Developing an Analysis System for Road Infrastructure Deterioration and Its Effect on Regional Economy

O. OMAR, Y. HAYASHI, K. DOI, AND T. OKUDA

Managing an aging infrastructure under budget limitations is becoming a critical issue in many countries. A model system for supporting the process of road infrastructure management is presented. The system provides information on expected road performance in terms of pavement deterioration and need for repair. Also, the direct impacts on the users of the facility and indirect impacts on the regional economy are quantified and given at each performance level. The system is supported by a geographic information system as a tool to facilitate decision making. A case study is carried out using the developed system to analyze the performance of a selected road network under different budget levels. It is shown how losses incurred by users and the regional economy vastly exceed savings from road budget reduction. Therefore, the importance of applying such a system to quantify direct and indirect impacts of road performance is highlighted throughout this analysis.

Until now, necessary road maintenance cost in Japan has been almost fully budgeted through treasury loans and investment. However, with the rapid increase in road infrastructure stock and the aging of the network, it will become difficult to budget for all the maintenance required. Under such circumstances, a certain level of deterioration and increase in road user costs might be inevitable. This may also bring about negative impacts on the regional and national economy as has occurred in other countries, such as the United States (*1*). Therefore, it is necessary to provide information on when, where, and how to repair to minimize the possible future damage cost due to budget shortage. Such information should also include the amount of direct and indirect costs incurred at any damage level.

Having recognized the importance of this issue, we have developed a model system to provide such information, focusing on highway pavements as a typical example. The system is composed of the following elements:

- Model to forecast future deterioration and need for repair, which treats deterioration and repair as stochastic phenomena. It can be applied on the network level to predict the performance of a road network under different repair strategies and budgets (*2,3*).
- System to quantify the direct impacts of deterioration in the form of changes in vehicle operating costs (VOCs) and travel speed. Accordingly, generalized travel cost (GTC) between regions and zones within a study area can be quantified under any road performance level (*4*).
- Model to forecast indirect impacts of road deterioration on the regional economy. It combines an input-output model with a business-industrial location model. The model can estimate the change in the production levels of the sectors of the economy (*4*).
- Geographic information system (GIS) base to support the decision-making process regarding deterioration and repair. This system provides reports and maps that can facilitate further analysis of information (*5,6*).

This paper briefly describes the outlines of each of these elements and how they function together. An example application of the system is also given. More details on model formulation and parameters can be found elsewhere (*2–6*).

SYSTEM OBJECTIVES

Modeling pavement deterioration is regarded as an essential need for the proper management of road infrastructure. Such a need becomes more critical if such management has to be carried out under budget constraints. Applying such models, road infrastructure renewal strategies commonly based on the "fire-alarm strategy" are likely to be abandoned in favor of strategies based on predicted information, leading to efficient use of the available budget. However, under the current trend of governments worldwide to neglect infrastructure repair, such models are not enough. It is also important to ascertain how much direct and indirect cost will be incurred if the infrastructure is left to deteriorate. If such information is known, the repair budget is likely to be raised. It is also important to adapt new technologies to develop computerized systems that can help the management process. With such systems in hand, systematic analysis can be conducted and the aspects of the issue can be clarified.

The main target of this research is to develop a system that can handle the required analysis. The elements and flow logic of a developed model system are shown in Figure 1. Each element is briefly discussed in the following section.

SYSTEM ELEMENTS

Deterioration and Repair Model

The purpose of the deterioration and repair model is to estimate the future performance of the road network considering its pavement condition. Future condition is governed by the deterioration mechanism and repair applications. Thus, a model is developed to simulate two simultaneous processes: (a) deterioration with age and (b)

O. Omar, Y. Hayashi, and T. Okuda, Nagoya University, Chikusa-ku, Nagoya 464-01, Japan. K. Doi, Tokyo Institute of Technology, Meguro-ku, Tokyo 152, Japan.

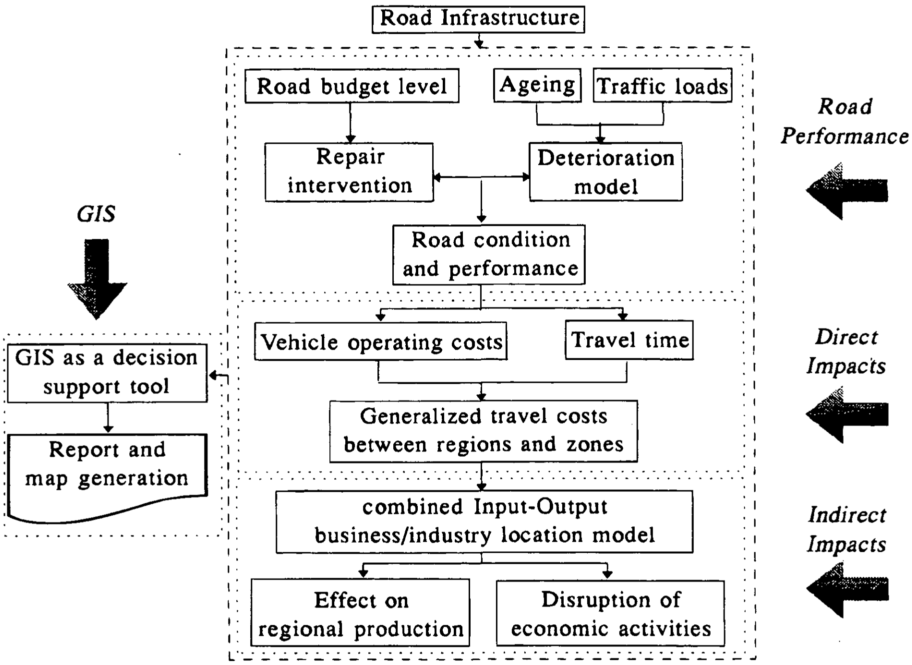


FIGURE 1 Study elements and flow logic.

repair need, application, and effect on condition. To account for the uncertainty in the deterioration mechanism and the subjective nature of repair decisions, the model treats these processes as stochastic phenomena.

Deterioration is represented as successive transitions over subsequent condition states. Condition is defined by the value of the maintenance control index (MCI, an index developed by the Japanese Ministry of Construction that is conceptually similar to the present serviceability index with maximum value of 10 for excellent pavement and minimum value of 0 for damaged pavement); and each state is defined by a range of MCI values. For example condition State 1 represents pavements with an MCI of 10-8, while State 2 has an MCI of 8-6, and so on. The pavement age at which any of such transitions may occur is treated as a stochastic variable. The model is developed for classes of pavements each of which has similar life expectation. Here, classification is based on pavement type, traffic level, and surrounding environment. For each class, a group of probability distribution functions is fitted to historical data on the age at which transition between condition states occurred. Each function gives the probability of transition between a certain pair of successive condition states as a function of pavement age. Therefore, given pavement age, current condition state, and its class, probable future condition state (a specific MCI range) can be predicted. The function used has the following form:

$$f(t) = P(t \le T \le t + \Delta t)/\Delta t = \frac{\alpha}{\beta}\left(\frac{t - t_o}{\beta}\right)^{\alpha - 1} \exp\left(-\left(\frac{t - t_o}{\beta}\right)^{\alpha}\right) \quad (1)$$

where $P(t \le T \le t + \Delta t)$ is the probability that transition will occur at age T, which is between t and $t + \Delta t$ years; t_0 is the minimum age at transition, α and β are parameters.

Equation 1 can be rewritten to yield a new indicator for performance evaluation based on pavement reliability, that is, the probability of staying in the current condition state, and can be given by

$$R(t) = P(T > t) = 1 - \int_0^t f(t)dt = \exp\left(-\left(\frac{t - t_o}{\beta}\right)^{\alpha}\right) \quad (2)$$

where $P(T > t)$ is the probability of no transition for at least t years.

In applying this model to estimate future deterioration, pavement sections divided into cohorts based on age and condition state are partially transferred to successive condition states with a yearly rate that equals

$$\lambda(t) = P(T < t + \Delta t \mid T > t)/\Delta t = \frac{f(t)}{R(t)} = \frac{\alpha}{\beta}\left(\frac{t - t_o}{\beta}\right)^{\alpha - 1} \quad (3)$$

where $P(T < t + \Delta t \mid T > t)$ is the probability that transition will occur before age $t + \Delta t$, given that it has not occurred at or before age t. Applying this rate, the probable condition of any section at any time, MCI_t, can be predicted.

As for repair modeling, transition is assumed to occur between only two states, the "repair not required" state (i.e., only routine maintenance is required) and the "repair required" state (i.e., overlay or reconstruction is required). The probability of occurrence of this transition depends on the pavement class and age. In this case, cohorts of pavement sections from the same class and age are partially selected for repair based on a yearly repair rate given by an equation similar to the transition rate given by Equation 3. Type of repair required is decided based on the class and condition state of sections selected for repair. The effect of repair is simulated as transition to a better condition state that depends on the probable efficiency of the selected repair type.

Prediction of future performance of a road network entails repeating the process of estimating the expected yearly transitions in condition and selection for repair (and thus cost) and its effect, year by year over an analysis period. Since the process is stochastic, it must be repeated a sufficient number of times to obtain the most probable future performance and repair needs. Effect of different budget levels on performance can be estimated by adjusting the repair rate to reflect the change in budget.

The prediction of pavement longitudinal roughness, LR, was also modeled since it is the major distress influencing travel speed. This was done as a linear regression relation between the expected amount of roughness and pavement condition (MCI_t) and age.

Evaluation System for Direct Impacts

A second element is used to evaluate the effects of road condition on the direct users of the facility. The effects considered here are the change in VOCs and operating speed, and thus travel time. The total impact is given as GTC between any two zones, including both of the previously mentioned cost factors. The evaluation is based on the estimated road condition according to the deterioration and repair model. The following relations are employed:

1. VOCs:

$$VOC_{tc} = \psi_c + \phi_c \exp(-MCI_t) + \epsilon_c \frac{1}{V_{tc}} \tag{4}$$

in which

$$V_{tc} = V_{oc} - \omega_c LR_t \tag{5}$$

where

VOC_{tc} = VOC of vehicle type c on a given pavement section at time t (yen/km);
MCI_t = expected pavement condition at time t;
V_{tc} = average operating speed of vehicle type c (passenger cars and trucks) on a pavement with condition MCI_t (km/hr),
$\psi_c, \phi_c, \epsilon_c, \omega_c$ = regression parameters that depend on vehicle type c;
V_{oc} = running speed of vehicle type c on similar section with new pavement (km/hr); and
LR_t = longitudinal roughness at time t (mm).

2. Travel time:

$$T_{tc} = \frac{60L}{V_{tc}} \tag{6}$$

where

T_{tc} = average travel time of vehicle c on a given road section at time t (min); and
L = length of road section (km).

3. GTC between zones:

$$C_{ij} = \min \sum_{ij} \sum_{c} (VOC_{tc}L + T_{tc}C_c) r_c \tag{7}$$

where

C_{ij} = GTC from zone i to zone j at time t;
C_c = value of time for vehicle type c (yen/min); and
r_c = ratio of vehicle type c in the traffic stream.

The first summation in Equation 7 is done over the road sections of each alternative route from i to j. Resulting minimum travel cost is taken as the GTC.

Evaluation System for Indirect Impacts

In this study, the indirect impacts are represented by the change in the productivity of each of the economy sectors. Unlike input-output analyses, the change is analyzed on the regional and zone level assuming no change in the total national product. The main purpose of this analysis is to show the consequences of cutting the road repair budget in the study region. A budget reduction might result from a general decline in road budget or a reallocation with a lower share for the study region. The developed model estimates the shares of demand and supply for each production sector located in each region and zone of the nation. Change in accessibility to any region or zone causes rearrangement of the demand-supply shares between regions and zones and thus losses to some sectors at certain locations. The GTC to a region or zone is assumed to reflect its accessibility and thus the attractiveness of production activities in exchange with other regions and zones.

The mathematical model is obtained by combining the concepts of input-output analysis with those of a business-industrial location model. The formulation is as follows (*4*):

The basic relation in the model is the equilibrium between supply and demand as given by

$$X^k = \sum_m A^{mk} X^m + F^k \tag{8}$$

where

X^k = total products of any sector k;
X^m = total products of sector m, ($m = 1, 2, \ldots, k, \ldots, \ldots$);
A^{mk} = input coefficient of materials and services to sector m from sector k (amount of product k required for producing one unit m); and
F^k = final demand for sector k.

The implemented business location model uses the number of employees in each sector rather than the amount of products. Thus, Equation 8 is rewritten as

$$E^k = \sum_m \theta^{mk} E^m + B^k \tag{9}$$

in which

$$\theta^{mk} = \frac{\omega^{mk}}{\sum_m \omega^{mk}}, \quad and \quad \omega^{mk} = x^{mk} \frac{E^k}{X^k} \tag{10}$$

where

E^k = number of employees in sector k;
E^m = number of employees in sector m;
θ^{mk} = input coefficient of employee to sector m from sector k (number of employees in k to serve one employee in m);
B^k = number of employees in k to serve the final demand; and
x^{mk} = sales of k products to sector m.

Equation 9 represents the market only under the assumption that demand creates equal supply. However, in reality, the existence of demand only increases the chance of supply. Thus, Equation 9 has to be written twice, once from the viewpoint of demand and again from the viewpoint of supply. Solution of the two equations yields the market equilibrium.

Equation 9 can be rewritten from the viewpoint of demand, while taking into account the distribution of demand on products of any sector k over g regions ($g = 1, 2, \ldots, h, \ldots, \ldots$), which are further divided into j zones each ($j = 1, 2, \ldots, i, \ldots, \ldots$), as follows.

For any zone i in any region h,

$$D^k_{hi} = \eta^k \sum_m \theta^{mk} \sum_g \sum_j S^m_{gj} P^{mk}_{hij} + \kappa^k \sum_g \sum_j R_{gj} P^k_{hij} \qquad (11)$$

in which

$$P^{mk}_{hij} = \frac{S^k_{hi} \exp(\delta^{mk} C_{hij})}{\sum_g \sum_j S^k_{gi} \exp(\delta^{mk} C_{hij})} \qquad (12)$$

and for the whole region,

$$D^k_h = \sum_j D^k_{hj} \qquad (13)$$

where

- D^k_{hi} = demand (number of required employees) for sector k located in zone hi (i.e., zone i located in region h);
- S^m_{gj} = supply (employees) by sector m located in zone gj;
- R_{gj} = population in zone gj;
- P^{mk}_{hij} = probability of selecting zone hi to supply k to sector m located in zone gj;
- P^k_{hij} = probability of selecting zone hi to supply k to final demand sector located in zone gj;
- η^k, κ^k = regression parameters;
- δ^{mk} = diminishing parameter reflecting the effect of transport cost on the marketing of product of sector k to sector m;
- C_{hij} = the GTC from zone hi to zone gj; and
- D^k_h = total demand (employees) for sector k located in region h.

The physical meaning of Equation 12 is that demand probability rises with the scale of the producer (S) and its closeness to the market (C).

From the viewpoint of supply, the choice of suppliers in this model is where to locate their activities to cover the demand. Under this condition, supply will be located as follows.

For region h,

$$S^k_h = S^k \frac{D^{k\gamma}_h \exp(\delta^k U^k_h)}{\sum_g D^{k\gamma k}_g \exp(\delta^k U^k_g)} \qquad (14)$$

in which

$$U^k_h = \sum_m \theta^{mk} \ln\left[\sum_g D^m_g \exp(\delta^k C_{hg})\right] \qquad (15)$$

for any zone i in any region h,

$$S^k_{hi} = S^k_h \frac{D^{k\gamma k}_{hi} \exp(\delta^k U^k_{hi})}{\sum_j D^{k\gamma k}_{hj} \exp(\delta^k U^k_{hj})} \qquad (16)$$

in which

$$U^k_{hi} = \sum_m \theta^{mk} \ln\left[\sum_j D^m_{hj} \exp(\delta^k C_{ij})\right] \qquad (17)$$

where

- S^k_h = supply (employees) by sector k located in region h;
- S^k = total supply (employees) by sector k;
- δ^k = diminishing parameter reflecting the average effect of transport cost on the marketing of product of sector k;
- C_{hg} = the average GTC from region h to region g;
- γ^k = regression parameter;
- U^k_h = expected extreme utility for producing k (considering transport cost) if located in h;
- S^k_{hi} = supply (employees) by sector k located in zone hi; and
- U^k_{hi} = expected extreme utility for producing k (considering transport cost) if located in zone hi.

Equations 15 and 17 mean that business considers both the amount of demand and its distance while evaluating the utility of each possible location for its activities.

The solution of the group of Equations 11 through 17 can be obtained by iteration under the condition

$$D^k_{hi} = S^k_{hj} \qquad (18)$$

GIS Base as a Decision-Supporting Tool

Road networks are inherently geographic as they are extended over a wide area and intersect with different land topography, such as rivers, mountains, buildings, and other roads. Also, network components and events taking place within the network are locational in nature. For example, the extent and shape of links, road intersections, accidents, and pavement conditions cannot be completely defined unless the geographic location of the component or event is given. Thus, spatial considerations in the analysis for different road activities, including maintenance and repair management, are essential and can vastly improve the quality of the decision-making process. However, highway infrastructure management systems are usually based on a central data bank in which only descriptive data are handled. More advanced systems are also supported by computer-assisted drafting systems for map generation. None of these systems permits spatial operations on the data. GIS as a system with spatial analysis capabilities—besides having the characteristics of the above-mentioned systems—particularly matches the geographic nature of road networks. Therefore, we coupled the previously discussed elements with a GIS. The developed system includes the following components:

- A spatial data base that stores data describing the spatial distribution of geographic features in the study area. Examples of such features are roads, city borders, land use, and main utility lines. Each feature is stored as a separate layer and is related with the other features by location as a common key.
- An attribute data base in which representative nongeographic information on the spatial features is stored. Examples of such

information for a road segment are road inventory, traffic volume, and pavement condition.

- An analysis module in the form of computer programs that represent the previously mentioned three elements and use data from both the spatial and attributes data bases. Spatial integration of different types of data is also possible to produce new information.
- An output-generation module to summarize data and information and produce reports and maps. The generation of such output can be achieved through programs, user textual queries, or user geographic queries.

The resulting system has the following main advantages: automation of map generation, powerful geographic queries, network analysis and simulation, and spatial analysis and data integration.

SUMMARY OF RESULTS

The developed model system was applied to a part of the trunk road network within the Aichi region of Japan. The purpose of the application was to examine the performance of this network under different levels of repair budget. The corresponding direct and indirect costs were quantified. Also the merits of introducing GIS to the system were examined. This section briefly gives some of the results. Detailed results can be found elsewhere (*2–5*).

Figure 2 illustrates predicted performance in terms of reliability and MCI of the average section of the network at the 80 percent and 60 percent repair budget levels (total 13-year cut of about 4 and 8.1 billion yen, respectively) compared with those at the 100 percent level (current investment level). The results indicate that a 20 percent reduction in the budget from its current level would result in a 20 percent and 17 percent decrease in the possible attainable reliability and MCI by the year 2000, respectively. On the other hand, a 40 percent reduction would result in a 44 percent and 38 percent decrease, respectively. The increasing damage-cut ratios show the effect of cumulative damage due to budget shortage.

Comparison between the trends of curves in Figure 2 indicates that the use of reliability as a performance indicator can lead to conclusions similar to those obtained using a condition index such as the MCI. However, the use of reliability has the advantage of it being able to link directly to the expected total repair need.

As for prediction accuracy, the predicted average MCI value in 1991 under the assumption of current budget level is estimated to be 6.54, while the true average obtained from the condition survey for the same year is 6.44. Comparison with prediction results obtained using other deterministic models reveals that predictions using the developed stochastic performance model are more accurate.

Besides physical damages to the network, the model was employed to estimate the financial losses due to budget cuts. A rapid increase in the yearly budget required for routine maintenance is expected (see Figure 3). Another virtual loss is the increase in the total repair needs of the network that will be incurred if all condition deficiencies are to be properly repaired in a certain future year (cost to recover condition). The expected future recovery costs are indicated in Figure 3. As shown, the costs in the year 2000 are about two and three times as much as the total cut in budget in the 80 percent and 60 percent budget levels, respectively.

Budget limitations cause both physical deterioration to the road system and financial losses to the road agency. However, it is possible to cope with such a situation to minimize these negative impacts by changing policies. The model was employed to examine such policy changes. For example Figure 4 illustrates the progress of the average MCI over the simulation period for the 80 percent budget level assuming different priority ranking criteria (based on pavement age, condition state, and traffic level). It is indicated that such a policy change can result in considerable change in performance level and ultimate condition. The curves indicate that the age-state-traffic ranking criteria are optimal in this case. However, further analysis of different budget levels reveals that it is not necessary that this ranking criteria always be the optimal.

As for the direct user impacts, the yearly relative savings or losses in total VOC were computed (see Figure 5). As indicated, an exponential increase in cumulative VOC losses to the direct users in the cases of limited budgets compared with an almost stable VOC in the 100 percent case. Doubling budget cuts results in more than twice the loss as indicated by the increasing divergence between loss curves in the figure. As a result of the increase in VOC and longer travel time, an increase in the GTC between the region's zones will follow. Figure 5 also depicts the percentage change in average GTC

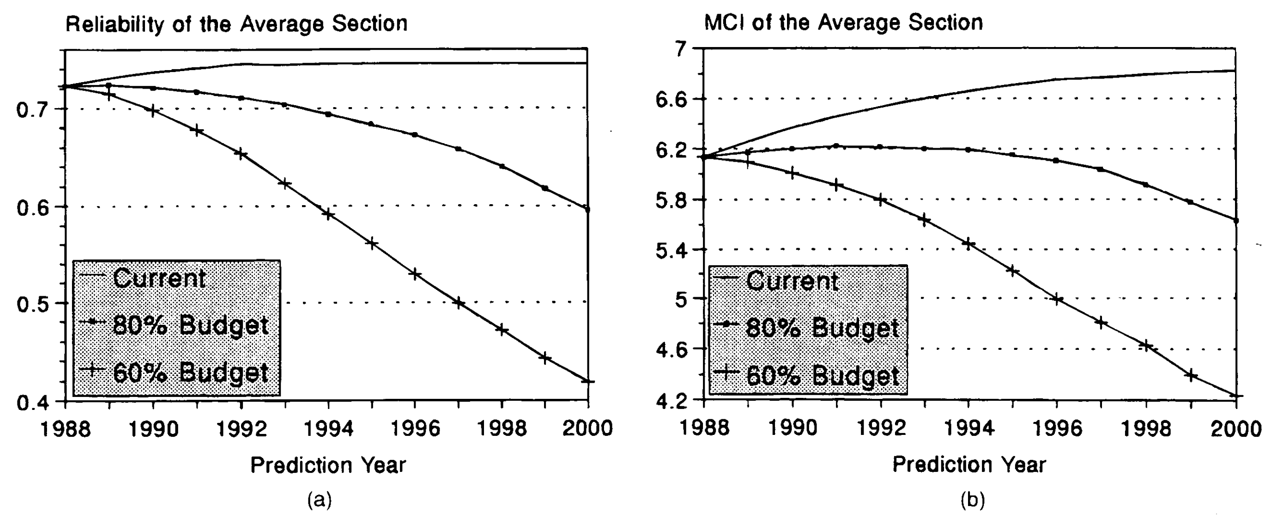


FIGURE 2 Predicted 1988–2000 performance under different repair budget levels: (a) reliability, (b) MCI.

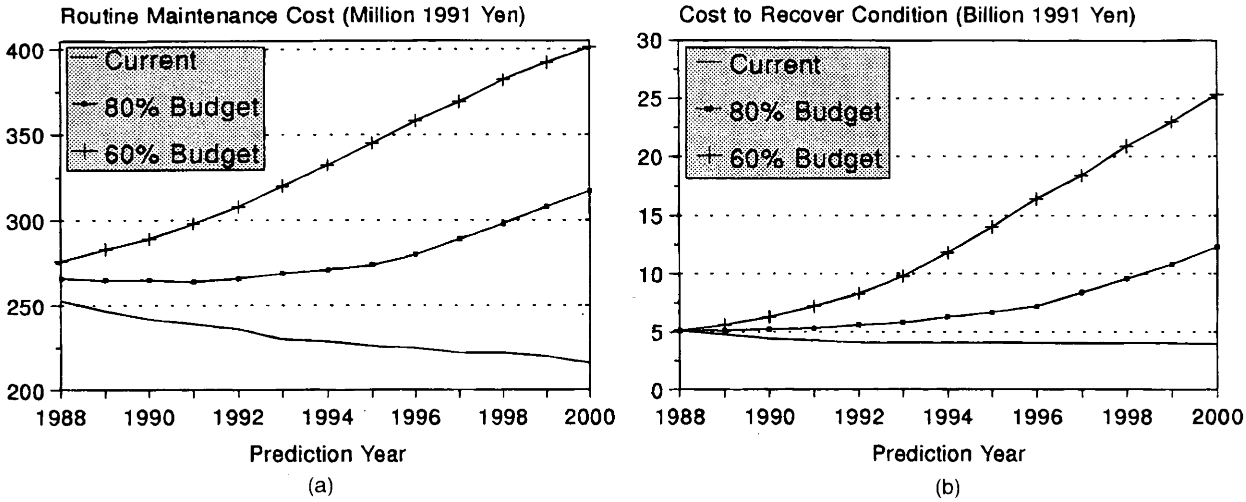


FIGURE 3 Anticipated financial losses due to budget costs: (a) routine maintenance, (b) recovery costs.

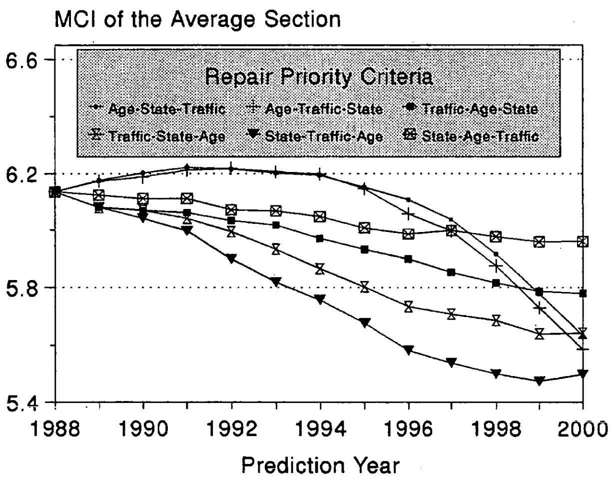


FIGURE 4 Performance assuming different allocation priority criteria.

for each zone at the 10th year of the analysis period. As indicated, rapid increase in such changes is expected with increasing budget cuts. It is also indicated that the differences in the magnitude of the impacts on different zones are almost negligible in the 100 percent case. However, such differences become more noticeable with the increase in budget cuts, clearly illustrated in the 60 percent case. This indicates a possible disruption in the spatial pattern of transportation costs across the region.

As for the indirect impacts, the number of employees in each sector was computed for each road performance level and thus GTC pattern. These numbers were then multiplied by the productivity of the employees in each sector to get the amount of the sector's production. The change in the amount of production of all sectors as a result of different road conditions was considered as the effect on the economy of the study region and its zones.

The impacts in monetary terms on a selected zone, as an example, is illustrated in Figure 6 for each sector under the 80 percent and 60 percent budget levels. Most of the loss is in the manufacturing sector, which is the main economic activity in this zone. Total produc-

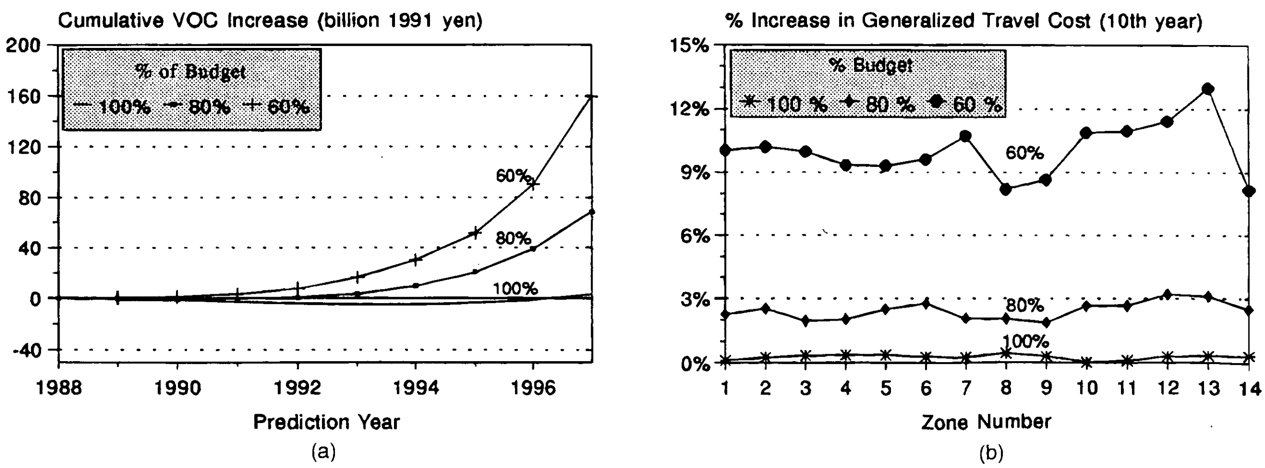


FIGURE 5 Direct impacts: (a) change in VOC, (b) change in GTC.

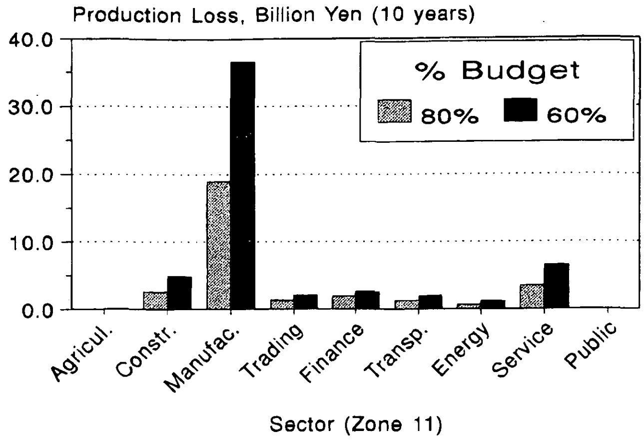


FIGURE 6 Indirect impacts: losses by sector for a selected zone.

tion losses over 10 years account for 30 and 56 billion yen for the 80 percent and 60 percent budget levels, respectively. These losses increase rapidly with time so that the cumulative losses over 20 years, for example, become about 20 times the losses after 10 years.

From the foregoing analysis, it is clear that the losses to the road agency, road users, and the economy largely exceed the savings by repair budget cuts. Such a result can be used to amplify the importance of satisfactory infrastructure performance and thus budget justification.

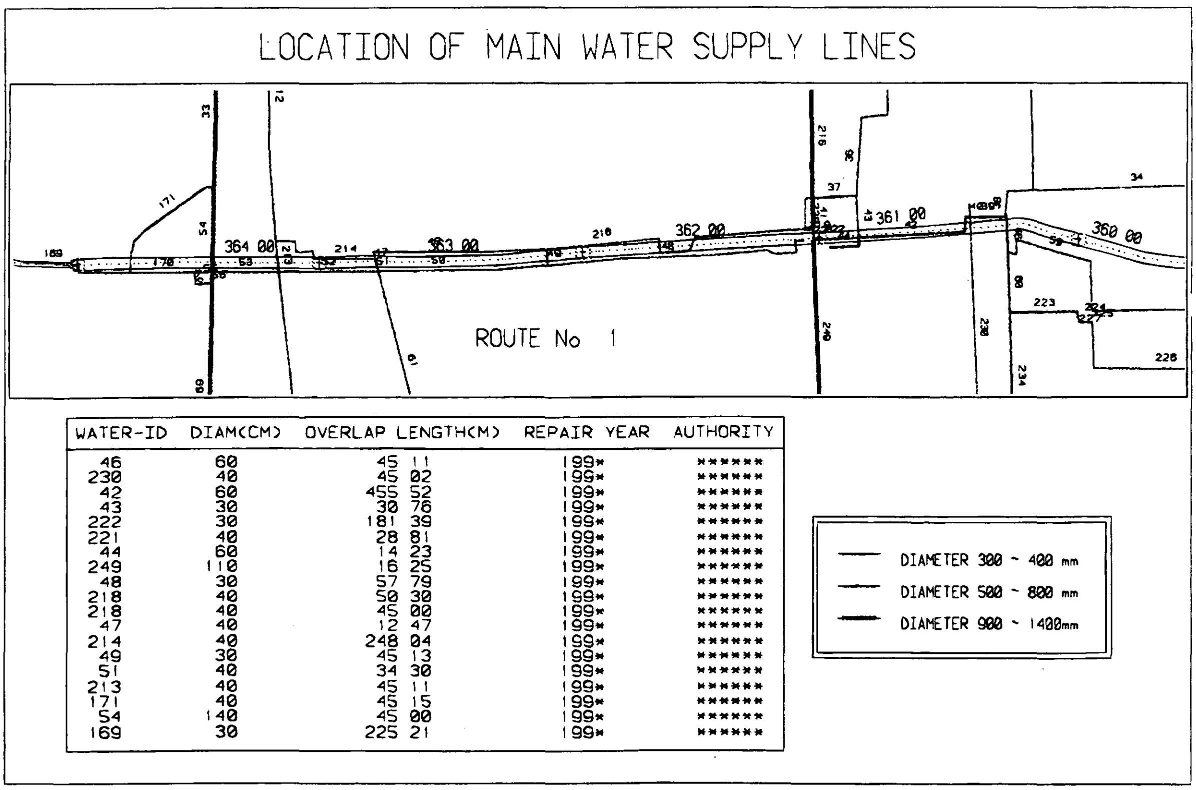
As for the GIS application, Figure 7 provides an example of an analysis type that becomes possible by introducing GIS to the system. The figure depicts an overlay between a road section scheduled for future rehabilitation and the main waterlines underneath this section. The overlay gives the location, characteristics, and future repair year and authority of those lines intersecting with that road section. Better coordination between timing of road repair and utilities repair and installation can be realized with such analysis.

CONCLUSIONS

This paper briefly discussed the development of a model system for supporting road infrastructure management. The system can be implemented on the network level to examine pavement performance under different repair policies and budgeting levels and scenarios. More importantly, the system can be used to quantify negative impacts on road agency, road users, and the regional economy due to unsatisfactory performance levels as a result of repair budget cuts. The results of such a system can be used to amplify the importance of satisfactory infrastructure performance level and, thus, justify required budgets.

Some of the findings obtained throughout system development and application are as follows:

- Modeling deterioration and repair as stochastic phenomena is more realistic. This yields more accurate simulation and prediction of future performance.
- Estimation of the direct and indirect costs incurred at any road performance level is essential to clarify the importance of keeping satisfactory conditions. The results indicate that such costs are much larger than the cost of proper repair of the infrastructure.



WATER-ID	DIAM(CM)	OVERLAP LENGTH(M)	REPAIR YEAR	AUTHORITY
46	60	45 11	199*	******
230	40	45 02	199*	******
42	60	455 52	199*	******
43	30	30 76	199*	******
222	30	181 39	199*	******
221	40	28 81	199*	******
44	60	14 23	199*	******
249	110	16 25	199*	******
48	30	57 79	199*	******
218	40	50 30	199*	******
218	40	45 00	199*	******
47	40	12 47	199*	******
214	40	248 04	199*	******
49	30	45 13	199*	******
51	40	34 30	199*	******
213	40	45 11	199*	******
171	40	45 15	199*	******
54	140	45 00	199*	******
169	30	225 21	199*	******

FIGURE 7 Coordination between timing of road repair and utilities repair and installations.

• Adaptation of new technologies, such as GIS, in the area of infrastructure management is promising and can vastly improve the quality of the decision-making process.

Finally, the developed system framework can also be adapted for other types of infrastructure. With such systems in hand, infrastructure renewal strategies commonly based on the fire-alarm strategy are likely to be abandoned in favor of strategies based on predicted information.

REFERENCES

1. Choate, P., and S. Walter. *America in Ruins.* Council of State Planning Agencies, 1981.
2. Omar, O., Y. Hayashi, and K. Doi. A Method of Maintenance Policy Evaluation Considering Highway Network Reliability, *Selected Proc., 6th World Conference on Transport Research*, 1992, pp. 2363–2374.
3. Hayashi, Y., O. Omar, and S. Kikukawa. A Probabilistic Performance Model for Transport Infrastructure Management: The Case of Highway Pavement, *Journal of Infrastructure Planning and Management* (Japan Society of Civil Engineering) Vol. IV-19, No. 464, 1993, pp. 135–141.
4. Hayashi, Y., O. Omar, K. Doi, and T. Okuda. Effect of Road Pavement Deterioration on the Regional Economy: A Case Study. *Proc. 20th PTRC Summer Annual Meeting*, 1992, pp. 145–157.
5. Hayashi, Y., O. Omar, K. Doi, and K. Kawamata. A GIS-Based Highway Network Deterioration Analysis. *Proc., 19th PTRC Summer Annual Meeting*, 1991, pp. 137–150.
6. Omar, O., Y. Hayashi, and K. Doi. Application of GIS to Highway Infrastructure Management. *Proc., Civil Engineering Annual Meeting*, Chubu Branch, Kanazawa, Japan, 1992.