A Case Study on Sustainability

Through the Application of the Principles of Pavement Management

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Abstract

Sustainable transportation often targets a shift in mode of transportation from cars to transit vehicles and increases in vehicle fuel efficiency. However, even where these shifts are successful, the transportation network generally remains the road network. This paper focuses on the sustainable preservation and maintenance of a road network through the application of the principles of pavement management.

One of the key fundamentals of effective pavement management is that keeping roads in good condition through timely rehabilitation costs less than allowing roads to deteriorate to the condition where more robust treatments, such as partial or full depth reclamation or reconstruction, become necessary. These timely treatments, in addition to having lower capital costs, are also more sustainable in that they typically require less input of raw materials, less construction effort, and reduced duration of construction and associated user delay.

The road network represents a major area of investment in transportation and one of the highest value assets in most municipalities. As the infrastructure ages and deteriorates, it is essential to preserve that investment, and to do so with good management of limited funds.

In this case study, the City of Abbotsford's pavement management system is used to demonstrate the use of pavement deterioration and maintenance cost forecasting models, which makes it possible to perform a complete life cycle cost analysis on pavements. There are usually many alternative feasible strategies for preserving a given pavement segment. Each alternative strategy can include one or more successive treatments. Each alternative strategy is also associated with different routine preservation and maintenance costs. All of the theoretically possible strategies are generated with analysis software and can then be optimized and prioritized under various budget scenarios. This allows for the rigorous economic justification of comprehensive programs that minimize the net present value costs and maintain pavement networks in a sustainable manner. Moreover, the City uses this system to arrive at network funding levels which are not only saving it citizens millions of dollars in direct and indirect costs but is also reducing the City's GHG gasses.

The study shows that not only do "Good Roads Cost Less" in terms of direct maintenance and rehabilitation cost, they also significantly reduce road user costs and overall Green House Gas emissions.

1.0 INTRODUCTION

The City of Abbotsford is a municipality with a population of 160,000 situated in the lower mainland of British Columbia. It has a paved road network encompassing 305 centreline-km of arterial and collector roads, known as major roads, over half of which are rural. Figure 1 shows the City's major and local road networks.

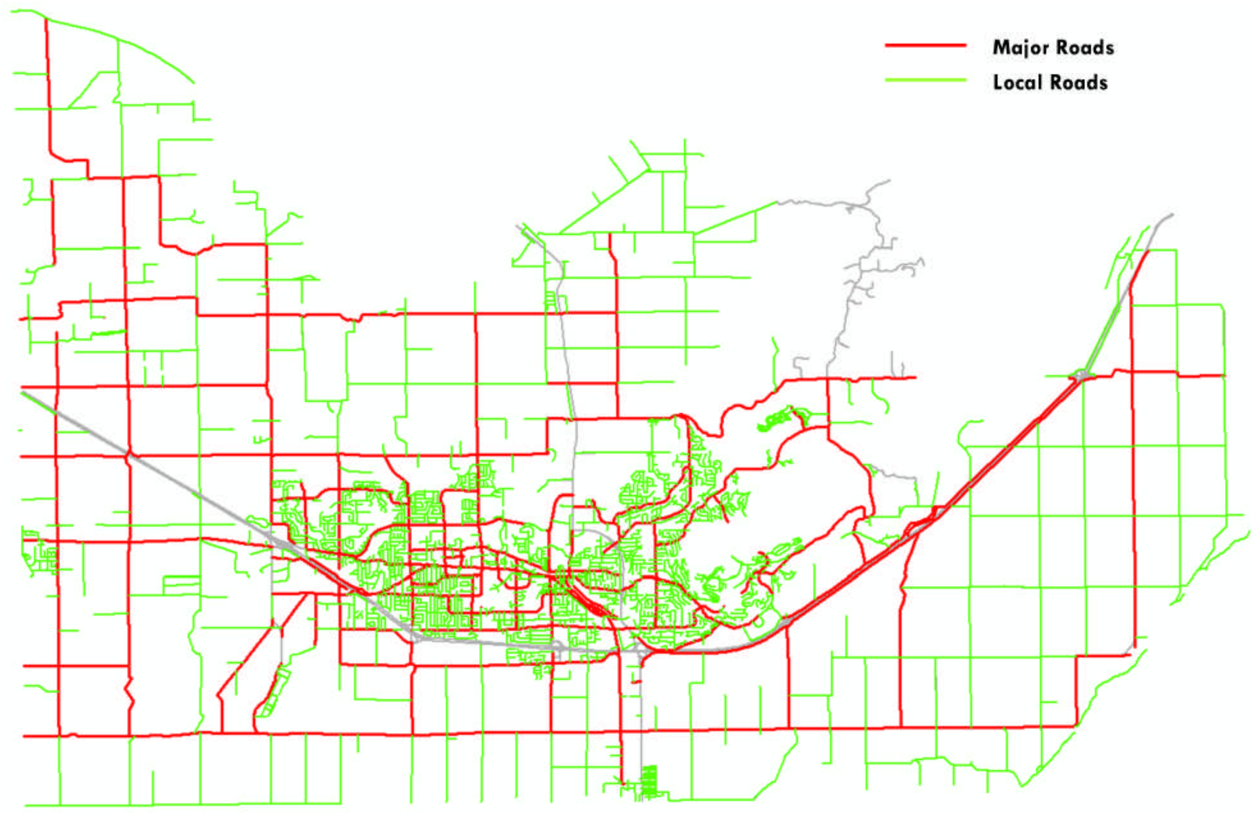

Figure 1 – Road Network

A road network condition assessment determined that the condition of the major road network in 2004, in terms of cracking as a percentage of surface area was on average of 7.7 %, as shown in Figure 2. It was also determined that in 2004 the average International Roughness Index (IRI) was 2.1 mm/m, Figure 3.

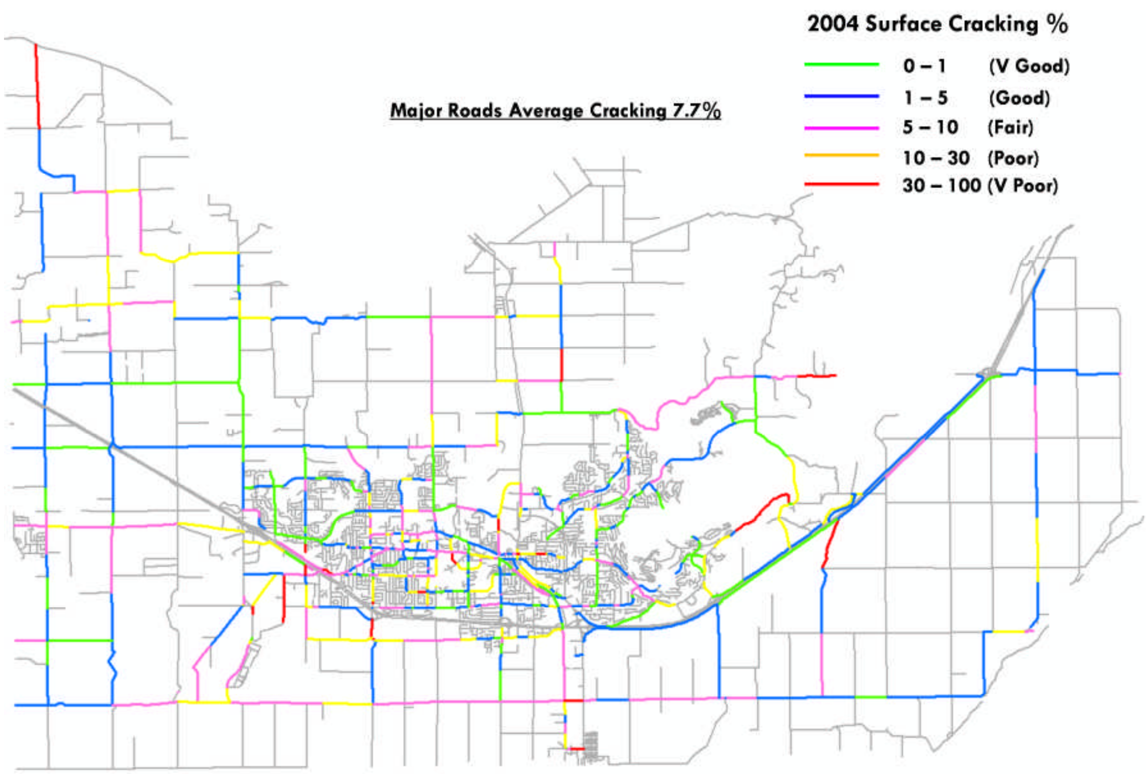

Figure 2 – 2004 Surface Cracking

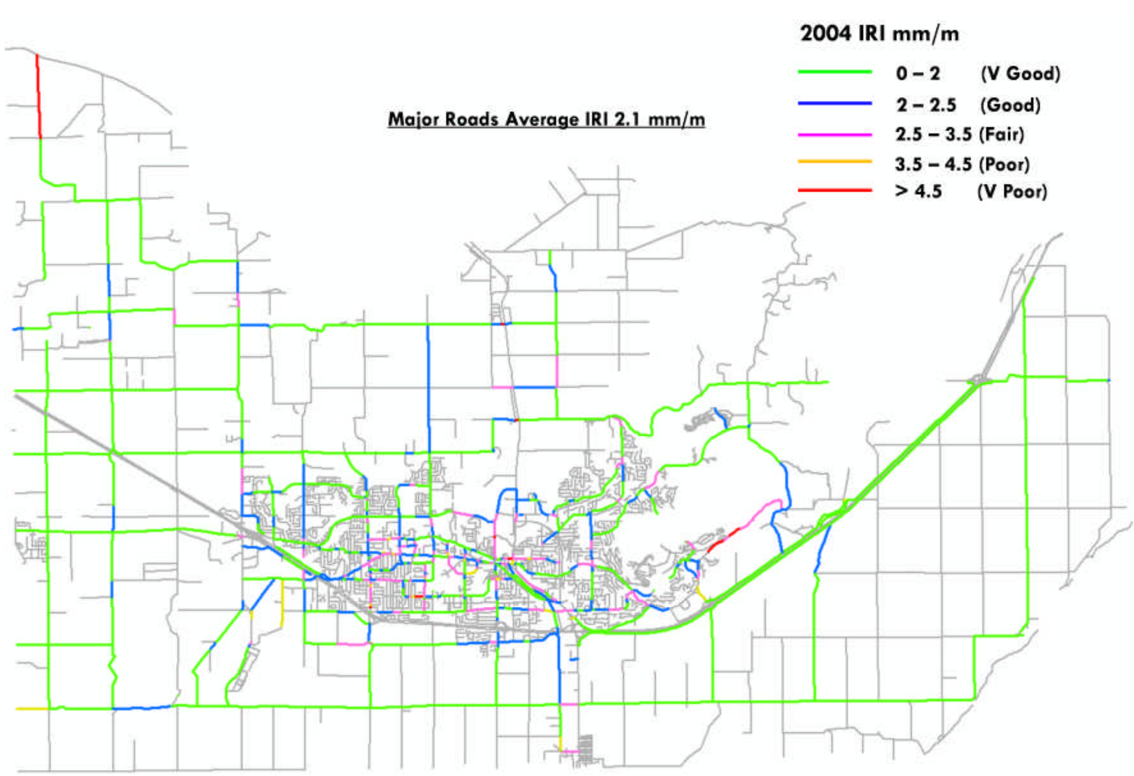

Figure 3 – 2004 IRI

In 2004 the City developed and implemented a pavement management system based on locally calibrated pavement performance prediction models. As a result, the City has the ability to predict the condition of its road network in terms of thermal and fatigue cracking, rut depth, and roughness under various funding levels in any given year.

The pavement performance models were used predict the conditions in 2023 under several funding level scenarios ranging from $1.5 million, (the funding in place in 2004), up to $5.0 million in order to establish a funding level which would maintain the major road network at 2004 condition levels. Ultimately an annual funding level of $3.8 million was adopted. Figures 4 and 5 compare the predicted IRI on each pavement segment in 2023 for the $1.5 million and $3.8 million funding scenarios.

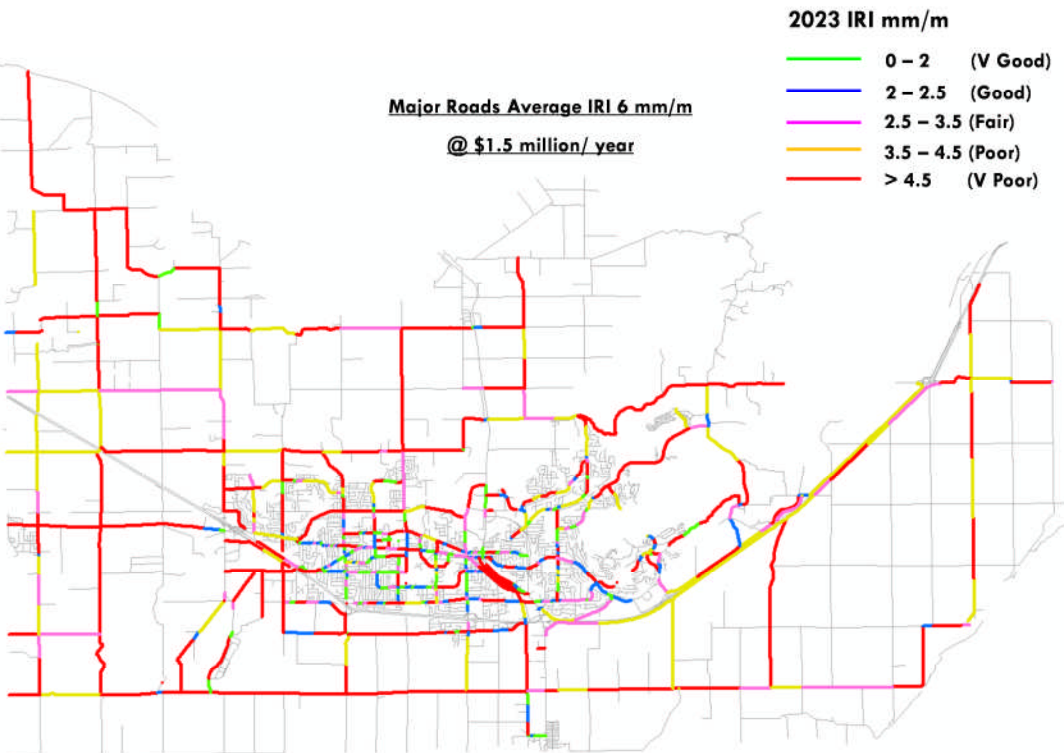

Figure 4 – Predicted 2023 IRI at $1.5 million annual funding

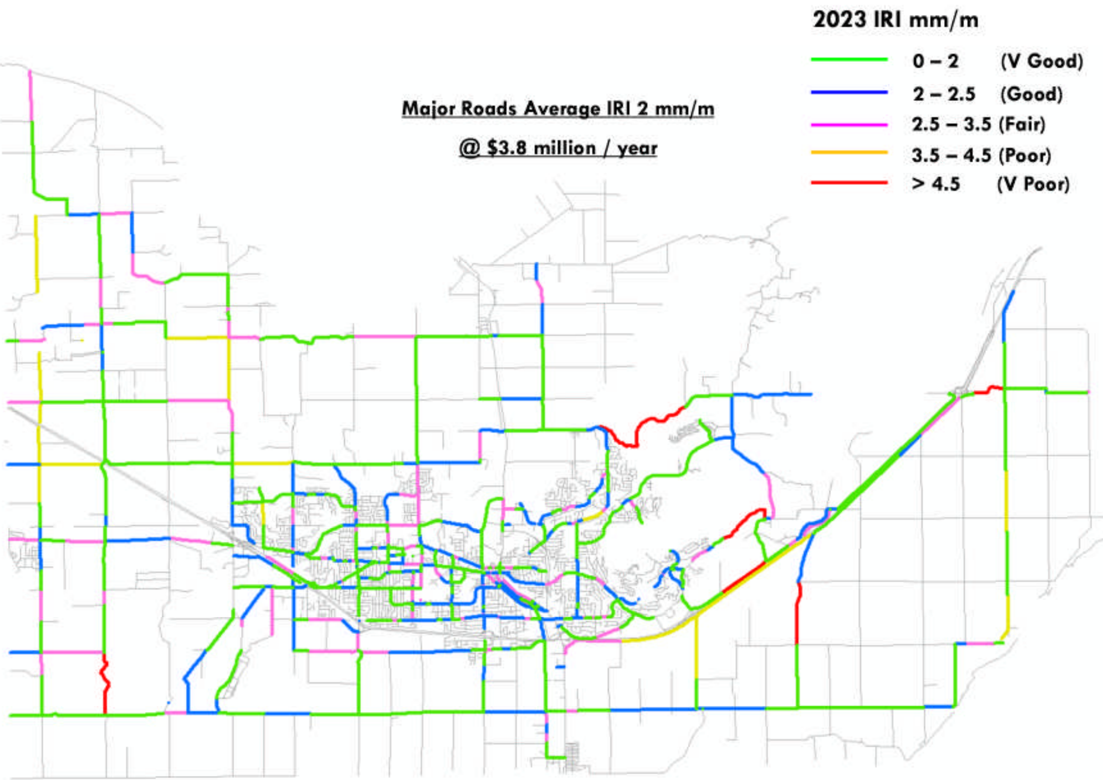

Figure 5 – Predicted 2023 IRI at $3.8 million annual funding

In order to validate the long held conviction that "good roads cost less", this paper uses the City of Abbotsford's pavement management system as a tool to quantify and compare the direct maintenance and rehabilitation costs, including the costs to eliminate resulting backlogs under these two funding scenarios between the years of 2004 and 2023.

In addition however, this study also quantifies the difference in vehicle operating costs between the two scenarios as well as the difference in Green House Gas (GHG) emissions generated as a result of the both construction and maintenance activities as well as those generated by the increased Vehicle Operating Costs (VOC) which would have resulted from under funding the rehabilitation program.

2.0 PAVEMENT MANAGEMENT SYSTEM

The Pavement Management System (PMS) as developed and implemented for The City of Abbotsford is a subsystem of an overall infrastructure management process. The process is a series of activities and analysis steps carried out by various Municipal staff members spanning several different business units within the municipality including, Geographic Information Systems (GIS), Engineering Planning, Traffic Engineering and Operations. The work described in this paper uses the software tools and technologies developed in order to incorporate "Life Cycle Cost Analysis" and "Budgeting Optimization" tools into existing business processes.

2.1 Pavement Management Theory

The condition of asphalt concrete pavement structures behaves generally as shown in the Figure 6 below:

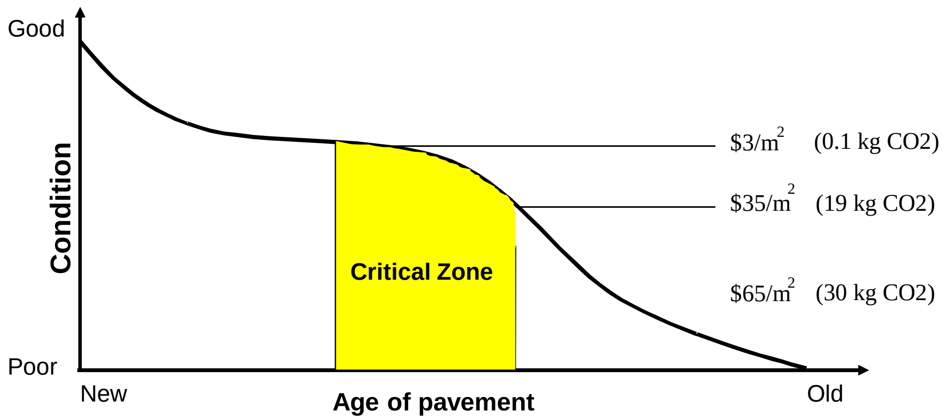

Figure 6

At the period in a pavement's life labeled “Critical Zone”, the pavement begins to fail and rapidly deteriorates until full reconstruction may be required.

Once pavements reach this zone, they are often referred to as needs or backlog, analogous to “debt” and they require maintenance, analogous to “interest on the debt”. As pavements pass through the zone, the cost of rehabilitating the pavement to as-new condition rises annually as ever more strength is lost through additional cracking. With more cracking, more underlying repair work is required prior to overlay. Once a significant portion of the surface has lost strength it is no longer cost effective to repair the underlying surface prior to overlay - a complete surface replacement is required at a cost an order of magnitude higher than that of a pavement entering the zone. Since the cost of annual maintence also rises by an order of magnitude as the pavement deteriorates, the analogy between maintenance and interest holds true.

Underfunding a network causes pavements to fall further down the deterioration curve prior to rehabilitation so an ever larger portion of the funding is directed towards maintenance rather than backlog reduction. Setting a performance target that maintains the status quo will hold the backlog and associated maintenance at current levels.

In the absence of a pavement management system, pavements are often managed on a “worst first” basis. With a “worst first” method, the pavement segments are ranked from worst condition to best condition. The worst condition pavements are selected starting from the top of the list until the budget is expended. If there is insufficient budget to address all of the roads that have passed through the zone, there will never be enough funds to address the less costly critical zone pavements. If all pavements are allowed to progress past the zone, there is no opportunity for rehabilitation cost savings.

The sophistication of a Pavement Management System is dependent on the amount and quality of data available and the level of accuracy of the pavement predictive modeling. If many years of detailed construction history, traffic and pavement condition data has been collected and stored, a highly accurate prediction model can be devised and, therefore, accurate projections concerning the period during which a road section will pass through the zone can be made.

The aim of Abbotsford’s pavement management system is to be able to predict the initiation of the critical zone, (the initiation of fatigue cracking), and the rate of crack propagation for each road in the network such that in any given year the maintenance costs and the cost to rehabilitate any given road segment is known.

2.2 Available Pavement Management Data

Abbotsford made a significant investment in data acquisition and in ensuring the accuracy of the predictive modeling. The following dataset was assembled for each of the 770 homogeneous major road pavement sections.

- Road Definition – Location, length, survey control points;
- Pavement Inventory – pavement width (area) and surface type, number of driving lanes, existence of C&G, open ditch drainage;
- Road Surface Condition Data ASTM D6433-03 definitions at 50% coverage;
- Traffic – Estimated AADT/% Commercial Traffic/Traffic Growth Rate at 100% coverage;
- Falling Weight Deflectometer (FWD) Pavement Deflection Data at 100% coverage and 100m spacing;
- International Roughness Index (IRI) Roughness Data and Rut Depth;
- Construction History Data – Surface age, pavement thickness.

2.3 Pavement Predictive Modeling

Recognizing the convergence between network and project level pavement design and management the City implemented a pavement management predictive modelling methodology that could be used at both the network and project level for each of the 770 homogeneous pavement project sections in the Major road network. For project level work, the quantity and type of individual pavement distresses in any year of the analysis period must be known (measured or predicted).

In 2004 when the City's system was developed, the American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide (1993) was the most widely used project level design methodology in North America. The AASHTO methodology is based on the concept of the layer strength and the pavement layer thickness derived structural number (SN). Although this methodology is relatively simple to adopt for network level pavement modeling, it predicts only a single composite Pavement Serviceability Index (PSI) comprising among other things, cracking and roughness. Although PSI can be calculated from cracking and roughness, it is not possible to back calculate roughness and cracking from the predicted PSI.

In other parts of the world, the World Bank had developed a field calibrated empirical model built around AASHTO's SN. This work was driven by the need to predict roughness because of its effects on vehicle operating costs. The World Bank methodology called Highway Design and Management (HDM), now in its 4th iteration, was first published in 1987 and has been widely validated through long term pavement performance on roadway networks throughout the world including, since 1992, on several 1,000 kilometers of roads in neighboring municipalities in the lower mainland of British Columbia. Furthermore, it is readily used for both project and network level modeling.

2.4 HDM4 Modelling and Performance Forecasting

The methodology evaluates the present and future road condition based on individual distresses, such as, cracking, deflection, rutting and roughness. The intent is to expand the usefulness of the data in selecting and estimating appropriate maintenance and rehabilitation treatments. In order to forecast the amount of crack sealing that will be required on a given road segment in any given year, the amount of low severity, linear cracking must be known. In order to calculate the cost of an overlay 10 years into the future, the amount of deep structural patching that will be required must be known. As different distresses would require specific treatments, it becomes critical to understand whether the road is showing poor condition due primarily to cracking, rutting, roughness, or a lack of strength.

The HDM4 methodology forecasts crack initiation and propagation rates, rutting, potholes, weathering and ravelling and ultimately roughness as shown in Figure 7 below.

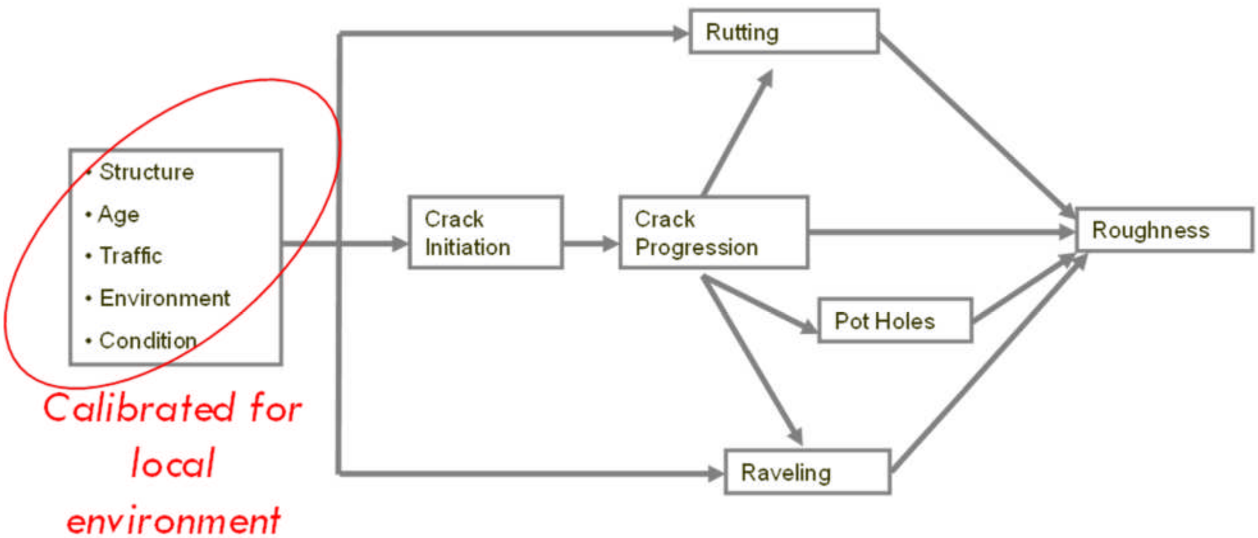

Figure 7: HDM4 Structural Modeling and Performance Forecasting

Since the models were based primarily on field observations and the ultimate goal was to predict roughness, it was observed that roughness itself accelerates fatigue damage and ultimately causes more roughness. Therefore an important input to the HDM predictive process is initial pavement conditions and in particular starting roughness state.

For these reasons, the HDM models were developed as incremental models, the next year's predicted condition state is based on the current year's state. An example taken from Abbotsford's HDM analysis showing two different initial roughness values is given in Figure 8.

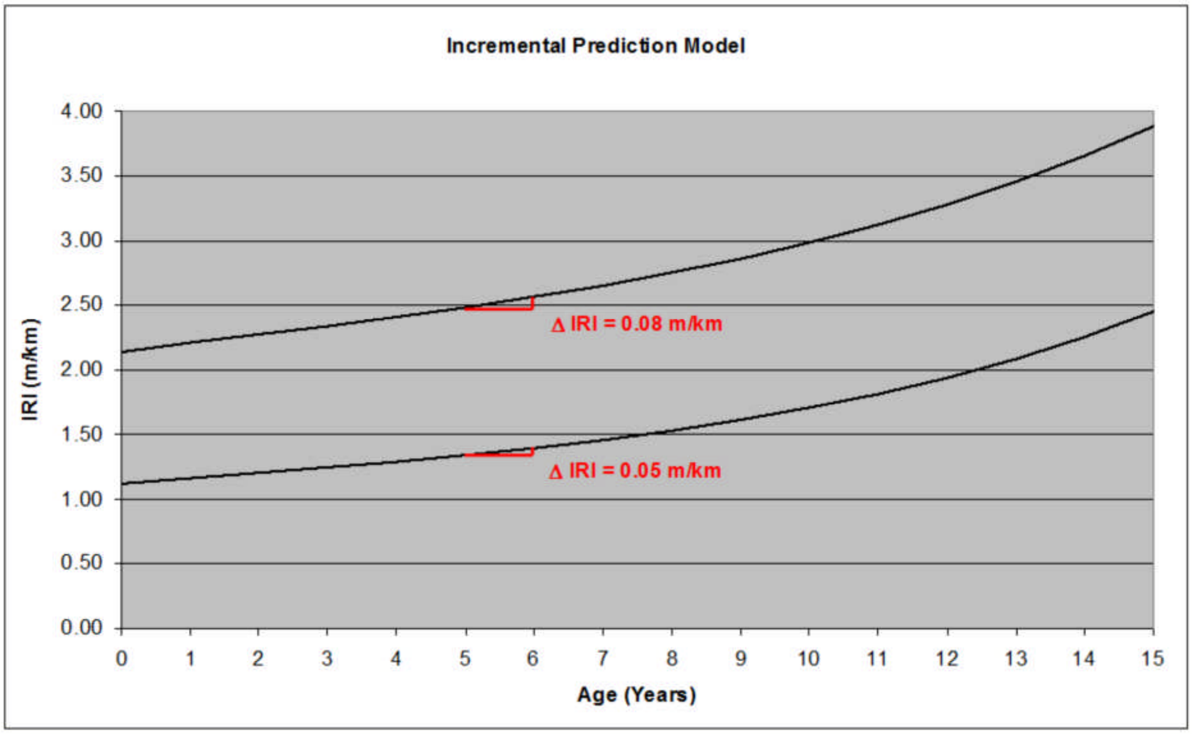

Figure 8: Incremental Prediction Model for Roughness

The smoother pavement exhibits a lower rate of roughness deterioration. After the fifth year of life, a pavement constructed with an initial pavement roughness, (expressed in International Roughness Index (IRI) units), of 1 m/km will be gaining 0.05 m/km/yr of IRI versus a 0.08 m/km/yr increase in roughness for a pavement initially constructed to an IRI of 2 m/km.

In the HDM models, the annual change in roughness is broken into individual components representing the change in roughness due to strength loss, cracking, rutting, potholes and environmental conditions. The mathematics that describes the annual change in each of these components of roughness is well documented in the HDM 4 documentation (www.hdm4.piarc.org).

Also for this reason, (when well calibrated for site conditions and construction practices), they are more accurate at predicting performance than other methodologies. Because of their widespread use in Western Canada, they have been locally calibrated and validated many times over the past 18 years.

Although all raw ASTM D6433-03 defined distresses collected as part of condition measurements are retained within the City's pavement management database, they are also converted to a format suitable for use by the HDM 4 modeling methodology. This approach extends the usefulness of the raw data while retaining its usefulness for other pavement performance modeling methodologies as may be developed on the future.

Aside from the pavement's initial pavement surface conditions, (roughness, cracking (thermal and fatigue), and rutting), the HDM model input parameters include a modified AASHTO structural number (SNP) derived from FWD measurements, traffic levels in terms of ESALs/year, climatic/environmental coefficients, coefficients for pavement construction defects as well as the pavement age at the point when the pavements initial condition was measured.

With the models in place, it was possible to predict a 40 year stream of expected pavement conditions in terms of low and high severity fatigue cracking, thermal cracking, weathering, rut depth, roughness and pavement strength.

3.0 GENERATING ALTERNATIVE PAVEMENT PRESERVATION STRATEGIES

The objective of pavement management is to provide and preserve pavement as economically as possible. There are usually several alternative strategies for preserving a given pavement segment. Each alternative strategy is comprised of one or more treatment options. Each alternative strategy is also associated with different routine maintenance and operating costs. Figure 9 below illustrates three example strategies:

- The Do-Minimum strategy (maintenance-only)
- Strategy 1 – comprised of a single thick overlay
- Strategy 2 – comprised of three thin surface treatments

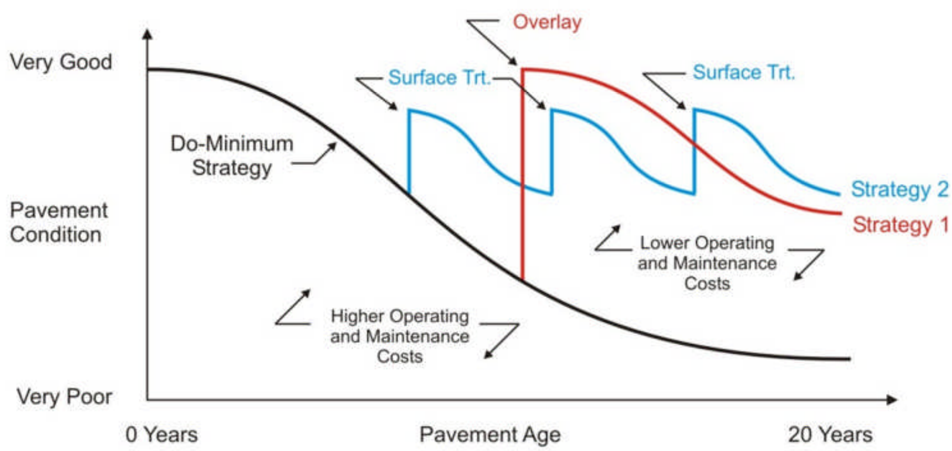

Figure 9

The do-minimum strategy will result in no capital/ rehabilitation treatment costs but extremely high reactive maintenance and operating costs. It will also have associated with it a large backlog (rehabilitation "debt"). Strategy 1 will have a higher initial treatment cost than strategy 2 however, strategy 2 involves three lower cost treatments spread over a period of several years. For a given road, it is not immediately obvious which strategy or even which year of strategy initiation results in the lowest possible operating and maintenance cost. Indeed, for a network it is generally not possible to pick the best option for each road segment as that may exceed the available funding in one or more years.

3.1 Treatment Types and Costs

A set of Maintenance and rehabilitation treatments, their costs and triggering criteria, are established based on actual as-built costs as recorded by Abbotsford and elsewhere in the lower mainland. The cost of asphalt has fluctuated wildly over the past several years however those used for this study are those as assembled in 2004 and are given in Table 1.

Table 1: Treatments unit costs used in the analysis

Treatment Type	Treatment Cost
Crack Sealing	$1.50/l-m
Surface Patching	$14.00/m^2
Deep Patch Repairs	$65.00/m^2
Overlay (50 mm)	$14.00/m^2
Mill & Fill (50 mm)	$18.00/m^2
Reclaim	$37.00/m^2
Reconstruction	$65.00/m^2

3.2 Treatment Triggers

The feasibility of applying a treatment on a given performance section is usually limited by physical or other constraints. For example, thick overlays cannot be directly applied to sections with curb and gutter. Similarly, a treatment should never be applied in the absence of any surface distress and an overlay should not be considered if the pavement is too severely distressed. To ensure that only feasible strategies are explored a set of "triggers" are developed. The triggers limit the number of strategies to those that can feasibly be applied.

The analysis triggers were modified to restrict major treatment applications to be dependent upon the scheduled replacement years for both the water main and sanitary systems. Pavement rehabilitations were not permitted for eight years prior to utility replacement but could occur after the utility's replacement year. This technique minimizes the potential for wasted fiscal and natural resources due to the excavation of recently replaced pavement structure when a utility is upgraded.

3.3 Treatment Resets

With the selection and application of any given treatment, the performance of a road will improve. For example, with a 50mm overlay, ruts would be filled, cracking would be removed, and roughness would decrease and strength would increase. Therefore, to predict performance over time and account for and compare possible interventions, the performance models have to adjust the individual distress data to reflect the application of the treatment. These changes to the value of the analysis variables as a result of the application of a treatment are called resets. Some heavy rehabilitation treatments, such as reconstruction, might reset virtually all of the analysis variables.

3.4 Life Cycle Cost Analysis

In this case study only four initial rehabilitation treatments overlay, mill/inlay, reconstruction and road reclamation are considered. However the timing of the initiation of a rehabilitation treatment is also variable. There is a window of opportunity to apply an overlay that spans several years. The amount of cracking and pavement failure that must be deep patched prior to application of the overlay increases in each year so the overall cost of the overlay increases each year. The analysis is further complicated by the fact that subsequent treatments can also be applied over a span of several years. In fact for a given road way segment there are hundreds of feasible strategies, each with its own stream of predicted pavement conditions, (as defined by the models and the resets), its own stream of rehabilitation and maintenance costs and its own stream of benefits. The set of strategies generated for this study averaged 250 strategies for each of the 770 unique pavement analysis segments resulting in a database of 200,000 strategies. Without a definition of Cost and Benefit it is not immediately obvious which strategy or even which year of strategy initiation results in the most cost effective strategy.

The overall cost of rehabilitation treatments and routine maintenance and operating costs required to preserve the pavement under a given strategy is called the Life Cycle Cost (LCC) of the strategy. In general, the LCC of a pavement is defined as the total cost over the analysis period expressed in terms of today's cost i.e. – Present Value (PV). The total costs are comprised of four parameters:

$$\mathbf{LCC_{pv} = CC + (R+M)C_{pv} - SC_{pv}}$$

Where:

$\mathbf{LCC_{pv}}$	=	Present Value of all Life Cycle Costs
CC	=	Initial construction costs of the pavement structure
$\mathbf{(R+M)C_{pv}}$	=	Present value of the sum of all rehabilitation and maintenance costs over the analysis period.
$\mathbf{SC_{pv}}$	=	The present value of the residual pavement structure components at the end of the analysis period (also called salvage value)

Note however, when preservation planning, the pavement structure already exists. Therefore the initial construction cost term, **CC**, does not apply. In addition, the analysis period can be made long enough (40 years or more) to ensure that the residual value of the pavement surface is either negligible (in terms of present value), or equal for all alternative strategies. In this way the $\mathbf{SC_{pv}}$ term can also be ignored. The LCC costs for these implementations are therefore defined as:

$$\mathbf{LCC_{pv} = (R+M)C_{pv}}$$

3.5 Real Discount Rate

The real discount rate represents the time value of money and is equal to the difference between inflation rates and interest rates. It is now generally agreed that the long-term difference between these rates averages 4%. However, many agencies believe that a somewhat higher rate should be used to take into account potential future improvements in construction and maintenance techniques etc. However, over the last several years, the discount rate has been very low, (less than 3%). These factors were considered and it was judged that the recent trend toward lower discount rates will offset the potential for future improvement and a real rate of 4% was selected for this analysis.

The models calculate and store within a system data file, a 20 year stream of maintenance and rehabilitation costs for each of the 200,000 strategies generated. Also stored is the LCC_{pv} which is referred to in this paper as PVCost.

4.0 BENEFITS AND OPTIMIZATION

The City's system is capable of selecting optimal strategies, (for establishing a rehabilitation programme), by a number of different processes including; Minimizing Life Cycle cost to meet a performance criteria or Maximizing Incremental Benefit/Cost.

With the first process, the user defines some performance criteria, (such as IRI must remain below 3.5), and the analysis will select the strategy with the lowest life cycle costs that will achieve that specified performance. This process is independent of budget levels, it simply puts forward the lowest cost solution. The lowest cost solution however is most often not feasible because an agency might not have resources enough, in some years, to implement the lowest cost solution.

The second process calculates a Benefit/Cost (B/C) ratio for each strategy of each pavement segment. The B/C ratios are then sorted in order of decreasing B/C ratio. The optimization selects from this list attempting to choose the highest B/C ratio for a given pavement segment that can be done for a given budget. With an unlimited budget, the process would simply pick the highest B/C ratio for each pavement segment. With limited budgets, this is an iterative process with the system making multiple passes through the set of B/C ratios always attempting to select higher ratios for a given pavement segment and to maximize the B/C ratio for the network as a whole. The City's system also allows the user to define "benefits".

4.1 Maximum Benefit-Cost Analysis

Considerable effort has gone into selecting a measure of benefit suitable for North American Agencies. Most agencies in North America do not consider road user cost savings - so traditional benefit cost analysis cannot be done. Since the introduction of the Public Sector Accounting Board PSAB) accounting standards, the use of asset value as a measure of benefit has become increasingly popular. This was the measure of benefit used in the initial 2004 City of Abbotsford analysis and is used for this study. The measure of benefit based on asset value is as follows:

1. **Asset value** = Replacement Cost – Written Down Replacement Cost (WDRC):

Pavement Structure consists of asphalt, base gravels and a sub-base structure. If any one of these layers weakens the road will eventually fail. If the base or sub-base fails the costs to rehabilitate the road increases as the road will require reconstruction. It is important to maintain the surface asphalt as it protects the base structure from being damage from water. As water migrates in the base and sub-base weakens and will ultimately fail.

a. **Replacement Cost** is the total cost of constructing the pavement structure:
   i. Excavation costs - $50/m^3$;
   ii. Cost of the sub-base in-place - $12/tonne
   iii. Cost of base course in-place - $15/tonne
   iv. Cost of Asphalt in-place - $60/tonne

b. **WDRC** is the cost to bring the pavement from current (or predicted), condition to as new condition:
   i. Costs to deep patch fatigue failure cracking - $65/m2;
   ii. Costs to mill and inlay other cracking - $18/m2;
   iii. Costs to add additional asphalt thickness to bring design life to 15 years;

By this method, the benefit is calculated based on the increase in asset value resulting from the application of a given strategy. The 40 year stream difference in asset values of a given pavement segment between the do-minimum strategy and any other strategy can be considered to be an area between two curves. The benefit of a given strategy is considered to be the Present Value of the area weighted by traffic volume, (in order to provide some measure of user benefit).

Using this methodology in 2004, the City was able to compare two optimized funding scenarios, one based on the 2004 level of funding and another based on a recommended level of funding which would preserve the network at its 2004 level of service. The results of which are given in Table 3.

Table 3 – Pavement Management Analysis Results

Annual Budget	$3.8 million		$1.5 million	
	2010	**2023**	**2010**	**2023**
Resulting Average Cracking	7.7%	5.4%	12.6%	32.7%
Resulting average IRI	2.1	2.1	2.5	5.7
Cost Maint ($mill)	$1.53	$4.10	$2.20	$12.00
Cost Rehab ($mill)	$22.56	$68.70	$8.04	$17.60
Cost Backlog ($mill)	$16.50	$11.00	$32.18	$90.00
Total Cost (mill)	**$40.59**	**$83.80**	**$42.42**	**$119.60**
Total Cost PV (mill)	**$35.34**	**$56.66**	**$33.46**	**$61.45**

Although this initial work confirms that good roads cost significantly less in real dollar terms it also suggests that good roads may not cost much less in terms of present value. However, it has been shown that for the range of IRI values between 2mm/mm and 5mm/mm typical of roads in North America, there is a significant increase in vehicle operating cost directly attributable to roughness[1].

Image 1 is a picture of a road with an IRI of 2mm/m and 5% cracking. Image 2 is a picture of a road with an IRI of 5mm/m and 35% cracking.

Image 1 – IRI 2mm/m

Image 2 – IRI 5mm/m

The City of Abbotsford's 2004 funding level had already been established at $1.5 million however the City elected increase annual funding going forward to $3.8 million dollar annual level. The

[1] According to NCHRP Web Document 1, "Smoothness Specifications for Pavements". 1997, fuel consumption increases by 3% within the pavement serviceability range of 0.9 to 4.4.

further study discussed in this paper attempts to quantify the cost saving that may have accrued to the road users and tax payers of Abbotsford as a result of this increased funding.

5.0 VEHICLE OPERATING COSTS DUE TO ROUGHNESS

Major studies funded by the World Bank have attempted to quantify the effects of roughness on vehicle operating costs. Based on this work, the Transportation authority in New Zealand developed some vehicle operating cost models for use with their nation wide pavement asset management practices. These models were reviewed and modified in 1999 and 2000 [Bennett 1999] and form the basis for the Vehicle Operating Costs (VOC) used for this study. The cost models were adjusted for inflation and $NZ to $CAN. The models are based predominantly on rural roads with operating speeds typical of New Zealand and rural Abbotsford. The NZ models measure four VOC components affected by road roughness: Fuel consumption, tire consumption, maintenance parts and labour consumption and depreciation. Maintenance parts and labour costs are difficult to compare between the two nations and although significant, have been ignored in this study.

5.1 Fuel

The increase in fuel consumption for the range of roughness being considered in this study, can be considered as a linear relationship with IRI and is quite small. The additional cost of fuel (at $1/ litre), for a single passenger car to drive on a one kilometer length of pavement with an IRI of 5mm/m versus 2mm/m is measured in 10ths of a penny. However when many vehicles use a road each day, the total costs can be significant. Figure 10 shows the magnitude of these costs on a single kilometre of road with varying levels of traffic, over the period of one year, due only to roughness.

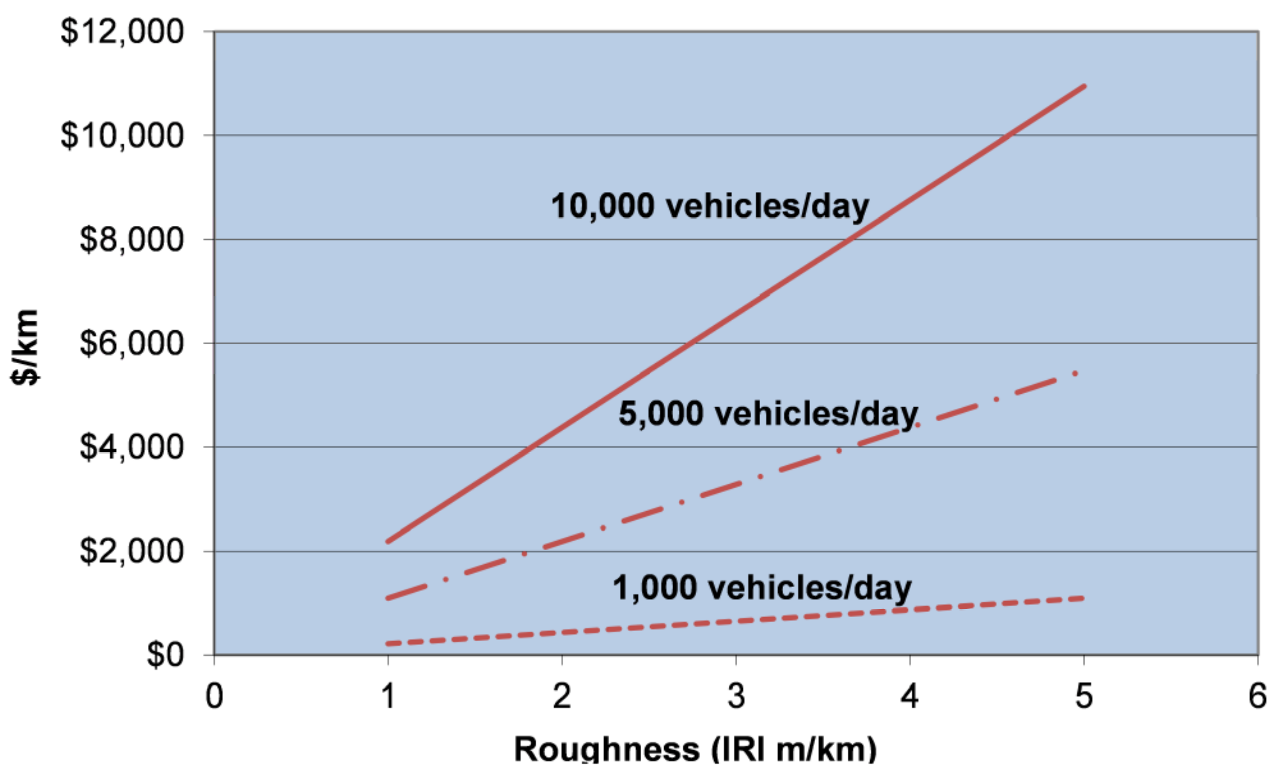

Figure 10 – Relationship Between Fuel Costs and Roughness.

5.2 Tires

With smooth highway driving, a set of tires might last 100,000 km's or more. However typical drivers in the lower mainland of British Columbia replace tires at 40,000 to 60,000 kilometres. This corresponds to road roughness in the range of 2mm/m to 3mm/m, typical of the region's road network. Figure 11 shows the relationship between tire wear and road roughness.

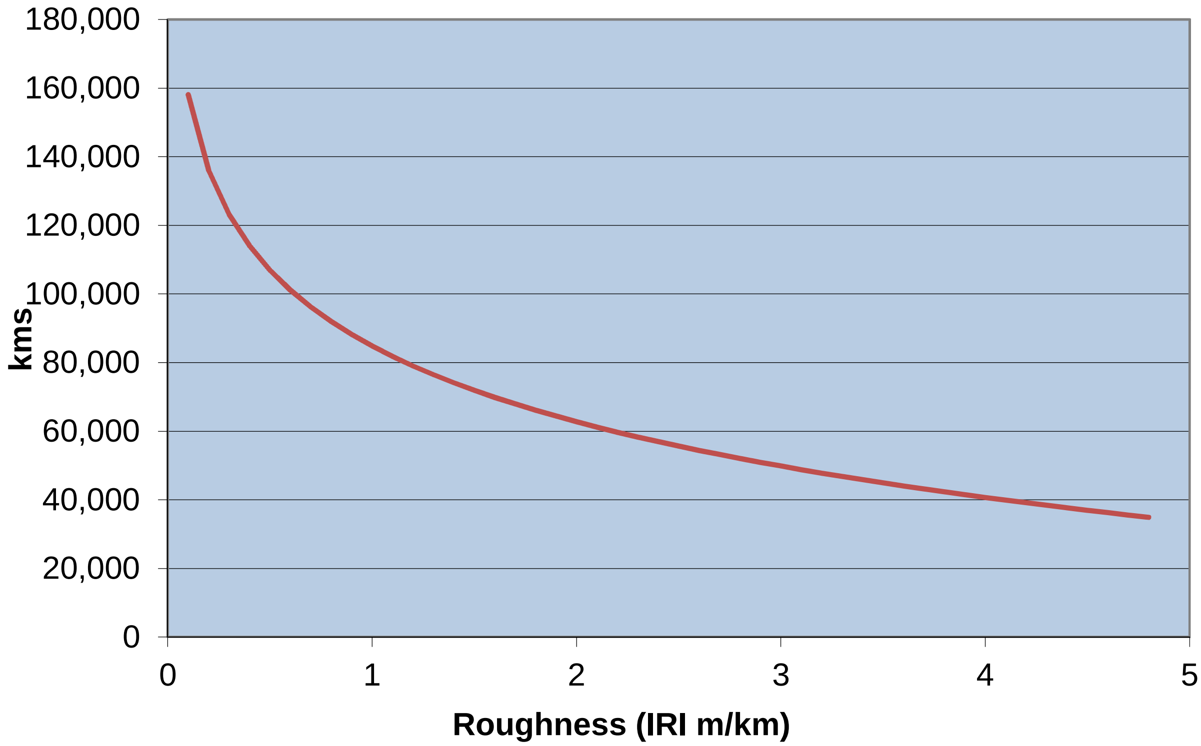

Figure 11 – Road Roughness Effects on Tire Consumption

There is a 30% loss of tire life due to continually driving on pavements with an IRI of 4mm/m versus pavements with an IRI of 2mm/m. Tires need replacing every three years instead of every four years an extra cost to vehicle owners of $50/year. This in itself would be enough to fund the additional rehabilitation required to maintain the roads to a smoother standard.

5.3 Depreciation

Another significant contributor to VOC is increased depreciation. On roads with an IRI of 2mm/m or less there is no additional depreciation related to roughness, a vehicle might last 200,000km or more. If a vehicle were to travel its entire life on roads with an IRI of 4mm/m it would lose 2% of its life equivalent to 40,000 km of usefulness. This is equivalent to adding $5,000 to the price of each car. Figure 12 compares the loss of vehicle service life due to roughness at various IRI levels.

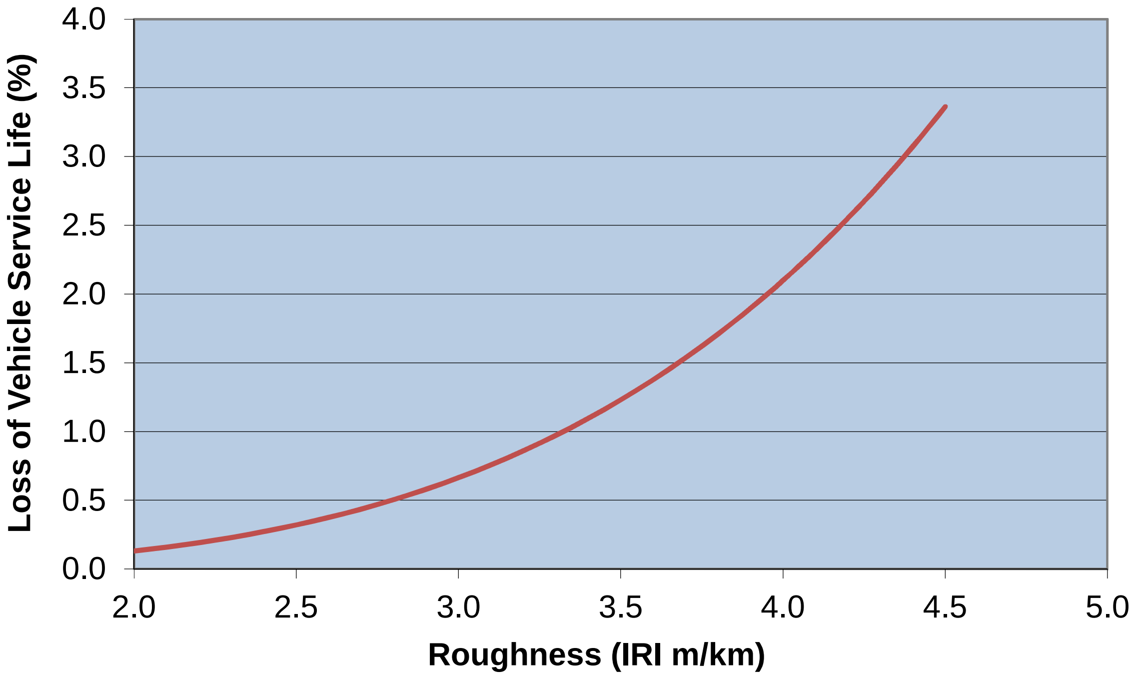

Figure 12 – Annual Vehicle depreciation Due to Road Roughness

5.4 Combined Vehicle Operating Costs

The VOC as developed for New Zealand, as discussed in sections 5.1 through 5.3, have been scaled back by as much as an order of magnitude for this study to account for potentially lower vehicle operating speeds and to ensure that they are not overstated. Effects of VOC on total costs are added to the direct maintenance and rehabilitation costs in Table 4. The VOC costs represent only the difference in VOC between the two funding scenarios and are therefore given as zero in the higher funding scenario.

Table 4 – Network Funding

Annual Budget	**$3.8 million**		**$1.5 million**	
	2010	**2023**	**2010**	**2023**
Resulting Average Cracking	7.7%	5.4%	12.6%	32.7%
Resulting average IRI	2.1	2.1	2.5	5.7
Cost Maint ($mill)	$1.53	$4.10	$2.20	$12.00
Cost Rehab ($mill)	$22.56	$68.70	$8.04	$17.60
Cost Backlog ($mill)	$16.50	$11.00	$32.18	$90.00
Cost dVOC ($mill)	$0.00	$0.00	$4.11	$25.68
Total Cost Incl. VOC	**$40.59**	**$83.80**	**$46.53**	**$145.28**

As of 2010, the increased funding scenario has saved the people of Abbotsford $6 million in real dollar terms. By 2023 this will rise to $60 million, as the pavements deteriorate at an increasing rate with the lower funding level.

Over the 20 year analysis period, the VOC saving of $25 million would in itself fund half of the addition rehabilitation work completed under the $3.8 million funding scenario. At the same time the backlog, (or infrastructure debt), will be reduced from $90 million to $11 million.

6.0 GREEN HOUSE GAS (GHG) EMISSIONS

According to research [Santero 2009] on the global warming potential related in general to asphalt due to "Road Roughness, when compared to other characteristics of pavements, had the highest global warming potential". The GHG emissions are generated from several road roughness related activities, producing and applying road construction materials, traffic delay costs while applying the maintenance and rehabilitation treatments, and the GHG generated in replacing the vehicles, tires and fuel that are used up as a result of excessive road roughness.

6.1 Treatment Related GHG Emissions

The strategies generated for the study were comprised of various combinations and quantities of the treatments discussed in section two. Application of a treatment has a GHG footprint associated with each treatment as shown in Table 5. These cost include production, haul and application related emissions.

Table 5 – GHG Resulting From the Production, Haul and Application of Treatments

Treatment	GHG Emissions[2] Kg CO2 – eq/m²
Crack Sealing	0.1
Surface Patching	9
Deep Patching	30
Overlay (50mm)	6
Mill and Fill (50mm)	11
Surface Reclamation	22
Reconstruction	30

[2] Derived from: Chehovits, J. and Galehouse, L., Energy Usage and GHG of Pavement Preservation processes for Asphalt Concrete Pavements; ASI/Best Foot Forward Limited; Holt, C., O'Toole, L., and Sullivan, P. Quantifying GHG Emissions Reductions When Utilizing Road Recycling Maintenance Processes, 2010 TAC; Robinette,C and Epps, J. Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation and Material; and BC MoT.

For each of the 770 road segments and for each selected strategy for the given budget level, the GHG footprint was calculated in terms of maintenance related GHG, rehabilitation related GHG and backlog elimination related GHG.

Delay costs for the heavier treatments such as road reclamation and reconstruction are very much greater than those of the lighter treatments such as overlay since the lighter treatments can be accomplished in off peak hours. Since the application of heavy treatments also have a two to three times greater GHG footprint, it is clear that the application of several lighter treatments will have less of an emission footprint overall. In this study therefore, delay costs have been ignored.

6.2 Increased GHG Due to Roughness

Through vehicle operation, 2.289 Kg of CO2-eq are emitted for every litre of gasoline or 2.663 Kg of CO2-eq when diesel is consumed. In addition, the manufacture of one litre of fuel produces 0.67 kg of CO2-eq [Samaras 2008]. Therefore, knowing the traffic volumes and having once calculated the additional fuel consumption due to the difference in roughness in each year between each pavement section in each of the two funding scenarios, the difference in GHG emissions due to additional fuel consumption (dGHG Fuel) can be calculated.

To manufacture a tire, 97 Kg CO2-eq/ per product are emitted [PIER 2005]. This study assumes 4 tires per car and 10 tires per truck. Therefore, knowing the traffic volumes and having calculated the additional tire consumption due to the difference in roughness between each pavement section in each of the two funding scenarios, the difference in GHG emissions due to additional tire consumptions (dGHG Tire) can be calculated.

Auto Manufacturing, as reported by the State of California, emits 12,000 Kg CO2-eq /unit for the entire life cycle of the vehicle including disposal and recycling. For this study a truck is assumed to weigh 12 times as much as a car and therefore its production would emit 12 times the CO2-eq or 144,000 Kg CO2-eq/unit. Therefore, knowing the traffic volumes and loss of vehicle life due to the difference in roughness in each year between each pavement section in each of the two funding scenarios, the difference in GHG emissions due to vehicle depreciation (dGHG Depreciation) can be calculated. Table 6 summarizes the GHG emissions values used for this study.

Table 6 – GHG Emissions Related to Vehicle Production and Operation

	Make New	Dispose / Burn
AUTO MANUFACTURING (kg CO2-eq/ unit)		
Manufacture a Car	12,000	N/A
Manufacture a Truck	144,000	N/A
TIRES		
Car	388	1.16
Truck	970	2.9
FUEL (per litre)		
Gas	0.67	2.289
Diesel	0.67	2.663

Table 7 summarizes the results of the GHG emissions comparisons between the two scenarios.

Without including the VOC related GHG, the underfunded scenario has a significantly larger GHG footprint. Once VOC related GHG are included the difference is almost 20,000 Tonnes or $440,000 dollars worth at the current carbon trading rate of $25/Tonne.

Table 7 – GHG Analysis Results Summary

Annual Budget	$3.8 million		$1.5 million	
	2010	**2023**	**2010**	**2023**
GHG Maint (Tonnes)	961	2475	1303	7248
GHG Rehab (Tonnes)	14150	43143	5100	11053
GHG Backlog (Tonnes)	8380	20209	17000	56520
GHG dVOC (Tonnes)	0	0	1374	8577
GHG Total (Tonnes)	**23491**	**65827**	**24777**	**83398**

7.0 SUMMARY AND CONCLUSIONS

The City of Abbotsford has a tool that allows for the quantification of direct maintenance and rehabilitation costs at the project level for all 770 pavement project segments within its major road network. It has used this tool to arrive at network funding levels which are not only saving it citizens millions of dollars in direct and indirect costs but is also reducing the City's GHG gasses.

The GHG reductions are significant. By way of comparison to other GHG reduction initiatives, according to the Natural Resources Canada (http://www.nrcan.gc.ca/mms-smm/busi-indu/iar-ilr/gge-gge-eng.htm), "if all the residential scrap metal currently[3] discarded were to be recycled, then Canada would reduce its GHG emissions by 226 000-456 000 Tonnes of eCO2 annually." This means that all of the residential metal recycling in Abbotsford would amount to a GHG savings of between 1,000 and 2,000 tonnes/year.

The GHG reductions resulting from the City's adoption of the $3.8 million funding scenario has now reached 1,300 Tonnes and could total more than 17,000 Tonnes over 20 years.

[3] AMRC study (4 communities) in which 76% ferrous and 24% nonferrous; B.C. waste composition data, Sperling Hansen Associates, 2001, Summary of Phase 1 & 2 Solid Waste Composition Study, Capital Regional District (85% ferrous, 15% nonferrous); merged Alberta data from Calgary 1998 and Edmonton 2001 (77% ferrous and 23% nonferrous).

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