Effective Infrastructure Management Solutions Using the Analytic Hierarchy Process and Municipal DataWorks (MDW)

James Smith, Ph.D., E.I.T
Member Services/Infrastructure Coordinator
Ontario Good Roads Association
1525 Cornwall Road, Unit 22
Oakville, ON L6J 0B2
Ph: (289) 291-6472 Fx: (289) 291-6477
james@ogra.org

Paper prepared for presentation at the
Transportation Innovations and Opportunities in Small Municipalities Session
of the 2012 Conference of the
Transportation Association of Canada
Fredericton, New Brunswick

ABSTRACT

The economic success of a nation, province, or municipality is closely tied to the condition of their civil infrastructure. Ontario roads and bridges built throughout the 1950s and 60s are quickly approaching the end of their design life. Without the necessary funding, the declining condition of these assets can result in roads with compromised safety and increased road user cost.

Historically, there has been an underinvestment in maintaining our infrastructure at an acceptable level. Small municipalities are the most seriously affected by this underinvestment and are continually placed in a position where they are required to do more with less. In 2008, the Ontario provincial government, the Association of Municipalities of Ontario (AMO), and the City of Toronto published the Provincial-Municipal Fiscal and Service Delivery Review that identified a $60 billion investment was required over 10 years to bring our aging physical structures and facilities back to an acceptable standard *(1)*. Of this amount, $28 billion would need to be dedicated to upgrading Ontario's roads and bridges.

The paper focuses on how small municipalities can effectively manage and improve the condition of their aging road infrastructure based on several funding scenarios. To achieve this, best practices in the area of infrastructure management and capital investment planning will be explored using the Ontario Good Roads Association's asset management software, Municipal DataWorks (MDW).

INTRODUCTION

The management of municipal infrastructure assets (road network, structures, water and sewer networks, facilities, …) has been undergoing change, adopting private sector practices to attempt to maintain the condition of these assets at an acceptable level with decreased funding. Some of these changes have incorporated developing new goals, polices, methods of priority programming optimization, the addition of feedback loops and accounting for public input into a municipal infrastructure management paradigm. These advancements allow the small municipality to achieve better infrastructure management while taking into account the entire road network to satisfy the overall performance and condition of the assets and maximizing public satisfaction (2).

Municipal DataWorks (MDW) was originally created as a data repository for Ontario municipalities to store road and bridge condition data along with attribute information. Recent upgrades to the MDW program have seen the creation of an asset valuation module to assist with Public Sector Accounting Board (PSAB) compliance and a capital planning tool *(3)*. Using the Analytic Hierachy Process (AHP) within Municipal DataWorks (MDW) to prioritize capital investment spending on road network project will allow municipalities to stretch their limited funding farther to improve the condition of their assets.

ANALYTIC HIERARCHY PROCESS

In the 1970's Dr. Thomas Saaty developed Analytic Hierarchy Process, a multicriteria decision tool to mathematically support the selection of the selection of the best/preferred option *(4)*. The AHP allows decision makers to incorporate both the qualitative and quantitative aspects of a decision into the process. This is accomplished by reducing the complex decision of finding the best/preferred option to a series of one on one comparisons, while providing a defendable result. In addition the AHP can be used to intuitively and rationally deal with risk and uncertainty in complex settings *(5,6)*.

The AHP uses a rating scale from one (1) to nine (9), Table 1, and contains a number of assumptions. An example of the assumptions, if Option A is weakly preferred to Option B and Option B is weakly preferred to Option C, than Option A must be absolutely preferred to Option C. There is also a potential to skew the results to achieve a desired outcome if the criteria are not objectively defined *(7)*. Despite the inherent assumptions associated with the AHP provides a beneficial decision making strategy *(8)*.

Table 1. AHP Rating Scale

Value	Interpretation
9	Extreme preference/importance A over B
7	Very strong preference/importance A over B
5	Strong preference/importance A over B
3	Moderate preference/importance A over B
1	Equal preference/importance A and B
1/3	Moderate preference/importance B over A
1/5	Strong preference/importance B over A
1/7	Very strong preference/importance B over A
1/9	Extreme preference/importance B over A

The basic steps of the AHP are as follows *(9)*.

1. Identify the decision to be made called the goal. Structure the goal, criteria, and alternatives into a hierarchy. The criteria may be more than one level to provide additional structure to very complex problems.
2. Perform pairwise comparisons for the alternatives. Pairwise comparison is an evaluation of the importance or preference of a pair of alternatives. Comparisons are made for all possible pairs of alternatives with respect to each criterion. The comparison is done by giving each pair of alternatives a value according to Table 1. These values are placed in a pairwise comparison matrix (PCM).

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix}$$

3. Priority weights for the alternatives are calculated by normalizing the elements of the PCM and averaging the row enteries.
4. Perform pairwise comparison for the criteria. Similar to the process in Step 2 of comparing the alternatives, all pairs of criteria are now compared using the AHP value scale. Similar to Step 3, a PCM is determined, and priority weights are calculated for each of the criteria.
5. Alternative priority weights are multiplied by corresponding criteria priority weights and summed to give an overall alternative ranking.

CASE STUDY

The intent of road infrastructure management is too provide the highest quality road network through preserving roads that are in good condition and reducing the need for expensive rehabilitation and reconstruction. Through expanding criteria used to prioritize the allocation of infrastructure funding from an age based system or a single condition value the municipality can allocate funding to maximize their goals and objectives.

The purpose of this Case Study is to show how small municipalities can incorporate the AHP to account for multiple forms of condition values to prioritize the spending of their infrastructure dollars.

Criteria

Maintenance, Rehabilitation and Reconstruction (M,R&R) activities within a municipality are typically triggered based on age or the condition of the roadway as defined using the Pavement Condition Index (PCI). Through incorporating additional performance criteria the entire condition of the roadway assed and used in the decision making process. In addition to the PCI, five (5) condition criteria are included:

- Pavement priority number;
- Road classification;
- Ride quality/pavement roughness;
- Structural adequacy; and
- Surface friction.

Pavement Condition Index
The PCI expresses the condition of the pavement on a scale from 0 being the poorest possible condition to 100 the best based on severity and density of the observed distresses *(10)*. Evaluation of the pavement structure in MDW is based upon the Ontario Ministry of Transportation (MTO) Manual for the Condition of Flexible Pavements or the Manual for the Condition of Rigid Pavement, SP-024 and SP-026 respectively.

Table 2 presents the breaking down of the PCI categories used in the study and the assigned rankings to be used in creating the PCM.

Table 2. PCI Criteria

Ranking	Condition	PCI Value
0	Good	85 – 100
1	Satisfactory	70 – 85
2	Fair	55 – 70
3	Poor	40 – 55
4	Very Poor	25 – 40
5	Serious/Failed	0 – 25

Pavement Priority Number
The Pavement Priority Number (PPN) characterizes the condition of the roadway within the right-of-way. It is based on a simplified version of the Road Sufficiency Index (RSI) incorporating four (4) factors that can be evaluated by the municipalities Public Works staff. These factors include:

- Traffic (I_t);
- Economic (I_e);
- Road width (I_w); and
- Road profile (I_p).

The PPN is calculated by adding the corresponding rankings of each factor together to a maximum value of 20 indicating the most serious need.

$$PPN = I_t + I_e + I_w + I_p$$

The ranking and descriptions of each of the PPN factors are shown in Tables 3 through 6.

Table 3. PPN Traffic Criteria

Ranking	I_t Description
5	Where four (4) or more left turn related collisions occur per year or where six (6) or more left turn collisions occur within a two (2) year period
4	Deficient intersection stopping sight distance
3	Road section is congested for > one (1) hour a day every day of the week
2	Road section is congested for < one (1) hour a day and/or < five (5) per week
1	Average operating speed is less than minimum tolerable speed
0	Traffic moves freely

Table 4. PPN Economic Criteria

Transportation of Goods and Services	Percent Trucks		
	> 15%	5 – 15%	< 15%
Road is used seven (7) days per week, 52 weeks per year	5	4	3
Road is used < five (5) days per week, > six (6) months per year	4	3	2
Road is used < five (5) days per week, < six (6) months per year	3	2	1

Table 5. PPN Road Width Criteria

Ranking	I_w Description
5	Additional lanes required for current traffic volume
4	Continuous left turn lane required
3	Narrow lanes
2	Narrow shoulder
1	Parking lane required
0	Adequate road width

Table 6. PPN Road Profile Criteria

Ranking	I_p Description
5	Inadequate vertical or horizontal stopping sight distance
4	Inadequate vertical or horizontal alignment
3	Inadequate longitudinal grade
2	Inadequate clear zone
1	Inadequate ditching/sewers
0	Adequate road profile

Road Type

Road classification or type is based on the importance of the roadway within the municipality. Roads such as freeways and arterials experience large daily volumes of traffic and are used in the transportation of goods and service in and around the municipality. If access was to these roadways was disrupted the traffic flow would be severely impacted and carry a higher ranking than the collector and local roads. The ranking and descriptions of each of the road types are shown in Tables 7.

Table 7. Road Type Criteria

Ranking	Road Type Description
5	Freeway
4	Arterial
3	Collector
2	Local

Structural Number

The structural number (SN_{eff}) deals with the ability of the pavement to carry the traffic loads. Roads that have an inadequate structure to support the traffic loading are assigned a higher priority. Table 8 shows the criterion ranking and description.

Table 8. Structural Number Criteria

Ranking	Description
5	Inadequate
0	Adequate

Pavement Roughness

Pavement roughness is concerned with the smoothness of the road and vehicle passenger comfort. It is classified using a measurement scale called the International Roughness Index (IRI) and is measured in the units of meters per kilometer *(11)*. A road with no vertical displacements (absolutely smooth) has an IRI value equal to 0 m/km. As the IRI values increases, the smoothness of the road decrease. The breaking down of thepavement roughness categories used in the study and the assigned rankings to be used in creating the PCM are presented in Table 9.

Table 9. Pavement Roughness Criteria

Ranking	Condition	IRI Value
5	Poor	> 2.68 m/km
3	Fair	1.5 – 2.68 m/km
1	Good	1.0 – 1.5 m/km
0	Excellent	< 1.0 m/km

Pavement Friction

Pavement friction is a safety factor that aids in the stopping the vehicle that is due to microtexture (0 – 0.2 mm) and macrotexture (0.2 – 3.0 mm) of the aggregate in the pavement *(12)*. Virgin aggregate used during the construction of new pavement will provide the greatest coefficient of friction. Over time tire/pavement interaction and weather will degrade the pavement surface friction. Pavement friction is calculated as a skid number (SN_{40}).

$$SN_{40} = 100 \times {}^{F}\!/_{L}$$

where: F = friction resistance force in the travel direction, and
L = vertical load.

Table 10 shows the ranking and description for the pavement friction criteria.

Table 10. Pavement Friction Criteria *(12)*

Ranking	Skid Number (SN_{40})	Accident Problem
5	< 31	Yes
4	31 – 34	Yes
3	< 34	No
1	35 – 40	No
0	> 40	No

Priority Weights

Ranking values, Table 11, were assigned to the priority weights based on their influence on the overall condition of the pavement structure.

Table 11. Priority Weights Criteria

Ranking	AHP Criteria
5	Pavement Condition Index (PCI)
4	Pavement Priority Number
4	Road Type
3	Pavement Roughness (IRI)
3	Structural Number (SN_{eff})
1	Pavement Friction (SN_{40})

Example Calculation

To illustrate the steps associated with AHP, sample calculations are shown for the steps in creating the priority weights for the valuation criteria. The same process is used for all the decision making criteria.

The creation of the first row of the PCM is accomplished through comparing alternative weights.

- Compare PCI to PCI, 2(5 – 5) + 1 = 1
- Compare PCI to PPN, 2(5 – 4) + 1 = 3
- Compare PCI to Road, 2(5 – 4) + 1 = 3
- Compare PCI to IRI, 2(5 – 3) + 1 = 5
- Compare PCI to SN_{eff}, 2(5 – 3) + 1 = 5
- Compare PCI to SN_{eff}, 2(5 – 1) + 1 = 9

The process is repeated for the for the remaining rows in the matrix.

	PCI	PPN	Road	IRI	SN_{eff}	SN_{40}
PCI	1	3	3	5	5	9
PPN	$1/3$	1	1	3	3	7
Road	$1/3$	1	1	3	3	7
IRI	$1/5$	$1/3$	$1/3$	1	1	5
SN_{eff}	$1/5$	$1/3$	$1/3$	1	1	5
SN_{40}	$1/9$	$1/7$	$1/7$	$1/5$	$1/5$	1

Priority weights for the alternatives are created by normalizing the PCM and calculating row averages.

	Priority Weights
PCI	0.424
PPN	0.193
Road	0.193
IRI	0.082
SN_{eff}	0.082
SN_{40}	0.026

Methodology and Priority Programming Strategy

In this Case Study the municipality has developed a 25-year capital plan to manage their road infrastructure assets. Figure 1 shows the anticipated cost required to bring the identified deficient pavement sections back to an acceptable condition. The municipality has an annual road infrastructure budget of $1.125 million, but would require an average of $2.45 million per year to address all their road infrastructure needs. Infrastructure projects are not to be spread out over multiple years and funding not used in the current year is not able to be held in reserve fund to be used in subsequent years.

Selection of the project to be completed each year was based on a near optimization technique using the priorities based on PCI alone and the output from the AHP.

1. Projects are ranked in order of need based on PCI and AHP for a given year.
2. Based on the ranking order the first project is selected and the associated cost is compared to the amount of available funding. If the cost of the project is less the available funding the project is selected. Alternatively, if the cost exceeds the available funding the project is deferred until next year.
3. Individually, additional projects are selected and the process is repeated until no further projects can be selected for the given year due to a lack of available funds.

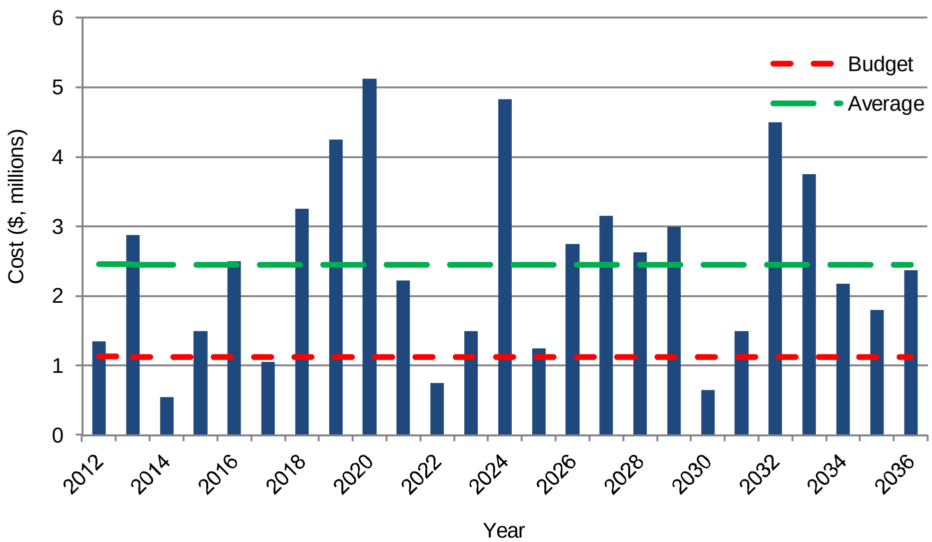

Figure 1. Identified 25-year Road Infrastructure Funding Needs

Results

The results of both prioritization methods, using PCI alone and the AHP are presented in Table 12. Over the first five (5) years of the capital plan using the AHP to prioritize the capital project resulted in the competition of four (4) extra projects and was able to reduce the funding backlog by $0.39 million.

Table 12. Case Study Results

Year	PCI Only			AHP		
	Projects	Cost ($)*	Backlog ($)*	Projects	Cost ($)*	Backlog ($)*
2012	1	0.7	0.65	2	1.025	0.325
2013	3	1.075	2.45	3	0.975	2.225
2014	1	0.825	2.175	2	0.995	1.78
2015	2	1.05	2.625	3	1.045	2.235
2016	3	1.125	4.0	4	1.125	3.61

* Cost and Backlog values are in millions of dollars

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Case Study shows how the implementation of a multicriteria decision making such as the AHP can be implemented within a municipality to better allocate limited budgeting resources to complete more project within a specified time period, reducing the dollar value associated with backlog of deferred projects, and improve the overall condition of the road network.

Recommendations

The Case Study presents a first investigation into incorporated the AHP into municipal infrastructure capital planning. For the method to become widely used, consistent and predictable results need to be obtained. To achieve this, further studies in the following areas are necessary:

1. Evaluation over the entire 25-year analysis period;
2. Evaluation on multiple datasets;
3. Conduct sensitivity analysis to ensure validity of selected weighting values;
4. Investigate the impact of different funding scenarios; and
5. Investigate project selection options allowing for the creation of a capital reserve fund.

REFERENCES

1. Ministry of Municipal Affairs and Housing. *Provincial-Municipal Fiscal and Service Delivery Review: Facing the Future Together*. Queen's Printer for Ontario, October 2008.

2. Cowe Falls, Lynne, R. Hass, S. McNeil, and S. Tighe. *Using Common Elements of Asset Management and Pavement Management to Maximize Overall Benefits.* Transportation Research Board 80th Annual Meeting, Washington, D.C., January 2001.

3. Ontario Good Roads Association. *Municipal DataWorks*. www.municipaldataworks.ca, Accessed December 1, 2012.

4. Satty, T.L. *The Analytic Hierarchy Process*. McGraw-Hill Publishing, New York, NY, 1980.

5. Satty, T.L. *Fundamentals of Decision Making: The Analytic Hierarchy Process*. RWS Publications, Pittsburg, PA, 1994.

6. Satty, T.L. *Multicriteria Decision Making: The Analytic Hierarchy Process*. RWS Publications, Pittsburg, PA, 1990.

7. Smith, J.T., and S. Tighe. *The Analytic Hierarchy Process as a Tool for Infrastructure Management*. Transportation Research Board 85th Annual Meeting, Washington, D.C., January 2006.

8. Deyer, J.S., and R.E. Wendell. *A Critique of the Analytic Hierarchy Process*. Department of Management, University of Texas at Austin, Texas, 1985.

9. Fraser, N.I., E.M. Jewkes, and M. Tajima. *Engineering Economics in Canada, 2nd Edition*. Prentice Hall Canada Inc., Scarborough, ON, 2000.

10. ASTM. *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. ASTM D6433. American Society for Testing and Materials, Weast Conshohocken, PA, 1999.

11. Smith, J.T., and S. Tighe. *Assessment of Overlay Roughness in Long-Term Pavement Performance Test Sites: Canadian Case Study*. Transportation Research Board 83rd Annual Meeting, Washington, D.C., January 2004.

12. TAC. *Pavement Design and Management Guide.* Transportation Association of Canada, Ottawa, ON, 1997.