Defining Needs for Optimized Management of Gravel Road Networks

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Abstract

Unpaved roads account for approximately 60% of Canada's public road network. Maintaining gravel roads is a major activity for many municipalities and requires regular interventions to provide smooth and safe riding surfaces for road users. Municipalities spend millions of dollars every year on gravel road maintenance and rehabilitation activities. A comprehensive road management system that includes their gravel road network could significantly improve a municipality's ability to manage their operating and capital budgets. In 2017, the authors undertook a survey of Canadian municipalities related to gravel road maintenance practices. A total of 97 municipalities responded to the survey, representing around 40,000 km of gravel roads. The survey's main goal was to capture the state-of-practice in gravel road management used by Canadian municipalities and to investigate to what extent municipalities collect data about their gravel roads. This paper discusses the results of that survey and investigates the need for better decision support tools to manage gravel roads. The paper also discusses the required components of a gravel road management system (GRMS), key operational and maintenance consideration, and the implementation of a GRMS through a case study.

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INTRODUCTION

In many countries, road networks are still predominately low volume unpaved gravel roads. In Canada, gravel roads comprise approximately 60% (about 626,000 KM) of the public road network (Statistics Canada 2003) and 53% (about 2.6 million KM) of the national road network in the US (FHWA 2015).

In the context of road network management, gravel roads typically represent lower volume road segments with an annual average daily traffic (AADT) of less than 400 vehicles per day and therefore receive less management attention than paved roads. Gravel roads, however, play a critical role in functioning societies. They are an important means of product transport, are the lifeblood of many agricultural communities, provide access to remote communities and recreation areas, and serve local residents, especially in semi-urban and rural areas. Maintaining gravel roads is a major activity for many municipalities and requires regular interventions to provide safe and smooth roads for users. Municipalities spend millions of dollars every year on an array of gravel road maintenance and rehabilitation activities.

Considering the size and cost of maintaining gravel roads, a comprehensive road management system that includes gravel roads can have a significant positive impact on a municipality's operating and capital investment efficiency, in addition to long-term road network performance.

Within a pavement management system (PMS), gravel roads require a dedicated analytical module due to the significant differences in distress modes, rates of deterioration and treatment options for maintenance and rehabilitation, as compared to paved roads. A gravel road management system (GRMS) provides the means of data collection and database management, gives better insight into the existing conditions and the history of network performance, allowing municipal officials to make better informed decisions. In order to perform an economic evaluation of different alternatives and maintenance strategies, a GRMS needs to utilize quantifiable deterioration models (Watanatada et al. 1987; Henning et al. 2008). This can be achieved by incorporating roughness progression and surface material loss models within a GRMS (Paterson 1991). In addition to performance modeling, effective operational and maintenance practices need to be combined with systematic decision-making procedures to maximize physical performance.

A further growing consideration with respect to management of gravel road networks, is the recognition that we need to better manage environmental impacts. The depositing of unwanted sediments into streams and waterways represents one of the largest pollution problems in North America, and improperly maintained dirt and gravel roads are major contributors to this problem (PENNDOT, 2006, Massachusetts Department of Environmental Protection, 2001). Gravel roads are contributors to negative impacts on streams from erosion, sediment and dust.

This paper discusses the current state of gravel road management in Canada, presents the main components of a GRMS and their functions, suggests methods of modeling gravel roads performance and key operation/maintenance considerations that affect physical performance, and finally presents an example of implementing a GRMS.

STATE OF GRAVEL ROAD MANAGEMENT IN CANADA

A survey of Canadian municipalities related to gravel road maintenance and management practices was conducted in 2017 (ISI 2017). A total of 97 Canadian municipalities responded to this survey, representing around 40,000 km of gravel roads. A majority of the participants represent rural municipalities with higher proportions of gravel roads. Figure 1 shows the population distribution of survey participants. The survey's main goals were to capture the state-of-practice in gravel road management used by Canadian municipalities, to investigate to what extent municipalities collect condition data and other historical data about their gravel roads, and to identify if there is a need for better decision support tools to handle gravel roads. We collected information as it pertains to:

- the average frequencies and maintenance schedules for different gravel maintenance activities based on different traffic levels;
- whether municipalities collect roughness data, pavement condition details, gravel thickness, or other performance-related data for their gravel roads;
- the frequency at which municipalities record the history of maintenance and rehabilitation activities; and
- the typical cost of different gravel maintenance activities.

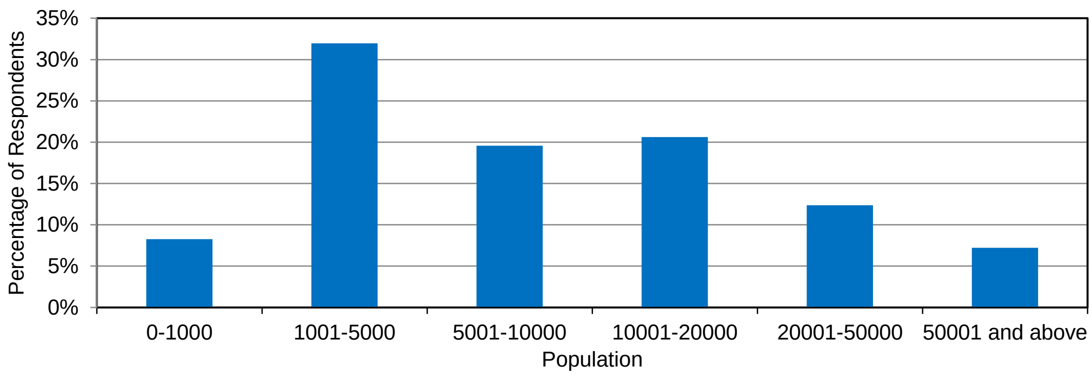

Figure 1: Population distribution of the survey participants

One of the critical inputs to a road management system is the physical condition of road sections. In the case of gravel roads, however, the collection of condition assessment can be more challenging for a variety of reasons. For example, gravel road conditions change rapidly through the impact of traffic and harsh weather. From an analytical perspective, however, if condition data is not collected using a well-defined rating system, the results can be subjective and hard to interpret as different inspectors might assign different condition values to a road in the same physical condition. Any form of rational pavement management requires a consistent condition rating system.

Gravel road sections frequently experience underlying distresses that will undermine the benefits of routine maintenance and cause more rapid deterioration and loss of serviceability. Such underlying distresses can comprise localized flooding and wash-outs; poor ditching and missing or damaged culverts; soft or organic subgrades; substandard vertical or horizontal profiles; and, inadequate granular materials or structure. These conditions will not be addressed by normal maintenance and will need to be identified through inspection and documented for future remedial treatments.

The survey results show that the majority of municipalities do not collect condition data about their gravel roads (Figure 2). A perceived lack of benefit from a time and cost investment perspective seems to discourage municipalities from maintaining a detailed database inventory of their gravel road network, with regular condition assessment updates. Also, the lack of a simple gravel road management system to help with the condition assessment and data collection process is a contributing factor. The survey also shows that gravel thickness, which is needed to evaluate structural adequacy and is useful in analyzing the benefits of re-gravelling operations, is rarely collected by municipalities.

Although a high percentage of municipalities do not collect condition data, they generally do document the maintenance history of their gravel roads to some degree (Figure 3). The maintenance history records can be effectively used within a gravel road management system to monitor surface deterioration rates and inform management and maintenance strategies.

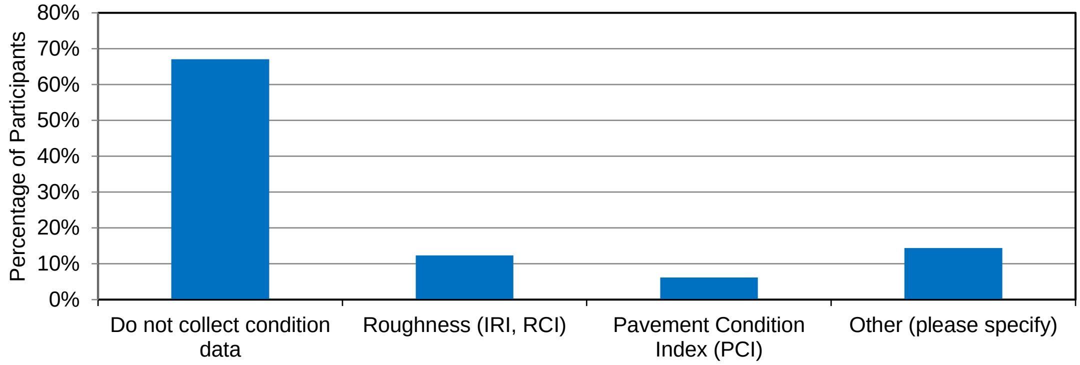

Figure 2: Gravel roads condition data as collected by municipalities

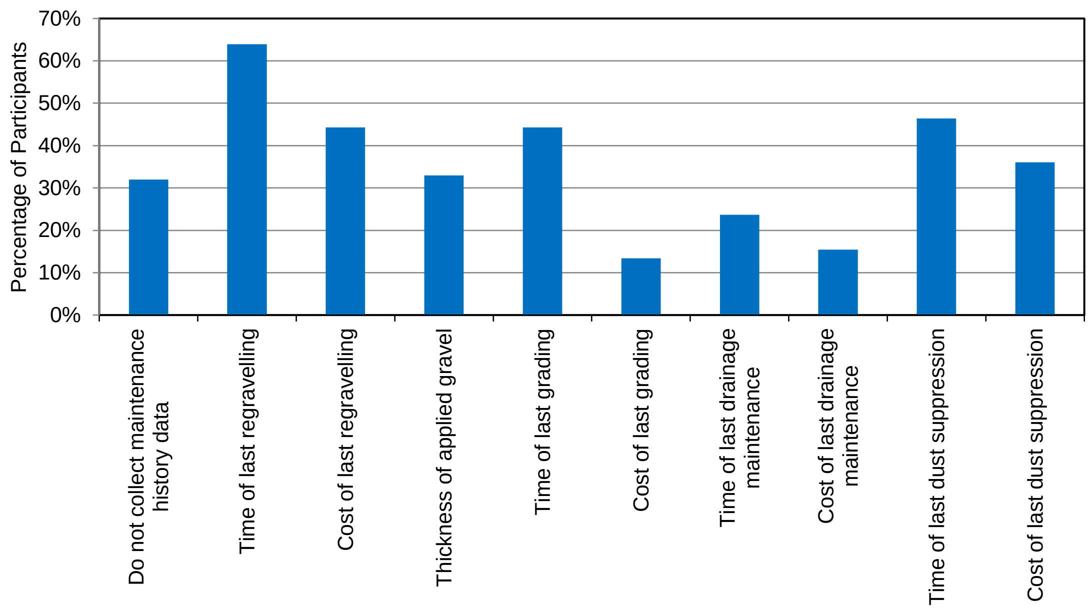

Figure 3: Maintenance history data collected by municipalities

Although the survey results showed that the majority of municipalities currently schedule their maintenance and rehabilitation activities for gavel roads on an ad-hoc basis, almost all of the municipalities who manage a gravel network with a total length of more than 50 km, expressed the opinion that having decision support tools available to assist with gravel road management would be a benefit. The desired features of such a gravel road network management tool, based on the survey feedback, would be the ability to:

- manage inventory, condition data, and maintenance history of their gravel roads in conjunction with their paved roads;
- establish refined priority policies using network-wide priority settings based on various physical attributes, such as traffic, functional class, roadside environment, minimum maintenance standards, etc., in addition to socio-economic factors for individual road segments;
- specify detailed routine maintenance polices based on local knowledge or pre-set schedules;
- incorporate robust gravel loss models to allow prediction of the need for and extent of re-graveling operations;
- identify when gravel roads should be upgraded to surface treated;
- compare the longer-term impacts of multiple scenarios with different policy and budget settings; and
- generate a 10-year capital plan with road lists, budgeted costs, annual schedules, and map visualizations.

The message from the survey results and feedback, is that an effective gravel road management system needs to be simple to operate and maintain, without the need for frequent or meticulous data input. For widespread adoption, such a system needs to deliver value and cost savings, without excessive demands for condition data input. Using the knowledge from a municipality's current gravel management strategy and the local knowledge of the road managers and supplementing with gravel deterioration models can provide the underpinning for an improved road management system. An enhanced management system would help managers store network inventory data, visualize and determine the overall performance of the network and individual road sections over time, identify immediate, short-term and long-term needs, establish network priorities, and evaluate the level of investment required to achieve acceptable service levels.

GRAVEL ROAD MANAGEMENT SYSTEMS

Basic Components

A road management system is a necessary tool for road managers and decision makers to reduce future financial risk, evaluate their investment strategies and to develop cost-effective maintenance and rehabilitation plans. A properly implemented GRMS would also facilitate an analysis of the financial trade-offs and the long-term implications of various management decisions, such as upgrading a gravel road to surface treated (i.e., chip sealed). Gravel road management is typically a sub-system of a broader road management system that deals with both paved (i.e., hot mixed asphalt (HMA), concrete, composite, and surface treated) and unpaved gravel segments. Accordingly, a GRMS should have the same basic components and functions as a conventional pavement management system, however, the analytical procedures are different due to the different characteristics of gravel road performance. In general, a comprehensive road management system needs to incorporate a central database that stores and manages inventory, condition, and repair history data of both paved and gravel roads. A subset of data is then used to perform analysis on the gravel road segments. Figure 4 shows a simplified chart of basic components of a comprehensive road management system with both paved and gravel road segments.

Agency Policies
One of the key requirements in analyzing gravel roads is the ability to capture the local experience, knowledge and preferences of municipalities with regard to the frequencies and maintenance cycles that are used. This information needs to be combined with performance prediction models to perform a reliable analysis with practical recommendations. A maintenance policy can simply be represented by a table that indicates defined frequencies for a range of gravel surface maintenance activities. For example, a road supervisor might indicate that for a gravel road with an AADT between 50 and 100, re-gravelling is performed every 3 years, drainage maintenance every 4 years, grading twice a year, and dust control once per year. A policy can be set to also link the applied gravel thickness to the subgrade condition and traffic levels. For example, a gravel segment with a weak or frost susceptible subgrade (e.g., a CBR value of less than 5) and high traffic (e.g., more than 200 vehicles per day) should receive a greater thickness of gravel in the re-gravelling operation as compared to a segment with a competent subgrade and only moderate traffic. Maintenance policies should be recorded and used as part of the gravel road analysis process to ensure maintenance and rehabilitation recommendations are aligned with owner practices and policies.

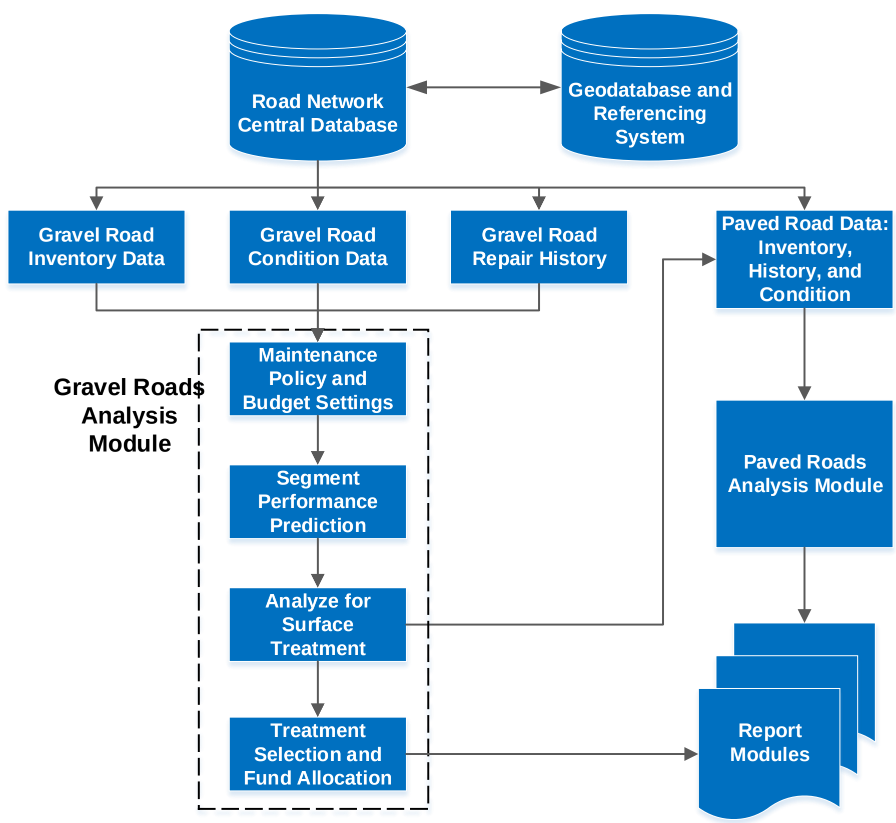

Figure 4: Gravel road management as part of a comprehensive road asset management system

Predicting Deterioration Rates

In addition to capturing maintenance policies, performance prediction models need to be employed to predict the improved performance and loss of service over time based on a range of maintenance interventions under traffic conditions. Gravel road deterioration models, however, are not well understood and municipalities often rely solely on experience to schedule their maintenance and rehabilitation activities. A versatile GRMS should incorporate deterioration models that can predict future network-level performance so as to allow reliable economic evaluation. Such an analysis helps road managers to appreciate the long-term impact of their maintenance policies, analyze and compare different budgeting strategies, and ultimately produce a cost-effective maintenance and rehabilitation plan.

Gravel roads are subject to a wide variety of distress modes depending on a large number of factors related to their construction details, environment and traffic volume and mix. For analysis purposes, it is reasonable to associate surface deterioration with a progressive increase in roughness and/or by a loss of surface material (Paterson 1991). Roughness progression affects the ride quality and operational safety of gravel roads. In addition, as surface roughness increases, crown is lost and more water ponds on the surface and infiltrates which accelerates the rate of deterioration of ride quality, both due to successive cycles of saturation and drying and/or through frost action. Over time, with the impact of traffic, surface roughness, which can be represented by indices such as IRI (International Roughness Index) or RCI (Ride Comfort Index), increases. The rate of increase in roughness is not only a function of traffic, but also depends on factors such as annual precipitation, gravel material properties, drainage conditions, road geometry, and the frequency of maintenance activities. Various models of roughness progression with time for gravel roads have been developed based on extensive studies on the performance of large samples of gravel roads (Watanatada et al. 1987; Henning et al. 2008).

Ideally, a roughness progression model can be used to predict physical performance of gravel roads; identify future maintenance and rehabilitation needs; determine optimum regrading cycles; and evaluate upgrade options to a surface treated road section. The output of a roughness progression function is the expected roughness of a gravel road at a future time based on several input parameters. A roughness progression model usually uses inputs such as AADT, percentage of heavy traffic (typically a gross vehicle weight of more than 3,500 kg), mean monthly precipitation, a road geometry factor, such as average absolute longitudinal gradient, gravel material gradation properties, plasticity index of the gravel material, time since last grading, and a series of model calibration coefficients. Roughness progression models can become complex since they require a range of inputs and data items and are not universally applicable or are subject to large prediction errors. In many cases, the input data, such as the calibration coefficients, is not readily available. The inputs related to gravel material properties, however, can be determined through proper sampling and laboratory testing. Physical-mechanical testing such as MicroDeval testing can be used to evaluate aggregate durability, especially in wet and saturated conditions. Testing can be very useful in ensuring that good quality material is being used and also to identify the source of performance problems so as to gradually improve the overall quality of the gravel road network. A good surface gravel with proper gradation can significantly improve the ride quality and long-term performance of gravel roads and substantially reduces the cost of maintenance and rehabilitation activities.

Gravel loss is another mode of deterioration caused by a combination of traffic action, precipitation, and motor grader activity over time. Gravel loss reduces the structural strength of a gravel road, leads to loss of crown and is associated with rutting and other surface defects under traffic loading. It also leads to clogging of ditches and culvert inlets and has negative environmental impacts in terms of sedimentation and dust generation. A gravel loss function can be used to determine the average change in the gravel thickness over time. Within a GRMS a gravel loss model can act as the primary determinant for the prediction of time to the next re-gravelling operation. The output of a gravel loss model is the expected gravel loss in millimeters of thickness over a time period based on input parameters such as daily traffic, percentage of heavy traffic, mean monthly precipitation, and road geometry.

Gravel loss models are generally less complex and require a smaller amount of input data when compared to roughness progression models. Considering the cost and importance of re-gravelling operations as one of the main rehabilitation activities, and considering that loss of crown is a good indicator of loss of service, accurate gravel loss calculations can be very useful in predicting the performance of gravel roads and identifying the optimum timing for re-gravelling activities. Figure 5 shows an example of using a gravel loss model to predict reduction in gravel thickness over time. Using a minimum acceptable thickness based on the maintenance policy settings, the time of next re-gravelling can be determined as the time when gravel thickness reaches its minimum acceptable level. Gravel loss models can be used to analyze gravel road networks and identify optimum timing for re-gravelling operations considering budgetary constraints and other municipal objectives. It can also be used to determine the remaining service life of a gravel road, establish performance indicators, and help with communicating maintenance strategies or other managerial decisions with stakeholders.

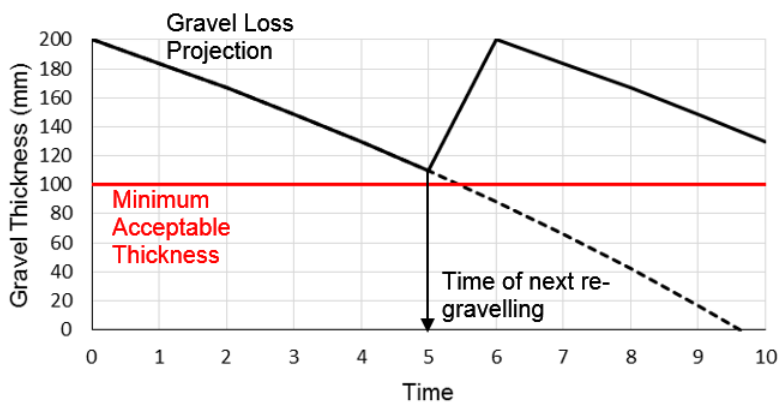

Figure 5: Example of a gravel loss model used to determine the time of next re-gravelling

Decision to Upgrade to Surface Treatment

Another component of the analysis module of a GRMS is to determine if surface treating (i.e., chip seal) a gravel road is a sensible option. A financial analysis (i.e., discounted cash flow analysis) can be performed based on the initial cost of upgrading and the cost of subsequent maintenance activities in both cases. Figure 6 shows an example of a financial analysis on two gravel road segments. First segment is 476 m long with AADT of 250 and the other segment is 973 m long with AADT of 50. The analysis uses an inflation rate of 1.5% and a nominal discount rate of 3%. In the first case (AADT of 250), the cost of maintenance as a gravel road (i.e., the cost of re-gravelling, drainage maintenance, grading, and dust control) over the next 20 years in today's dollars is estimated at about $69,000. By surface treating this segment the 20-year maintenance costs are reduced to about $37,000 (i.e., the initial cost of a double chip seal with subsequent slurry seals and single chip seal treatments). It is, therefore, more cost effective to chip seal this segment. In the second case (AADT of 50), however, the cost of maintaining the segment with a gravel surface is around $22,000 less compared to surface treatment.

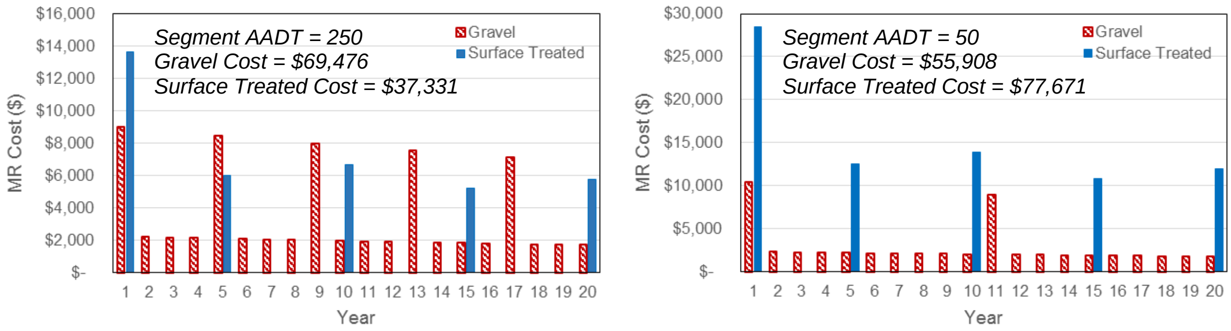

Figure 6: Financial analysis of upgrading gravel roads to surface treated

Performing financial analysis indicates that traffic is a major determinant of the time of upgrade for a gravel road. In addition to financial analysis, other considerations that should factor in the decision are described below:

- **Structural Capacity**: When a gravel road is upgraded, the surface treatment acts as a sealant and reduces moisture penetration. It also prevents surface gravel loss, eliminates dust generation, and increases user satisfaction by providing a smoother ride and better appearance. A surface treatment, however, does not improve the structural capacity of a gravel road. A gravel road with structural or subgrade defects, needs to be structurally enhanced or rehabilitated before upgrading to surface treatment. The cost of rehabilitation and stabilization should be added to the initial cost of the surface treatment as part of a financial analysis. Upgrading a gravel road with structural defects can significantly reduce the service life of the surface treatment and result in poor performance.
- **Drainage**: Similar to structural capacity, adequate drainage provision of a surface treated road is imperative to achieving satisfactory long-term performance. Surface treated roads are less forgiving to frost damage than gravel surfaces. Poor drainage conditions will reduce the useful life of a surface treatment and make it expensive to maintain.
- **Traffic Characteristics**: Types of traffic can significantly affect the performance of surface treated roads. In some cases, a gravel road can be an agricultural or mining access road that experiences heavy or overloaded trucks on a regular basis. In general, if a gravel road serves heavy traffic, upgrading to surface treated can become an expensive decision since heavy trucks are more damaging to a surface treated road and the cost of rehabilitation is higher. In this case, it may be better to retain the gravel surface and upgrade to a superior load-bearing hot mix asphalt pavement when sufficient funds are available.
- **Road Geometry**: When a gravel road is upgraded to surface treated, it encourages drivers to drive faster and therefore operational speed increases. It may also increase traffic volumes as more motorists decide to use it. Substandard geometric features such as horizontal and vertical alignments, sight distances, lane widths, shoulder widths, superelevations, in addition to lack of signage, can result in safety hazards and a higher risk of accidents. It might be necessary to improve the geometric features of a road before upgrading to surface treatment and the cost of these improvements should be taken into account as part of a financial analysis.

- **Opinions of Local Residents**: While it is usually assumed that local residents will support an upgrade to surface treatment, this is not always the case. Local users may prefer to retain a gravel road rather than encouraging more traffic, higher speeds and greater use of the route by commuters. It should also be noted that from a context sensitivity perspective, gravel surfacing may be more compatible with the road environment and community setting.

Decision Analysis

After defining the network condition and constraints, the last step in the gravel analysis process is selecting segments for maintenance and rehabilitation over a predefined planning horizon (typically 5 to 10 years) and identify the most cost-effective fund allocation strategy. This can be achieved through a multi-criteria decision analysis process considering physical performance in addition to other socio-economic attributes, or by using detailed optimization algorithms. Detailed optimization using mathematical programming is beyond the scope of this paper and has been discussed in other publications by the authors (Rashedi & Hegazy 2014; Rashedi et al. 2017). In the case of fund allocation analysis for gravel roads, constraints can be applied to both operational and capital budgets (e.g., maintenance or major rehabilitation). A seamless integration is therefore required to ensure both types of constrains are taken into account during the fund allocation analysis. There should also be a direct link between gravel and paved roads analyses so that the central database and network performance details can be updated in the case of upgrading a gravel segment to paved status. The results of the what-if scenario analyses and policy comparisons can be then effectively used to identify the best maintenance policies or budgeting strategies for gravel roads in conjunction with paved.

KEY CONSIDERATIONS FOR OPERATIONS AND MAINTENANCE

This section discusses some general guidelines and recommendations on utilizing best maintenance practices and management concepts for gravel roads, based on a review of published literature (Watanatada et al. 1987; Chong & Wong 1989; Skorseth et al. 2000; Massachusetts Department of Environmental Protection 2001; PENNDOT 2006; Douglas et al. 2007; Henning et al. 2008; FHWA 2015), the results of the aforementioned survey (ISI 2017), and discussions with experts from the industry, as well as local governments.

Building a Proper Cross Section

Building a proper cross section is the primary objective of gravel road maintenance operations. A properly shaped cross section with adequate crown and shoulder crossfalls drains water away from the pavement structure and extends its service life. A typical crossfall for the traveled lanes is between 4% and 5%. The crossfall deteriorates over time and reaches a point at which it no longer sheds water and deteriorates more quickly. Without adequate crossfall, water accumulates on the road surface and softens the crust and penetrates into the subgrade.

Inadequate crowns can quickly result in surface distresses such as potholes, rutting, or deformation, especially under heavy traffic loading. Many studies show that poor performance of gravel roads can be attributed mostly to lack of crossfall and inadequate surface drainage, even in semi-arid regions. Excessive crowns (i.e., crossfalls more than 6%) are not recommended either due to safety issues. Excessive crowns can cause loss of control while driving and encourage road users to drive in the middle of the road regardless of the surface width.

A gravel road cross section should also be adjusted at curves to provide adequate superelevation. By raising the outer edge of a curve on a road above the inner edge, a superelevation reduces the effect of centrifugal force on vehicles and provides better control while turning. Lack of superelevation or improper transition from a crown to a superelavation can become a safety hazard and increases the risk of accident. During maintenance operations, the grader operator should build a gradual transition from a crowned surface to a straight superelevated surface.

Typical lane widths for a gravel road are 3.5 m, but can vary from 3.0 m to 3.7 m. Shoulders are graded at around 6% to provide adequate drainage by directing water further from the road surface into the foreslope and the ditch. Frequently, gravel roads might not have defined shoulders. Road shoulders should be kept at the same level as the edge of the road surface. Sudden drop-offs can lead to safety hazards while high shoulders prevent water from draining off the road surface into the ditch. High shoulders can result in a secondary ditch along the side of the road that erodes gravel material and subgrade soil resulting in various defects. High shoulders are usually the result of poor maintenance practices.

Ditches are also important to drain water away from the roadway subgrade. Ditches need to extend to below top of subgrade and require periodic cleaning to ensure debris, vegetation, or excess gravel material migrating from the road surface are removed. Similar to ditches, culverts should be maintained periodically to ensure there is no obstruction to prevent the natural flow of water under the road and to ensure that the culverts are not perforated, crushed or distorted. Care should be taken during maintenance and installation of culverts to ensure proper inlet/outlet elevations, and alignment with the flow line of the ditch is achieved to avoid any washout or erosion around the outlets.

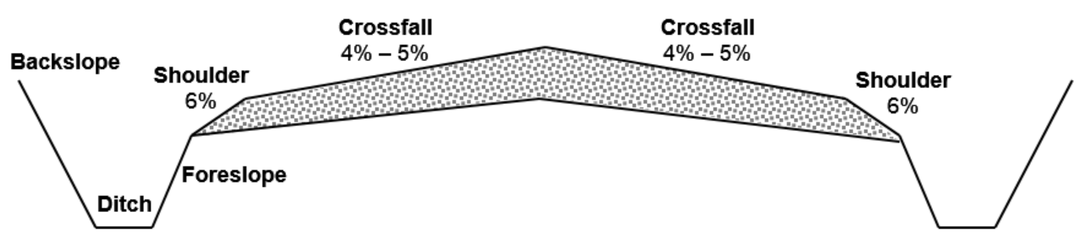

Figure 7: A typical gravel road cross section

Materials for Use

While many agencies use granular road base materials for surfacing on gravel roads, it is not necessarily the ideal material for use in terms of serviceability and maintenance. Road base granular materials are designed to have high structural capacity as well as good drainage characteristics. While structural capacity is also good for a gravel road, the free draining nature of the surfacing is not necessarily an advantage.

Construction granulars can be pit run, produced from a quarry source (in which case they will be 100 per cent crushed) or a partially crushed pit source material (partly crushed). The crushed content of an aggregate improves its structural capacity since the rough crushed faces provide better granular interlock compared to rounded particles. Crushed products are preferred for gravel roads. Irrespective of the percent of crushed particles, the particles themselves must be hard and durable. A good test for this is the MicroDeval test. Road surfacing gravels should have maximum MicroDeval losses on the coarse fraction of less than 25%.

In most granular road base materials, there is 15 to 20 percent allowance of coarse materials larger than 19 mm. In general, gravel road surfacing should be 100% finer than 19 mm since it provides a smoother ride quality and is less prone to segregation. It also needs an adequate percentage of sand sizes to fill the voids. Typical granular bases will have 45 to 70 percent passing the 4.75 mm sieve. For gravel road surfacing, the sand sizes should be at the higher end of this range.

There is a lot of practical experience that indicates that surfacing gravels with a higher percentage of fines (material finer than 0.075 mm) perform better. For road base granular materials, the fines are usually restricted to 8 to 10 percent maximum, so as to not impede drainage. However, many agencies prefer fines content up to 15 percent for surfacing gravels. They will also allow the materials to have Plasticity Indices of 4 to 12 percent, while for most road base granular materials the fines are required to be non-plastic. In a road surfacing application, the higher fines content bind the material and allow a crust to form on the surface which can reduce material loss.

Some agencies also allow the addition of Recycled Asphalt Product (RAP) in road surfacing granulars. With increasing use of cold milling for road maintenance, large volumes of RAP are readily available. In general, the addition of RAP should not be greater than 30 percent as above that, the material may no longer be “unbound” and so maintenance regrading activities become more problematic.

Proper Grading Operation

Several studies have been published on proper grading techniques (e.g., FHWA 2015). This section does not provide a detailed review of proper grading techniques, however, discusses some of the main issues and considerations. Operating speed should be slow enough to avoid bouncing and creation of cut depressions on the road surface. A speed range of 5 to 10 km per hour is typically recommended, however, factors such as the quality of material, moisture, or subgrade strength can affect the proper operating speed. Operators should maintain a proper blade angle, typically between 35 to 45 degrees, during the grading maintenance to recover material and avoid spilling from the toes of the blade. To achieve proper mix and to avoid material loss, it is also important to use a proper blade pitch. Excessive backward pitch can result in poor mixing action and high shoulders. Excessive forward pitch, on the other hand, may result in poor mix and lack of enough penetration to remove surface defects and may not create a smooth ride quality. A proper blade pitch and angle result in a good mixing action with enough penetration to fix surface defects with minimum material loss during the grading operation.

Dust Control

Gravel roads give off dust under traffic action. The amount of dust generation can be affected by factors such as gravel material properties, the percentage of fines, annual precipitation, and the level of daily traffic. Excessive dust from gravel roads can cause health issues, poor air quality to nearby residents, environmental damage, and increase the risk of accidents. The most common dust suppressants are calcium chloride and magnesium chloride. These are typically applied in liquid form from a tanker with spray bar. Calcium chloride draws moisture from the air resulting in a damped road surface that reduces the amount of dust generation. Proper dust control can also reduce gravel loss and required grading maintenance cycles. For effective dust control operations, gravel roads should have optimum moisture to allow for complete absorption of the dust suppressant.

IMPLEMENTATION OF A GRAVEL ROAD MANAGEMENT SYSTEM

This section shows an example of implementing a gravel road management system using decision support software technologies developed in Canada. The case study is a small/medium size municipality with 400 centerline kilometers of roads. Figure 8 shows an example of data visualization and GIS mapping of the road network within a road management software application. Around 59% of the network is gravel, 40% HMA, and 1% surface treated. The overall network performance in terms of PCI (pavement condition index) is estimated at 64 representing an overall fair condition. The detailed distribution of segments in the poor (PCI less than 50), fair (PCI between 50 and 65), good (PCI between 65 and 80), and excellent (PCI between 85 and 100) categories for different surface types are shown as well. The mapping visualizations enable road managers and municipal councilors to access geospatial, inventory attribute, and condition data for any gravel or paved road segment at any time. Using layered mapping, gravel and paved sections can be easily analyzed together or individually (Figure 8-d).

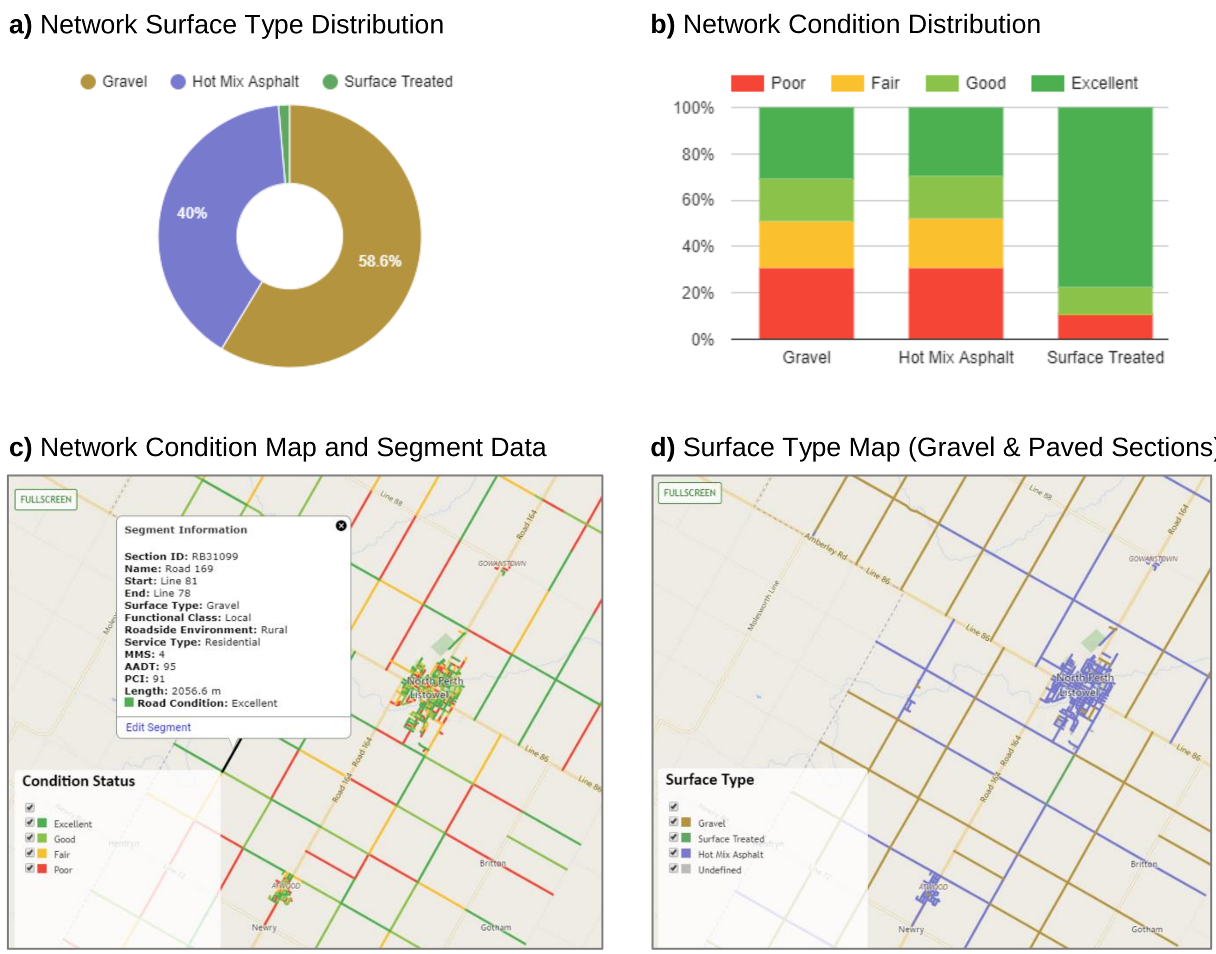

Figure 8: Network information visualization using gravel road management technologies

As for paved roads, the condition data collected for gravel roads should be in the form of a pavement condition index (PCI), which is a combination of the extent and severity of the relevant visible surface defects and distresses. Since the PCI data is used within the system to inform the decision-making process, it must encapsulate the distresses that directly impact road serviceability and timing and extent of maintenance interventions. It is only when this information can be effectively captured that higher investment efficiency can be achieved.

Practical condition rating schemes have been developed by different organizations (Chong & Wong 1989; MTO 2009; ASTM 2018). The Ministry of Transportation of Ontario rating system based on evaluating condition under a set of distress modes in conjunction with an evaluation of the ride quality has been used in this study. This produces an estimate of PCI. A distress manifestation index is calculated from the evaluation of the road condition under eight distress modes as listed in Table 1. A range of maintenance treatments can then be assigned based on the PCI and major distress types as shown in Table 2. Such a systematic approach for condition assessment of gravel roads provides consistent and representative condition ratings and identifies the predominant surface defects while performing a network-level analysis. It also allows the identification of any underlying conditions that decrease the effectiveness of routine maintenance.

Table 1: Gravel roads distress manifestation (Chong & Wong 1989)

Distress Mode	**Distress Type**
Surface Defects	Loose Gravel Dust Potholes Break-up
Surface Deformation	Washboarding Rutting Flat / Reverse Crown Distortion

Table 2: Example of using PCI data to determine proper MR actions

PCI Range	**Treatment**
80-100	Routine maintenance
60-79	Routine maintenance. Dust control may be necessary for residential areas.
40-59	Increased routine maintenance necessary. Addition of gravel and dust control additives become necessary.
20-39	Maintenance with addition of gravel necessary. Dust control a must for residential areas. Some portions may need rehabilitation.
0-19	Rehabilitation necessary.

By implementing a GRMS, two scenarios with different budgeting strategies are compared over a 10-year planning horizon, in addition to investigating potential upgrades to surface treated. Scenario 1, represents an adequate level of investment for maintenance and the network condition improves over the planning horizon, while, scenario 2 is an under-budget situation. As shown in Figure 9, the overall performance outputs indicate that Scenario 2 results in a decay of performance over time while Scenario 1 results in a consistent performance with slight improvement. Condition distribution charts also indicate that a significant portion of the network is expected to reach unsatisfactory poor condition by the end of the planning cycle. These outputs can be further analyzed to identify potential level of risk to segments with higher minimum maintenance or serviceability requirements and also to project backlog accumulation over the planning horizon. Also the required level of capital and operational investments can be identified. These outputs not only help road managers to determine short- and long-term needs, but also enables them to easily communicate with other stakeholders, such as council members or government funding agencies, to establish funding requirements and strategic priorities. A combination of financial analysis with other upgrade criteria, such as heavy vehicle traffic and subgrade strength, are used to identify gravel segments that are candidates for surface treatment upgrades. In this example, around $194,000 was allocated to upgrade a number of segments as shown in Table 3.

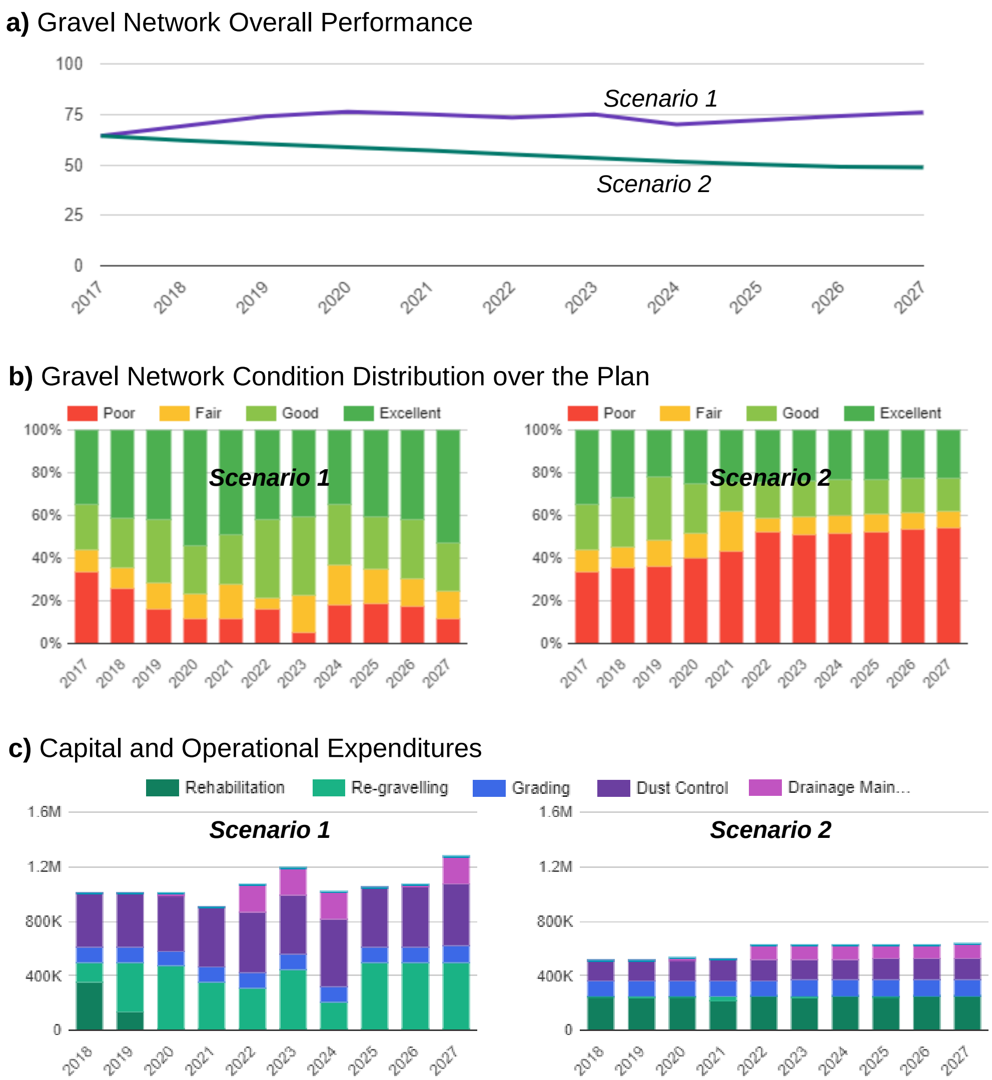

Figure 9: Example of network analysis and scenario comparison outputs

Table 3: Selected segments for upgrade from gravel to surface treated

Section ID	Gravel Cost	Surface Treated Cost	AADT	Subgrade Strength	Upgrade Candidate
RB32050	$69,476	$37,331	250	Strong	Yes
RB32051	$195,978	$105,302	280	Strong	Yes
RB32051B	$204,878	$110,084	280	Strong	Yes
RB32052	$405,684	$217,980	270	Strong	Yes
RB33040	$13,201	$8,662	150	Strong	Yes
RB33163C	$34,005	$17,023	250	Strong	Yes
RB33198D	$29,692	$14,864	300	Strong	Yes

CONCLUSIONS

Gravel roads account for the majority of the public road network in Canada and many other countries. Although gravel roads typically represent lower volume segments in a road network, they play a critical role in functioning societies by providing means of product transport, access to remote communities, and serving local residents in semi-urban and rural areas. Preserving and managing gravel roads is therefore a major activity for many municipalities that cost millions of dollars every year. In order to effectively manage gravel roads, a comprehensive road management system that considers both paved and unpaved gravel roads is required. A gravel road management system (GRMS) is a necessary tool for road managers and decision makers to reduce future financial risk, evaluate their investment strategies, and develop cost-effective maintenance and rehabilitation plans. A properly implemented GRMS would also facilitate an analysis of the financial trade-offs and the long-term implications of various management decisions, such as upgrading a gravel road to surface treated.

This paper discussed the result of a current survey in Canada, with 97 municipal participants, showing the majority of municipalities do not collect condition data about their gravel roads due to a perceived lack of benefit and availability of easy-to-use gravel road management system to help with the condition assessment and data collection process. The survey results also indicated that the majority of municipalities schedule their maintenance and rehabilitation activities for gavel roads on an ad-hoc basis, however, almost all of the municipalities who manage a gravel network of more than 50 km, expressed the opinion that having decision support tools available to assist with gravel road management would be a benefit.

This paper also discussed the main components and functions of a comprehensive road management system with a gravel analysis module. In addition, general guidelines and recommendations on utilizing best maintenance practices and management concepts for gravel roads were presented, based on extensive review of published literature, the results of the survey, and discussions with experts from the industry, as well as local governments. Subsequently a case study on implementing a GRMS for a medium size municipality was discussed. The example presented demonstrates that provided we have a reliable system for characterizing the condition of gravel roads and predicting rates and modes of deterioration, they can be treated in a similar manner as paved roads for the purposes of a road asset management system. Thus for municipalities with large gravel road networks, the ability to include the gravel roads within their 10-year budgeting cycle on a par with their paved roads, has significant advantages in terms of optimizing the return on their overall investment in delivering a serviceable road network to road users.

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