A municipal infrastructure management systems model

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Abstract: The Municipal Infrastructure Management System (MIMS) is a computer model to assist systems operations engineers manage public service infrastructure more effectively. The MIMS model predicts infrastructure condition performance, establishes treatment schedules, and determines infrastructure asset valuation. The infrastructure model is capable of multiple infrastructure type (i.e., water lines, roads, etc.) evaluation. MIMS models all infrastructure segments in a simultaneous analysis. MIMS uses Markovian probabilistic modelling principles on a segment level analysis. A Markovian segment level analysis combined with detailed treatment strategies enables realistic, accurate costing and performance prediction. Treatment strategies consider societal costs (i.e., agency, non-agency, tangible, and non-tangible costs). Effectiveness calculations enable alternatives evaluation and a comparative integrated evaluation between different infrastructure types. Optimization methods use the effectiveness calculations and network operational constraints (i.e., budget limits) to provide the most effective treatment schedules based on principles of minimizing treatment costs. A case study applied to an asphalt concrete road network shows the utility of MIMS to analyse a range of decision-making issues.

Key words: infrastructure, segment, network, condition, extent, severity level, treatment.

Résumé : Le modèle informatique des Systèmes de Gestion des Infrastructures Municipales (SGIM) a été conçu afin d'accroître l'efficacité de la gestion des infrastructures des services publiques par les ingénieurs de système d'opération. Le programme SGIM prédit la performance des infrastructures, établit des horaires de traitement et détermine la valeur monétaire des infrastructures. Le modèle est en mesure d'évaluer les différents types d'infrastructure (i.e., réseau d'égout et d'aqueduc, réseau routier, etc.). Le SGIM modélise tous les segments de l'infrastructure de manière simultanée. Le programme SGIM utilise les principes de modélisation probabilistique de Markov pour chaque segment. Une analyse markovienne segmentée jointe à un traitement détaillé des stratégies permet d'obtenir une prédiction réaliste des performances et des coûts associés. Les stratégies de traitement considèrent les coûts sociaux (i.e., les coûts agent, non agent, tangibles et non tangibles). Des calculs d'efficacité permettent d'évaluer les alternatives et d'établir une évaluation comparative entre les différents types d'infrastructure. Les méthodes d'optimisation utilisent les calculs d'efficacité et les contraintes opérationnelles du réseau (i.e., les limites budgétaires) afin d'établir les horaires de traitement les plus efficaces tout en minimisant les coûts. Une étude de cas concernant un réseau routier de béton et d'asphalte démontre l'utilité du programme SGIM pour l'analyse d'une gamme de paramètres affectant la prise de décision.

Mots clés : infrastructure, segment, réseau, condition, étendue, niveau de sévérité, traitement.
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Introduction

This paper describes the methods used in the development of the Municipal Infrastructure Management System (MIMS) model, and the components and sequence of procedures employed by the MIMS model. To illustrate its utility as a decision-making model, MIMS is applied to one type of infrastructure, an asphalt concrete road network. The case study shows the utility of MIMS to analyse a range of decision-making issues.

MIMS development is derived from the theory of pavement management systems modelling. However, a need exists to accommodate a number of underground and aboveground infrastructure types (e.g., watermains, storm sewers, and sidewalks), which employ modelling theory beyond traditional pavement management systems modelling.

The approach in MIMS uses the Markov chain, a traditional network probabilistic performance prediction method, for application at the segment level of analysis.

MIMS has been developed as an optimization model type to (*i*) allocate limited budget resources effectively by selecting agency treatment schedules based on realistic principles of minimizing costs; (*ii*) increase public accountability in justifying the resulting infrastructure condition impact and monetary impact due to the selected treatment schedule; (*iii*) answer questions concerning deviations in the use of all or part of the infrastructure network, and evaluate the performance impact and monetary impact of this deviated use; and (*iv*) evaluate all infrastructure types and individual segments on an equitable level.

MIMS performs the following functions: (*i*) it models select multiple infrastructure types within a municipal network; (*ii*)

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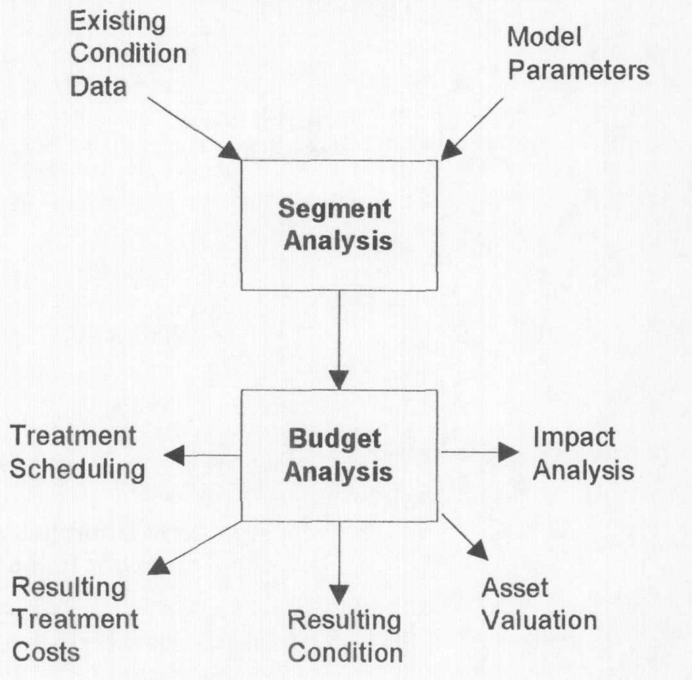
it determines the most cost-effective treatment schedule that will work within the operational constraints of the agency; (*iii*) it measures the resulting condition of each identified infrastructure segment due to the determined treatment schedule; (*iv*) it measures the resulting change in value of the infrastructure asset due to the determined treatment schedule; (*v*) it predicts the condition and monetary impact of changed use beyond normal operations; and (*vi*) it compiles and summarizes output for decision making by senior management.

Methodology

MIMS is comprised of two main analyses. The segment analysis evaluates each infrastructure segment independently and determines alternate treatment paths rated on the effectiveness of minimizing treatment costs over the simulation period or life of the infrastructure segment. The second analysis, the budget analysis, takes the segment treatment paths determined from the segment analysis, and provides the most effective treatment schedule for each segment given the network operational constraints of the agency. Figure 1 illustrates the basic input and output of the MIMS model.

Figure 2 illustrates the modular components of the MIMS model. Throughout the modelling process, a continuous interaction exists within many of the program modules.

Fig. 1. Municipal Infrastructure Management Systems basic inputs



Segment analysis

Performance prediction

The performance prediction module analyses condition data according to relative performance criteria. Resulting performance indices provide the systems operations engineer with a relative measure of the infrastructure condition. Performance measure groupings integrate into the treatment strategies of other model components.

Performance prediction is based on the principles of the Markov chain. The Markov chain calculates the condition deterioration through a series of algorithms using Markovian probability matrices and condition extents. For each condition type, predicted condition extents combine with other model parameters (i.e., threshold levels of extent) to compute condition indices. Condition indices are a measure of performance. Set ranges of condition indices determine condition states. Condition states are used to set treatment strategies. This section discusses the Markovian probability matrices, condition extent calculations, condition indices calculations, and the derivation of condition states.

Condition deterioration is modelled for select condition types from field condition measurements. The deterioration rate is dependent on any or all of the following groups: (*i*) previously applied treatment(s) and proportion of previously applied treatment(s) within the infrastructure segment; (*ii*) functional classification (i.e., functional use of the infrastructure); (*iii*) structural classification (i.e., strength group); (*iv*) environmental classification (i.e., surrounding environment, including moisture, soil, temperature, etc.); (*v*) capacity classification (i.e., expected use in relation to the design or normal use of the infrastructure); and (*vi*) current age in proportion to the design life.

The Markov chain is a probabilistic approach to performance prediction. In application, the probability matrices represent probabilities of severity level changes in a 1-year period. The probabilities can be derived through monitoring historic data, experimentation, expert judgement, or any combination. Markovian modelling is applied throughout the model for each condition type of each infrastructure segment according to the classification grouping described above. Table 1 illustrates a typical Markovian deterioration probability matrix.

The Markovian probabilities of moving from one severity level to another severity level work with condition extents to predict condition extents in subsequent years. Table 2 illustrates the simulated extent level calculations.

The classification grouping (functional, structural, environmental, and capacity) and age to design life comparison remains uniform within any infrastructure segment in any simulation year. The combinations of the grouping, which categorizes the infrastructure, set the Markovian probabilities used in the extent calculations. The applied treatments also impact these probabilities and calculations. As a result, the extent calculations are further broken down by treatment type applied to the infrastructure segment throughout the simulation period. The resulting extent calculations at the end of each simulation year is weighted by the proportion of each treatment type applied to the infrastructure segment.

Consider the following example relating the extent calculations of one condition type (fatigue cracking) within a single asphalt concrete road infrastructure segment. Assume the following: (*i*) it is the first year in the simulation period; (*ii*) the existing fatigue cracking extents at each severity level are 92% (none), 4% (minor), 3% (moderate), 1% (major), and 0% (severe); (*iii*) of the 8% fatigue cracking, 6% was never treated and 2% was previously treated with a spot seal; and (*iv*) Tables 3 and 4 illustrate the Markovian probability matrices for the untreated treatment and the spot seal treatment respectively.

Consider the extent level calculation at the minor severity level. For the infrastructure segment proportion currently

Fig. 2. Municipal Infrastructure Management Systems model components.

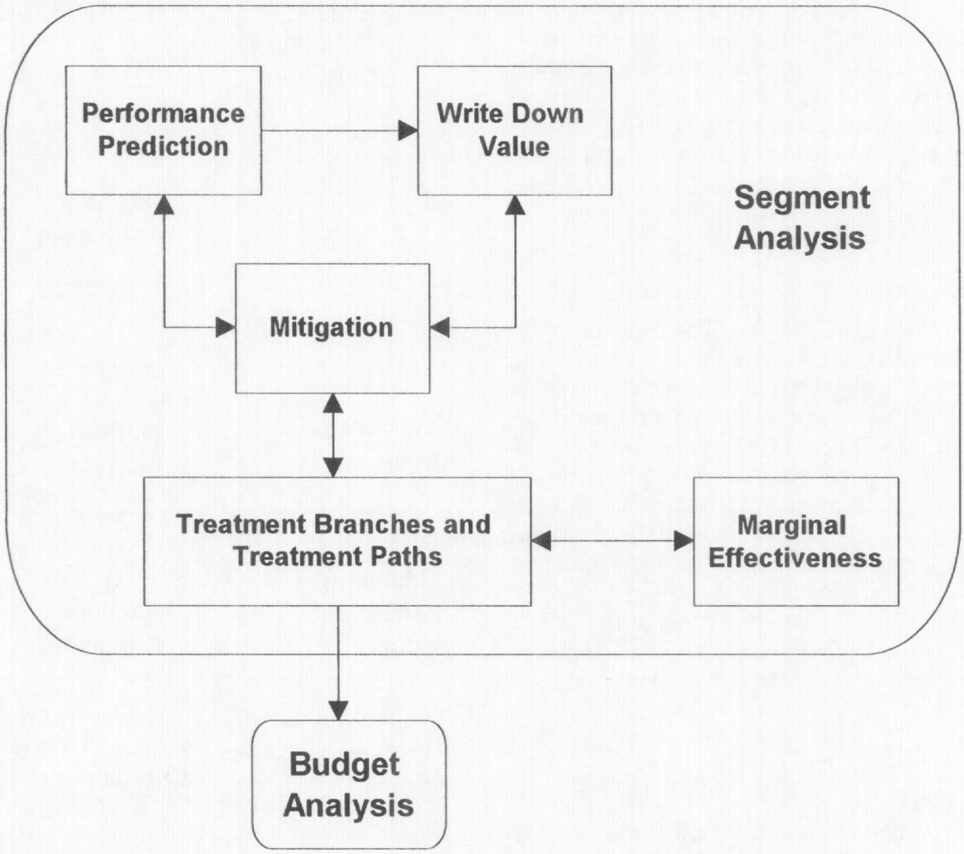


Table 1. Deterioration probability matrix.

	To					
From	None	Minor	Moderate	Major	Severe	Total
None	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	1.0
Minor	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}	1.0
Moderat	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}	1.0
Major	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}	1.0
Severe	P_{51}	P_{52}	P_{53}	P_{54}	P_{56}	1.0

untreated, the resulting fatigue cracking extent expected for simulation year 1 is

$$\begin{aligned} E_{02} &= E_{01}P_{12} + E_{02}P_{22} + E_{03}P_{32} + E_{04}P_{42} + E_{05}P_{52} \\ &= 0.92 \times 0.00 + 0.04 \times 0.94 + 0.03 \times 0.03 \\ &\quad + 0.01 \times 0.02 + 0.00 \times 0.01 \\ &= 0.0387 \end{aligned}$$

For the spot seal treatment, the resulting condition extent is

$$\begin{aligned} E_{02} &= E_{01}P_{12} + E_{02}P_{22} + E_{03}P_{32} + E_{04}P_{42} + E_{05}P_{52} \\ &= 0.92 \times 0.00 + 0.04 \times 0.88 + 0.03 \times 0.10 \\ &\quad + 0.01 \times 0.01 + 0.00 \times 0.01 \\ &= 0.0383 \end{aligned}$$

Given the treatment proportion historically applied to the infrastructure surface area, the resulting weighted average minor fatigue cracking condition extent is

$$E_{02} = (0.0387 \times 6\% + 0.0383 \times 2\%) \,/\, 8\% = 0.0386$$

By the same formulation, Table 5 illustrates the extent calculation results for all severity levels.

These extent calculations are repeated for all condition types within each infrastructure segment. Each infrastructure type (i.e., asphalt concrete roads, steel water mains) has a set of condition types and relevant parameters to model from. Condition extents are the building blocks for the performance measure indices.

Condition indices are calculated performance measures based on comparing the condition extents with preset threshold levels of extent (tolerance levels). Threshold extent levels provide the systems operations engineer with the opportunity to consider multiple aspects when predetermining acceptable threshold levels of operation. Many aspects, such as agency costs and some user costs, can be calculated into the analysis for setting threshold extent levels. Other societal costs such as the risk of safety are, for the most part, intangible. As a result, other quantitative analysis methods are required to derive the threshold levels of extent. Often, expert judgement and other influences (i.e., political) may impact the derivation of these levels. Once established, threshold extent levels may be adopted as agency standards for operation.

As with the Markovian probability matrices, the classification groupings (functional, structural, environmental, and capacity) enable varying threshold extent levels for select

Table 2. Simulated extent calculations.

	Extent levels within each severity rating					
Year	None	Minor	Moderate	Major	Severe	Index
Y_0	E_{01}	E_{02}	E_{03}	E_{04}	E_{05}	I_0
Y_1	$E_{01}P_{11} + E_{02}P_{21} + E_{03}P_{31} + E_{04}P_{41} + E_{05}P_{51}$	$E_{01}P_{12} + E_{02}P_{22} + E_{03}P_{32} + E_{04}P_{42} + E_{05}P_{52}$	$E_{01}P_{13} + E_{02}P_{23} + E_{03}P_{33} + E_{04}P_{43} + E_{05}P_{53}$	$E_{01}P_{14} + E_{02}P_{24} + E_{03}P_{34} + E_{04}P_{44} + E_{05}P_{54}$	$E_{01}P_{15} + E_{02}P_{25} + E_{03}P_{35} + E_{04}P_{45} + E_{05}P_{55}$	I_1
Y_2	$E_{11}P_{11} + E_{12}P_{21} + E_{13}P_{31} + E_{14}P_{41} + E_{15}P_{51}$	$E_{11}P_{12} + E_{12}P_{22} + E_{13}P_{32} + E_{14}P_{42} + E_{15}P_{52}$	$E_{11}P_{13} + E_{12}P_{23} + E_{13}P_{33} + E_{14}P_{43} + E_{15}P_{53}$	$E_{11}P_{14} + E_{12}P_{24} + E_{13}P_{34} + E_{14}P_{44} + E_{15}P_{54}$	$E_{11}P_{15} + E_{12}P_{25} + E_{13}P_{35} + E_{14}P_{45} + E_{15}P_{55}$	I_2
Y_n						I_n

Table 3. Markovian probability matrix for the untreated treatment.

Condition: Fatigue cracking
Treatment: Untreated
Functional class: Major arterial
Structural class: Asphalt concrete/base/subbase
Environmental class: Till subgrade — nommal moisture levels
Capacity class: Normal loading
Age/design life: 0.8

	To					
From	None	Minor	Moderate	Major	Severe	Total
None	0.97	0.02	0.01	0.00	0.00	1.00
Minor	0.00	0.94	0.03	0.02	0.01	1.00
Moderate	0.00	0.00	0.92	0.06	0.02	1.00
Major	0.00	0.00	0.00	0.91	0.09	1.00
Severe	0.00	0.00	0.00	0.00	1.00	1.00

Table 4. Markovian probability matrix for the spot seal treatment.

Condition: Fatigue cracking
Treatment: Untreated
Functional class: Major arterial
Structural class: Asphalt concrete/base/subbase
Environmental class: Till subgrade — nommal moisture levels
Capacity class: Normal loading
Age/design life: 0.8

	To					
From	None	Minor	Moderate	Major	Severe	Total
None	0.92	0.05	0.02	0.01	0.00	1.00
Minor	0.00	0.88	0.10	0.01	0.01	1.00
Moderate	0.00	0.00	0.86	0.12	0.02	1.00
Major	0.00	0.00	0.00	0.85	0.15	1.00
Severe	0.00	0.00	0.00	0.00	1.00	1.00

infrastructure classes within each infrastructure type. For example, with asphalt concrete roads, varying functional classifications (arterial, collector, and local access) may require varying levels of service. As a result, the threshold levels of extent for most condition types would be lower (i.e., tolerate less surface distresses and deteriorating conditions) for the more travelled arterial roads compared to the other functional classes.

Condition indices are calculated for each condition type of each infrastructure type for each year within the simulation period. To weigh the relative importance of each condition type when computing the total performance measure (summation of condition indices within each infrastructure type), each index is multiplied by a threshold value (THV). The resulting index value is an open-ended scale. The higher the index, the worse is the performance and condition of the infrastructure segment. The following describes the components within the condition index calculation:

Table 5. Extent calculations for the untreated and spot seal treatments.

Treatment	Year	None	Minor	Moderate	Major	Severe
Untreated	0	0.9200	0.0400	0.0300	0.0100	0.0000
	1	0.8935	0.0387	0.0282	0.0091	0.0000
Spot seal	0	0.9200	0.0400	0.0300	0.0100	0.0000
	1	0.8576	0.0383	0.0270	0.0085	0.0000
Weighted average	1	0.8845	0.0386	0.0279	0.0090	0.0000

Table 6. Typical ranges for condition states.

Index/threshold value	State
0.0 – 0.5	1
0.5 – 1.0	2
1.0 – 1.5	3
1.5 – 2.5	4
> 2.5	5

$$\text{INDEX} = \text{THV}\left(\frac{\%\text{Se}}{\text{SeTH}} + \frac{\%\text{Ma}}{\text{MaTH}} + \frac{\%\text{Mo}}{\text{Moth}} + \frac{\%\text{Mi}}{\text{MiTH}}\right)$$

where INDEX is the calculated index for a given condition type; THV is the threshold value; %Se, %Ma, %Mo, and %Mi are the measured percentages of extents at the severe, major, moderate, and minor levels, respectively; and SeTH, MaTH, MoTH, and MiTH are the threshold levels of extent for the severe, major, moderate, and minor condition levels, respectively.

On completion of each index calculation, condition states are determined for each condition type. Condition states are used within present treatment strategies to determine the governing states (most deteriorated condition type within the infrastructure segment). Given the governing states, alternate treatment strategies are selected.

Condition states are calculated from a user-defined set of index to threshold value ranges. Table 6 illustrates typical ranges for the five allowable condition states.

The segment modelling processes access two treatment strategy sets. One treatment strategy set determines appropriate mitigation options. The second treatment strategy set is used in the computation of the asset write down value for each infrastructure segment of each simulation year.

Mitigation

Treatment strategies exist for each condition type. Treatments are selected within the governing condition types for the appropriate condition state. These are governing treatments. The treatments may or may not have an effect on other condition types depending on how the user sets the treatment strategies.

The first item set in the treatment strategies is the condition states used to establish possible governing treatments. Table 7 illustrates typical condition states to implement treatments within a fatigue cracking treatment strategy.

In Table 7, minor treatments, such as a seal coat, are initiated earlier as a preventative maintenance practice. Major treatments, such as a structural rehabilitation, are not required until more deterioration occurs. No set rules exist for the treatment strategy selection. Strategy selection depends on the discretion of the systems operations engineer. However, the consideration of all treatments in all condition states would consume significantly more computer time and disk space. The treatment strategies would also be unrealistic. For example, major treatments, such as the structural overlay, are not applied in a near new condition state.

The second item within the treatment strategies enables the systems operations engineers to set the operations procedures and predict the proportion of extents mitigated for each treatment type. Table 8 illustrates typical mitigation extent proportions within a fatigue cracking treatment strategy.

In Table 8, the systems operations engineer predicts the spot seal treatment as being effective to mitigate 100% of moderate and major fatigue cracking severity levels. The treatment strategy also establishes a field staff procedure to mitigate only 50% of the minor fatigue cracking severity levels. The proportion of extents mitigated is activated for each condition type each time the treatment is activated. The treatment strategy impact is unique for each condition's treatment strategy. During each simulation year, the condition extents are reset by the proportions established within the treatment strategies. Following the condition extent recalculations, the condition indices and condition states are also recalculated for another cycle.

The final item set in the treatment strategies is the unit costs. Table 9 illustrates typical treatment unit costs for fatigue cracking treatment strategies. Treatment costs are typical of agency costs. The network budget parameters, discussed later, directly relate to the treatment costs.

Two cost types exist within the Table 9 treatment strategies. The first cost type applies the unit price costing formula to the condition area only at each severity level (minor, moderate, major, and severe). In this example, the spot seal is this type of treatment. The cost is applied only to the condition area treated. Therefore, the calculated treatment costs vary with the extents. The varying unit cost increases treatment strategy reality. At the minor severity level, a regular spot seal is applied. For the moderate and major severity levels, a regular spot seal is not effective. The actual treatment is more extensive. As a result, the unit cost increases from \$1/m^2 at the minor severity level to \$80/m^2 at the major severity level.

The second cost type applies the unit cost to the entire segment surface area. The structural rehabilitation is an example of this treatment type. The unit cost does not vary with the condition extents. The unit cost is applied to the entire segment surface area.

Write down value

Treatment strategy calculations are also used to determine the segment write down value for each year in the simulation period.

The write down value is the asset depreciation, and measures the treatment cost to restore the segment to a near new

Table 7. Condition states to implement treatments for fatigue cracking.

Infrastructure type	Treatment	Treatment selection for each condition state*				
		1	2	3	4	5
Asphalt concrete road	Untreated	T	F	F	F	F
Asphalt concrete road	Spot seal	F	T	T	F	F
Asphalt concrete road	Seal	F	T	F	F	F
Asphalt concrete road	Nonstructural rehabilitation	F	F	T	T	F
Asphalt concrete road	Structural rehabilitation	F	F	F	F	T
Asphalt concrete road	Flush seal	F	F	F	F	F
Asphalt concrete road	Strip seal	F	F	F	F	F

*T, true; F, false.

Table 8. Proportion of extents mitigated in treatment strategy for fatigue cracking.

Infrastructure type	Treatment	Proportion of extents mitigated			
		Minor	Moderate	Major	Severe
Asphalt concrete road	Untreated	0.00	0.00	0.00	na
Asphalt concrete road	Spot seal	0.50	1.00	1.00	na
Asphalt concrete road	Seal	1.00	0.80	0.30	na
Asphalt concrete road	Nonstructural rehabilitation	1.00	1.00	1.00	na
Asphalt concrete road	Structural rehabilitation	1.00	1.00	1.00	na
Asphalt concrete road	Flush seal	0.10	0.00	0.00	na
Asphalt concrete road	Strip seal	0.40	0.30	0.10	na

Table 9. Treatment unit costs in treatment strategy for fatigue cracking.

Infrastructure type	Treatment	Unit cost ($\$/m^2$)				
		Minor	Moderate	Major	Severe	Segment area cost
Asphalt concrete road	Untreated	0.00	0.00	0.00	na	—
Asphalt concrete road	Spot seal	1.00	20.00	80.00	na	—
Asphalt concrete road	Seal	—	—	—	na	1.06
Asphalt concrete road	Nonstructural rehabilitation	—	—	—	na	6.00
Asphalt concrete road	Structural rehabilitation	—	—	—	na	10.00
Asphalt concrete road	Flush seal	—	—	—	na	0.16
Asphalt concrete road	Strip seal	0.00	0.00	0.00	na	—

condition. Table 10 illustrates a typical write down value treatment strategy for fatigue cracking.

In Table 10, state 1 is considered a near new condition for the fatigue cracking condition type. The near new condition state requires no treatment (i.e., treatment field is null). If fatigue cracking is the governing condition type, the corresponding treatment to the governing state is applied. When a treatment is applied, it is applied to all relevant condition types according to the treatment strategies discussed earlier. The calculated treatment costs are added to the previous treatment costs to bring the condition state to a near new condition. If any of the condition types are not a near new condition, more appropriate treatments are applied. The process continues until all condition types are in near new condition. The write down value is the summation of all applied treatment costs for that segment in that simulation year.

Treatment branches and treatment paths

Treatment branches are generated throughout the modelling process each time a treatment strategy is invoked. Treatment branches store information containing the treatment alternative considered and the simulation year. Treatment branches also contain prior and post condition information of extents, resulting indices, and resulting states.

Through the initial stages of the modelling process, treatment branches are stacked with no connection to the preceding and following treatments. When the modelling is complete, the branches are connected to form a tree-like structure. Each path along the tree structure from the initial simulation year (year 0) to the end of the terminal treatment, or simulation period, comprises a treatment path. Figure 3 illustrates a typical treatment tree structure containing treatment branches and paths.

By path termination in the simulation year, data are assured

Table 10. Write down value treatment strategy for fatigue cracking.

Infrastructure item	Treatment	Write down value condition state
Asphalt concrete road		1
Asphalt concrete road	Seal	2
Asphalt concrete road	Nonstructural rehabilitation	3
Asphalt concrete road	Nonstructural rehabilitation	4
Asphalt concrete road	Structural rehabilitation	5

for all simulation years for all infrastructure segments when predicting future condition performance and asset write down value. Otherwise, terminating the treatment paths at a set treatment will omit some segments out of a network evaluation in the latter simulation years. However, path termination at key treatments (i.e., rehabilitation type) enables the model to base its analysis on minimizing costs over the life of the infrastructure, where rehabilitation is the regeneration treatment to a new condition state.

Marginal effectiveness

The marginal effectiveness calculation provides a relative measure in the budget analysis to compare all infrastructure segments of all infrastructure types on an equitable level. Marginal effectiveness is also the relative measure for selecting and quantifying the most cost-effective alternative treatment paths within the individual infrastructure segment.

For each treatment path of each infrastructure segment, the marginal effectiveness is computed as the ratio of uniform annual costs (UAC), that is,

$$\text{marginal effectiveness} = (\text{UAC of treatment path with lowest UAC})/(\text{UAC of considered treatment path})$$

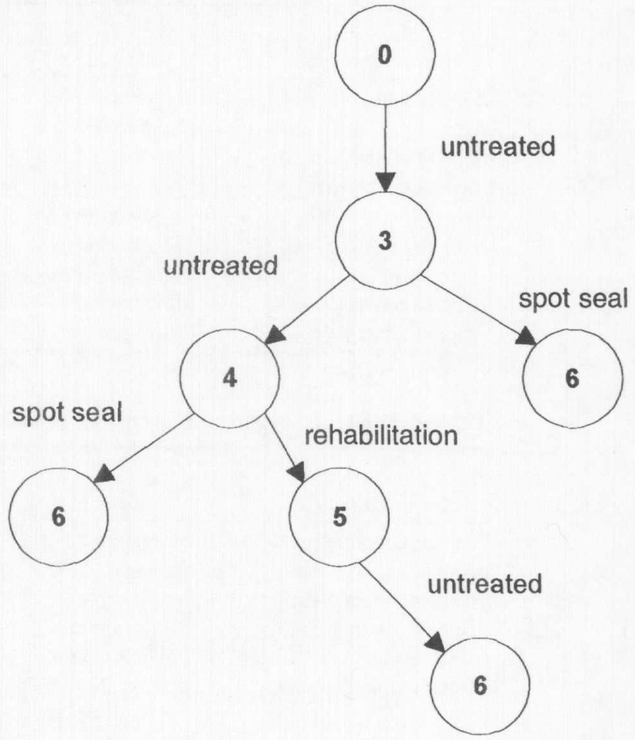
A marginal effectiveness of 1 is the treatment path with the most effective treatment combination. The marginal effectiveness calculation is computed internally within each infrastructure segment. However, the numerical analysis is generic for all infrastructure segments of all infrastructure types. As a result, the marginal effectiveness plays a key role in the budget analysis when trading off effectiveness for the network's required treatment and budget constraints.

During the model run, it is not unlikely that several thousand treatment paths are generated from the modelled infrastructure segments within the network. To ensure that only the most effective treatment path alternatives are considered further in the analysis, only a select number of the most effective treatment paths from each segment are retained. Deleting the less effective treatment paths also frees up disk space which has a significant effect on increasing computing speed.

Budget analysis

The budget analysis selects the most effective treatment schedule, given the required operational constraints of the agency. The operational constraints include required treatment constraints and budget constraints.

Fig. 3. Treatment branches and paths.



With the alternate treatment paths retained from the segment analysis, the required treatment constraints place desired treatments on select infrastructure segments at a select simulation year. This constraint is sometimes required owing to carry-over work from previous season or other decision-making processes committing desired treatments to specific infrastructure segments. During the modelling process, all infrastructure segments prioritize treatment paths by order of the effectiveness calculation. Given the required treatment constraint, the segment treatment path with the highest effectiveness value that complies with the required treatment constraints is initially selected (tagged) among the vast number of alternate treatment paths.

The budget constraints comprise upper and lower budget limits within each infrastructure type for the total annual budget and each treatment type budget. The modelling optimization process considers the simultaneous interaction of all budget levels of all infrastructure types. The user can specify up to 10 treatment types for each infrastructure type. The user can also specify up to 10 budget years even though the simulation period may be longer. As an example, Table 11 illustrates typical budget constraints for two infrastructure types.

The budget constraint process checks if the existing tagged paths are within the required budget constraints. If they are not, the process checks the next most effective treatment path(s). These are test paths. All costs are recalculated using the test path. If the test path meets the previous required treatment constraints and has a positive gain towards meeting the budget constraints, then the test path is tagged and the tag for the previous treatment path of the infrastructure segment is removed. The gain calculation is undertaken for each upper and lower limit of the total budget and each treatment type budget for each year within the simulation period and each infrastructure type. The total gain is the summation of the individually

Table 11. Typical budget constraints.

Infrastructure type	Budget year	Total budget ($)		Treatment 1 budget ($)		Treatment 2 budget ($)	
		Upper	Lower	Upper	Lower	Upper	Lower
Asphalt concrete roads	0	500 000	—	90 000	50 000	200 000	150 000
	1	480 000	—	90 000	50 000	180 000	140 000
	2	470 000	—	90 000	50 000	170 000	140 000
Steel water	0	75 000	25 000	20 000	—	50 000	25 000
	1	75 000	25 000	20 000	—	50 000	25 000
	2	75 000	25 000	20 000	—	50 000	25 000

Notes: Treatment 1 is a granular spot seal on the asphalt concrete road infrastructure segments and a spot repair on the steel water main infrastructure segments. Treatment 2 is a surface rehabilitation on the asphalt concrete road infrastructure segments and a pipe flushing operation on the steel water main infrastructure segments.

calculated gains for each of these limits. Since the process is indiscriminate over infrastructure type, all infrastructure segments compete for treatment on an equitable level.

The tighter the constraints, the less effective is the resulting treatment schedule. Without budget constraints, the determined treatment schedule is usually too variant to work within the operations of the agency. The budget analysis is an important tool for providing annual budget stability. However, the systems operations engineer must consider the monetary value of providing less effective treatment to ensure annual budget stability.

A case study

A case study (Molnar 1995) shows the application of the Municipal Infrastructure Management System (MIMS). The case study represents the first prototype test of the working model and shows the utility of MIMS to analyse a range of decision-making issues.

Due to the data integrity verification from traditional pavement management system methodology, a traditional asphalt concrete road is used for this prototype analysis. The model algorithms, however, are designed to work beyond the single infrastructure type analysis. The infrastructure type used in the case study is asphalt concrete roads. The network consists of 62 segments within the Area 34 management area of Saskatchewan Highways and Transportation. Area 34 is centrally located around Elfros, Saskatchewan, Canada.

Fatigue cracking, ravelling, rutting, transverse cracking, and roughness are the condition types modelled in the case study. The strip seal, flush seal, seal coat, sand sulphur, nonstructural rehabilitation, structural rehabilitation, and untreated are the treatment types used within the treatment strategies to mitigate the given condition types.

In this study, the treatments are classified into two groups. The maintenance- classified treatments are generally routine in-house treatments. These treatments include the spot overlay or seal, the strip seal, the flush seal, the seal coat, and the sand sulphur. The rehabilitation-classified treatments are contracted treatments. This treatment classification includes a major repair or reconstruction of the road surface.

Issue 1: treatment scheduling and performance prediction

The objective of the first issue is to provide the most effective treatment schedule that minimizes agency costs subject to various operational constraints of the agency.

The most cost-effective treatment schedule results without the application of any constraints. However, the resulting budget contains significant annual variation unacceptable to the operations of the agency. Table 12 summarizes the unconstrained resulting treatment costs, write down value, and total area-weighted condition index for all 62 segments within a 4-year reporting period.

To add annual stability within the constraints of the agency, the optimization process within the budget analysis determines the most cost-effective treatment schedule given the desired annual required treatment and budget constraints. Table 13 illustrates the constrained resulting treatment costs, write down value, and total area weighted condition index.

The constraints stabilize the annual agency expenditures to an acceptable level. The resulting condition index remains relatively similar between the unconstrained model run and the constrained model run. However, since the constraints incorporated less effective treatments, the treatment costs increased by $636 368 ($5 453 962 – $6 090 330). Even with this expenditure increase, the value of the asset still managed to decrease by $509 804 ($13 169 010 – $13 678 814). As a result, the total price paid to stabilize the 4-year annual budget is $1 146 172 ($636 368 + $509 804).

Similar analysis is used to determine the treatment cost required to hold the value of the asset at its current level. This type of analysis provides a dollar-to-dollar evaluation of alternate budget scenarios. It provides a comprehensive base for explaining to senior management and elected officials justification for the recommended budget level.

Issue 2: impacts and user fees

MIMS models and values the impact of changed use in part of the network. To recover the additional expenditures resulting from the impact, the agency applies MIMS to establish a users fee.

The impacted segments involve a concentrated haul on the Highway 16 segments of the Saskatchewan Highways and Transportation Area 34 asphalt concrete road system. To optimize the treatment scheduling to meet the network operational constraints, the analysis considers the interaction of all segments within the road network.

The concentrated haul starts in the current year (year 0) and continues for 4 years. The model simulation period is 6 years.

Table 12. Unconstrained model run summary output.

	Treatment cost ($)				
End of year	Rehabilitation	Maintenance	Total	Total write down value ($)	Total index
Initial				11 072 784	51
0	463 092	416 525	879 617	13 772 807	61
1	377 794	234 917	612 711	15 188 169	77
2	1 285 285	522 234	1 807 519	14 924 616	85
3	1 911 267	242 848	2 154 115	13 169 010	91
Total			5 453 962		

Table 13. Constrained model run summary output.

	Treatment cost ($)				
End of year	Rehabilitation	Maintenance	Total	Total write down value ($)	Total index
Initial				11 072 784	51
0	1 278 587	395 957	1 674 544	12 993 176	59
1	1 130 601	278 295	1 408 896	13 988 690	71
2	636 341	660 468	1 296 809	14 464 291	84
3	1 451 926	258 155	1 710 081	13 678 814	92
Total			6 090 330		

Table 14. Impact analysis summary for design loading and concentrated haul model runs.

	Treatment cost ($)		Total index	
End of year	Design loading	Concentrated haul	Design loading	Concentrated haul
Initial			51	51
0	1 674 544	1 870 921	59	62
1	1 408 896	1 574 590	71	72
2	1 296 809	1 973 465	84	81
3	1 710 081	1 600 288	92	90
Total	6 090 330	7 019 264		

During the simulation, MIMS switches deterioration probability matrices of the impacted segments between the concentrated haul period and the design haul period. Treatment strategies are slightly altered until the total index network value of design loading (constrained model run) becomes significantly similar to the concentrated haul model run. The difference in network treatment costs is the impact value to the agency of the concentrated haul. Table 14 summarizes the impact analysis results.

The concentrated haul impacting cost is the expected 4-year additional treatment cost the hauler places on the agency. This value is $928 934 ($7 019 264-$6 090 330). This is the value the agency would propose recovery from the hauler during negotiations of a users fee.

Conclusions

The following conclusions are derived from the development of the Municipal Infrastructure Management System (MIMS) model:

1. MIMS uses Markovian probabilistic modelling principles during the segment analysis. Traditional research and practice applies the Markov chain to an area-wide network average for predicting condition deterioration over time.
2. Individual segment Markovian probabilistic modelling and development of treatment strategies allows for detailed performance prediction, mitigation, treatment cost calculations, and asset write down value calculations.
3. Threshold levels and the developed treatment strategies consider the impacts of all costs to society. The marginal effectiveness calculation and budget analysis optimize these strategies based on minimizing agency costs.
4. The marginal effectiveness calculation is generic to all infrastructure types. The budget analysis was able to integrate all infrastructure types in a simultaneous analysis. Thus, all infrastructure segments compete for treatments on an equitable level.
5. The budget analysis interaction of segment level effectiveness calculations and network level operational constraints minimizes the loss of treatment effectiveness due to these operational constraints. As a result, optimization occurs on a combined segment level and network level analysis.
6. A case study shows the ability of MIMS to evaluate a range of decision-making issues. These issues include standard operational practices for establishing effective treatment schedules, predicting performance and resulting asset valuation, and answering questions concerning program justification. The case study also shows MIMS application to value impacts on the infrastructure use and set user fees to compensate the agency for the impacts beyond normal operations.

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