【土木計画学研究・講演集 No.15(1) 1992年11月】

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

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Management of the aging infrastructure under budget limitations is becoming a critical issue in many countries. This paper presents a model system for supporting the process of road infrastructure management. 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 GIS as a tool to facilitate decision making. The developed system can be easily adapted for the other types of infrastructure.

1. INTRODUCTION

In Japan, the necessary road maintenance cost has been almost fully budgeted through treasury loans and investment, so far. However, in the future, according to 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 occurred in other countries, such as in the US (1). Therefore it is a necessity to provide information on when, where and how to repair in order 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 the above 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:

1) Model to forecast future deterioration and need for repair, which treats deterioration and repair as stochastic phenomena. It can be applied to predict the performance of a road network under different repair strategies (2,3).

2) System to quantify the direct impacts of deterioration in the form of changes in vehicle operating costs and travel speed. Accordingly, generalized travel cost between regions and zones can be quantified under any road performance level (4).

3) Model to forecast indirect impacts on the regional economy due to road deterioration. 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).

4) Geographic Information System (GIS) base to support the decision making process regarding deterioration and repair. This system provides reports and maps which can facilitate further analysis of information (5,6).

This paper briefly describes the development of each of the components and how they function together. Example application of the system is also given.

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2. 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 give figures on how much are the direct and indirect costs that will be incurred if the infrastructure is left to deteriorate. If such figures are known, the repair budget is likely to be raised. Also it is important to adapt new technologies to develop computerized systems which can help the management process. With such systems in hand, systematic analysis can be done and the aspects of the issue can be clarified.

The main target of this research work is to develop a system which can handle the required analysis. The sub-elements and flow logic of a developed model system are shown in Fig. 1. Each sub-element is briefly discussed in the following chapter.

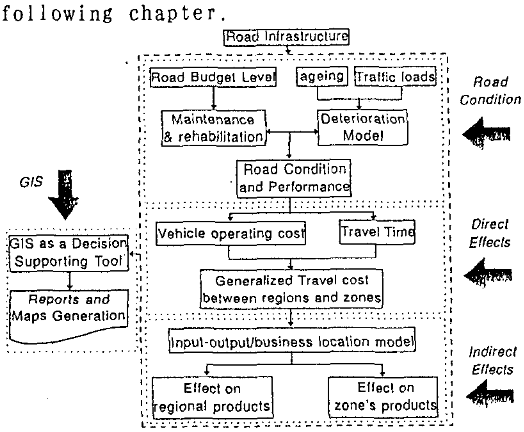

Fig 1: Study Sub-Elements and Flow Logic

3. SYSTEM SUB-ELEMENTS

3.1 Deterioration and Repair Model

The purpose of this sub-element 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 processes: 1) deterioration with age and 2) 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 probabilistic phenomena.

Deterioration is represented as a successive transitions over subsequent condition states. Condition is defined by the value of the maintenance control index (MCI); and each state is defined by a range of MCI values. The pavement age at which any of the transitions may occur is treated as a stochastic variable. The model is developed for classes of pavements with similar life expectation. For each class, a group of probability distribution functions is fitted to historical data on the age at which such transitions occurred. Each function gives the probability of transition between a certain pair of successive condition states as a function of pavement age. The used function 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_o is the minimum age at transition, α and β are parameters.

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 equals:

$$\lambda(t) = P\{T < t+\Delta t \mid T > t\}/\Delta t$$

$$= \frac{\alpha}{\beta}\left(\frac{t-t_o}{\beta}\right)^{\alpha-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

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.

This model also gives 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:

$$R(t) = P\{T > t\} = \exp\left[-\left(\frac{t-t_o}{\beta}\right)^{\alpha}\right] \quad \ldots\ldots(3)$$

where, $P\{T>t\}$ is the probability of no transition for at least t years.

As for repair modeling, transition is assumed to occur between only two states, "repair not required" state and "repair required" state. 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 (2). The effect of repair is simulated as transition to a better condition state which 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 its effect, year by year over an analysis period. Since the process is probabilistic, it must be repeated a sufficient number of times to get the most probable future performance. 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.

3.2 Evaluation System for Direct Impacts

This sub-element is to evaluate the effects of road condition on the direct users of the facility. The effects considered here are the change in 1) vehicle operating costs (VOC) and 2) operating speed, and thus travel time. The total impact is given as generalized travel cost between any two zones which includes both of the previously mentioned cost factors. The evaluation is based on the estimated road condition by the deterioration and repair sub-element. The following relations are employed:

<u>1- Vehicle operating costs (VOC):</u>

$$VOC_{tc} = \psi_c + \phi_c . \exp(-MCI_t) + \varepsilon_c \frac{1}{V_{tc}} \quad .....(3)$$

in which

$$V_{tc} = V_{oc} - \omega_c . LR_t \quad ....(4)$$

where,

VOC_{tc}: VOC of vehicle type c on a given road section at time t (yen/km)

MCI_t : pavement condition at time t

ψ_c, ϕ_c, ε_c, ω_c: regression parameters which depend on vehicle type (passenger cars and trucks)

V_{tc}: average running speed of vehicle type c on a given road section at time t (km/h)

V_{oc}: running speed of vehicle type c on similar section with new pavement (km/h)

LR_t: longitudinal roughness at time t (mm)

<u>2- Travel time:</u>

$$T_{tc} = \frac{60.L}{V_{tc}} \quad ....(5)$$

where,

T_{tc} : average travel time of vehicle c on a given road section at time t (min)

L : Length of the road section (km)

<u>3- Generalized travel cost between zones:</u>

$$C_{ij} = MIN[\sum_{ij} \{\sum_c ((VOC_{tc}.L + T_{tc}.C_c).r_c)\}] \quad ..(6)$$

where,

C_{ij}: the generalized travel cost from zone i to zone j

C_c : the value of time for vehicle type c (yen/min)

r_c : the ratio of vehicle type c in the traffic stream

The first summation in Equation (6) is done over the road sections of each alternative route from i to j. Resulting minimum travel cost is taken as the generalized travel cost.

3.3 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 zonal level assuming no change in the total national products. The main purpose of this analysis was to show the consequences of cutting the maintenance and rehabilitation budget in the study region. A budget reduction might result from a general decline in road budget or a re-allocation 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 re-arrangement of the demand-supply shares between regions and zones. The generalized travel cost to a region/zone was assumed to reflect its accessibility and thus the attractiveness of production activities in exchange with other regions/zones.

The mathematical model was 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:

$$X^k = \sum_m A^{mk} . X^m + F^k \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where,

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

The implemented business location model employs the number of employees in each sector rather than the amount of products. Thus, Equation 7 is re-written as:

$$E^k = \sum_m \theta^{mk} . E^m + B^k \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which,

$$\theta^{mk} = \frac{\omega^{mk}}{\sum_m \omega^{mk}}, \quad \text{and} \quad \omega^{mk} = x^{mk} . \frac{E^k}{X^k} \quad \ldots (9)$$

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
x^{mk} : sales of k products to sector m

Equation 8 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 8 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 8 can be re-written 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:

$$D^k_{hi} = \eta^k . \sum_m \theta^{mk} \sum_g \sum_j S^m_{gj} . P^{mk}_{hij} + \kappa^k \sum_g \sum_j R_{gj} . P^k_{hij} \quad \ldots\ldots\ldots\ldots (10)$$

in which,

$$P^{mk}_{hij} = \frac{S^k_{hi} . \exp(\delta^{mk} . C_{hij})}{\sum_g \sum_j S^k_{gj} . \exp(\delta^{mk} . C_{hij})} \quad \ldots\ldots (11)$$

and for the whole region:

$$D^k_h = \sum_j D^k_{hj} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where,

D^k_{hi} : demand (in terms of the number of required employees to cover this demand) for sector k located in zone hi (that is 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 generalized travel cost from zone hi to zone gj
D^k_h : total demand (employees) for sector k located in region h

The physical meaning of Equation 11 is that demand probability gets higher 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 follow:

for region h:

$$S^k_h = S^k \frac{D^{k\,\gamma^k}_h . \exp(\delta^k . u^k_h)}{\sum_g D^{k\,\gamma^k}_g . \exp(\delta^k . u^k_g)} \quad \ldots\ldots\ldots (13)$$

in which,

$$u_h^k = \sum_m \theta^{mk} . \ln(\sum_g D_g^m . \exp(\delta^k . C_{hg})) \quad \ldots(14)$$

for any zone i in any region h:

$$S_{hi}^k = S_h^k \frac{D_{hi}^{k\,\gamma^k} . \exp(\delta^k . u_{hi}^k)}{\sum_j D_{hj}^{k\,\gamma^k} . \exp(\delta^k . u_{hj}^k)} \quad \ldots\ldots(15)$$

in which,

$$u_{hi}^k = \sum_m \theta^{mk} . \ln(\sum_j D_{hj}^m . \exp(\delta^k . C_{ij})) \quad \ldots(16)$$

where,

S_h^k : 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 generalized travel cost form region h to region g
γ^k : regression parameter
u_h^k : expected extreme utility for producing k (considering transport cost) if located in h
S_{hi}^k : supply (employees) by sector k located in zone hi
u_{hi}^k : expected extreme utility for producing k (considering transport cost) if located in zone hi

Equations 14 and 16 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 10 through 16 can be obtained by iteration under the condition:

$$D_{hi}^k = S_{hi}^k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

3.4 GIS Base as 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, other roads, etc. 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 CAD systems for maps generation. None of these systems permits spatial operations on the data. GIS as a system with spatial analysis capabilities besides having the attributes of the above mentioned systems is particularly matching the geographic nature of road networks. Therefore, we coupled the previously discussed sub-elements with a GIS. The developed system includes the following components:

1) A spatial data base which stores data describing the spatial distribution of geographic features in the study area. Example of such features are, roads, city borders, land use, and main utility lines. Each of the features is stored as a separate layer and related with the other features by location as a common key.

2) An attributes data base in which representative non-geographic information on the spatial features are stored. An example of such information for a road segment is road inventory, traffic volumes, and pavement condition.

3) An analysis module in the form of computer programs which represent the previously mentioned three sub-elements; and utilize data from both the spatial and attributes data bases. Spatial integration of different types of data is also possible to produce new information.

4) An outputs generation module to summarize data and information and produce reports and maps. The generation of such outputs can be done through programs, user textual queries, or user geographic queries.

The resulting system has the following advantages:
1- Automation of maps generation.
2- Powerful geographic queries.
3- Network analysis and simulation.
4- Spatial analysis and data integration.

4. SUMMARY OF OBTAINED RESULTS

The developed model system was applied to a part of the trunk roads network within the Aichi region, 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 chapter briefly gives some of the results. Detailed results are given in references 2,3,4 and 5.

Fig. 2 shows the future performance of the network, given as network average reliability, under different repair levels and different allocation priority criteria. The figure shows that allocation of limited budget would be more efficient if higher priority is given to older road sections and then to those with higher traffic. It also shows that the effect on the network reliability due to reducing the repair budget by 40% from its current level would be 3 times as high as the effect of 20% reduction. This shows the effect of cumulative damage due to budget cuts. Fig. 3 shows the performance in terms of estimated average future MCI.

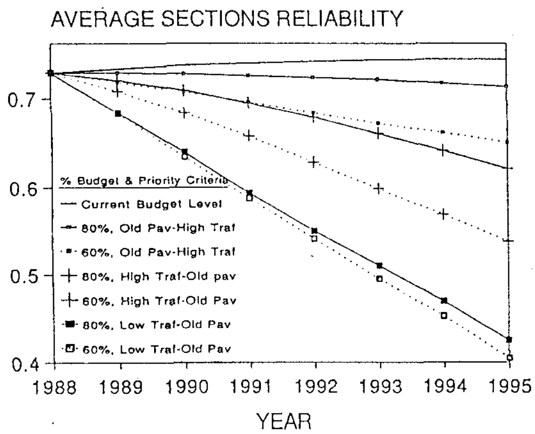

Fig 2: Average Network Reliability

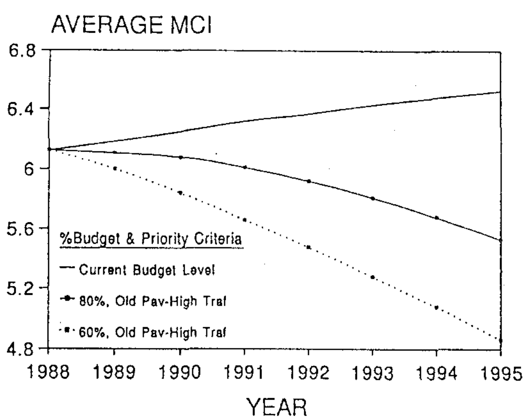

Fig 3: Average MCI of the Network

The yearly relative savings/losses in total VOC were computed for a part of the network as shown in Fig. 4. As shown, only the 100% (keep current average MCI) and 90% budget levels would result in future savings in VOC. All other levels result in losses which were as high as 160 billion yen in the 20th year for the 50% budget level (a cut of 3.25 billion yen a year). The required yearly additional rehabilitation and maintenance costs to raise the average condition of the network to MCI = 8 are shown in Fig. 5. Such costs are considered as another direct cost due to the cumulative damage resulting from repair deferment due to budget limitations.

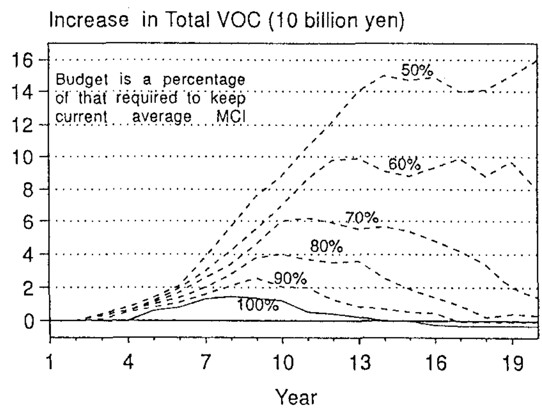

Fig 4: Increase in Total Yearly VOC

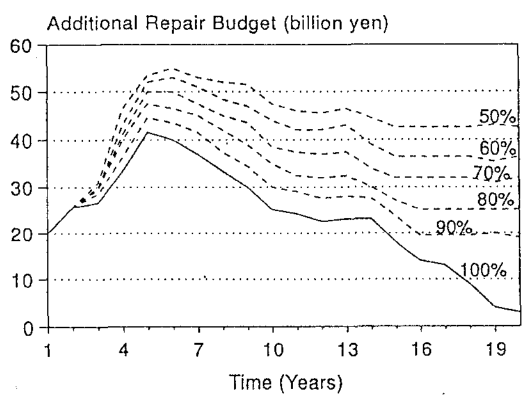

Fig 5: Required Yearly Additional Budget

As for the indirect effects, the number of employees in each sector were computed for each road performance level. These numbers were then multiplied by the productivity of the employees in each sector to get the amount of production for this sector. 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 final analysis, however, was done only on the regional level.

Fig. 6 shows the total amount of loss

due to the increase in travel cost and decrease in production. The loss is shown for budget level 60%. As shown in this figure, the direct loss due to the increase in travel cost is generally less than 25% of the indirect loss. The indirect loss in the eighth year of the analysis period totaled 214 billion yen. This amount corresponds to 0.92% of the current Gross Regional Products (GRP) of the study region. Such loss is expected to become 1.3% in the sixteenth year. Regarding the cumulative indirect loss compared with the cumulative reduction in road budget, the indirect loss was found to be as high as 40 times the reduction in budget over the first eight years. Such a ratio was found to uniformly increase with time so that it almost double after an additional eight years.

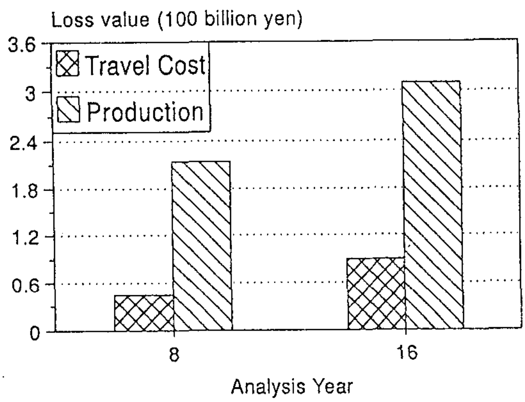

Fig 6: Loss in Production and Travel Cost

Fig. 7 shows an example of analysis type which becomes possible by introducing GIS to the system. The figure shows an overlay between a road segment scheduled for future rehabilitation and the main water lines. The overlay gives the location, characteristics, and future repair year and authority of those lines intersecting with that road segment. Better coordination between timing of road repair and utilities repair and installation can be realized with such analysis.

5. CONCLUSIONS

This paper briefly discussed the development of a model system for supporting road infrastructure management. The system is composed of the following elements:

1) A model to forecast future deterioration and need for repair.
2) An evaluation system for direct costs incurred by facility's users due to deterioration.
3) A model to forecast indirect impacts in the form of negative effect on the economy due to the increase in user cost.
4) A GIS base to support the decision making process.

Some of the findings through system development and application are:

1) Modeling deterioration and repair as probabilistic phenomena is more realistic. This yields accurate simulation and prediction of future performance.
2) Estimation of the direct and indirect costs are essential to clarify the importance of keeping satisfactory condition. The results shows that such costs are much larger than the cost of

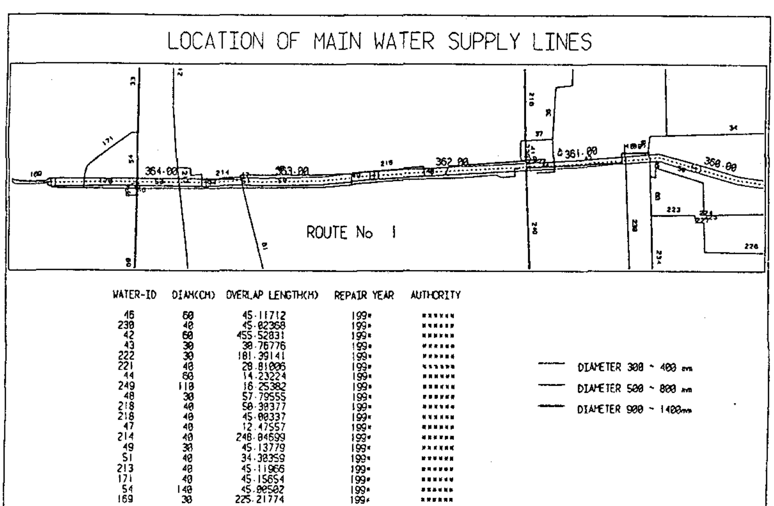

Fig 7: Overlay Between a Road Segment and Main Utility Lines

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

Finally, the developed system can be also easily 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.

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