Using Enhanced Data Collection for the Optimization of Pavement Design and Asset Management for P3 DBFO Projects

A.G. (Art) Johnston, C.E.T., Chief Technologist, Transportation, Tetra Tech

Bryan Palsat, P.Eng., Pavements Engineer, Transportation, Tetra Tech

Gary St. Michel, P.Eng., Principal Specialist, Transportation, Tetra Tech

Martina Riessner, E.I.T., Pavements Engineer, Transportation, Tetra Tech

D.P. (Dave) Palsat, M.Sc., P.Eng., Senior Project Director, Transportation, Tetra Tech

Paper prepared for presentation
at the Advances in the Data Collection and Usage for Pavement Management Systems Session
of the 2015 Conference of the
Transportation Association of Canada
Charlottetown, PEI

1.0 INTRODUCTION

With increasing frequency, roadway corridor development and improvement projects are being procured through Design-Build-Finance-Operate (DBFO) Public Private Partnerships (P3s). In these procurement environments the nature of the pavement design and engineering requirements change in several significant ways compared with the traditional Design-Bid-Build (DBB) in that the consequences of poor pavement performance (risk) in most aspects is transferred from the Owner to the DBFO partners, the Designer, Constructor and Operator/Concessionaire.

This paper illustrates how enhanced pavement data collection and performance modelling is key to optimizing the initial pavement design solution during the pursuit stage. It also demonstrates how enhanced data collection and performance modelling can be adapted for asset management on behalf of the facility operator to optimize maintenance and rehabilitation during the operating period, thereby maximizing profits while meeting specified performance requirements.

Also discussed are the requirements of pavement design and engineering components through the bid, build, transfer (from Constructor to Concessionaire), operations and handback (to the Owner) DBFO process. A description is provided of the methodology for arriving at the lowest Net Present Value (NPV) life-cycle cost that meets the project's pavement performance and handback requirements.

Observations regarding the role of the pavement engineers in DBFO delivery and the challenges posed by the relationships between Builder, Operator/Concessionaire and Owner, are presented.

Entities in a DBFO include the Owner, Owner's Engineer (OE), Equity (Financiers), Concessionaire, Design Build Joint Venture (DBJV), Constructors (or Joint Venture, JV), and Concession/Operator. Data collection, asset management and pavement engineering services can be provided directly, or indirectly to all of these entities. Relevant DBFO related descriptions [FHWA] are:

- Owner – Agency that serves as the sponsor of a DBFO and is typically a department of transportation, transit agency or local government.
- Owner's Engineer – Consulting engineering entity that serves as the Owner's representative in the DBFO.
- Equity – The entity that secures long term funding for the private concession.
- Concessionaire – The private sector entity that uses Equity funding, and with the support of the DBJV develops the bid and financing structure for the overall delivery of the DBFO.
- DBJV – The consortium of consulting engineers and constructors that delivers the design and construction bid for a DBFO Project, and if successful the delivery of the initial construction.
- Constructors or Joint Venture – The group of companies that represent the construction component of the DBJV.
- Concession/Operator – The entity whom the Concessionaire secures to undertake operations and maintenance and potentially undertakes or arranges for rehabilitation activities throughout the Operational Term.

This paper specifically deals with roadway transportation DBFO projects and the pavement related elements of those projects. It should be noted that other assets typically included in DBFO projects (e.g., bridge structures, drainage structures, etc.) can also be the subject of asset management.

For the purposes of clarity the following definitions are provided:

- Reference Concept or Functional Plan – The Owners preference in terms of geometric configuration, typically undertaken prior to the Request for Qualifications (RFQ). Details with respect to pavement design are seldom included.
- Pursuit – The term typically used for the Request for Proposals (RFP) response, including both a Technical Submission followed by a Financial Submission.
- Operations, Maintenance and Rehabilitation (OM&R) – The activities undertaken to maintain the facility in compliance with the performance criteria.
- Operational Term or Period – The length of time for which the DBFO contract extends and OM&R activities are subject to conformance with the performance criteria (typically 30 to 40 years).
- Substantial Completion – The point in time when the facility is operational. Substantial Completion is required on or before the construction period or penalties come into effect.
- Handover – The point in time when the Concessionaire takes possession of the facility from the Constructor.
- Handback – The point in time when the facility, at the end of the Operational Term and meeting all the performance requirements at Handback, is conveyed from the Concessionaire back to the Owner.

2.0 BACKGROUND

2.1 The P3 Model

Many public agencies are starting to utilize the P3 model to finance the expansion and rehabilitation of existing infrastructure that would have otherwise been completed through traditional project development. One of the primary reasons public agencies consider the P3 model is the expanded economic capacity generated from the upfront financing through private equity and the commitment of federal investment (i.e., Partnerships Canada). Diversifying the potential source of funding has allowed public agencies to pursue large infrastructure projects that otherwise may have been unaffordable.

Another primary motivation behind the P3 model is risk allocation. Table 1 presents how risk is allocated for different project delivery types.

Table 1: Project Risk Allocation by Project Delivery Type

Project Delivery Type	Design[1]	Construction	Finance	OM&R[2]	Traffic
Traditional Design-Bid-Build	O	C	O	O	O
Design-Build	C	C	O	O	O
Design-Build-Finance	C[1]	C	E	O	O
Design-Build-Finance-Operate (no toll concession)	C[1]	C	E	CO	O
Design-Build-Finance-Operate (with toll concession)	C[1]	C	E	CO	CO

Where: O - Owner; C - Constructor; E - Equity (Financier); CO - Concessionaire/Operator

Design[1] - Includes design traffic loadings

OM&R[2] – Operations, Maintenance and Rehabilitation

Risks arise in all projects, regardless of the procurement approach. In a P3, project risks are transferred to the party best able to manage them. By making the private sector responsible for managing more risk, governments reduce their own financial burden. The private sector bids a fixed price for the bundled contract, and must pay out of pocket should any unforeseen expenses arise (e.g., cost escalation, construction defects, unexpected maintenance requirements, etc.). [PPP Canada].

Appropriately structured P3s can provide incentives for better asset management and on-time and on-budget delivery. With long term operation, maintenance, and rehabilitation periods (OM&R), the private partner is provided incentive to consider the long term performance of the asset, and therefore find the optimal balance between initial construction and ongoing life-cycle costs.

2.2 Current P3 State-of-the-Industry – Canada and the USA

The P3 model has been used in both Canada and the USA for a number of decades, although there is a noted trend towards increased interest in both countries. As of October 2013, there were over 200 and 550 funded or planned infrastructure P3s in Canada and the USA respectively. These projects collectively represent over $77B and $175B in capital investment in the two countries. Infrastructure types can be grouped into four key sectors:

1. Buildings,
2. Water,
3. Rail, and
4. Roadways.

Overall, roadway transportation projects represent approximately 18% of all P3 projects in Canada (35% of all P3 investment), whereas they represent over 30% of P3 projects in the USA (56% of all P3 investment). Figure 1 shows a breakdown of P3 projects by key sector in both Canada and the USA.

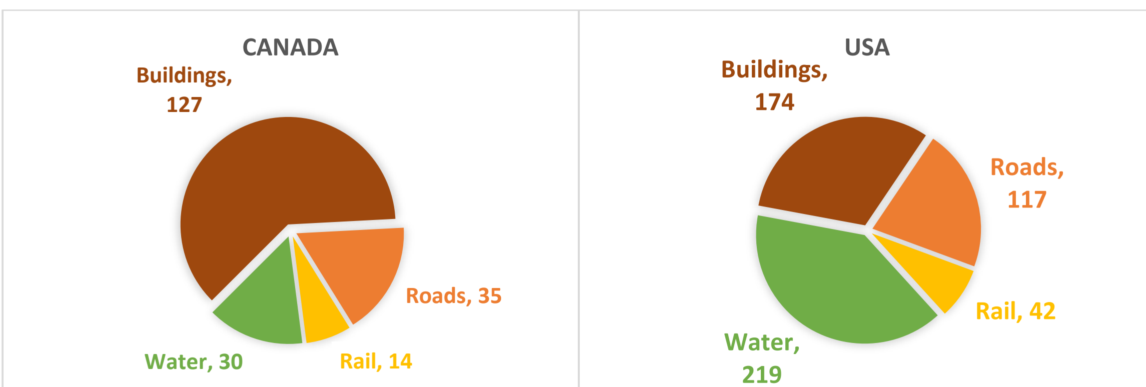

Figure 1: Total Number of P3 Projects Funded and Planned by Infrastructure Type as of October 2013

Figure 2 shows a breakdown of P3 investment by key sector in both Canada and the USA.

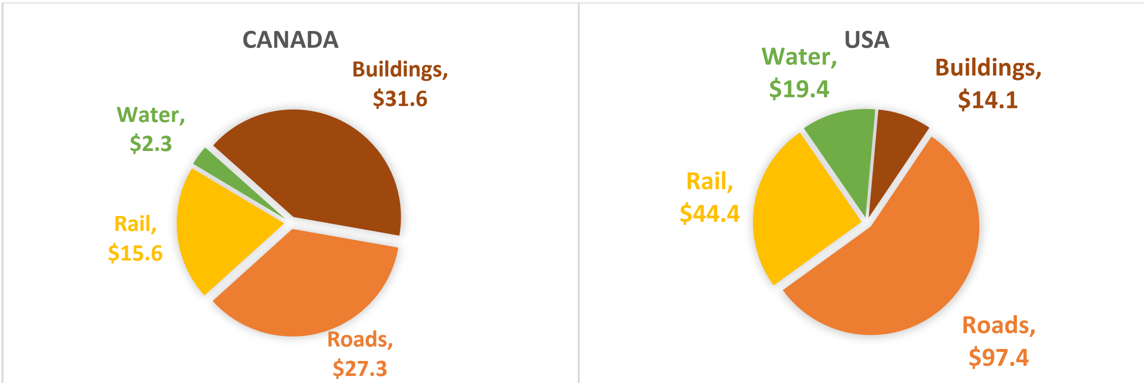

Figure 2: Total Value of P3 Projects Funded and Planned by Infrastructure Type as of October 2013 (Billions)

Source: Data taken from Public Works Financing "International Major Projects database" 2013. See PWFinance.net
Public Works Financing • 227 Elmer Street • Westfield, NJ

To help put these numbers into perspective, Figure 3 shows the relative value of P3 projects for six countries (as a percent of total percentage of total Gross Domestic Product) where the P3 procurement model is considered, including Canada and the USA.

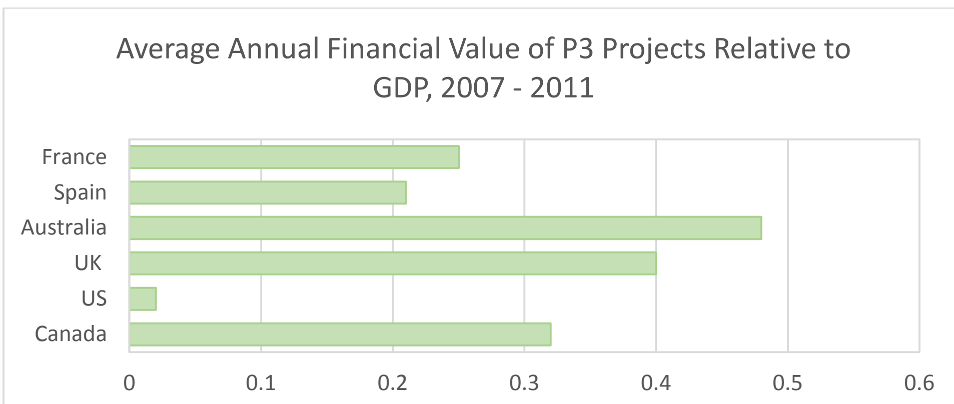

Figure 3: Value of P3 Projects Relative to GDP (2007 – 2011)

Source: Infrastructure Journal online database, NationMaster.com The Conference Board of Canada.

In general, Figure 3 shows that P3s represent a relatively low percentage of GDP. Although comparing P3 value is not directly comparable to GDP, it can be used as a relative indicator of significance P3s have in the six countries presented. The relatively low percentage of GDP in the USA market provides insight into the potential size of the P3 market.

2.3 Transportation P3s Trends in Canada and the USA

There is an increasing trend in the investment in transportation (Rail and Roadways) P3s in both Canada and the USA. The review of capital investment data from 1996 shows a nearly three-fold increase in P3 spending in 2012, with projected annual investment in the $4B to $8B range by 2016 in Canada and the USA respectively.

Figure 4 shows the capital investment in P3s by year between 1989 and 2013.

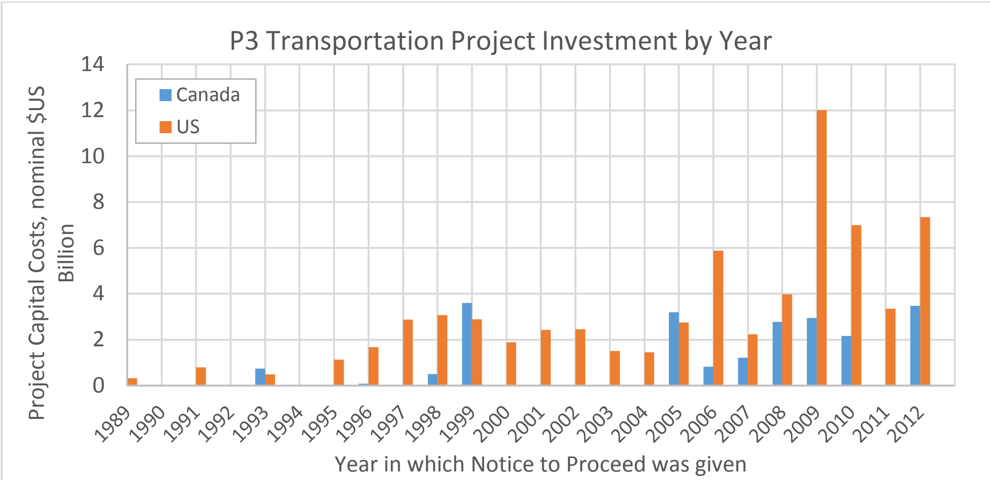

Figure 4: P3 Capital Investment Trend in Canada and the USA

Source: Data taken from Public Works Financing "U.S. & Canadian Transportation Projects Scorecard." See PWFinance.net
Public Works Financing • 227 Elmer Street • Westfield, NJ

Figure 5 shows the breakdown of P3 capital investment by province (as a percentage of the total) [PPP Canada].

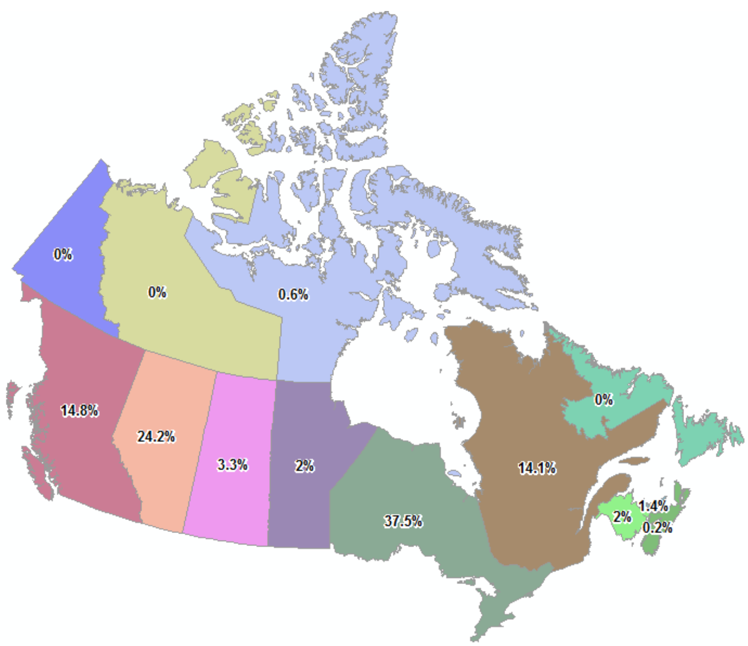

Figure 5: Estimated Transportation P3 Investment by Province (Funded and Planned) as a Percentage of Total P3 Investment in Canada

Within Canada, nearly all provinces now have experience with the P3 model, with Ontario and Alberta leading the country with a combined 61.7% (37.5% in Ontario) of all P3 investment (current and projected). British Columbia and Quebec are both well represented with approximately 14% of all P3 investment in each province. There is also a growing trend in the other Prairie Provinces where there is a noted increase in roadway and bridge transportation investment. Overall provincial governments continue to be the most significant public contributors in the Canadian P3 market, although there is a growing interest among municipalities in the P3 model.

In summary, Canada has maintained steady use of the P3 delivery model. Enhanced project delivery and standardization in project procurement has resulted in a competitive market for future P3 development. The continuance of municipal interest and investment in the P3 model will contribute to the growth and diversity of these sort of projects. While the USA is showing signs of potential growth, political resistance has limited the reach of alternative delivery projects. There will however, continue to be future opportunities to export Canadian expertise to the USA as prospects for growth become available.

2.4 The Performance-Based Design Philosophy

The philosophy of performance-based design requirements references back to the Babylonian law where the concept was present in Hammurabi's Code (c. 1795 to 1750 BC), which stated "a house should not collapse and kill anybody" [King 2005]. It is safe to say that the details that comprise this philosophy have evolved since ancient times, however the general concept stands true to the modern P3 environment.

A performance-based design approach is founded on the principal where the design and construction of an asset is completed to achieve a set of prescribed performance results. This is fundamentally different when compared to the traditional design approach which would specify a way and method to the design and construction process. In a performance-based approach, the focus of all decisions is on the level of service requirements and on the minimum required performance in use. This approach encourages the development of tools and methods that incorporate a whole life-cycle design and construction process, from the procurement and construction phases to the quantification and evaluation of results.
The four primary components to the performance-based design process are:

1. Identifying and formulating the relevant user requirements (how many lanes, what type of interchanges, what sort of river crossing, etc.);
2. Transforming the user requirements into performance requirements and measureable performance criteria (intersection serviceability, roadway ride quality, etc.);
3. The development of reliable design and evaluation tools that can measure whether potential design alternatives meet the stated criteria at a satisfactory level; and
4. Accurate and reliable evaluation of the completed infrastructure to verify compliance with the stated performance criteria.

As such, the performance-based approach focuses all stages of procurement, design, construction, and operation and maintenance, on the required performance in use and on the evaluations and testing of the constructed infrastructure.

3.0 DATA COLLECTION – STATE OF THE PRACTICE

The requirements for accurately referenced objective pavement performance data are extremely important as these data are used for design, performance evaluation, and ongoing acceptance during the operations period and final acceptance at Handback. In very recent years, the evaluation of pavement performance has become more sophisticated with developments in data storage and referencing systems, and of 3D pavement surface profiling systems and 360° mobile LiDAR. Available technologies and platforms available to measure roadway surface condition, pavement strength, pavement structure thickness, and surface friction attributes are discussed in the following sections.

3.1 Integrated Roadway Condition Data Collection

Sophisticated systems have been developed to provide integrated, continuous and high speed data collection capabilities for network and project-level roadway condition data collection. An important implication of the increasing use of P3 procurement methods is the convergence of network and project level data collection requirements. Alberta Transportation's (AT) current requirements for pavement data collection are presented as an example of the state of the practice in Canada [Palsat 2014].

Alberta Transportation has used integrated data collection vehicles for the Provincial Data Collection Program since 1995. These sophisticated vehicles collect all required data in a single pass, ensuring all data are accurately referenced and synchronized. AT's most current program requires data components that include pavement ride (IRI and rut), roadway geometrics, digital imagery, high resolution 360° transportation corridor LiDAR, and 3D pavement distress. Tetra Tech's PSP 7000 vehicles collect all of these data attributes. A schematic view of a Tetra Tech PSP 7000 survey vehicle is provided in Figure 6. The key components are described in Table 2.

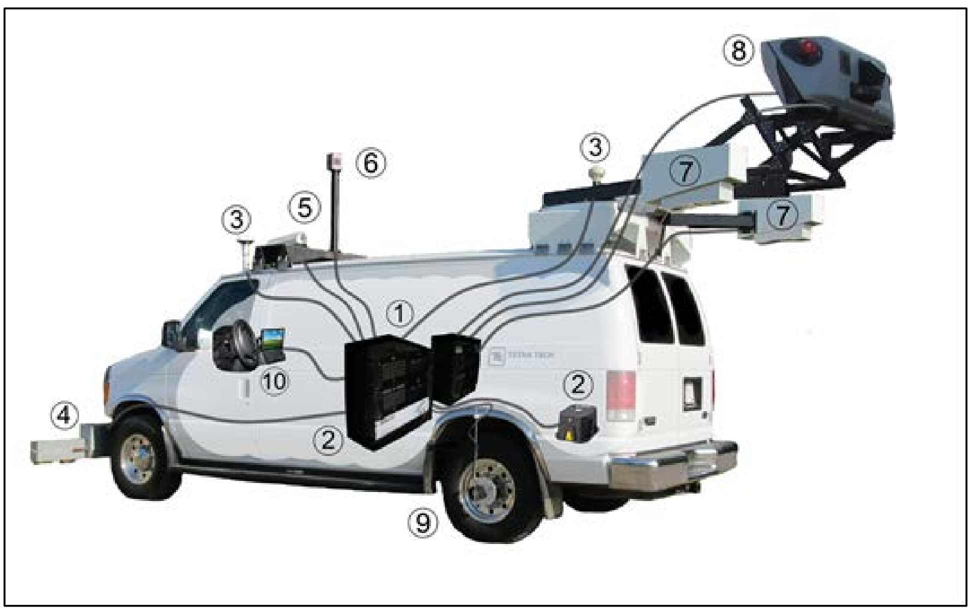

Figure 6: PSP 7000 Survey Vehicle Schematic

Table 2: Key Components of PSP 7000 Survey Vehicle

Key	Component Description
1	Synchronized data control, acquisition, and storage system
2	Inertial and GPS vehicle positioning and orientation system (POS)
3	High performance GPS and real-time DGPS correction receivers
4	Inertial longitudinal and transverse profiler providing the integrated IRI and fixed-point transverse rut measurements
5	Data synchronized and spatially referenced high resolution digital right-of-way image system
6	Data synchronized and spatially referenced high resolution digital 360° panoramic image system
7	3D pavement surface profiling system
8	Pavement surface LiDAR system providing 360° corridor point measurements
9	High resolution distance measurement wheel encoder
10	Fully integrated operator console

Vehicle Geospatial Position and Orientation System

Accurate vehicle position and attitude information is critical for the correct referencing and synchronization of all onboard measurement subsystems. In the PSP-7000, these functions are provided by a high performance inertially-aided GPS positioning and orientation system (POS). The POS provides spatial position (roadway centre line alignment) and orientation (vehicle chassis orientation and roadway geometry) measurements.

Vehicle survey alignments and dynamic vehicle attitude information is processed to produce horizontal alignment and tangent percent gradient; horizontal curve start and end locations, simple curve radius, tangent delta angle; and vertical curve start and end locations, vertical curve radius and k-value.

Inertial Profiler

Longitudinal profile, transverse rut, and IRI capabilities are provided by an International Cybernetics Corporation inertial profiler with 11 laser height sensors and two wheelpath accelerometers which exceeds both ASTM E950 and the profiling equipment specifications detailed in [TAC 2001]. Profile measurements are made at 32,000 per second and recorded every 19 mm. The IRI, average rut depth and maximum rut depth are reported for each wheel path for each 50 m reporting segment. Cross-slope and super-elevation are reported at a 20 m interval.

Digital Imagery

Digital imagery is collected through separate right-of-way (ROW) and panoramic video subsystems capable of acquiring high resolution images every 5 m. These imaging systems are fully integrated into the primary vehicle profile data acquisition system, ensuring that all image data are fully time synchronized and referenced with all other collected roadway and spatial reference data. The imaging systems allow the identification, inventory, and referencing of all discernible infrastructure and appurtenances located within the driven survey area.

3D Pavement Surface Profiling System

The automated laser based 3D pavement image system specified by AT must meet the requirements of AASHTO Designation PP 67-10 [AASHTO 2013] and P68-10 [AASHTO 2013].

The Pavemetrics 3D Laser Crack Measurement System (LCMS) provides high resolution (0.5 mm vertical, 1 mm transverse) transverse profiles every 5 mm along the roadway at survey speeds. These profiles can be combined to produce detailed 3D elevation maps of the pavement surface which are used to automatically detect and classify surface distresses. For each transverse scan, both elevation and intensity measures are recorded. The intensity data provides a detailed ‘picture’ of the roadway surface and allows identifying changes in pavement type, paint markings inventory and the calculation of lane widths, etc.. LCMS measured pavement surface maps are suitable for transverse profile measurements (complex ruts), automated objective cracking analysis, analysis and pavement texture analyses.

Post processing, analysis, and reporting software allow the automatic detection and reporting of crack severity and extent feature continuously across the survey lane. The default manufacturer libraries provide simple crack type classifications (longitudinal, transverse, other) and severity levels (low, medium, high). Supplemental libraries have been developed by Tetra Tech to provide detailed crack maps and additional pavement surface distress analysis capabilities including user defined severity levels, additional crack types, potholes, and curb details, summarized at any specified interval. Table provides AT survey requirements for distress data [Alberta Transportation 2012]. The reporting segment of pavement distress data is 50 m, consistent with that of the IRI and rut data.

Table 3: AT Distress Data Requirements

Distress	Unit
Longitudinal Crack	m
Fatigue Crack (Alligator)	m^2
Transverse Crack	m
Miscellanea crack	m
Heave/Depress/Faulting	m
Ravelling	m^2
Pothole	m^2
Continuous Patch Indicator	Indicator
Porosity	Index
Shoulder Crack	m

LiDAR

The PSP 7000 profiling platform is equipped with a state-of-the-art Trimble MX-8 360˚ cross-plane (two scan plan oriented at 90˚ to each other) mobile LiDAR system. This system is fully integrated and synchronized with all other data streams to produce 3D LiDAR point clouds (range, position, and intensity), which provide highly accurate location information for objects encountered during surveys. The high performance LiDAR system measures 1,100,00 points per second to a range of greater than 800 m with an accuracy of ±8 mm. The LiDAR system collects corridor terrain elevation data, which is used to calculate lane and shoulder widths, ditch depths, side and back slope, guardrail warrants, access road locations, overhead and side clearances (including wires), sign and appurtenance inventory (on both sides of the roadway regardless of direction of survey), and paint retro reflectivity.

3.2 Pavement Deflection Survey

Falling Weight Deflectometer (FWD) accurately simulate and measure the response of pavement system under a dynamic load. The FWD is an impulse-type testing device, which imparts a transient load upon the pavement surface. The magnitude and duration of the load closely approximates that of a single axle load at moderate speeds. FWD units can be configured to generate dynamic loads of between 7 and 120kN (1,500 to 27,000lbf), with nine radial geophone sensors.

FWD testing replaces empirical measures such as the Benkelman Beam, and allows the accurate back-calculation of a wide variety of fundamental pavement structural properties. This pavement response data is necessary for effective pavement rehabilitation design, pavement failure analysis, establishing pavement load limits, and as input into PMS-based remaining life computations. Data collection with FWDs represent a surface deflection measurement for each of the sensors at known distances from the load. This pavement surface deflection curve (bowl) is post-processed, in conjunction with layer thickness information, to calculate resilient E-modulus for the subgrade and each layer of the pavement structure.

3.3 Pavement Structure Survey

Accurate and referenced pavement structure thickness data are a key input required to back-calculate pavement and subgrade structural properties using FWD deflection measurements. These data care also used when considering in-situ recycling or reconstruction strategies of existing pavement systems. Although construction as-built inventory records inventory records can be used as an estimate of pavement layer thicknesses, their accuracy and referencing cannot be relied upon for detailed evaluation and design. Ground penetrating radar systems have been developed that allow accurate structural parameter measurements to be collected continuously and at highways speeds.

3.4 Pavement Friction Survey

Although the measurement of pavement friction and surface texture is not a common practice by most transportation jurisdictions, performance requirements for skid resistance are often included in P3 performance specifications. The most common method specified for measuring pavement friction in the U.S. is the locked-wheel method (ASTM E 274) [Hall 2009]. This method is meant to test the frictional properties of the surface under emergency braking condition for a vehicle without anti-lock brakes. The result of the locked-wheel test are report as a friction number (FN, or skid number [SN]).

4.0 DATA COLLECTION FOR DBFO PROJECTS

There is an increasing requirement for the high speed collection of accurate and reliable roadway assessment data throughout the life-cycle of DBFO projects. :

- Pre-RFQ Data;
  - In support of development of the Performance Specifications for Roadways;
  - In support of development of the Digital Data Room;
- Design and Construction Data;
  - In support of the bid;
  - In support of the design;
  - In support of the handover between constructor and operator;

- OM&R data;
  - Asset Management data collection;
  - Owner's compliance testing;
  - Handback from operator to Owner.

There are two specification types used in the DBFO method of procurement of roadway pavements:

- Performance Related Specifications (PRS) – Specifications where key end product attributes of the as-constructed pavement are defined (e.g. percent compaction, asphalt content, gradation, smoothness, segregation, pavement thickness, in-situ modulus). The contractor is given total control over the whole process of materials supply, mix design and construction. These specifications are provided to the contractor by the designer and are the specifications upon which the pavement designer relies to meet the Owner's performance specifications for the completed roadway. In the DBFO context the PRS may form the basis of contracts between prime and sub-contractors (e.g., between constructor and paving sub-contractor) and/or between Constructor and Operator. This type of specification is known as End Product Specification in the Design-Bid-Build environment where the pavement performance risk is transferred from the Constructor directly to the Owner immediately following construction.
- Performance Specifications for Roadways (PSR) – Also called Key Performance Indicators (KPI) depending upon jurisdiction, these are specifications that describe how the finished pavement should perform over the OM&R period. Performance is typically described in terms of changes in physical condition of the surface or its response to load [St. Michel 1998] [Chamberlain 1995]. PSRs include such measures as International Roughness Index (IRI), rut depth, pavements surface distresses, skid resistance, cross-fall and a measure of remaining service life. PSR form the basis for the agreement between the Owner and the DBFO Concessionaire/Operator over the OM&R term and at handback.

Section 4.1 describes the role of roadway assessment data collection in the development of PSRs and the provision of a data warehouse (digital data room) of historic pavement performance measurements to the DBFO bidding teams. Section 4.2 describes the uses of roadway assessment data for development of models to predict PSRs and the measurement of PRSs and PSRs prior to transfer of the pavement between the Constructor and the Concessionaire/Operator. The role of roadway assessment data collection in the auditing of PSRs and the management of the as-constructed roadway asset during the concession period are discussed in section 4.3.

4.1 Pre-RFQ Applications

4.1.1 Use of Roadway Assessment Data in Development of Performance Specifications

PSR thresholds are intended to be based on as-measured conditions of similar publically maintained infrastructure. A knowledgeable owner agency will review historic roadway data measured on roadways constructed under similar geotechnical, climate and traffic environments (called surrogate roadway data) to evaluate historical roadway performance. These data from this review are used to establish achievable target thresholds. Surrogate roadway data may include historic IRI, rut depth, skid resistance, cross-fall, pavement distresses and sometimes pavement thickness and subgrade modulus.

Care must be taken when selecting surrogate roadway data. The achievability of the PSR thresholds are in many cases governed by roadway attributes that do not exist on the surrogate roads. For example, urban sections that need be false graded for drainage or rural interchange ramps will have an inherently non-uniform profile when measured using the IRI methodology [Reggin 2008]. Additional care must be taken when applying rural, high speed roadway PSR requirements to lower speed urban projects. Roadways with at grade intersections will inevitably develop more rutting than roadway sections with uninterrupted traffic flow. The additional rutting at intersections causes increased roughness on the cross street. There is also inherently more roughness at transitions from flexible to rigid structures such as occur at bridge abutments and sub-surface pile caps.

Instances of PSR anomalies as described above can be detected prior to establishing PSRs through the use of well geo-referenced roadway assessment data in conjunction with geo-referenced objects representing roadway anomalies. Some roadway data collection agencies now geo-reference all roadway data including terrestrial LiDAR overlain by 360° digital Right-of-way imagery (Figure 7) which can be used to automatically or semi-automatically identify PSR anomalies in the historic roadway performance measurement data. This leads to an achievable set of PSRs. Unfortunately it is sometimes the case that the owner agency has insufficiently well location referenced roadway data to detect anomalies and/or may be unaware of some of these issues.

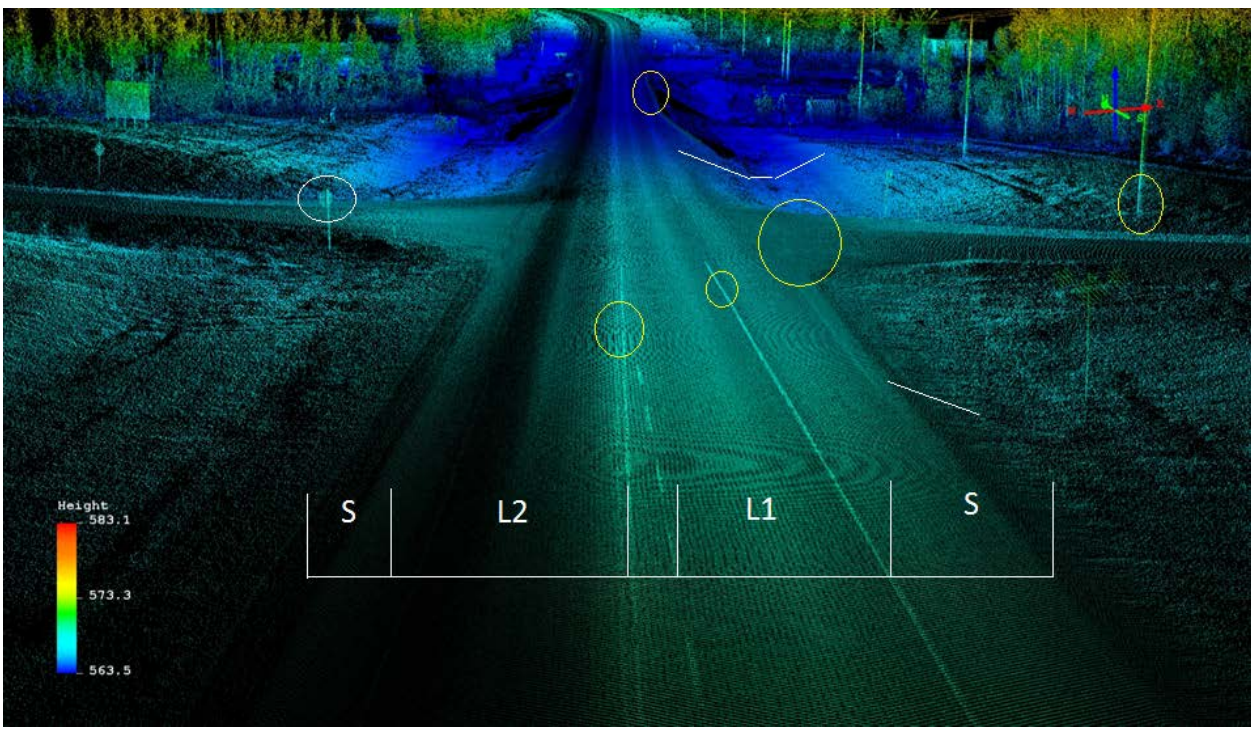

Figure 7: Geo-referenced LiDAR overlain by 360° Digital Imagery

When PSR thresholds are inadvertently established as difficult to achieve, the DBFO teams build in additional costs to protect themselves from the associated risk. The additional cost is ultimately borne by the public with little associated benefit in terms of reduced vehicle operation costs or reduced safety risk. A TAC paper published in 1998 [St Michel 1998] proposed an economics based methodology for establishing performance specifications for roadways by setting them in such a way as to minimize the combined user costs, and direct agency costs.

4.1.2 Development of the Digital Data Room

As part of the DBFO procurement process, the owner agency generally develops a preliminary design of the required infrastructure illustrating conceptually what is required of the bidding consortia; called the reference concept. In order to create the reference concept the Owner's engineers require topographical surveys, locations of existing and proposed utilities, cadastral mapping, geotechnical information, traffic projections as well as Asset Inventory and Condition Study (AICS) information relating to any existing infrastructure that might potentially form part of the concession. Terrestrial LiDAR can be ground truthed to detailed design appropriate accuracies while aerial LiDAR is sufficient for reference concept and bid preparation activities.

AICS data including existing embankments, ROW cut slopes, bridge and culvert locations and geometry, drainage appliances, guard rail, sign inventory, and surface utilities can be collected by automated or semi-automated processes using LiDAR based terrain models overlain by 360° digital images. Existing Bridge and Culvert condition assessments remain a manual field inspection process however this has become a much more rigorous process whereby an image of each distress is mapped to a three dimensional model of the structure using a known camera location, an viewing azimuth and altitude angle. Due to the current rigorous geo-referencing of roadway data, the process of assembling and using this data for developing reference concepts and the requirement to share the data with pursuit consortia lends itself to the use of a GIS. Increasingly these data are incorporated into a project GIS which would include not only the AICS and digital terrain data, but also the reference concept, borehole logs, underground utilities, as well as any historical roadway performance measurement (Figure 8).

Thoughtful owner agencies also include the historic roadway performance data on the surrogate roads used to develop the PSRs. These data are then shared with the bidding consortia through the use of a web based digital data room made accessible to interested bidders. The data are shared to insure a fair playing field between all pursuit consortia and reducing the risk to all parties.

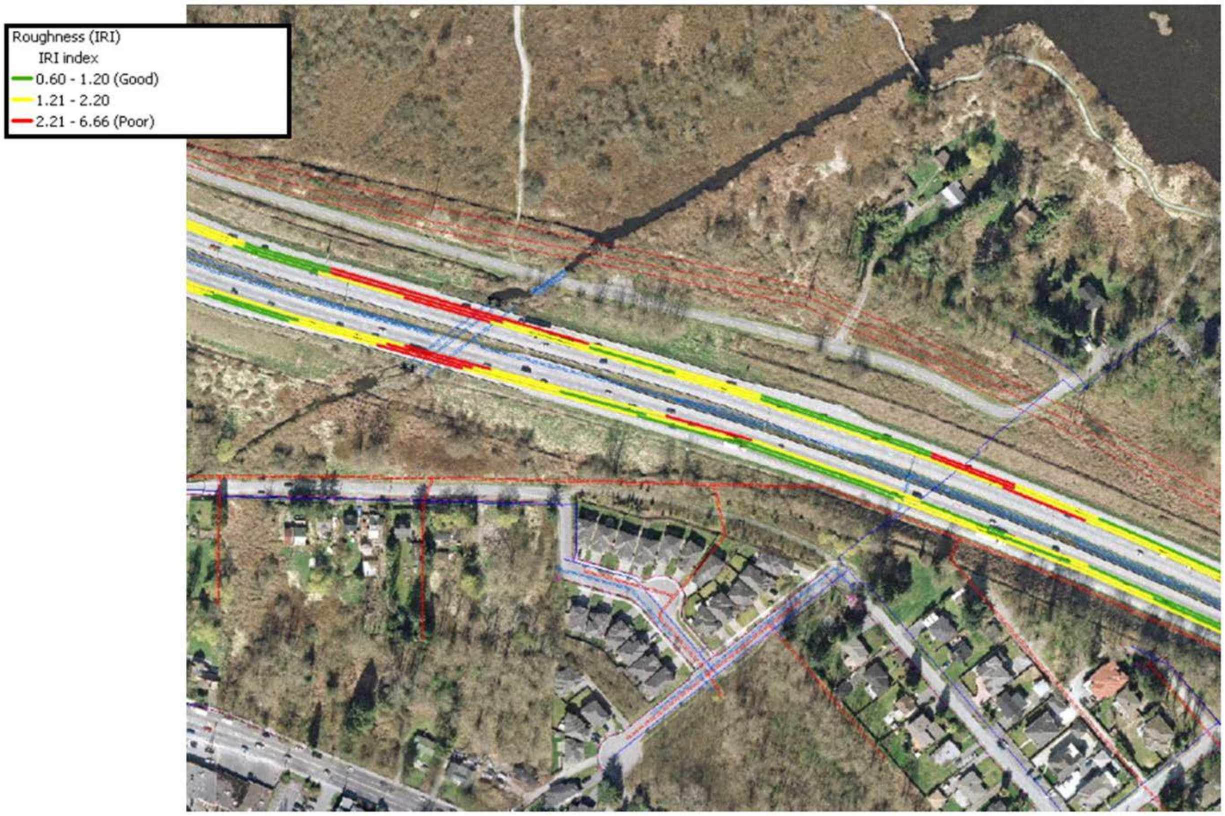

Figure 8: Data Room GIS showing Instances of Anomalous Roughness at Utility and Culvert Crossings

4.2 Pursuit and Detailed Design Applications

The introduction of the P3 model has fundamentally changed the way engineers approach the design of roadway pavement infrastructure. Where the traditional pavement design approach for Design-Bid-Build/Design-Build projects was based on a defined pavement Design Period and Service Life, the P3 philosophy requires consideration of the overall life-cycle of the pavement infrastructure including the initial construction, subsequent OM&R related activities and ultimate handback requirements. As a result, the pavement designer is required to model the future roadway condition in terms of specific and unique pavement distress types, and quantify the contribution each of these distresses has on the condition of the roadway. Through accurate and reliable performance modelling, the designer can forecast a future OM&R program that is compliant with the project performance requirements, and minimizes the total life-cycle costs over the OM&R period.

There are three typical roadway pavement design scenarios that may be encountered during the pursuit and detailed design phase of a P3:

1. Greenfields – typically include the design, construction, and OM&R of new infrastructure elements;
2. Brownfields - typically include the upgrading (including design, construction, and OM&R activities) of existing infrastructure elements; and

3. Brownfields – which can also include the incorporation of existing infrastructure elements in the OM&R phase of the project.

Although each of these three design scenarios can be very different, the objective is the same: Design for performance through the detailed modelling of individual pavement distresses. The general procedure followed in the development of the pavement distress prediction models is as follows:

1. Assemble a detailed database of pavement related information that contribute to overall pavement performance including:
    a. Pavement Structure
    b. Pavement Age
    c. Traffic Loading
    d. Existing and Historical Condition
    e. Local Environmental Conditions
2. Model the future initiation and progression of pavement distress types (flexible pavements for example) including:
    a. Rutting
    b. Fatigue Cracking
    c. Thermal Cracking
    d. Ravelling
3. Combine the predicted distresses in each evaluation year into the relevant performance index (e.g., IRI).
4. Calibrate the distress projection model based on local geographic and environmental conditions.

The collection and reporting of high quality pavement condition data is important in both building the initial pavement condition database, as well as in the calibration of the distress prediction models, both of which are discussed in more detail in the following sections.

Enhanced Data Collection in Pavement Condition Database Development

In both the pursuit and detailed design phases of Greenfield P3s, the majority of the pavement condition database is typically populated based on design. In other words, pavement structure, age and condition are generated as part of the design procedure based on subgrade support condition, traffic loading conditions, and environmental considerations.

Subgrade support characterization was traditionally completed through geotechnical investigations (drilling or test pitting) of the anticipated subgrade soil sources. Subgrade characterization can also be completed through the testing of surrogate roadways. Candidate surrogate roadways typically comprise of existing pavements in service, with anticipated similar subgrade support conditions in similar cross section and drainage conditions. Surrogate roadways are typically located near or within the proposed roadway right-of-way, and are ultimately used as prototype roadways providing general indication of long term subgrade strength and performance. Typically surface based deflection testing by Falling Weight Deflectometer (FWD), is the preferred method for characterization of surrogate subgrade strength.

Brownfield P3s require a much more in depth data collection program to assist in the population of the pavement condition database. The collection of existing roadway infrastructure condition data is paramount to developing a bid and design that will ultimately comply with the project construction and performance requirements. By analyzing and assessing the roadway elements existing age and condition provides insight to how the roadway will continue to perform in the future. This allows the designer to provide suitable options for rehabilitation or reconstruction to limit the risk of performance non-compliance. A typical roadway condition data collection program could include the following:

1. Establishing in-place pavement structure information (layer and thickness) through non-destructive methods such as ground penetrating radar or Road Radar;
2. Establishing in-place subgrade and pavement strength information through non-destructive deflection testing such as FWD;
3. Measuring existing pavement condition, including profile and roughness (IRI) and wheel path rut depths with a mobile integrated data collection platform;
4. Measuring existing pavements distress condition with a mobile laser crack mapping system (LCMS);
5. Survey existing roadway geometrics including cross-slope, super-elevation, and pavement widths with high resolution 360° transportation corridor LiDAR data; and
6. Summarizing and housing all the data elements described above in a GIS type interface.

All of these roadway condition data elements together provide the Designer the necessary information and tools to make the most appropriate pavement design choices that appropriately identify and quantify potential performance risks while minimizing the overall life-cycle costs.

Enhanced Data Collection in Model Calibration

One of the most important performance-based design elements is the calibration of the pavement distress prediction models. The reliable and accurate prediction of pavement distress type and severity is paramount when developing a suitable OM&R strategy for each roadway element. There are a number of industry accepted “off the shelf” pavement distress prediction models available to the pavement designer. However, these distress prediction models require calibration for local geographic and environmental conditions.

Model calibration is best completed through the review of existing multi-year roadway condition data of surrogate roadways. It can therefore be expected that the reliability of the calibrated model is therefore largely influenced by the quality of the condition data. This stresses the importance of having a well-defined roadway network condition database that was established though high quality data collection and location referencing.

Enhanced Data Collection During Construction

There are a number of potential uses for enhanced data collection during construction. One of the most common uses is through the completion of mid-construction assessments. Often the Constructor will complete Ground Penetrating Radar (GPR) or FWD data collection for validating that construction practices have achieved the required pavement layer thickness or subgrade strength. Conversely, the Concessionaire or Operator will complete pavement strength and IRI survey to validate the constructed works as well as provide a roadway condition base-line for the planning of future OM&R activities.

There are instances, particularly in the construction phase of brownfield projects, where the Constructor will propose the incorporation of existing roadway infrastructure into the final roadway that was not included during detailed design. A common example of this is the incorporation of existing roadway shoulders into new driving lane pavements. Through a pavement condition assessment including GPR and FWD data collection of the existing roadway shoulders, the designer can assess the suitability of the contractors proposed design change.

There are also instances where GPR data have been used by the Constructor to validate and confirm quality assurance records in the generation of as-built and project record drawings.

4.3 Operations Applications

It is common in the P3 model for the Owner to specify asset preservation and performance requirements throughout the length of the OM&R term. It is the intent of these requirements to ensure the roadway maintains a minimum level of service while limiting asset consumption prior to handback. It is therefore the objective of the Concessionaire to develop a pavement management strategy that meets or exceeds the minimum required annual performance measures.

For most P3 projects, the completed roadway infrastructure handed over by the Constructor to the Concessionaire is comprised of a network of paved travel lanes, shoulders, ramps, cross roads, side roads, etc. Most of these pavement elements have specified performance criteria, whether it be ride quality (IRI), rut depth, surface distress, cross-slope, or skid resistance. In addition, the performance of each roadway element we be a function of the constructed condition and future traffic loading. There is therefore incentive on behalf of the Concessionaire to collect ongoing pavement condition data for a number of reasons including:

- Demonstrating compliance of the various pavement element performance requirements to the Owner;
- Data can be used to further calibrate distress prediction models based on actual as-constructed conditions; and
- Data can be used to support the development of a network Pavement Management System.

Ultimately, it is the objective of the Concessionaire to manage the OM&R of the roadway network at the lowest cost while maintaining compliance with the project performance requirements, as well as any handback or remaining service life requirements. The ongoing collection of high quality pavement condition data enables the Concessionaire to optimize pavement management activities while limiting and managing non-compliance risks.

5.0 OBSERVATIONS

There is a web of inter-relationships within the DBFO entities as stewardship of the asset being created passes between parties to the agreement. Roadway assessment data facilitates these relationships and this transfer of stewardship. Increasingly enhanced and more detailed data passes from the Owner to Owner's Engineer to the Pursuit Consortium to the Designer, then Constructor to the Operator and ultimately back to the Owner. The higher the quality of these data, the more quantifiable are the risks associated with the asset at each transfer of stewardship. The better the quality of data and the more thorough the analysis of these data, the less the risk that is transferred between parties. This reduced risk is ultimately passed on as project cost savings to the Owner and hence to the public.

Owner / Owners Engineer

The Owner provides better quality data to the Owner's Engineer. The Owner's Engineer can use these quality data to develop reasonable and achievable PSRs as well as to populate the data room.

Owner Engineer / DBFO Pursuit Team

The data room of high quality data defines the risk of not meeting the PSRs to all pursuit teams.

Pursuit Team / Pavement Design Engineer

The pursuit teams augment the data room data with sufficient additional data to enable the pavement design engineer to accurately model the predicted performance and present value (PV) costs of a number of pavement life-cycle strategy alternatives. This enables the identification of the lowest PV cost alternative to meet the PSRs through the term of the concession as well as quantifying the risk of not meeting the PSR in any given year of the concession. The pursuit team then agrees on a bid price. The pursuit team that has the lowest PV cost strategy with the most quantified risk, would typically have the winning proposal on the pavement component of the fixed cost DBFO contract. Although this is the Owner's only opportunity for savings, it is a win/win relationship. The enhanced data and data analysis provided both by the Owner's Engineer and that augmented by the pursuit team enables the DBFO team to secure a profitable project while the Owner gets a lower price than would otherwise be the case, due to the high quality data provided to all teams.

Pavement Design Engineer / Constructor

The pavement design engineer sets achievable PRSs to facilitate the construction and QC/QA that will ultimately ensure all parties that the pavement is constructed so as to enable the predicted performance. The PRSs are monitored and recorded during construction and can be readily transferred to the Operator. Additional PRS testing is conducted prior to the hand over between Constructor and Operator to accurately identify the risks to meeting the PRSs.

Constructor / Operator

The data provided by the Constructor to the Operator may or may not result in a monetary transfer of risk between the parties but does facilitate an orderly transfer of stewardship of the asset.

Operator / Pavement Asset Management

While the pavement strategy developed as part of the bid in itself reduced risk and reduced costs to the Owner, there is further opportunity to save the Operator costs by refining the risk even further. Because the pavement's performance is monitored for compliance throughout the concession period, the Operator typically has access to a new set of road assessment data each year. Strategic Operators use these data to refine the performance prediction models and sub-divide the asset into increasingly smaller rehabilitation segments. In this way only sufficient pavement preservation treatments as required to minimally meet the PSRs are implemented. This exercise can potentially provide the Operator with substantial savings.

Operator / Owner

At handback, the Owner would have impeccable records of the assets past performance as well as a great degree of certainty with respect to the asset's future performance. A wise Owner would continue the process developed by the Operator and enable the optimal future preservation of the asset.

6.0 CLOSURE

For pavement engineers, DBFO P3 project delivery has "changed the game" in terms of designing for performance and weighing the competing aspects of cost effective "winning" solutions and mitigating the potential for unsatisfactory performance, including the financial consequences of non-compliance. This demands that consultants bring their "A Game and their A Team" to the front with the potential of possible financial loss, or significant financial gain. It appears that DBFO P3s are here to stay and as such the consulting industry will be tasked with continually meeting that challenge.

7.0 REFERENCES

Federal Highway Administration (FHWA) Office of Innovative Program Delivery" Public Private Partnerships http://www.fhwa.dot.gov/idd/p3/defined_design _bulid_finance_operate.aspx

PPP Canada. http://www.p3canada.ca/en/

King, L.W., 2005. "*The Code of Hammurabi: Translated by L.W.King."* Yale University.

Palsat, D., McMillan, C., Fuchs, C., Juhasz, M., and Mesher, D. 2014. "*Rehabilitation Design Using Laser and Lidar Technologies."* In 2014 Proceedings of the Canadian Technical Asphalt Association. Winnipeg, MB: Canadian Technical Asphalt Association.

Transportation Association of Canada (TAC). 2001 "*Standardization of IRI Data Collection and Reporting in Canada."* Ottawa, ON: Transportation Association of Canada

American Association of State Highway and Transportation Officials (AASHTO). 2013. *PP 67-10. "Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Images Utilizing Automated Methods*", AASHTO Provisional Standards, 2013 Edition, Washington, D.C.

Association of American State Highway and Transportation Officials (AASHTO). 2013. *PP 68-10. "Standard Practice for Collecting Images of Pavement Surfaces for Distress Detection*", AASHTO Provisional Standards, 2013 Edition, Washington, D.C.

Alberta Transportation. 2012. *"Terms of Reference: Integrated Data Collection Project".* Edmonton, AB.

St Michel, G., Palsat, D., and Dawley, C. 1998. "*Issues Relating to Performance Specifications for Roadways."* In 1998 Annual Conference and Exhibition of the Transportation Association of Canada: Financing Tomorrow's Transportation Systems. Ottawa, ON: Transportation Association of Canada.

Hall Jr., J.W., Smith, K.L., Titus-Glover, L., Wambold, J.C., Yager, T.J. and Rado, Z. 2009. "*National Cooperative Highway Research Program Web Only Document 108 – Guide for Pavement Friction*." Washington, DC: Transportation Research Board.

Reggin, A., Shalaby, A., Emanuels, R., and St Michel, G. 2008. "*Urban Considerations for Using Road Roughness to Manage Road Networks."* In 2018 Proceedings of the 7th International Conference on Managing Pavement Assets.