attribute item
100m evaluation	Date of investigation, road type, linear cracking rate (%), planar cracking rate (%), cracking rate (%), patching rate (%), linear sealing rate (%), planar sealing rate (%), sealing rate (%), rutting (maximum) (mm), rutting (average) (mm), flatness (mm), MCI, and MCI type number.

6.4.4.2 Current State of Pavement

Current state of pavement attribute is described by 100m and 20m evaluation. 100m evaluation shows road characteristic value predicted at the current state as in usual, whereas 20m evaluation deals with road characteristic value of the latest investigation. A detail data of cracking and the latest road properties measurements is provided in detailed information inside the table 6.6 which illustrates the attribute item concerning to current states of pavement.

6.4.4.3 Repair History

Repair history attribute is explained in different way with 2 data attribute previous (not based on 100m or 20m evaluation). A detail of item is also provided inside of table 6.7. Fully attribute item of repair history can be shown in table 6.7 in the following.

Table 6.6 Current States of Pavement Attributes

Attribute	Attribute item[1)]
100m evaluation	Km (start), Km (finish), predicted years, road type, cracking rate (%), patching rate (%), sealing rate (%), rutting (maximum) (mm), rutting (average) (mm), flatness (mm), and MCI. [Km (start), Km (finish), *(value at the time of road characteristic measurement)* inspection years, road type, linear cracking rate (%), planar cracking rate (%), cracking rate (%), patching rate (%), linear sealing rate (%), planar sealing rate (%), sealing rate (%), rutting (maximum) (mm), rutting (average) (mm), flatness (mm), MCI, MCI type number, *(current state of road characteristics value)* linear cracking rate (%), planar cracking rate (%), linear sealing rate (%), planar sealing rate (%), MCI type number].
20m evaluation	Km (start), Km (finish), date of measurement, road type, cracking rate (%), patching rate (%), sealing rate (%), rutting (mm), flatness (mm), MCI [Km (start), Km (finish), *(value at the time of road characteristic measurement)* date of measurement, road type, linear cracking rate (%), planar cracking rate (%), cracking rate (%), patching rate (%), linear sealing rate (%), planar sealing rate (%), sealing rate (%), rutting (mm), flatness (mm), MCI, and MCI type number].

[1)] *In the inside [] is a detailed item.*

Table 6.7 Repair History Attributes

Attribute	Attribute item[1)]
Repair history	Operation office name, construction name, construction section, construction type, construction area, remarks [arrangement number, finished fiscal year, electronic delivery, construction company, plant name, office concerned, construction reason, traffic classification, ordering condition, number of fatigue destruction, number of plasticity deformation, flatness, volume of water infiltration, other performance, others unit of performance, CBR design, equivalent thickness converted, CBR measurement, cutting depth, digging depth, sub-grade improvement, sub-grade improvement industrial, sub-grade improvement standard, sub-grade construction, sub-grade construction standard, route name 1, route name 2, route name 3, route name 4, route name 5, construction classification, finished year, finished month].

[1)] *In the inside [] is a detailed item.*

6.4.4.4 Road Parameter

Road parameter attribute is figure out in 4 types. Detail of attribute item of road parameter can be looked in table 6.8 in below:

Table 6.8 Road Parameter Attributes

Attribute	Attribute item
Road attribute	Urgent transportation road (the 1st, the 2nd, others), road around the cultural heritage (pertinent section, others), long distance section (pertinent section, others), annual event/festival route, shelter road (pertinent section, other)
Group	Number of grouping route
Evaluation point	Evaluation point of repair priority level
Road traffic census	Investigation unit section number, total traffic volume (unit), large-sized vehicle traffic (unit), traffic classification[*)], maximum speed (km/h) [*)] traffic classification: N7: traffic of large-sized vehicle/day > 3000 N6: 1000 > traffic of large-sized vehicle/day < 3000 N5: 250 > traffic of large-sized vehicle/day < 1000 N4: 100 > traffic of large-sized vehicle/day < 250 N3: 40 > traffic of large-sized vehicle/day < 100 N2: 15 > traffic of large-sized vehicle/day < 40 N1: traffic of large-sized vehicle/day < 15

6.4.4.5 Deterioration Index

As for deterioration index, the item can be found directly (without attribute item) from data listed in database as result of cracking and rutting by benchmarking evaluation.

6.4.4.6 FWD Investigation

Falling Weight Deflection (FWD) investigation performs evaluating of structure. Attribute item of FWD investigation can be perceived in table 6.9 as follows:

Table 6.9 FWD Investigation Attributes

Attribute	Attribute item
FWD investigation result	D0, D20, D150: (Deflection data position from loading point 0cm, 20cm, and 150cm) (μm), H1: Asphalt mixture thickness of layer (cm), CBR (%).

6.4.4.7 Repair Candidate Section

Repair candidate section attribute and fully attribute items can be seen in table 6.10 as in below:

Table 6.10 Repair Candidate Section Attributes

Attribute	Attribute item
Repair candidate section	Repair candidate section, structural investigation of necessary section, selection method, and priority level.

6.4.4.8 Examination Construction

Examination construction attributes consists of two attributes, candidate section and execution section. A detail item of execution section is provided in detailed information inside the table below. Table 6.11 illustrates the attribute item corresponding to examination construction.

Table 6.11 Examination Construction Attributes

Attribute	Attribute item[1)]
Candidate section	Examination construction candidate section
Execution section	Section, km (start), km (finish), section length (m), investigation years, road type, cracking rate (%), patching rate (%), sealing rate (%), cracking rate (%), rutting (maximum) (mm), rutting (average) (mm), flatness (mm), MCI, arrangement number, office concerned, repair method, date of construction [section, km (start), km (finish), section length (m), investigation years, road type, linear cracking (%), cracking rate (%), patching rate (%), linear sealing rate (%), planar sealing rate (%), sealing rate (%), cracking rate (%), rutting (maximum) (mm), rutting (average) (mm), flatness (mm), MCI, FWD investigation from 0m to 100m at 20m intervals by D0, D20, and D150(μm), material type and 1 surface thickness before and after construction, material type and 2 surface thickness, material type and 1 up to base thickness, material type and 2 up to base thickness, material type and 1 base thickness, material type and 2 base thickness, material type and 1 sub-grade thickness, material type and 2 sub-grade thickness, material type and 1 lower sub-grade thickness, material type and 2 lower sub-grade thickness, arrangement number, construction company, plant name, office concerned, construction reason, ordering condition, construction area, unit price design, repair method, date of construction, weather during construction, construction time zone, CBR design, equivalent thickness converted, CBR measurement, cutting depth, digging depth, sub-grade improvement, sub-grade construction, and remarks.

[1)] *In the inside [] is a detailed item.*

6.4.5 Strategy for Data Correspondence

As mentioned in previous, a database can provide a great number of data that is suitable for agencies or users needs. From enormous of data, there is an important consideration to make relation among of data. Corresponding of each data requires a plenty of time and of course resources for maintaining the data. In order to simplify this kind of work, it is noteworthy to establish a strategy for data correspondence. This is also in accordance with providing quality of data. May understandable that quality of data will guarantee the quality of database and at the end brings effect to quality or accuracy of pavement deterioration prediction model estimation.

This strategy is going to connect by closes-in-reality from the original data converting to this practical model. The strategy covers some activities as stage as below:

- Investigating of inconsistency or unrealistic condition
- Making priority target based on selecting variable
- Separating target section by each priority correspondence
- Question for each priority group to synchronizing data section
- Keeping of reality (closes-in-reality) by version revision approach

6.4.5.1 Investigating of Inconsistency or Unrealistic Conditions

One of the most problems in correspondence of data in this practical model is presence of inconsistency or unrealistic data. Inconsistency or unrealistic data more related to an inappropriate of data to the reality condition. Identification of inconsistency or unrealistic data could be categorized in 2 conditions. The first condition is has a zero value of data which means there is no data available from inspection or problems when entering data to database. The second one deals with has a value of data but looks like unsuitable or unconnected (incoherent) with previous section data and next section data concerning.

If the data has a zero value, it should be considered issuing the data from this model. Meanwhile, the data that has non-zero value, this means continue to look in detail about suitability of data. It is involved to modify the data when data is unsuitable finding (in “*no*” condition). Conversely, data would be moved to following strategy after data is suitable finding (by *“yes”* condition).

To more understanding about process of investigating both of conditions, figure 6.3 could explain easily.

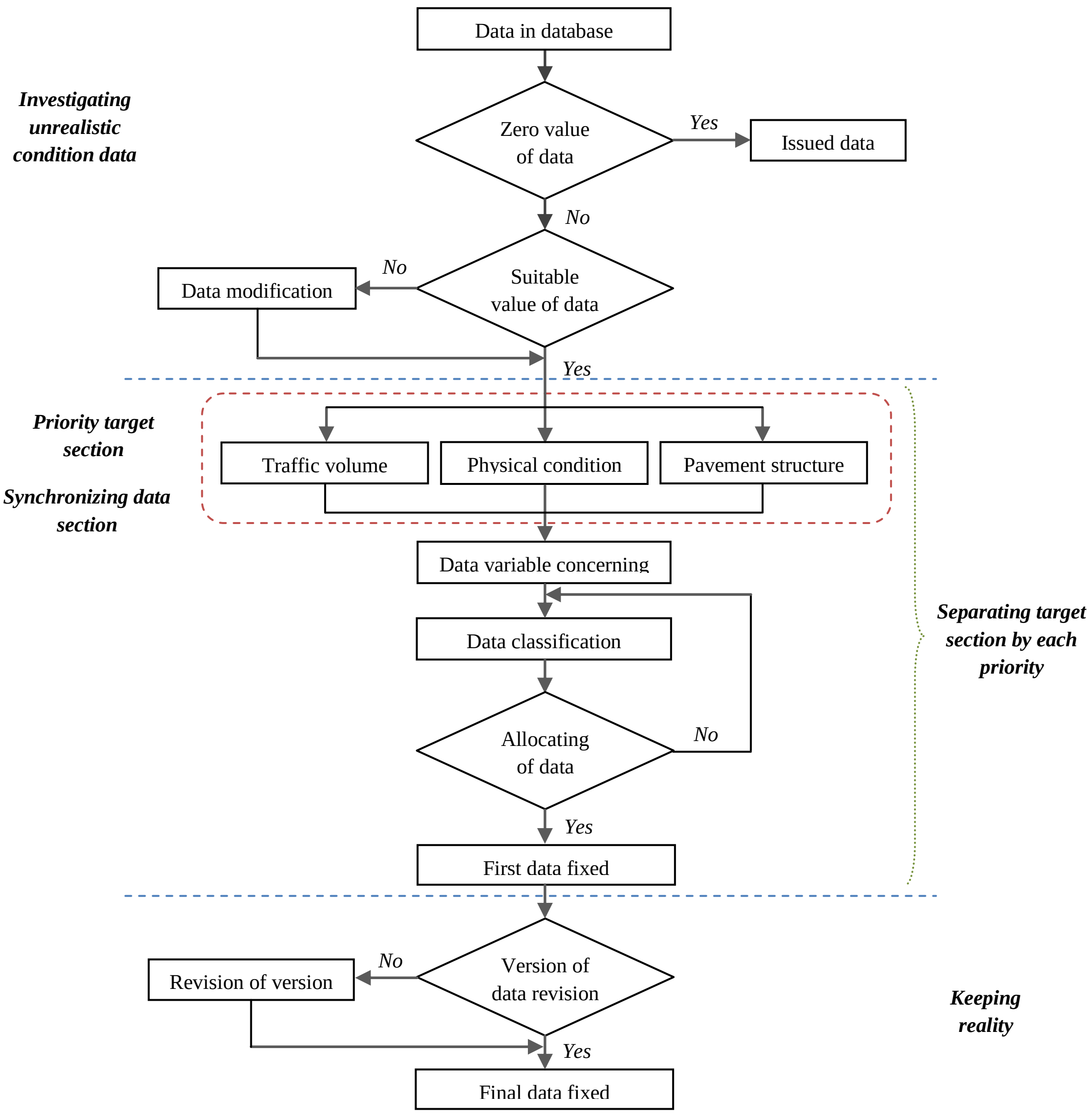

Figure 6.3 Strategy for Data Correspondence

6.4.5.2 Making Priority Target Based on Selecting Variable

Moving to the next activities concerning strategy of data correspondence, making priority target based on selecting variable data is conducted. Priority target refers to data variable that has to take into consideration by selecting variable group in data original. This priority target concludes considered items selected. By target of priority, it has already set up three of variable group. Each variable group is contained with some variable items.

The three group variable could be seen in below:

- ***1st priority: continuation of traffic volume***

  In this variable group, considered items are transportation volume, heavy vehicle, and also expected of heavy vehicle.

- ***2nd priority: physical condition***

  For this group, considered items are covering road width, road type and area.

- ***3rd priority: pavement structure***

  In pavement structure group, a considered item is pavement type.

6.4.5.3 Separating Target Section by Each Priority Correspondence

Related to priority target suggested in previous stage, the third stage is separating target section by each priority correspondence. Through this separating, some of procedures should be incorporated into priority target section variable. As for following of making priority target, the separating also consists of three parts, namely: traffic volume variable, physical condition variable, and pavement structure variable. Each part is described in the following section.

a. Traffic Volume.

In priority target of traffic volume, some of procedures are going to be done. The first activity is declared variable of data which is grouped to this traffic volume group. Variable declared are *transportation volume, heavy vehicle, and expected heavy vehicle.* After declared data variable concerning, classification of data set is executed. Classification of data is doing by classification which has a range or interval of data. The third activity allocates of data which has a big value or small number of point. If allocating data to group of different value or point number has been applied, it is time to move for last procedures. The last activity is first fixed of data position, means an early version of data (i.e. version 0) is arranged for called in next revision.

More in classification of data, for this activity, data set classified according to *number of variable, total section and total route for each variable*. A completely procedures is illustrated in flowchart as in figure 6.3.

b. Physical Condition.

As same as traffic volume priority target, some of procedures are also going to be done in physical condition priority target. Variable concerned are *road width, area, and also road type.* Next activities are similar with traffic volume.

More in classification of data as identical for traffic volume, in physical condition also, data set classified according to *number of variable, total section and total route for each variable*. A completely procedure for physical condition summarized in figure 6.3 is described as in general (one procedures for three variable priority similarly)

c. Pavement Structure

For the pavement structure priority target, variable concerned is *pavement type* as the first activity. All of procedures illustrated in flowchart as in figures 6.3.

Classification data of pavement structure also has some condition with two previous priorities. The different just located in variable concerned of pavement type. In pavement type case, only consists of 2 categories *(asphalt and concrete).*

6.4.5.4 Question for Each Priority Group to Synchronizing Data Section

Completing of separating target priority for each priority correspondence will continuous by activity of asked questions for each priority group target. Objective of these questions is synchronizing of data according to entire priority targets as in stage 3. After synchronizing of data, first fixed data as similar with stage 3 is figured out as result of synchronizing process.

6.4.5.5 Keeping of Reality *(closes-in-reality)* by Version Revision Approach

To make this practical model more interesting, activities for keeping reality of data should prepared. In this occasion, 2 principal approach suggestions to apply, that is to say:

- *Allocating of arterial data*; in example, allocating 15 % of arterial data from original data to this practical model data.
- *Randomizing of arterial data*; data which will use to this practical model could be randomized.

A procedure of keeping of reality figures in flowchart as in figure 6.3. To set up data became a final fixed data; some revision should be experimented until getting the best conditions.

6.5 Practical Model Structure and Module Support

6.5.1 Practical Model Structure

To determine database structure, it is prominent to understand desired functions and see the data in some form. In this practical model, section unit is defined as basic unit of database system which is referred by maintenance works. An aggregat unit is physical characteritiscs of road.

The database of practical PMS has most functions as mentioned in section 6.4. To realize the functions, 9 forms have been documented. Since each function has been seen by independent moduls (by a form), system building is easy and flexible. The system architecture of database of practical model is displaying in figure 6.4

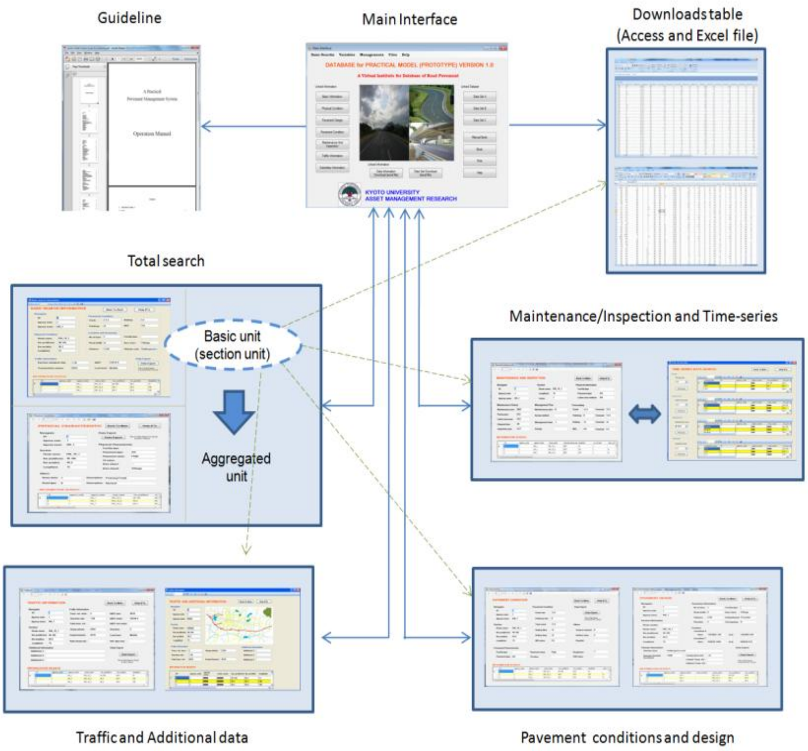

Figure 6.4 Practical Model Structures

6.5.2 Pavement Data Relation

One of most question in database is “how to define data tables and their contents?”. In this study, relation of pavement database is identified in five table relation. There is pavement road information, pavement inspection, pavement repair history, pavement current conditions, and pavement deterioration performance. The road information has in a whole relation with others. Inspection data is correspondence with repair history and current conditions. Mean while, deterioration performance data will working with road information. A complete relation can be found in figure 6.5.

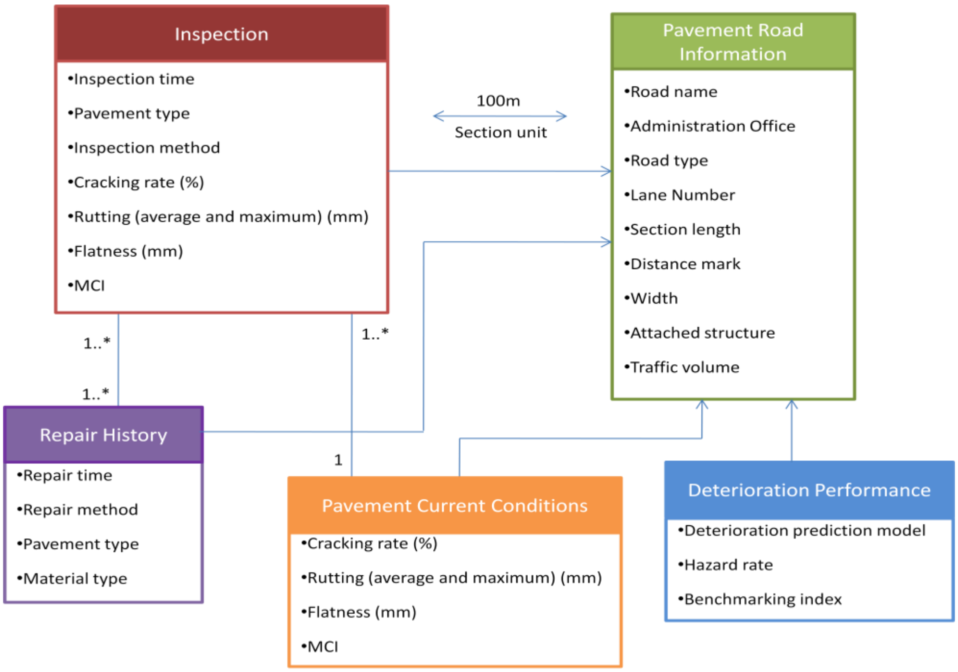

Figure 6.5 Pavement Data Relation

6.5.3 Relation between PMS Requirement and Practical Model Module

Relation between PMS requirement and practical model supported is arranged in figure 6.6. There are six requirement could be support by practical model, that is: pavement maintenance states, pavement maintenance condition, pavement maintenance life-cycle, pavement maintenance performance, pavement service level, and best maintenance strategy. These requirements will support by nine modules.

6.6 Benchmarking Evaluation in Practical Model

Benchmarking has intended to attempt and introduce exploring of best practice continuously and systematically, clarifies the work objective, and shows not just comparison of work results but by a quantitative indicator. Benchmarking evaluation is a concept that can be implemented at each stage of theory of evaluation by input - process - output - outcome. Furthermore, logic model is utilized to clarify evaluation process ties organically causal relation of activity in each stage of input - process - output – outcome.

The position and relation of benchmarking evaluation with functions system and pavement database is illustrating in figure 6.7. Based on the functions with a focus on pavement database is provided to support a decision making for rational pavement maintenance work.

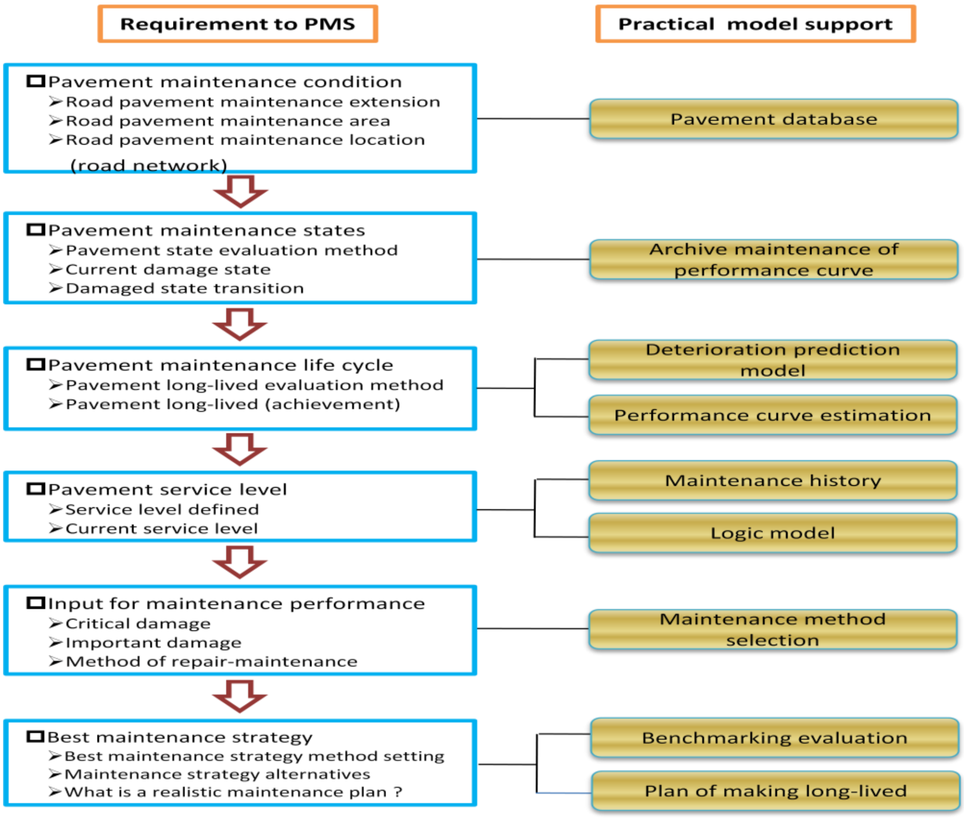

Figure 6.6 Relation between PMS Requirement and Practical Model Supported

As for the practical model PMS, accumulation of pavement data base in order to evaluate the performance becomes important. The logic model is intended to model entire pavement management cycle as shown in figure 6.7. The pavement data base is generated form pavement strategic management cycle, and can be defined as knowledge data to evaluate the logic model.

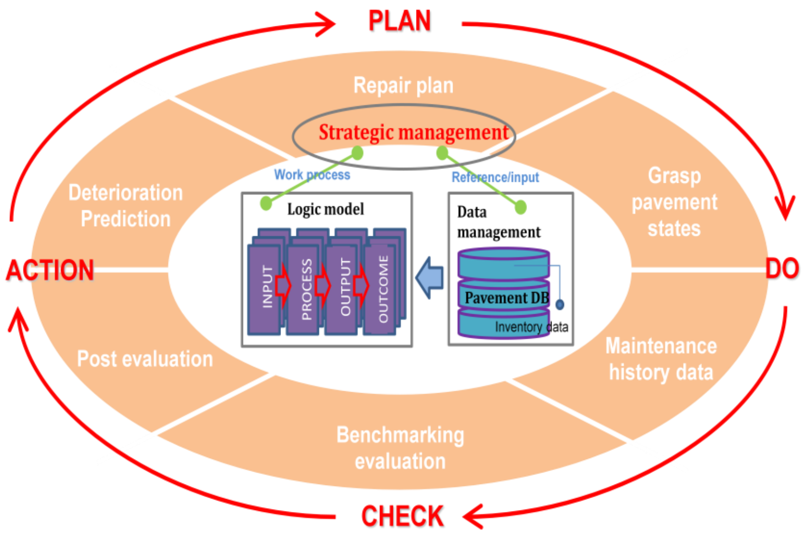

Figure 6.7 Decision Making for Benchmarking

6.7 An Empirical Applications of Practical Model

This section demonstrates the typical applications of practical model. The difference of result is different type of result regarding different of data used in simulations. It is noticed here that this is only a simple trial to portray application way of proposed model. Thus, the result should not be interpreted as representative of any location (country, province, and city) or any case.

6.7.1 Application Procedures

The application of practical model requires some procedures. Regarding to the features of practical model in figure 6.1, users should follow these procedures:

- Extracting required data from database concerning with application target
- Establishing predicting/forecasting standards (cracking and rutting)
- Applying maintenance standard and strategy

6.7.2 Simulation Planning

A simulation for demonstration has been arranged to understand the feature provided of two models (Kyoto model and Practical model) with used of different target sections. That is, the result should not be compared. The simulation schemes are summarized in table 6.12.

Table 6.12 Summary of Simulation Schemes

Simulation schemes	Case study A (Kyoto model)	Case study B (Practical model)
Contents	Actual data of Kyoto model	Correspondence data of Practical model database
Target sections	About 2.300 section	About 10.520 section
Simulation purposes	Find out maintenance time	Find out maintenance time
Predicting/forecasting model	Markov hazard model	Markov hazard model
Application standard	Refers to Japan standards	Refers to Japan standards
Main results	- Averaged network condition - Comparison of alternatives	- Averaged network condition - Comparison of alternatives

6.7.3 Details of Simulation

6.7.3.1 Characteristics of Target Sections

In the Practical model, target sections used for simulation can be summarized in table 6.13 as follows:

Table 6.13 Characteristics of Target Sections

Road with (m)	Total section (%)	Road type	Total section (%)	Area	Total section (%)
< 6	81.168	Normal	96.449	Urban	44.273
6 - 10	15.555	Bridge	3.417	Rural	40.220
10 - 14	2.257	Tunnel	0.134	Mountain	15.666
14 - 18	0.835				
> 18	0.185				

In road width, data classified into 5 ranks with road width < 6 as minimum value, among 6 to 18 value, and > 18 value. Whereas the road type and the area just consist of 3 categories.

6.7.3.2 Traffic Information

Information concerning to the traffic condition used in practical model data is divided into two types, that is traffic volume and heavy vehicle. The conditions illustrated in table 6.14 in the following:

Table 6.14 Traffic Information

Traffic volume	Total section (%)	Heavy vehicle	Total section (%)
< 1.000	22.976	< 500	66.272
1.000 – 5.000	43.665	500 – 1.000	14.741
5.000 – 10.000	15.894	1.000 – 1.500	8.553
10.000 – 15.000	9.652	1.500 – 2.000	3.973
15.000 – 20.000	4.971	2.000 – 3.000	3.435
20.000 – 25.000	1.965	3.000 – 4.000	1.641
25.000 – 30.000	0.387	4.000 – 5.000	1.056
> 30.000	0.490	> 5.000	0.329

Traffic volume data is classified into 8 ranks with < 1.000 value, some ranks between 1.000 to 30.000 and > 35.000. As for heavy vehicles, it is also classified into 8 ranks.

6.7.4 Application of Pavement Deterioration Prediction Model

As mention in previous chapter, Markov hazard model is employed in deterioration prediction estimation model. For application of Markov hazard model in this benchmarking case, in the first, rating standard should be prescribed concerning to the rutting and the cracking of pavement deterioration prediction model. An example of deterioration prediction using database of Kyoto model and Practical model is presented in the following:

Table 6.15 A Rating Standard for Kyoto Model

Rating	Cracking (%)	Rutting (mm)
1	0	< 4
2	1 - 4	4 - 9
3	5 - 9	9 - 14
4	10 - 14	15 - 19
5	15 - 19	20 - 24
6	19 - 24	25 - 29
7	24 - 29	> 29
8	30 - 34	-
9	34 - 39	-
10	> 39	-

Table 6.16 A Rating Standard for Practical Model

Rating	Cracking (%)	Rutting (mm)
1	0	< 5
2	1-5	6 - 10
3	6-10	11 – 15
4	11-15	16 – 20
5	>15	> 20

In this case, it is assumed that the rutting and the cracking occur independently in the same pavement condition. Table 6.15 and table 6.16 illustrate a rating standard for application of Markov hazard model by Kyoto model and practical model respectively.

Figure 6.8 shows deterioration performance curve of Kyoto model for rutting condition states. Similarly, figure 6.9 display the estimation result of cracking of Kyoto model.

Meanwhile, figure 6.10 shows deterioration performance curve that is drawn according to life expectancy and deterioration hazard rate along the route for rutting condition states. Deterioration hazard rate evaluates deterioration risk in each pavement section, and deterioration hazard rate of a large pavement section can be determined that a deteriorated possibility is high in the future independent from damage states of current pavement. Similarly, figure 6.11 display the estimation result of cracking. The vertical axis indicates the rating of condition states, meanwhile, the horizontal axis expresses elapsed year of deterioration.

By Kyoto model data, the data consist of 7 groups (N1-N7) which indicated by the color (marked in the right side of figure 6.8-6.9). The BM is benchmark condition (red line). In other ways, Practical model data is divided into 15 groups (N1-N15) which can be seen in the right side of figure 6.10-6.11, and also complemented by the BM condition.

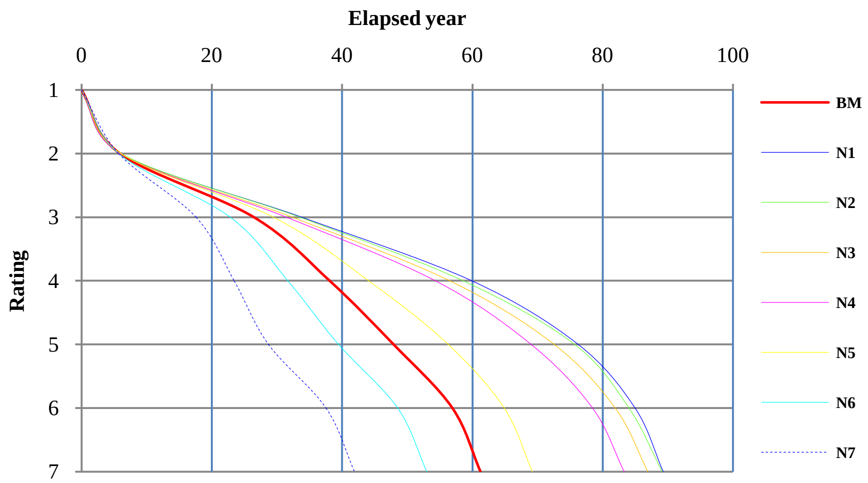

Figure 6.8 Deterioration Curve of Rutting (Kyoto model case)

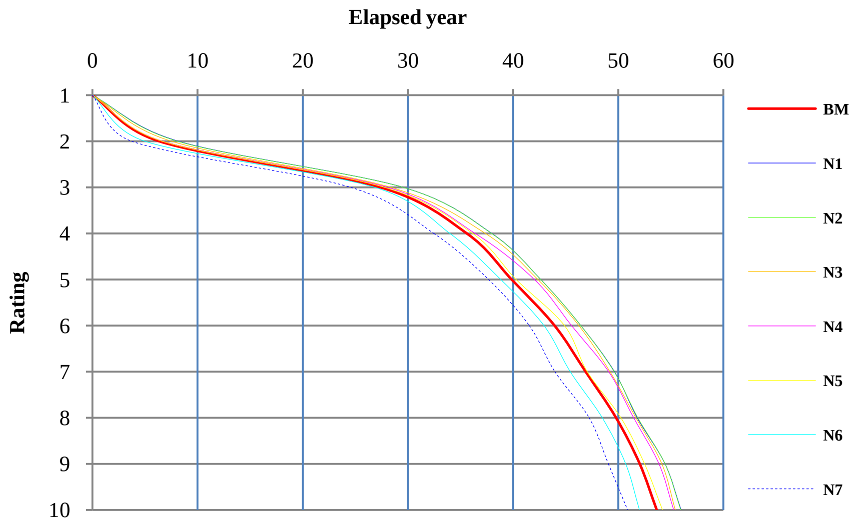

Figure 6.9 Deterioration Curve of Cracking (Kyoto model case)

Note) displays estimation result of deterioration prediction model of rutting (above) and cracking (below). The horizontal axis indicates elapsed years, while damage states rating of rutting (above) and cracking (below) in vertical axis.

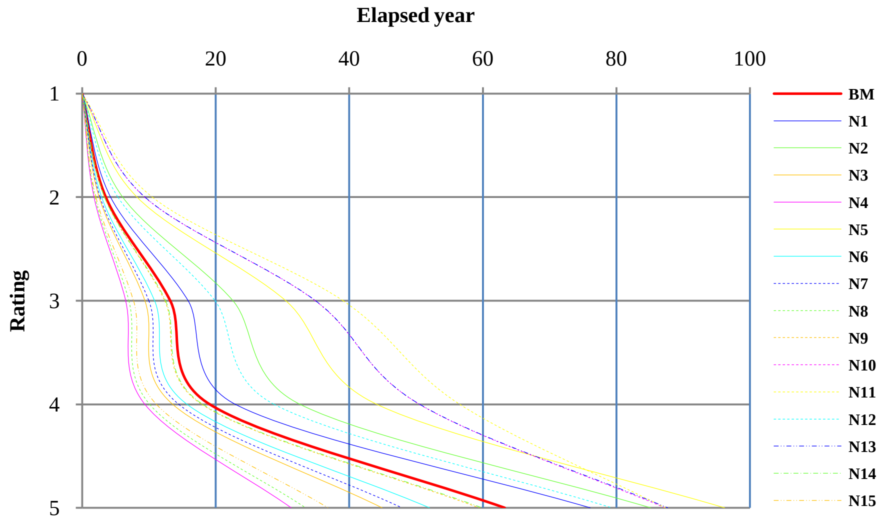

Figure 6.10 Deterioration Curve of Rutting (Practical model case)

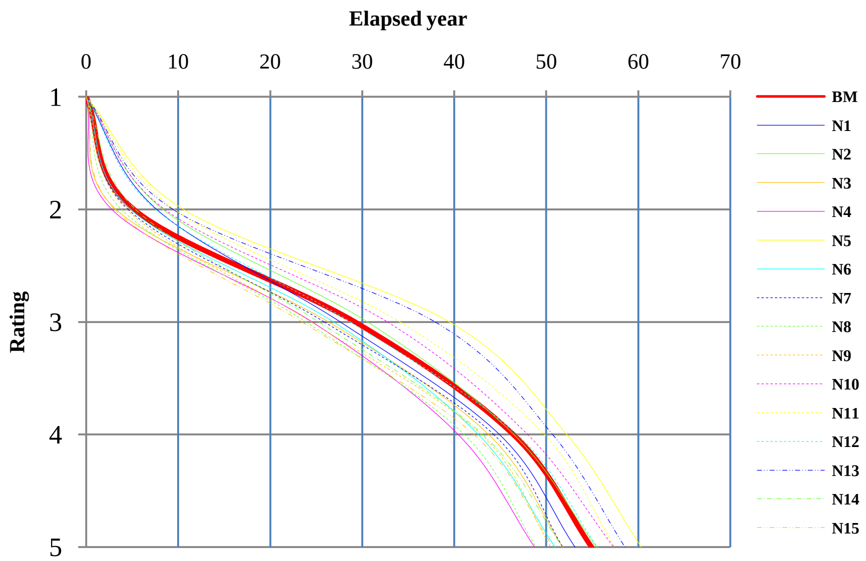

Figure 6.11 Deterioration Curve of Cracking (Practical model case)

Note) displays estimation result of deterioration prediction model of rutting (above) and cracking (below). The horizontal axis indicates elapsed years, while damage states rating of rutting (above) and cracking (below) in vertical axis.

From figure 6.8 - 6.9 (Kyoto model case) and figure 6.10 - 6.11 (Practical model case), a summary of deterioration models of rutting and cracking can be summarized as follows:

- The rutting strongly undertakes the influence of traffic
- The deterioration speed of the cracking is faster than rutting
- It is expected that the factor of repair is ruled by the cracking

6.7.5 Maintenance Methods Appropriate

In this practical model, the standard for maintenance method is referring to Japan standards. Within database of practical model, the MCI index of each unit section are defined as surface condition examination results. To standardize maintenance method, a maintenance method decision rule should be established. The maintenance method decision rule using in practical model is shown in table 6.17 as follows:

Table 6.17 Maintenance Method Decision Rule

Group	MCI index	Maintenance method
1-1	$3.5 < MCI$ $2.0 < MCI \leq 3.5$ $MCI \leq 2.0$	Overlay (1-1-1) Cutting overlay (1-1-2) Dig out/replacement (1-1-3)
1-2	$3.5 < MCI$ $3.0 < MCI \leq 3.5$ $MCI \leq 3.0$	Overlay (1-2-1) Cutting overlay (1-2-2) Dig out/replacement (1-2-3)
2-1	$3.0 < MCI$ $2.0 < MCI \leq 4.0$ $MCI \leq 2.0$	Overlay (2-1-1) Cutting overlay (2-1-2) Dig out/replacement (2-1-3)
2-2	$3.5 < MCI$ $3.0 < MCI \leq 3.5$ $MCI \leq 3.0$	Overlay (2-2-1) Cutting overlay (2-2-2) Dig out/replacement (2-2-3)

Whilst, distribution of MCI value in database of practical model is displayed in figure 6.12 in the following:

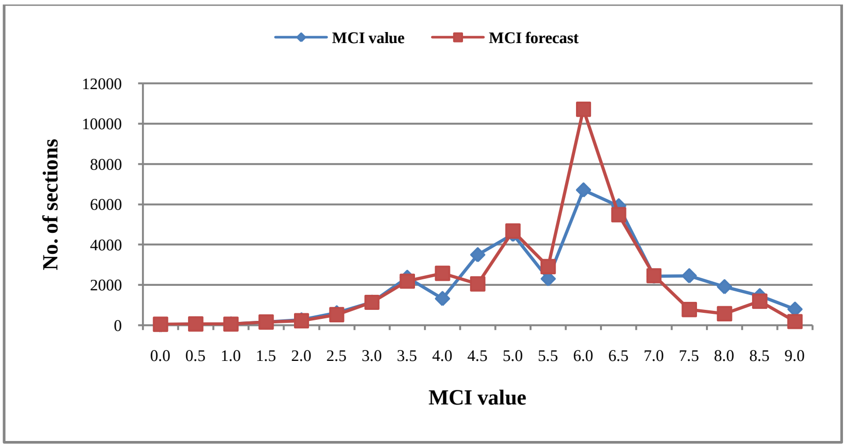

Figure 6.12 Distribution of MCI Value

6.8 Summary and Recommendations

This chapter has proposed a practical model approach for understanding of pavement management system in order to solve of problem related to lack of information of pavement condition due to minimum action of maintenance and inspection. Within this practical model, integrated database as a unification of several otherwise distinct files was an approach to sharing data and also enforcing standards to reach that goal. Having common open-source data is prominent effort in providing beneficial work purposes, for instance, in research, in academic, and in non-commercial works.

Development a practical model of PMS is the way of handling problem of open-source pavement inventory data. In this works, hypothetical approach is utilized. Virtual or imaginary but closes-in-reality as a point of view with the target of highway network in form of city (municipalities) or province (prefectures) level target. Following integrated pavement database forms as customized database by flexible structure in regard to user's options, and compatibility with external and internal models.

As for database development, this study proposes development procedures, main consideration in development database, main database functions, data contents and attribute information, strategy for data correspondence, and design of framework. In regard with PMS requirement, this practical model supports with several module.

However, several points should still to discuss which may be considered as topics considering in the future:

- This chapter focuses only a simple database functions which does not considered the update data of routine maintenance. In order to overcome this limitation, an additional function should be employed in future study relating this topic.

- The empirical study of this chapter just focused on a small scale application of benchmarking methodologies on the pavement maintenance, particularly in cracking and rutting. In accordance to find out best pavement technology, it is necessary to consider about updating and the quality of inspection data.

- Practical model is suggested for researchers, lectures and students to commence understand how to calculate deterioration model and performance curve in firstly. In future development, this model will be accommodated for more people within non-commercial approach.

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Chapter 7

Conclusion and Future Study

7.1 Summary and Recommendations

Main objective of this dissertation is developing a practical approach of empirical studies of pavement maintenance management systems. The practical model is provided as open system of database for practical orientation. Other objectives is understanding and elaborating deterioration prediction models by referring to application of Markovian deterioration hazard process for infrastructure asset management. Practically, focuses on the real world of pavement asset management systems. As for developing of practical approach, verifying and applying the Kyoto model Pavement Management Systems as a part of road pavement asset management systems with preferential on pavement database to support pavement maintenance work as international standard is suggested.

The whole dissertation consists of 7 chapters in which the following paragraph explains each chapter into more detail.

Chapter 1 describes a basic concept of the study about development practical model for pavement management system, rationale and objective of the study, as well as provides scope of study and expected contribution for each chapter.

Chapter 2 investigates an in-depth literature review on hazard model practice in infrastructure asset management typically in field of pavement asset management. In regard to the importance of infrastructure to support society activities, formulation a methodology to overtake the problem of deterioration process should get attention in more. By utilizing deterministic and stochastic model to determine the deterioration process, it can be seen that stochastic model is more applicable and close to reality in asking the problem of deterioration as many paper that has been disseminated. Markov chain model with role of visual inspection data proposes the answer of deterioration problem exhaustively.

Besides, this chapter is emphasized to solve the heterogeneity factor that exists in pavement group. Thus, the mixture model is presented for benchmarking study which is determined by means of heterogeneity factor ε. This model is utilizing semi parametric approach with following the function of Taylor series. Two estimation approaches with maximum likelihood estimation method is applied to estimate the heterogeneity factor. From the advantageous of the mixture hazard model, it is supposed to be an excellent tool for benchmarking study, which is employed to found the best technology in pavement management systems.

Chapter 3 has discussed a methodology of maintenance management with strategy and policy approach. The maintenance management strategy is represented by integrating of management functions appropriate in pavement maintenance. Based on these function, change in maintenance management processes are structured being a pavement management function.

The maintenance management policy is developed from viewpoint of mid/long-term maintenance plan. This policy is working with highway pavement maintenance. In order to verify the applicability of this policy, an empirical study was conducted on maintenance management in Kyoto City road pavement. This study has made a contribution to the field by comparison and benchmarking repair using maintenance policy approach. The maintenance policy approach represented can be extended to apply not only for main road pavement but to various other kinds of road facilities as well.

In *chapter 4*, deterioration risk in pavement section was evaluated by paying attention to road pavement maintenance issues, generates routine maintenance work using statistical data, and proposes concept of asset management system that continuously decreased deterioration risk. In addition, a methodology that requests maintenance strategy to aim at achieving reduction cost and making long-lived pavement was developed, and an approach that attempts in applying to actual maintenance work was considered. In that case, focuses on maintenance of road pavement that local government managed, constructs pavement logic model for highway, and proposes operation method. In addition, management system to perform steadily such as repair method selection and updating necessary data in order to propose benchmarking evaluation method at deterioration speed using statistical deterioration prediction model as a quantitative evaluation method to achieve cost reduction and pavement long-lived.

Furthermore, concept of a new management system of road pavement proposed by this research was applied to maintenance work of highway in Kyoto City, and a practical example which aims at rationalization pavement maintenance work was presented. Deterioration hazard rate was estimated using road characteristics investigation result and maintenance history information that has accumulated in Kyoto city in actual and also benchmarking evaluation of deterioration process of road pavement was applied. As a result, benchmarking evaluation empirically describes that it was an effective method in consensus forms between the person in charge who executed maintenance work at the project level and the decision makers who managed the network level. Additionally, this method is an efficient way to grasp not only damage state of road pavement but also developing of repair plan using deterioration risk in each pavement section in the future. Moreover, it is considered that concept in achieving cost reduction and making pavement long-lived is infiltrating in the organization regarded to maintenance of pavement because applied benchmarking evaluation based on logic model in practice of maintenance work, and the system to work on asset management was in order.

Chapter 5 has explained logic model and benchmarking evaluation that forms as basis of the Kyoto model more in detail, has discussed a basic concept of Kyoto model pavement management system that has evaluation function and customization which enabled to overseas standardization, and has satisfied requirement of ISO for road pavement based on trend concerning international standardization of asset management.

Furthermore, example of benchmarking evaluation was shown, and evaluation method that synchronized with logic model was confirmed. The Kyoto model wish to emphasize overall platform of PMS composed by logic model in more with database, application and evaluation system, mechanism, standard, in order to construct mechanism of PMS in average not merely aimed at standard application of PMS as pointed out but also while corresponding to each module and AM plan process. In addition, to form the strategic pavement management system in a long-term perspective, to construct PDCA cycle, and to synchronize with inspection function of ISO. When restructure asset management plan through Check and Action by ISO, the logic model is redefined. As a result, customization of asset management system is ensured, and standardization of PMS that has diversity is achieved.

In *chapter 6*, it has proposed a practical model approach for understanding of pavement management system in order to solve of problem related to lack of information of pavement condition due to minimum action of maintenance and inspection. Within this practical model, integrated database as a unification of several otherwise distinct files was an approach to sharing data and also enforcing standards to reach that goal. Having common open-source data is prominent effort in providing beneficial work purposes, for instance, in research, in academic, and in non-commercial works.

Development a practical model of PMS is the way of handling problem of open-source pavement inventory data. In this works, hypothetical approach is utilized. Virtual or imaginary but closes-in-reality as a point of view with the target of highway network in form of city (municipalities) or province (prefectures) level target. Following integrated pavement database forms as customized database by flexible structure in regard to user's options, and compatibility with external and internal models.

7.2 Future Study

This dissertation has proposed several contributions for pavement asset management and pavement database applicable for understanding pavement management system perspective. For extending study in the future, a few points should be emphasized as founded within this study, as follows:

- A positive introduction of new methods is necessary to make pavement long-lived and reduction of life-cycle cost. However, acquired data should be evaluated; validity and impact of new methods should be analyzed.

- The empirical application is implemented only on the pavement systems. However, this approach can be applied for various types of infrastructure. Understanding of structural characteristic and appropriate methodology is prominent in widely application of maintenance management policy approach.

- Mid/long-term practice is a necessary, for this relation, an important issue to accumulate and to update various data by executing evaluation based on logic model surely in order to achieve final outcomes such as cost reductions and making long-lived.

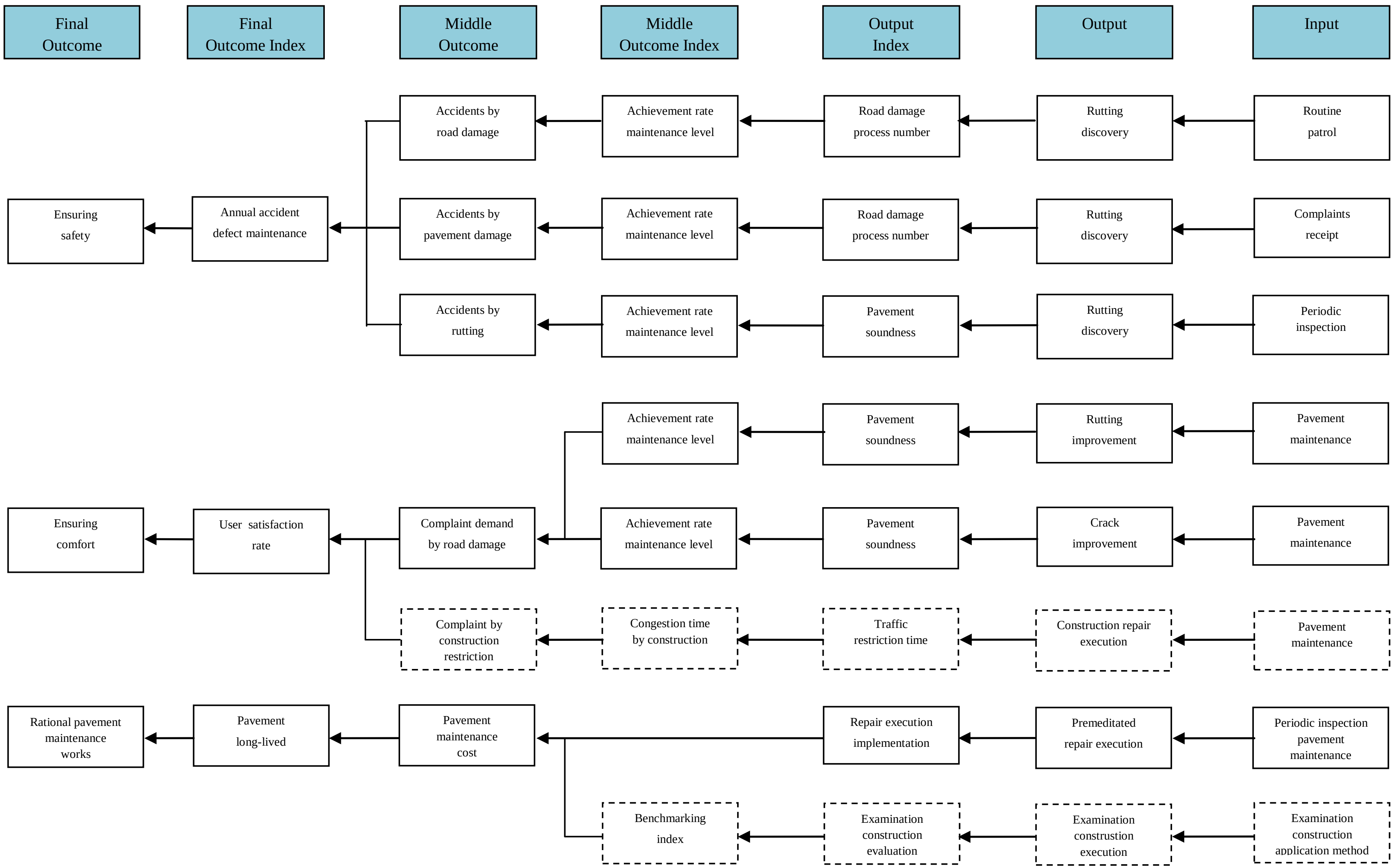
- It is necessary to practice in advance of pavement asset management that applies the Kyoto model within proceed discussion concerning international standardization of asset management in the future.

- The Kyoto model has learning function in actual, so that, achieving PMS as a standard model in the future can be supported by accumulation of several requirements especially mechanism of adjustment with other features.

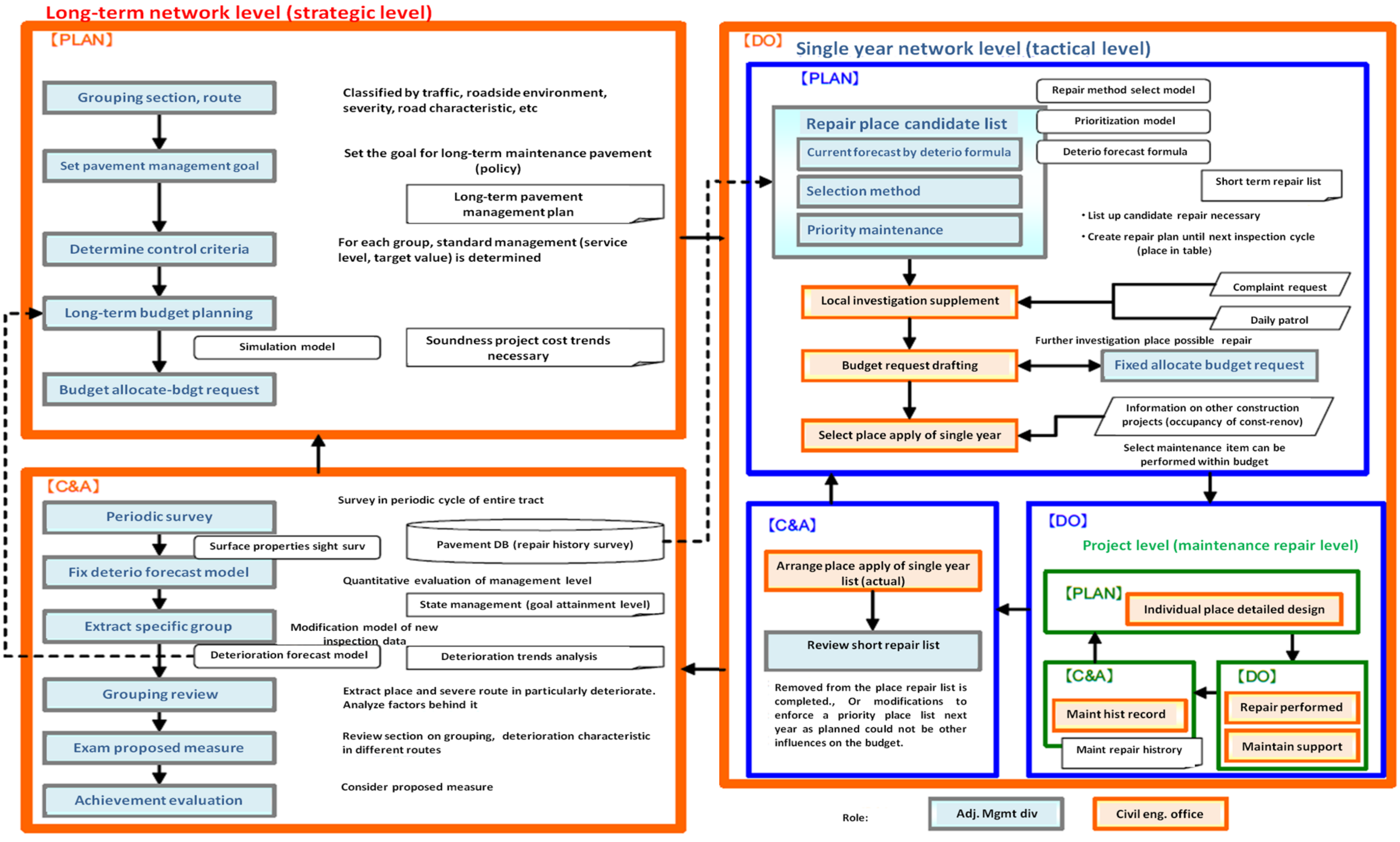
- The practical focuses only a simple database functions which does not consider updating data of routine maintenance. In order to overcome this limitation, an additional function should be employed in future study relating this topic.

- The practical model is suggested for researchers, lectures and students to commence understand how to calculate deterioration model and performance curve in firstly. In future development, this model will be accommodated for more people within non-commercial approach.

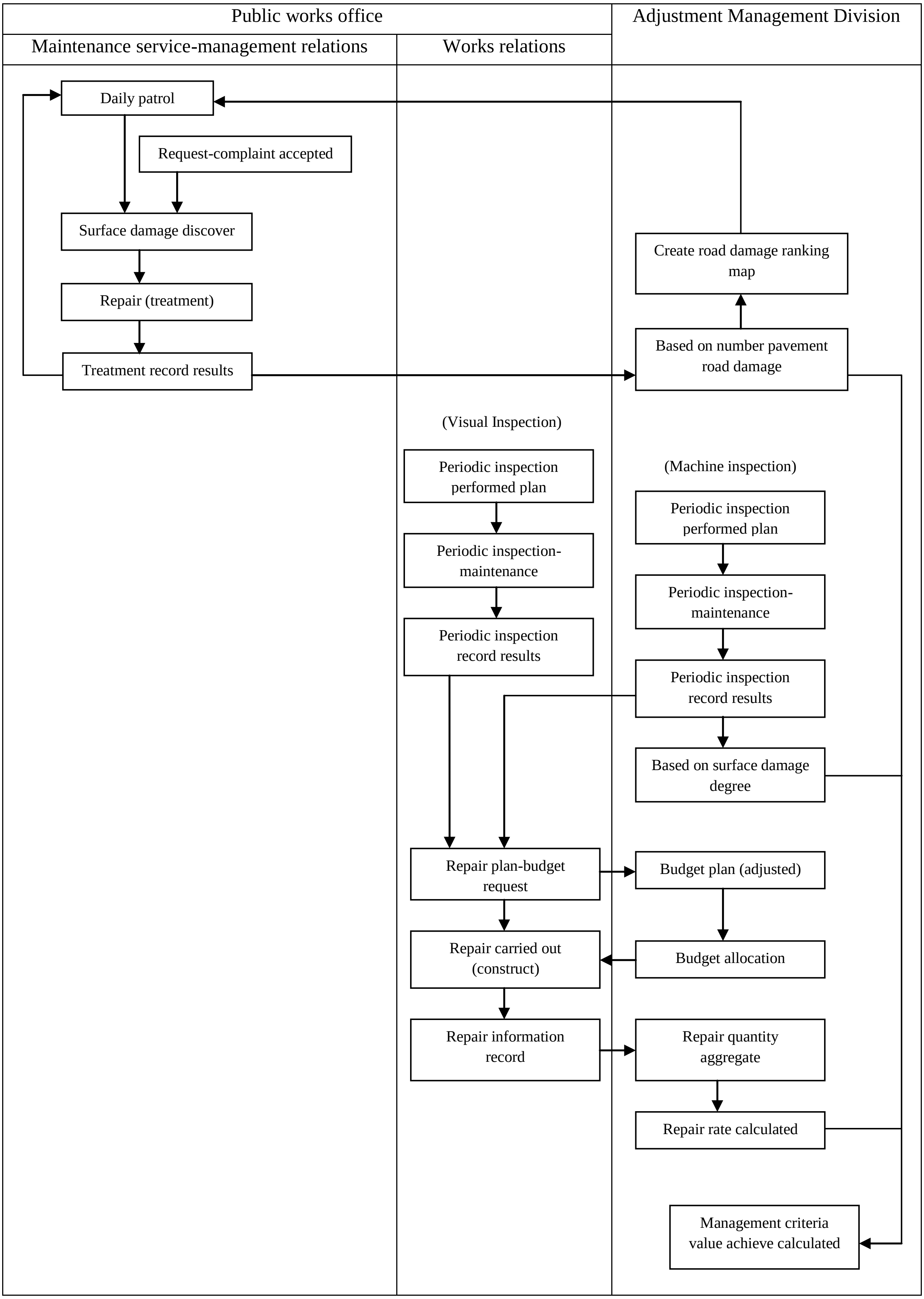
Appendix A   A Whole of Pavement Logic Model



Appendix B PDCA Cycle of Pavement Maintenance



Appendix C Work Flow in Pavement Maintenance



Appendix D Method of Deriving Evaluation Index

A) Output index

Index	Contents	Necessary data	Problem
Road damage process number	Road damage process number per unit section	Road damage generation part	Development of input tool of history information
Number of pavements of difference parts	Number per unit section of pavements of difference parts	Position of difference	Review of investigation specification
Pavement soundness	States of road (cracking, rutting and flatness)	States of pavement in each evaluation section	Reasonable setting at inspection cycle
Traffic time regulation	Construction regulation time annual for each unit section	Regulation time by construction	Maintenance method of regulation time
Repair execution rate	Execution repair construction to extract rate of repair part by inspection and repair plan	Repair execution record	Simplification of repair history data management

B) Middle outcome index

Index	Contents	Necessary data	Problem
Achievement rate maintenance level	Achievement rate to each level value by management objectives (%)	Each input index	
Congestion time by construction	Total of generation time of construction congestion (time)		Method of measuring congestion time
Benchmarking index	Relative evaluation index at deterioration speed in each pavement section	Periodic investigation and repair history	Accumulation of inspection data

C) Final outcome index

Index	Contents	Necessary data	Problem
Number of accident during year defect maintenance	Total values of accident number during year defect maintenance	Accident number total value defect maintenance	
User satisfaction rating	User and the citizens satisfaction rating concerning pavement maintenance	Opinion and CS investigation, etc. of the citizens	Method of evaluating user satisfaction rating
Pavement maintenance cost	Pavement maintenance cost	Repair history data	Accumulation of inspection data

Contact Information:

Suharman Hamzah

Email address: suharmanhamzah@gmail.com

Home address in Indonesia:

Jalan Sunu, Kompleks Universitas Hasanuddin Baraya Blok AX. 18

Makassar, Sulawesi Selatan, Indonesia 90214

Tel: +62-(0)411-434632

Office address in Indonesia:

Civil and Environmental Engineering Department

Faculty of Engineering, Hasanuddin University

Jalan Perintis Kemerdekaan Km. 10

Makassar, Sulawesi Selatan, Indonesia 90245

Tel: +62-(0)411-580505