Performance requirements in design-build contracts

Development of a risk assessment model

Iman Mirzadeh
Olle Eriksson
Robert Lundström

VTI rapport 1046A
Published 2020
vti.se/publications

Foto: Fotograf Satu AB, VTI

VTI rapport 1046A

Performance requirements in design-build contracts

Development of a risk assessment model

Iman Mirzadeh, VTI

Olle Eriksson, VTI

Robert Lundström, NCC

Authors: Iman Mirzadeh, VTI
Olle Eriksson, VTI, http://orcid.org/0000-0002-5306-2753
Robert Lundström, NCC
Reg.No., VTI: 2017/0392-9.1
Publication: VTI rapport 1046
Published by VTI, 2020

Abstract

The gradual shift in procurement of road infrastructures from traditional design-bid-build (DBB) to design-build (DB) contracts, have resulted in an ever-increasing need for contractors and consultants to assess and predict the technical performance of selected designs and corresponding risks. Moreover, there is a great interest for the road administration to better motivate the type of contract and the procurement strategy based on risks and outcomes in road projects. This report has focused on developing a model for evaluation of the impact of performance requirements in DB and design-bid-maintain (DBM) projects. The model can analyse the risk of exceeding the maximum requirements during the warranty period. Therefore, it can be applied by contractors for evaluation of the technical risk not only at the bidding stage but also during the warranty period. It can also be used by the road administration as a decision support tool for setting performance requirements at the project level.

Title:	Performance requirements in design-build contracts: development of a risk assessment model
Author:	Iman Mirzadeh (VTI) Olle Eriksson (VTI, http://orcid.org/0000-0002-5306-2753) Robert Lundström (NCC)
Publisher:	Swedish National Road and Transport Research Institute (VTI) www.vti.se
Publication No.:	VTI rapport 1046A
Published:	2020
Reg. No., VTI:	2017/0392-9.1
ISSN:	0347–6030
Project:	Assessment of technical risks in design-build projects
Commissioned by:	Trafikverket
Keywords:	Design-Build projects, functional requirements, Risks
Language:	English
No. of pages:	39

Referat

Gradvis utveckling eller förändringar inom upphandlingspraxis, exempelvis från traditionella utförandeentreprenader till totalentreprenader, har resulterat i ständigt större behov för entreprenörer och konsulter att kunna bedöma och prediktera teknisk prestanda hos valda konstruktioner, material och utförandemetoder. På ett motsvarande sätt finns det ett stort intresse hos beställare av infrastrukturprojekt att kunna bättre motivera val av entreprenadform och upphandlingsstrategi baserat på risker och tidigare utfall i entreprenadprojekt. Denna rapport har fokuserat på utveckling av en modell för analys av funktionskravens påverkan i totalentreprenader från Trafikverket och entreprenörernas perspektiv. Modellen kan analysera risken för att funktionskraven ska överskridas under garantitiden. Den kan därför användas av entreprenörer för utvärdering av den tekniska risken vid anbudsskedet och även under garantitiden. Modellen kan även användas av Trafikverket som ett beslutsstödsverktyg vid kravställning.

Titel:	Funktionella krav i totalentreprenader: utveckling av en modell för riskbedömning
Författare:	Iman Mirzadeh (VTI) Olle Eriksson (VTI, http://orcid.org/0000-0002-5306-2753) Robert Lundström (NCC)
Utgivare:	VTI, Statens väg- och transportforskningsinstitut www.vti.se
Serie och nr:	VTI rapport 1046A
Utgivningsår:	2020
VTI:s diarienr:	2017/0392-9.1
ISSN:	0347–6030
Projektnamn:	Utvärdering av risker i totalentreprenader
Uppdragsgivare:	Trafikverket
Nyckelord:	Kravställning, Totalentreprenader, Risk, Vägar
Språk:	Engelska
Antal sidor:	39

Preface

The project has been financed by the Swedish Transport Administration and their research program BVFF. Robert Karlsson has been the contact person. The results from this project have been presented at the national conference Transportforum in Linköping in January 2019. This documentation is the final report of the project "*Assessment of technical risks in design-build projects*".

Stockholm, October 2019

Iman Mirzadeh
Project manager

Quality review

Internal peer review was performed on 6 November 2019 by Jan-Erik Swärdh. Iman Mirzadeh has made alterations to the final manuscript of the report. The research director Leif Sjögren examined and approved the report for publication on 15 May 2020. The conclusions and recommendations expressed are the authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Intern peer review har genomförts 6 november 2019 av Jan-Erik Swärdh. Iman Mirzadeh har genomfört justeringar av slutligt rapportmanus. Forskningschef Leif Sjögren har därefter granskat och godkänt publikationen för publicering 25 maj 2020. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

Table of contents

Summary

Performance requirements in design-build contracts: development of a risk assessment model

by Iman Mirzadeh (VTI), Olle Ericsson (VTI) och Robert Lundström (NCC)

This report has focused on developing a model for evaluation of the impact of performance requirements in Design Build (DB) and Design-Build-Maintain (DBM) projects. The suggested model is based on a statistical analysis of several Swedish road sections extracted from Long-Term Pavement Performance (LTPP) and Pavement Management System (PMSv3) databases. The model can analyse the risk of exceeding the maximum requirements during the warranty period. Therefore, it can be applied by contractors for evaluation of the technical risk not only at the bidding stage but also during the warranty period. It can also be used by the road administration as a decision support tool for setting performance requirements at the project level. The suggested model has been validated using road surface data regarding several long-term warranty projects monitored by the Swedish construction company NCC. The application of the suggested model from the transport administration and the contractor's perspectives has been demonstrated in a case-study.

It was observed that the level of performance requirements regarding IRI and rutting as well as the length of the warranty period had a significant impact on the technical risk for the contractor. Moreover, the absence of the price adjustment clause for bitumen in DB contracts can increase the technical risk for the contractor.

Sammanfattning

Funktionella krav i totalentreprenader: utveckling av en modell för riskbedömning

av Iman Mirzadeh (VTI), Olle Ericsson (VTI) och Robert Lundström (NCC)

Denna rapport har fokuserat på utveckling av en modell för analys av funktionskravens påverkan i totalentreprenader från Trafikverket och på entreprenörernas perspektiv. Den föreslagna modellen är baserad på statistisk analys av vägytedata från databaserna LTPP och PMSv3. Modellen kan prediktera risken för att funktionskraven ska överskridas under garantitiden. Den kan därför användas av entreprenörer för utvärdering av den tekniska risken vid budgivningsskedet och även under garantitiden. Modellen kan även användas av Trafikverket som ett beslutsstödsverktyg vid kravställning. Den presenterade modellen har validerats baserat på vägytedata från ett flertal totalentreprenadprojekt som NCC har följt upp regelbundet under flera år. Tillämpningen av modellen från Trafikverket och entreprenörernas perspektiv har demonstrerats i en fallstudie.

Det observerades att kravnivåer rörande IRI och spårdjup såväl som längden av garantitiden hade en stor påverkan på den tekniska risken för entreprenören. Dessutom kan den tekniska risken i totalentreprenader öka där indexering av bitumenpriset inte existerar.

1. Aim

This report aims at developing a method for assessment of the impact of performance requirements and the associated technical risks in design-build (DB) and design-build-maintain (DBM) projects. In this case, the term *technical* implies any potential costs resulting from not meeting technical requirements (e.g. surface evenness measured by rutting and IRI) stated in contracts, while *risk* denotes the potential financial consequences.

2. The Swedish infrastructure project procurement context

In this section, some important aspects related to project-delivery and contracting methods are given in order to illustrate needs of adequately predicting technical performance of road infrastructure projects. Among the most important aspects of project contracting are (1) scope of contracted activities and (2) the definition of technical quality in terms of specifications expressed in construction contracts (Moynihan et al, 2009; Lundström 2013). Although other aspects, such as financing scheme, may be important for the overall result, for the sake of simplicity, a distinction is solely made between traditional and unconventional approaches to illustrate important differences and their impacts on the technical risk.

2.1. The traditional DBB approach

Historically, national road authorities, such as the Swedish Transport Administration (STA), have procured investment and maintenance works using the traditional so-called design-bid-build (DBB) approach. In this project delivery method, the client, often by the aid of external consultants, provides detailed drawings and so-called *procedural* specifications. After the project delivery, the contractor usually possesses a relatively short warranty period.

In DBB asphalt pavement projects, the structural design is typically based on a number of well-known material properties (moduli, fatigue resistance), traffic conditions (e.g. average annual daily traffic, vehicle weights), the road type (e.g. 2, 3 or 4 lanes), geological and climate conditions (e.g. frost heave, temperatures) which are all standardized in national design guides. The quality is measured by conformity between information in the national design guide and the road condition verified by laboratory and field test results. DBB projects generally have a 5 years long warranty period after the final inspection. Any deviations are handled during this inspection, usually with fee reductions, and only essential deviations require rework.

2.2. Unconventional procurement methods

The traditional DBB approach briefly indicated above can be compared with the so-called design-build (DB) approach. In DBs the contractor is responsible for design and construction of the project, whereas DBMs also include maintenance. Since 2008, STA has continuously increased the number of infrastructure projects based on DB delivery systems. The warranty periods have usually been around 10 years during which the contractor is responsible for the pavement design and its performance. During this time, the warranty implies an absolute liability to uphold the performance requirements and any needed maintenance.

In contrast to procedural specifications associated with the traditional approach, unconventional approaches are often based on performance specifications, where the technical quality of a given project is intended to be judged on measurable requirements. In the case of road infrastructures, the requirements are typically specified in terms of road surface indicators over the entire contract time. For example, instead of prescribing type and amount of materials to be used based on standards, the technical quality of a pavement structure may be characterized by physical variables, such as rut depth (RUT) and longitudinal evenness often expressed in terms of International roughness index (IRI).

The contractual obligations are controlled by periodic inspections, normally every second to third year, until the final warranty inspection. Significant deviations from the technical requirements during the contract period makes the contractor liable for correctional works. Consequently, road parts not fulfilling the requirements should be milled and replaced with new asphalt pavements.

Many of the studies devoted to DB and DBM contracts, are dedicated to comparing traditional project goals in terms of cost, time and quality (e.g. Shrestha et al, 2011). Often, emphasis has been limited to the construction phase and maintenance occurring during the remaining contract period have mostly been ignored. Consequently, in many cases such characteristics have been secondary to the initial construction cost and schedule (Warne, 2005; Shuler et al, 2007; Shrestha et al, 2011). In recent studies evaluating warranty and performance-based contracts (e.g. Singh et al, 2007; Bardaka et al, 2016; Sadeghi et al, 2016), different results have been reported regarding both technical quality and economic efficiency. Sadeghi et al, (2016) indicated that warranty contracts were more cost-effective irrespective of time frame compared to traditional contracts. Singh et al, (2007) reported that warranty contracts were approximately 30% more cost-efficient for warranty periods up to 5 years. However, their economic efficiency, compared to traditional contracts, increases to 70 percent for longer warranty times (Sing et al, 2007). Consequently, the time frame during which a project, contract type or delivery method is evaluated largely affects the results. This is largely due to asymmetries between actors' responsibilities and perception of the time value of money.

Performance specifications combined with extended warranty responsibility provided by DB or DBM arrangements are intended to increase productivity. A flexibility regarding the design is given to the contractors to employ any technology found suitable, while making them responsible for any maintenance costs during the comparatively long contract period. The anticipated advantages are often assumed to outmatch any perceived disadvantages including market failures related to the number of bidders, bid prices and ex post opportunistic behaviour.

In addition to clauses related to technical quality and correctional actions, contracts often involve price adjustment clauses (PACs) regarding costs of volatile resources such as fuels and bitumen. When applied, PACs may significantly decrease the risk profile regarding construction and maintenance costs for the contractors. It should be noted that corrective actions in DB contracts are not usually covered by such clauses.

3. Approaches to assess project performance, costs and technical risks

Risk is usually estimated as a function of probability and severity on negative consequences. In this study, an important risk category is the potential costs resulting from not meeting technical requirements stated in contracts. Such technical risks result in costs from corrective maintenance work not perceived during tendering.

3.1. Technical models

A common way of assessing pavement performance is using mechanistic-empirical design models in which the impact of traffic and environmental loading for a given pavement structure is analysed during a defined design life. However, design models such as the Swedish approach PMS Object, are somehow incapable of predicting pavement performance in terms of deterioration, e.g. rutting, or analysing the performance in term of contract conditions. The impact of longer warranty periods in decision-making for infrastructure projects is more significant when new materials, production or contract conditions are applied (Lundström & Johanson, 2015). While such traditional design models fit the traditional delivery context and client perspective, they appear to have lost their relevance in a context where project performance is important to predict the technical risk for contractors (Lundström et al, 2009; Ekblad and Lundström, 2018).

There are other methods for assessing pavement performance such as the probabilistic approach provided by state-based Markov chain models (e.g. Kobayashi et al, 2010; Thomas & Sobanjo, 2012) or time-based reliability models (Haas et al, 1994; Shahin, 1994; Butt et al, 1987; Cook and Lytton, 1987; Moynihan et al, 2009). While the former category implies analysis of continuous functions or survival analysis, the latter category typically segments infrastructure into groups of homogenous explanatory variables (e.g. traffic, climate, maintenance) and associate them with deterioration and state conditions (e.g. quality indicators 0-9). Probabilistic models can take a variety of different variables into account. However, it is problematic to explicitly utilize design-related parameters such as pavement structures and materials in these models (Madanat et al, 1995; Moynihan et al, 2009).

According to Cui et al, (2010), there is a great need within the construction industry for a methodology for assessing risks associated with performance requirements and lengths of warranties. The impact of such a risk is significant with warranties longer than five years in which considerable inflated bid prices has been observed (Bayraktar et al, 2004).

In order to take financial aspects into technical analyses, a number of statistical models are available. For example, Zhang and Damnjanovic (2006) developed a probabilistic method to model deterioration using AASHTO´s deterministic approach based on serviceability level to analyse technical risks for different contract lengths (up to 13 years). Gharaibeh & Shirazi (2009) evaluated the risk associated with warranties based on a survival analysis. Bardaka et al, (2016) used a statistical approach to evaluate the cost effectiveness for maintenance activities in traditional and warranty contracts. Gharaibeh & Miron (2008) evaluated deterioration and costs regarding maintenance activities based on a probabilistic model while Moynihan et al, (2009) modelled costs of successive deteriorations using a stochastic approach.

3.2. Models used in finance

Although life-cycle cost-benefit analysis (LCCA) is the common approach used by national road administrations in assessing infrastructure projects, the financial viability of a construction project from a contractor perspective is often perceived by the net present value (NPV) of accumulated discounted cash flows. If a given project is perceived to be subjected to risks, the discount rate can, as in the well-known model CAPM, be adjusted to reflect the increased risk (Berk and DiMarzo, 2014). Although the NPV and CAPM techniques are widely accepted to analyse financial risks, several challenges persist for broader applications, e.g. in infrastructure contexts where reliable CAPM data seldom are accessible. In addition, DB and DBM projects show significant risks on a relatively detailed level as costs are related to the actual technical performance during a warranty period as well as the associated contractual clauses. Moreover, certain features of infrastructure projects such as warranties and price adjustment clauses (PAC) result in asymmetric payoffs which cannot be assessed with traditional risk models such as CAPM (Huang & Pi 2013; Ho & Liu 2002; Mirzadeh & Birgisson 2015).

The term derivative is sometimes used in finance to address instruments such as options with asymmetric payoffs that give their holders the right to buy (call option), or sell (put option), a traded asset, such as a stock, at a given strike price at (European option) or up to (American option) a given time. In the case of a simple call option, the price at maturity, i.e. when the options expires, is equal to max $[0, S_T-X]$, where S_T is the price of the underlying asset at the maturity date and X is the strike price (Ho & Liu 2002). As long as the value of the asset is lower than the strike price, the value of the option is equal to zero. Once the price of the underlying asset exceeds the strike price, the option value increases linearly (Cui et al, 2008). A realistic model should, in addition to influence of underlying value and its changes, also be able to take the influence of time into account as the time left to expiry is the second parameter of interest for the value of options: the longer the time left to expiry, the higher the value.

A so-called *real option* is a right to make a business decision that typically is not traded in a competitive market such as investments in non-financial assets that provide managerial flexibility. Similar to their financial counterpart, they can be priced based on binomial pricing formulas or the so-called Black-Scholes model. Real options theory plays an important role in capital budgeting, especially in situations where more information successively becomes available. The actual value of a real option can be calculated as the difference between potential outcomes allowed by the flexibility provided by the option. Real options theory may provide advantages compared to other statistical models by explicitly taking aspects such as design, time and contractual issues into account.

Real options methodology has also been applied for assessing different aspect of infrastructure projects such as government revenue guarantees (Chiara, Garvin & Vecer, 2007; Cheah & Liu, 2006; Galera & Solino, 2010), risk allocations (Quiggin, 2005; Nombela & Rus, 2004) and price adjustment clauses (Mirzadeh & Birgisson 2015).Similar to a European call option, a warranty clause in DB contracts has an asymmetric payoff and can be exercised at a specific time (e.g. the end of the warranty period). The value of a given warranty arrangement, which also represents the technical risk for the contractor, is analogous to the value of a European call option at maturity date. For example, as long as the performance indicator (e.g. maximum allowed RUT) at the end of a warranty period is lower than the requirement, the value of the warranty option is zero. However, if the RUT exceeds the rutting requirement the warranty option will have a positive value. The value of the warranty option (i.e. potential costs to the contractor) depends on the penalty clauses and reconstruction costs embedded in the contract.

4. Model for analysis of the technical risk

In this section a model is suggested for the analysis of the risk due to non-conformity of road surface properties (e.g. IRI & rutting) to technical requirements. The scope of the suggested model is illustrated in Figure 1. The model can be used by the transport administration for setting performance requirements and bonus-malus systems. It can also be applied by contractors for analysing the technical risk in DB and DB(M) contracts during bidding, construction as well as Maintenance and Rehabilitations (M&R).

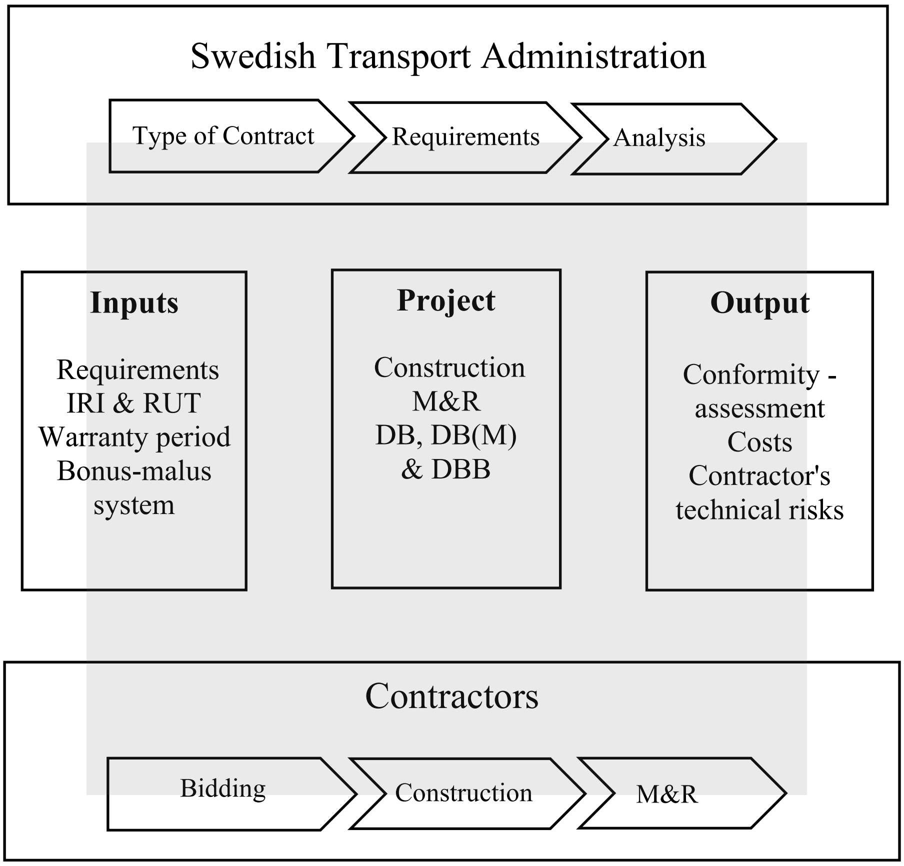


Figure 1. Scope of the suggested model.

4.1. Simulation of road surface properties

Performance indicators such as IRI and rutting are continuously measured over the road surface at certain intervals (often annually or biannually) and presented as 20 or 400 meter values in accordance with STA requirements. Given that the average value of these parameters increase from one year to the next, the monetary value of a given warranty clause (TR) is not deterministic but instead depends on the amount of individual 20 or 400 meter values exceeding the stated requirement. Consequently, the resulting cost for corrective maintenance depends on the distribution of parameters around its average value.

Predicting IRI and RUT values at a specific time during a warranty period (e.g. the end of the warranty period) can be based on parameters/variables such as mean values, standard deviations, the correlation between IRI and RUT and their autocorrelation. When investigating individual pavement sections Al-Omari & Darter (1994) reported no significant correlation between IRI and rutting values when individual pavement sections were studied. However, when the data were grouped and averaged for ranges of IRI and RUT a strong correlation between mean values regarding IRI and rutting was found

(Von Quintus et al 2001). Based on the measurements from the Swedish long-term pavement performance (LTPP) database, linear relations between the average IRI and RUT as well as RUT standard deviation are suggested in Figure 2. The studied Swedish LTPP road sections are listed in Table 1. The studied 10 LTPP sections is a sample of the complete LTPP database (66 sections), based on the traffic flow distribution, climate zones and amount of heavy traffic. The IRI and rutting measurements for different sections are grouped and averaged based on the corresponding pavement age (i.e. number of years after construction).

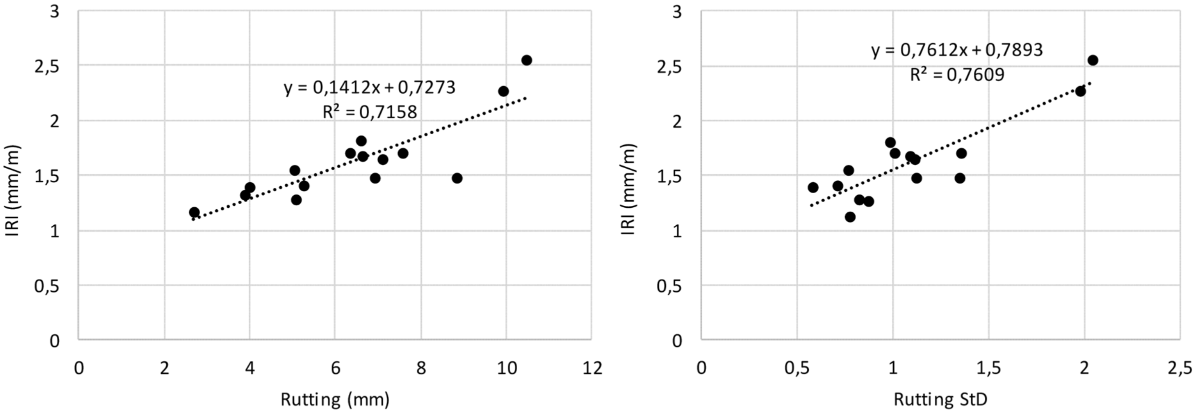


Figure 2. Relationships between mean IRI & rutting/rutting StD values for the studied Swedish LTPP sections.

Consequently, IRI can be estimated, based on a regression analysis, as a function of rutting by [1]. It should be noted that Equation 1 is based on the studied LTPP sections, which represent low to medium traffic roads.

$$IRI = 0.1412 \times RUT + 0.7273 \qquad [1]$$

An assumption for this analysis is that all random variations are in the IRI-dimension only, which is of course an approximation.

Adjacent measurements of IRI and rutting are correlated where there usually is a positive first-order autocorrelation of varying magnitude (Thomas, 2004). Based on the analysed data from the Swedish pavement management system version 3 (PMSv3), autocorrelation coefficients ranged from 0.2 to 0.7 for IRI and from 0.6 to 0.9 for RUT measurements (for 100 meters). It should be noted that more extreme values are possible.

Moreover, by analysing LTPP sections strong correlations was observed between average IRI and IRI standard deviation (StD) (Figure 3). For RUT, the corresponding correlation was only slightly lower Figure 3.

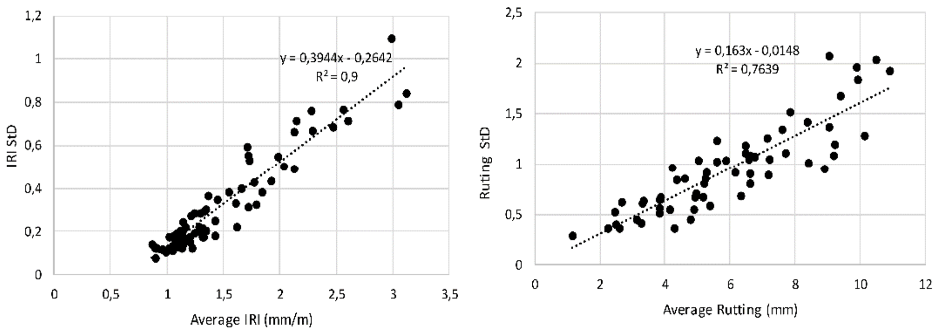


Figure 3 Relationship between average and standard deviation for IRI and rutting in Swedish LTTP sections.

Consequently, RUT and IRI standard deviations can be estimated based on Equations (2-3):

$$StD_{RUT} = 0.163 \cdot RUT - 0.0148 \qquad [2]$$

$$StD_{IRI} = 0.3944 \cdot IRI - 0.2642 \qquad [3]$$

Similar to the relation between IRI and RUT (Equation 1), in the regression analysis regarding Equations (2-3), it is assumed that all random variations are in the StD-dimension.

A certain level of expected StD causes a variation in the sample standard StD. The observed means and StDs in the LTPP-data are gathered closer than expected around the line in Figure 3, especially for IRI with $R^2 = 0.9$. It is accepted through the rest of this text that the means and StDs are distributed very homogenous around the line in the LTPP-data, but further research should be done to find an explanation. It should be noted that neither the traffic level nor the climate conditions had significant impacts on the relationships presented in Equations (1-3).

Table 1 The studied LTPP sections

LTPP Section	AADT	Climate zone	Number of 100 m sections
M-RV17-1	4000	1	10
U-508-1	400	2	8
C-292-1	839	2	9
T-205-1	1487	2	10
F-E4-2	6280	2	8
T-205-2	942	3	10
Y-RV90-1	1748	3	8
X-RV-68	2180	3	8
Z-E45-4	1243	4	8
Z-E45-3	2552	4	8

Here, we are not aiming for exact prediction of RUT and IRI. If that was within reach, there would be no uncertainty and no need for calculating risks. Instead we look at future RUT and IRI as random variables. Our aim here is to investigate the technical risk by generating a set of random RUT and IRI data that represents all subsections within an object with properties similar to those observed in the studied data (i.e. LTPP and PMS v3). Those properties include the relation between RUT and IRI, the relation between StD and mean for RUT & IRI, the correlation between StD and mean for RUT & IRI, the autocorrelation in RUT and in IRI and the correlation between RUT and IRI. It should be noted that the sample StD and autocorrelation in short segments of a long series are expected to be smaller than those in the long series they were sampled from.

By performing an iteration, one can approximate the distribution of RUT and IRI simultaneously. Subsequently, the technical risk for each section and for the whole length of a road project can be calculated by Equations (1-2).

To perform a Monte-Carlo simulation concerning a specific object, the first step is to evaluate RUT at the end of the warranty period. RUT can be evaluated based on different available methods such as mechanistic-empirical (ME) pavement design approaches. For example, AASHTO model which is included in the ME Design Guide (MEPDG), can be applied for predicting permanent deformation in different layers of asphalt pavements (ARA, 2004). Subsequently, IRI can be estimated based on the expressed relationship between IRI and average RUT in Equation 3. Both StD and mean values are random variables, therefore, a generated data averaged over one object should not necessarily match their expectations, but have a variation similar to what is seen in Figure 2. Compared to **Fel! Hittar inte referenskälla.**, they should rather be of the same size as variation in mean for a given StD and variation in StD for a given mean. This describes the size of the variation but not the structure. Data is never supposed to have variation in one variable while the other is fixed. If one bullet deviates from the line in Figure 3, one cannot generally state if it deviates in mean direction, in STD direction or both.

For an expected RUT one can use Equation (2) to find StD for RUT and Equation (3) to find StD for IRI. These StDs represent the variation between 100 meter sections within one object. Consequently, for an expected RUT and an expected IRI, a distribution of the mean for RUT & IRI and a distribution of the StD for RUT & IRI can be obtained.

The sample standard deviation underestimates the true standard deviation slightly, but that is not a serious problem in the procedure suggested in this report. However, the standard deviation must be adjusted for autocorrelation. Here, we only discuss positive autocorrelation. Positive autocorrelation means that there is a tendency that one observed value will be followed by a similar value. In a long autocorrelated series, there is a high probability that one will have data of representative density from the entire distribution. In a short series, it may happen that data does not span the entire distribution. Therefore, to generate a short autocorrelated series with a certain standard deviation, one should not generate a long series with that StD and cut a short series from it. When generating longer series, the standard deviation should be corrected to a higher value than that obtained by Equations (2-3), because these equations are based on data of LTPP-length. The correction depends on the autocorrelation and the length. LTPP objects typically consist of 10 sections with a length of 100 meters. Therefore, for analysing an object, the road section should be divided into several 100 meter sections.

If there is an autocorrelation in a longer series, the autocorrelation in shorter subseries tends to be smaller. Therefore, it is preferred that autocorrelation is estimated on objects longer than the LTPP length. The autocorrelations for several road sections (longer than 3 km) from the PMSV3 database were investigated. Both RUT and IRI were found to be autocorrelated on those longer objects. The autocorrelation ranged from 0.6 to 0.9 for RUT and from 0.2 to 0.7 for IRI. It should be noted that the StDs found by Equations (2-3) are only valid for sections of LTPP length (i.e. 100 meter sections). For longer sections, a correction factor, D, in Table 1 must be used. By generating long series with autocorrelations described above and investigating the StD of sections longer than LTPP, adjustment factor D has been simulated for different section lengths (Table 1). The adjustment factor has been set to 1 for objects of size 10 (i.e. ten 100 meter sections). The value N in the table refers to the number of 100 meter sections in an object.

There is a relation between variations in StD and the variation in the corresponding mean value, and we will call that relation A. By using the same simulation described for the correction factor D above, one can generate a long series of autocorrelated data and divide it into several short subseries. By looking at mean and StD for each subseries, the variation in StD can be compared against variation in the mean value. We found that this relation is a function of autocorrelation and length. Based on a simulation analysis, coefficient A was found for typical autocorrelations and different lengths, *Table 2*.

The regression line in Figure 3 shows how StD on average varies with the mean while the scatter shows how the variation in StD varies with the level of StD. With higher mean values, the StD is higher on average and the variation in StD becomes higher. The variation of StD generally grows with higher expected StD in theory which can also be observed in the data presented in Figure 3. Therefore, there is no need for applying an extra correction factor. However, the variation in StD is rather small compared to the level of StD. To reach the same correlation between StD and mean as in Figure 3 one can shrink the standard deviations. The shrink factor, K was also found based on a simulation approach. However, a more computer intensive process was applied to test if a starting value of K gives the desired correlation. Subsequently, K was adjusted and tested repeatedly until a correlation within small error margins to the desired correlation was reached.

The correlation between RUT and IRI for 100 meter subsections within an object is approximately zero. Hence, RUT and IRI values in the simulation process can be generated separately.

Table 2 Relationship between average and standard deviation for IRI and rutting in Swedish LTTP sections.

	IRI			**RUT**		
N	*D*	*K*	*A*	*D*	*K*	*A*
10	1.00	0.21	0.50	1.00	0.63	0.35
20	1.06	0.20	0.52	1.15	0.55	0.41
30	1.08	0.20	0.52	1.22	0.51	0.44
40	1.09	0.19	0.52	1.25	0.49	0.45
50	1.10	0.19	0.53	1.28	0.48	0.46
60	1.10	0.19	0.53	1.29	0.48	0.47
70	1.10	0.19	0.53	1.31	0.47	0.48
80	1.11	0.19	0.53	1.31	0.47	0.48
90	1.11	0.19	0.53	1.32	0.46	0.48
100	1.11	0.19	0.53	1.33	0.46	0.48

To clarify the procedure a simplified workflow is summarized below:

If the expected mean (for RUT or IRI) at the end of the warranty period is $\mu_{\bar{X}}$ and the coefficients of Equations (2-3) are b_0 (intercept) and b_1 (slope), then

$$\mu_S = (b_0 + b_1 \cdot \mu_{\bar{X}}) \cdot D$$

$$\sigma_{\bar{X}} = \mu_S \cdot K$$
$$\sigma_S = \sigma_{\bar{X}} \cdot A$$

where μ_S is the average standard deviation (for IRI or RUT) and σ_S is the corresponding variation in standard deviation.

The Monte Carlo simulation starts by generating one series with the proper autocorrelation. It should then be adjusted to have a mean sampled from $N(\mu_{\bar{X}}, \sigma_{\bar{X}})$ and StD sampled from $N(\mu_S, \sigma_S)$. Subsequently, by simulating a second series based on these means and StDs and inserting IRI (or RUT) in Equations (2-3) one can evaluate the technical risk.

As an example, we demonstrate how to generate RUT and IRI data for a 5 kilometer object:

The number of 100 meter sections in the object, N, is 50. By estimating RUT based on a ME approach (or another method) we assume that the expected value for rut is 9 millimetres.

Generating RUT data

Equation (2) gives $b_0 = -0.0148$ and $b_1 = 0.163$. From Table 1, we find $D = 1.28$, $A = 0.46$ and $K = 0.48$.

1. $\mathrm{\mu_S = (b_0 + b_1 \cdot \mu_{\bar{X}}) \cdot D} = (-0.0148 + 0.163 \times 9) \times 1.28 = 1.859$
2. $\mathrm{\sigma_X = \mu_S \cdot K} = 1.859 \times 0.48 = 0.892$
3. $\mathrm{\sigma_S = \sigma_X \cdot A} = 0.892 \times 0.46 = 0.410$

Generate a long series with autocorrelation of the same size as was observed for longer objects. From that, sample a series of 50 observations. Subtract the mean and divide by the StD to standardize the series. A new mean value can be found by sampling from $\mathrm{N}(9, 0.892)$. Similarly, a new standard deviation can be obtained by sampling one value from $\mathrm{N}(1.859, 0.410)$. The series should be adjusted by multiplying the sampled StD and adding the sampled mean.

IRI data

With expected RUT of 9 millimetres, expected IRI can be estimated to 1.998 by Equation (1). Equation (3) gives $b_0 = -0.2642$ and $b_1 = 0.3944$. From Table 1, we find $D = 1.10$, $A = 0.53$ and $K = 0.19$.

1. $\mu_S = (b_0 + b_1 \cdot \mu_{\bar{X}}) \cdot D = (-0.2642 + 0.3944 \times 1.998) \times 1.10 = 0.576$
2. $\sigma_X = \mu_S \cdot K = 0.576 \times 0.19 = 0.109$
3. $\sigma_S = \sigma_X \cdot A = 0.110 \times 0.53 = 0.058$

Generate a long series with autocorrelation of the same size as was observed for longer objects. From that, sample a series of 50 observations. Subtract the mean and divide by the StD to standardize the series. A new mean value can be found by sampling from $N(1.998, 0.109)$. Similarly, a new standard deviation can be obtained by sampling one value from $N(0.576, 0.058)$. The series should be adjusted by multiplying the sampled StD and adding the sampled mean.

For future development and use of this procedure, the correlation between mean and StD for longer objects should be sought. We currently have this information for LTPP-length objects only and also use that for longer objects, which is probably an approximation. We also assume that both mean and StD are closely enough approximated by normal distributions, though probably it is skewed with a tail on its right-hand side.

4.2. Model Validation

In order to validate the suggested model, the percentage of different pavements exceeding the rutting requirements for several long-term DB contracts, monitored by the construction company NCC, were compared with estimated results based on the method presented in section 4.1, Figure 4.

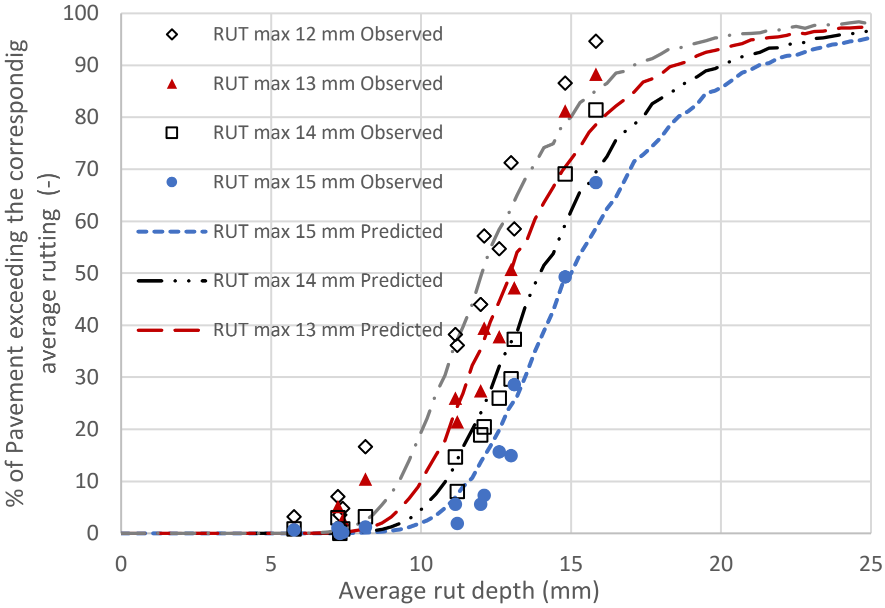


Figure 4 Percentage of pavement (100 m sections) exceeding rutting threshold as function of average RUT for different rutting requirements (10-15 millimetres).

The points in Figure 4 (observed), represent the percentage of the studied road sections exceeding different maximum rutting requirements based on their corresponding rutting averages (Appendix 1). Dotted lines in Figure 4 (predicted), represent the percentage of pavement exceeding the rutting threshold as a function of an average RUT, based on the method presented in 4.1. The correlation between the observed and predicted percent of pavement exceeding different rutting thresholds is presented in Figure 5.

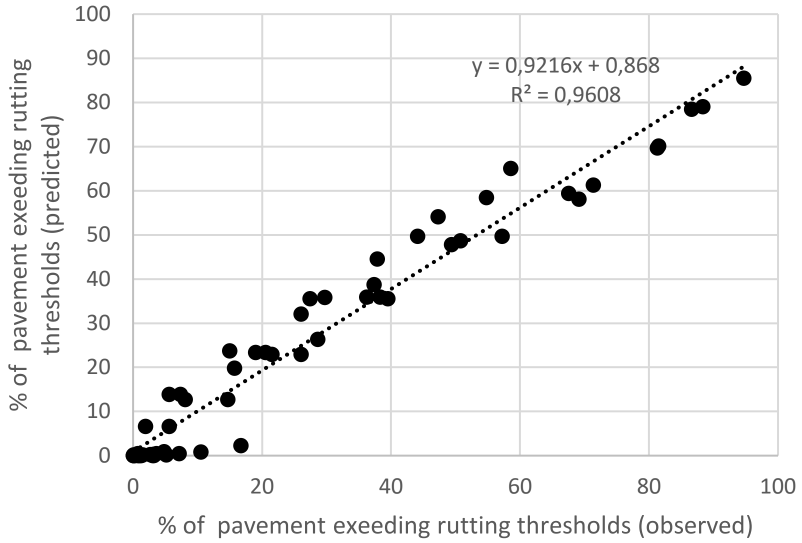


Figure 5 Correlation between the observed and the predicted percent of pavement exceeding different rutting thresholds.

The rutting values are simulated for different average values and controlled against the maximum allowed RUT. It should be noted that coefficients in the simulation process have been obtained based on (N=100). It is evident that there is an excellent agreement between the predicted results based on the suggested model and the observed data based on the road surface measurements.

4.3. Financial consequences

The financial consequences for the contractor during the warranty period in a DB or DB(M) contract is mainly due to correctional maintenance for the road sections that do not fulfil the requirements. The presence or absence of price adjustment clauses (PACs) has an impact on the severity of the technical risk imposed to the contractor.

4.3.1. Maintenance costs

If the measured value of any performance indicator (e.g. rutting or IRI) for a road section i is greater than the corresponding requirement, the value of the warranty option (or the contractor's technical risk) can be estimated by using Equation (4).

$$tr_i = \begin{cases} 0 & \text{if} \quad RUT_i \le RUT_k \quad \text{and} \quad IRI_i \le IRI_k \\ mc & \text{if} \quad RUT_i > RUT_k \quad \text{or} \quad IRI_i > IRI_k \end{cases} \qquad [4]$$

where RUT_i and IRI_i are values regarding RUT and surface smoothness for the road section; RUT_k and IRI_k are the functional requirements regarding rutting and smoothness and mc is the required maintenance cost for the road section.

Consequently, the total discounted value of the warranty option (technical risk for the contractor) can be obtained by Equation (5).

$$TR = \frac{1}{(1+r)^L} \sum_{i=1}^{N_s} tr_i \qquad [5]$$

where r is the discount rate; L is the length of the warranty period and N_s is the number of road sections. It should be noted that the road performance indicators such as rutting and IRI are usually measured for 20 meter or 100 meter sections.

4.3.2. Influence of price adjustment clauses (PAC)

One of the significant risks to contractors in DB projects, is the cost of oil products, e.g. bitumen and fuel oil which stands for more than 50 percent of the cost of asphalt pavements (Mirzadeh et al, 2014; Ilbeigi et al, 2015). Consequently, contractors in fixed-price contracts usually include risk premiums and other contingencies for dealing with the high material price volatility, which may extensively increase bid prices (Damnjanovic et al, 2009). The risk regarding material price volatility can be partly (or entirely) transferred to the transportation administration by offering price adjustment clauses (PAC). PACs are risk-sharing mechanisms which distribute the risk of material cost fluctuations between the authority and contractors. The contractor's cost and risk in the presence of a PAC can be determined according to Equation (6). The unadjusted cost, R, is a $N(mc, \sigma_c)$ random variable and the standard deviation also plays the role of being the volatility. z is the minimum threshold for material price escalation above which the contractor should be compensated for. The adjusted cost, C, is limited to the range $mc(1 \pm z)$ according to Equation (6).

$$C = \begin{cases} (1-z)mc & \text{if} \quad (1-z)mc > R \\ R & if \quad (1-z)mc \le R \le (1+z)mc \\ (1+z)mc & \text{if} \quad (1+z)mc < R \end{cases} \qquad [6]$$

The ceiling for the upward cost fluctuations is similar to a European call option in which the contractor has the right to claim cost reimbursements from the road authority. The floor clause, however, is equivalent to a put option where the road authority has the right to make adjustments for the lower prices.

Instead of being sensitive to minor price fluctuations, PACs should be triggered by significant changes in the chosen index. Moreover, they should not be susceptible to manipulation by contractors. Mirzadeh et al, (2014) suggested an equivalent inflation index which represents the cost fluctuation of asphalt pavement projects. Moreover, they presented a volatility regarding the cost of asphalt pavement projects (σ_c) which was suggested to be around 15 percent of the average cost for Swedish asphalt pavements (Mirzadeh et al, 2016).

Other contractual clauses such as minimum amount of maintenance (e.g. work of at least 100 meters) may significantly affect the risks. If such clauses are stated in a contract, the extra cost could be estimated by multiplying the maintenance cost by additional area concerned. Another potential clause concerns so-called essential deviations where the client may require additional warranty time if too much maintenance has been required during the warranty period. For example, if all wearing course layers need to be replaced due to excessive rutting, an additional warranty time of additional 10 years may occur (i.e. 10+10 years).

5. Case-study

In this section, three different pavement types are evaluated in accordance with the DB project delivery context. The case-study has focused on the analysis of the impact of performance requirements regarding rutting and IRI as well as financial consequences due to contractual clauses such as price adjustment clauses. Risk is considered as the cost of corrective maintenance from the distribution of rutting and IRI around a given average value.

The business context spans the technical requirements expressed in typical Swedish contracts with 5-20 years of warranty depending on used project delivery and contracting methodology. The risk for the contractor in a DB contract with 15 years warranty period is analysed for the three pavement alternatives.

5.1. Investigated pavement designs

Traditionally, roads in Sweden have been constructed as flexible pavements comprising relatively thick unbound layers and thin bituminous bound layers. The choice of Swedish pavement structure has been affected by the availability of high-quality aggregate and relatively low traffic volumes. In DBB projects, high-volume roads are usually designed as traditional SMA and gravel aggregate (AG) mixtures with high-quality aggregates having a binder penetration of 70/100 or 160/220 according to specified quantities, material composition and execution. During 1995-1996 the Swedish Transport Administration (STA) decided to perform a full-scale test in connection to a major reconstruction of an existing road in order to promote technical development and knowledge regarding innovative designs. The purpose of the test was to make a fair comparison of different pavement structures, consisting of different bitumen-bound and Portland cement-bound layers, regarding long-term performance, primarily with respect to rutting and IRI. In this report, three test sections are used to illustrate the impact of technical requirements and contractual clauses.

The pavement structures for the three investigated test sections are illustrated in Figure 6. Both the *reference pavement (REF)* and the *high-performance flexible pavement* (HPA) comprised in a total of 235 millimeters bitumen-bound layers while the Lean concrete pavement constituted 90 millimeters bitumen-bound layers and 240 millimeters lean concrete (330 millimeters bound layers). The REF consisted of the same traditional Swedish layer configuration according to the prevailing STA technical descriptions. For the second design, HPA, is fulfilling strict demands regarding performance-related properties as determined by laboratory testing on the mixtures and layers. The third design concerned a standard, but (in Sweden) unusual, semi-rigid pavement Lean-concrete base (LCB) comprising a cement-bound base and asphalt. The reference and the LCB pavements were designed for a traffic loading of >19 million ESALs over 20 years. The entire road was opened for traffic on 13 November 1996 and by 2006, rutting data for 10 years were available. For a more thorough description of the test-stretches, pavement types and materials used, the reader is referred to Lundström et al, (2009) and Ekblad and Lundström (2018).

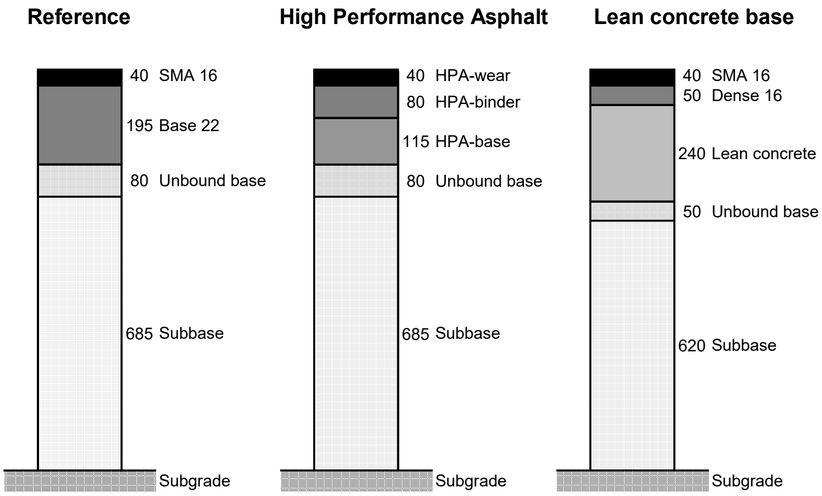


Figure 6. The three pavement types investigated.

Production and maintenance costs

Table 3 shows costs for the bound layers of the three pavement types. As indicated, the HPA pavement is approximately 5 percent more expensive to produce compared to the reference, while the LCB pavement is approximately 14 percent more expensive. The higher cost is mainly related to higher material costs. For simplicity, costs of correctional maintenance due to failure of meeting performance requirements during the contract period is approximated to be \$15 and 16.5 per m^2 for milling and replacing the SMA and HPA wearing course layers, respectively. These costs are assumed to include additional relevant costs for Swedish DB (M) contracts.

Table 3. Costs for the pavement types investigated: asphalt construction and maintenance costs (\$/m2)

Pavement types	**Material layer**	**Costs (\$/m^2)**	
		Construction	**Maintenance**
REF	40 mm SMA 16	11.30	15.00
	65 mm Base 22	11.10	
	65 mm Base 22	11.10	
	65 mm Base 22	11.10	
	Sum	44.60	
HPA	40 mm HPA-wear	12.43	16.50
	80 mm HPA-binder	17.50	
	100 mm HPA-base	18.40	
	Sum	48.33	
LC	40 mm SMA 16	11.30	15.00
	50 mm Dense 16	9.60	
	240 mm Lean concrete	32.80	
	Sum	53.70	

The average yearly RUT of the three pavement structures have been investigated in Figure 8. The reference pavement (REF) exhibits the highest rate of rutting while the HPA and LC pavements show approximately the same rutting rates. Although the pavements show some differences regarding initial rutting, those small differences are not believed to be due to any systematic material performance.

However, a positive set-off in initial rutting at year 0 can potentially affect future rutting and, consequently, time to maintenance. Judging from Figure 7 and assuming linear extrapolation, it seems that the total average rutting in year 18 for LC design is similar to those of HPA and REF designs in years 17 and 10, respectively.

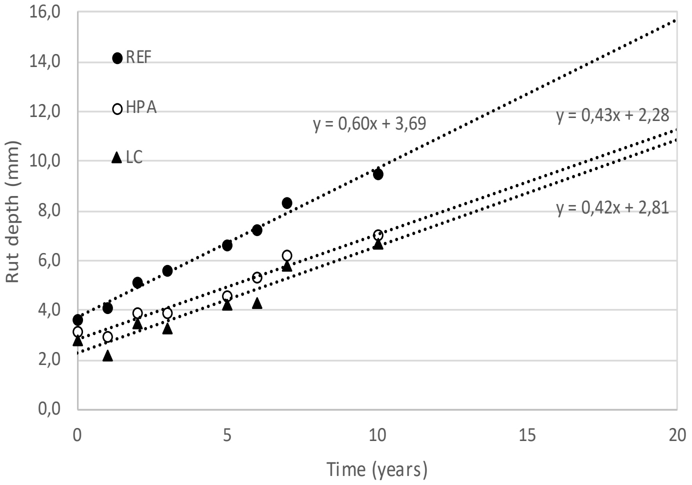
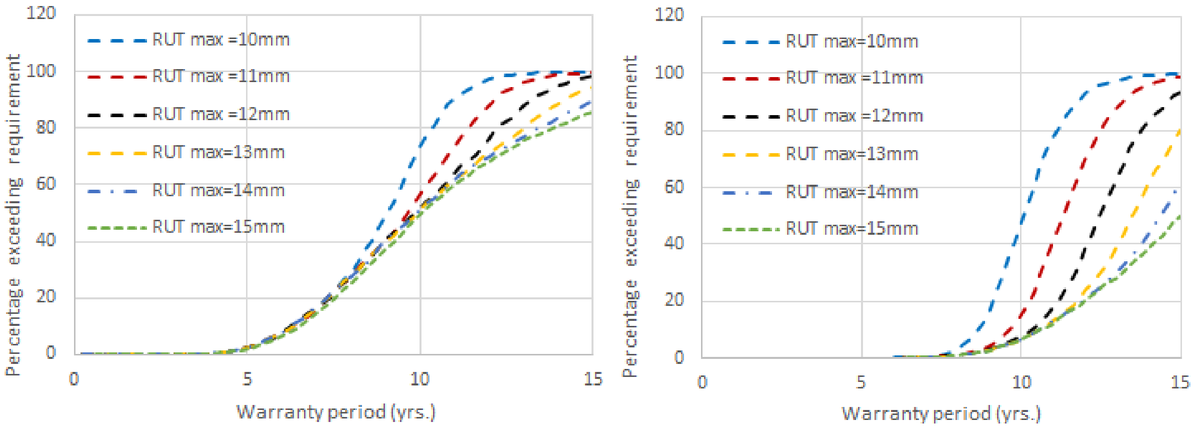


Figure 7. Measured RUT for the three different pavements and extrapolated RUTs for an additional 10 years (average RUT of each stretch).

5.2. Results

In this case-study the average RUT at the end of the warranty period was analysed based on the RUT measurements during the first 10 years (Figure 7). The average IRI values at the end of the warranty period can be investigated as a function of average RUT (Equation 3). The standard deviations regarding IRI and rutting are obtained based on Equations (4-5). Based on the suggested model in section 4.1 and the production and maintenance costs of Table 3, it is possible to evaluate and compare the impact of performance requirements, risks and total costs for the different pavement structures.

The amount of technical risk imposed to the contractor is a function of the length of the warranty period and the maximum allowed RUT. The portion of REF section exceeding the requirement has been illustrated in *Figure 8* as a function of RUT requirement and the length of the warranty period. For relatively short warranty times (<7 years), the maximum allowed RUT did not have a significant impact on the results. However, for longer warranty periods, the maximum allowed RUT had a substantial impact on the portion of the road requiring maintenance.



(a) (b)

Figure 8. Percentage of pavement (REF section) exceeding rutting requirement as a function of the length of warranty period and the maximum allowed RUT. (a) maximum allowed IRI =2,3 mm/m (b) maximum allowed IRI =2,8 mm/m.

As indicated in Figure 8, the maximum allowed RUT and IRI have great impact on the technical risk for the contractor since the portion of pavement needing maintenance increases rapidly with the decrease of the threshold level. For example, a rutting requirement of 10 millimeters for each 20 meter section has resulted in 80-90 percent of the REF pavement exceeding the requirement depending on threshold level for IRI. While the same IRI requirement has resulted in 40-85 percent of the pavement exceeding the requirement for a 15 millimeter rutting requirement.

It is evident that tougher threshold levels and longer warranty times generally impose more maintenance needs and consequently higher costs. However, any unforeseen maintenance activity also imposes a risk due to future material (e.g. bitumen and fuel) price fluctuations. The cost of bitumen and other oil products constitute about 50 percent of the total cost of asphalt pavements. Considering the high volatility regarding the price of these products, a significant risk is imposed to contractors in the absence of PACs (Mirzadeh et al, 2014). The risk of material price fluctuations for a 15 years warranty period is presented in Figure 9in the absence and presence of PAC with different threshold levels. It can be observed from Figure 10 that in the absence of PAC for bitumen and fuel, a potential cost increase of 0.2-1.5 $\$/m^2$ can be imposed to the contractor. Moreover, the amount of risk imposed to the contractor is more significant in contracts with longer warranty periods.

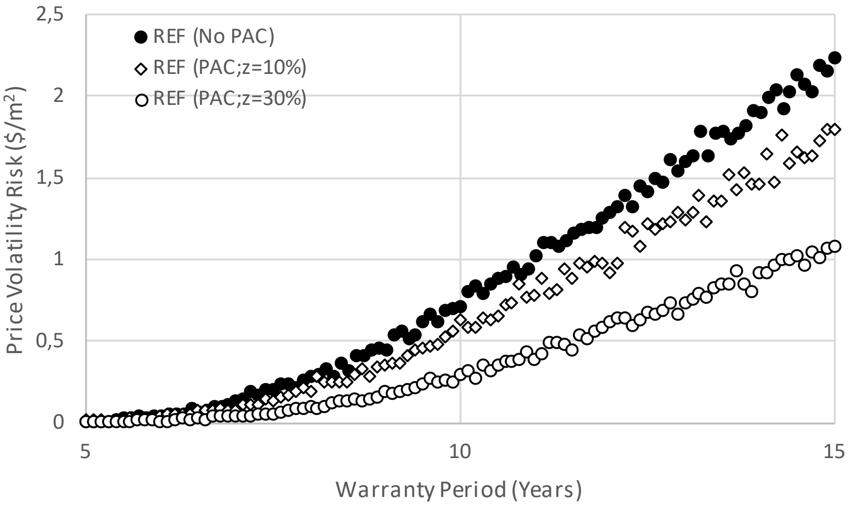


Figure 9. The risk due to material price fluctuation for the contractor as function of the length of the warranty period.

The total costs for each design considering the impact of the technical risk is presented in Figure 10. The technical risk is the cost regarding the eventual unforeseen maintenance due to non-conformity of the measured RUT to a rutting requirement of 15 millimeter. As indicted in Figure 10, the REF results in lowest overall costs until a contract length of approximately 11 years. For longer warranty periods (>11), the rapid increase of rutting for REF makes HPA pavement type the most cost effect alternative. Therefore, the reference pavement is the rational choice in short to medium contracts while the HPA design is preferable at longer contract times given the threshold level of 15 millimeter rutting.

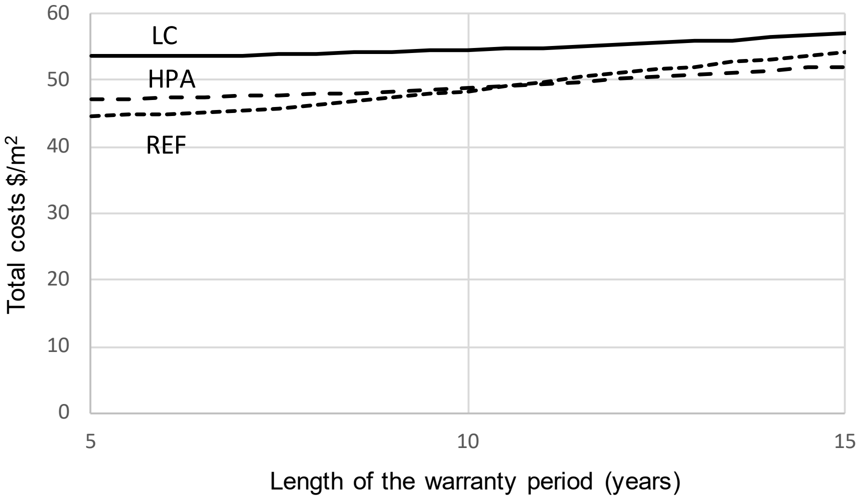


Figure 10. The total expected cost for the contractor for the design alternatives (given 15 millimetres of rutting requirement without PAC).

The LC pavement did not become a preferable alternative given the assumed contract conditions. However, if the rutting requirement is reduced to 10 millimetres, the LC pavement type is preferred over the REF pavement for longer warranty periods. However, the comparatively low production cost and performance of the HPA still results in lower total costs compared to the LC design for short to medium contracts.

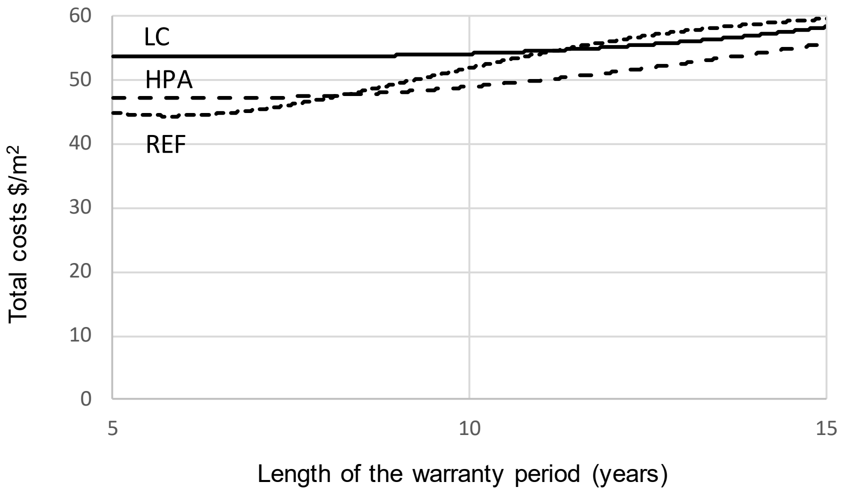


Figure 11. The total expected cost for the contractor for the design alternatives (given 10 millimetres of rutting requirement without PAC).

The relatively low cost of the reference pavement (REF) can be counteracted by the relatively high amount of maintenance need for unfavourable combinations of warranty time and rutting thresholds. For example, a significant maintenance cost can be imposed to the contractor for a warranty time of 15 years and a rutting threshold level of 10 millimetres. Given these conditions, the lower rate of rutting of the HPA and LC designs can result in lower maintenance costs. It is evident from Figure 10 and Figure 11 that the economic advantage of each pavement compared to others is highly dependent of the level of the performance requirements as well as the length of the warranty period. However, the combination of the warranty length and the requirements should be considered in any risk assessment.

6. Discussion and conclusions

This report presents a model for analysing relatively detailed technical risks in DB and DBM contracts and resulting costs of corrective maintenance. Although, the entire complexity of a given delivery or contracting system may be difficult to consider, different conditions such as technical requirements, contract lengths and contractual mechanisms such as warranty clauses and PACs are studied in this report. The presented approach provides several advantages that can benefit the construction industry specially in DB and DBM contexts where a substantial technical risk is allocated to contractors. The method can be used by the Transport Administration, as a decision-support tool, for setting performance requirements at the project level. Moreover, it can be applied by contractors for assessing the technical risk at the bidding stage as well as during the warranty period. The suggested method is validated against road surface data for several long-term DB contracts, monitored by the construction company NCC.

A significant part of the risks identified in this report is related to technical and contractual aspects. Four main prerequisites may affect the contractor risk namely (1) technical performance of a given pavement design, (2) the length of the contract, (3) the actual performance requirement and, (4) consequences of nonconformity to contract requirements and clauses, where tougher conditions result in higher risks due to the needs of corrective maintenance.

The technical quality was mainly determined by rutting and longitudinal unevenness as motivated by international and Swedish contracting practices and experiences. However, other deterioration mechanisms, such as cracking, ravelling, friction, texture and crossfall may also be of interest, especially for pavements subjected to less traffic and warmer climate. Such alternative distress mechanisms and resulting financial impacts should be incorporated into the model if available data could be provided and deemed necessary. In additions, the impacts of bonus-malus systems which potentially can contribute to the financial outcome, may also be evaluated using the suggested model.

The impact of the PAC for bitumen in the context of DB and DBM contracts was analysed. It was observed that in the absence of a PAC, the technical risk for the contractor can increase significantly. The potential extra costs are due to the high fluctuation of the price of oil products (e.g. bitumen and fuel oil) and the fact that maintenance activities are not included in DB contracts. However, in the case of DBM projects in which maintenance activities are usually included in the contract, the risk is transferred to the transport administration.

References

Al-Omari, B., & Darter, M. I. (1994). Relationships between international roughness index and present serviceability rating. Transportation Research Record, (1435).

Applied Research Associates (ARA). (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures. *NCHRP Project Rep. 1-37A Prepared for National Cooperative Highway Research Program*.

Bardaka, E., Zhang, Z., Labi, S., Sinha, K. C., & Mannering, F. (2016). Statistical assessment of the cost effectiveness of highway pavement warranty contracts. Journal of Infrastructure Systems, 22(3), 04016017.

Bayraktar, M. E., Cui, Q., Hastak, M., & Minkarah, I. (2004). State-of-practice of warranty contracting in the United States. Journal of Infrastructure Systems, 10(2), 60-68.

Berk, J., & DeMarzo, P. (2014). Corporate finance (3. utgave).

Butt, A. A., Shahin, M. Y., Feighan, K. J., & Carpenter, S. H. (1987). *Pavement performance prediction model using the Markov process* (No. 1123).

Cheah, C. Y., & Liu, J. (2006). Valuing governmental support in infrastructure projects as real options using Monte Carlo simulation. Construction management and economics, 24(5), 545-554.

Chiara, N., Garvin, M. J., & Vecer, J. (2007). Valuing simple multiple-exercise real options in infrastructure projects. Journal of infrastructure systems, 13(2), 97-104.

Cook, W. D., & Lytton, R. L. (1987). Recent developments and potential future directions in ranking and optimization procedures for pavement management. In *North American Conference on Managing Pavements, 2nd, 1987, Toronto, Ontario, Canada* (Vol. 2).

Cui, A. P., Liu, W., & Zhang, X. (2008). Capability coordination in logistics service supply chain with options contract under Stackelberg game model. In *2008 International Conference on Machine Learning and Cybernetics* (Vol. 7, pp. 4051-4056). IEEE.

Cui, Q., Johnson, P. W., Sharma, D., & Bayraktar, M. E. (2010). Determinants of industry acceptance for highway warranty contracts: Alabama case study. Journal of Infrastructure Systems, 16(1), 93-101.

Damnjanovic, I., Anderson, S., Wimsatt, A., Reinschmidt, K., and Pandit, D. (2009). "Evaluation of ways and procedures to reduce construction cost and increase competition." Texas Transportation Institute, Texas A&M Univ. System, College Station, TX.

Ekblad, J., & Lundström, R. (2018). Causes of rutting in flexible and semi-rigid test sections after 14 years of service. Road Materials and Pavement Design, 19(4), 878-897.

Galera, A. L. L., & Soliño, A. S. (2010). A real options approach for the valuation of highway concessions. *Transportation Science*, *44*(3), 416-427.

Gharaibeh, N. G., & Shirazi, H. (2009). Risk-based model for pricing highway infrastructure warranties. Journal of Infrastructure Systems, 15(4), 378-382.

Gharaibeh, N. G., Miron, A. G. (2008) "Warranty specifications for highway construction – current practices and evolution to advanced quality systems." Transportation Research Record, No. 2081, pp. 77-82.

Haas, R., Hudson, W. R., & Zaniewski, J. P. (1994). *Modern pavement management*.

Ho, S. P., & Liu, L. Y. (2002). An option pricing-based model for evaluating the financial viability of privatized infrastructure projects. Construction Management & Economics, 20(2), 143-156.

Huang, Y. L., & Pi, C. C. (2013). Real-option valuation of build-operate-transfer infrastructure projects under performance bonding. Journal of Construction Engineering and Management, 140(5), 04013068.

Ilbeigi, M., Ashuri, B., & Shayegh, S. (2015). Price adjustment clauses and submitted bid prices for major asphalt line items in highway projects. Journal of Construction Engineering and Management, 142(5), 04015103.

Kobayashi, K., Do, M., & Han, D. (2010). Estimation of Markovian transition probabilities for pavement deterioration forecasting. KSCE Journal of Civil Engineering, 14(3), 343-351.

Lundström, R. (2013). Comparing Procurement Methods in Road Construction Projects: Influence on Uncertainty, Interaction and Knowledge (Doctoral dissertation, Företagsekonomiska institutionen, Uppsala universitet).

Lundström, R., Karlsson, R., Wiman, L. W. (2009) "Influence of pavement materials on field performance – evaluation of rutting on flexible, semi-rigid and rigid test section after 7 years of service." Road Materials and Pavement Design Vol 10/4 - 2010 - pp.689-713

Lundström, R., Johanson, M. (2015) *A comparison of traditional and unconventional construction project procurement methods*. *The 31th IMP conference*, 25-29 August 2015, Kolding, Denmark.

Madanat, S., Mishalani, R., & Ibrahim, W. H. W. (1995). Estimation of infrastructure transition probabilities from condition rating data. *Journal of infrastructure systems*, *1*(2), 120-125.

Mirzadeh, I., Butt, A. A., Toller, S., & Birgisson, B. (2014). Life cycle cost analysis based on the fundamental cost contributors for asphalt pavements. *Structure and infrastructure engineering*, *10*(12), 1638-1647.

Mirzadeh, I., & Birgisson, B. (2015). Evaluation of highway projects under government support mechanisms based on an option-pricing framework. Journal of construction engineering and management, 142(4), 04015094.

Mirzadeh, I., & Birgisson, B. (2016). Accommodating energy price volatility in life cycle cost analysis of asphalt pavements. Journal of Civil Engineering and Management, 22(8), 1001-1008.

Moynihan, G., Zhou, H., & Cui, Q. (2009). Stochastic modeling for pavement warranty cost estimation. Journal of Construction Engineering and Management, 135(5), 352-359.

Nombela, G., & de Rus, G. (2004). Flexible-term contracts for road franchising. *Transportation research part A: policy and practice*, *38*(3), 163-179.

Quiggin, J. (2005). Public–private partnerships: options for improved risk allocation. *Australian Economic Review*, *38*(4), 445-450.

Sadeghi, L., McDaniel, R., & Haddock, J. E. (2016). Effectiveness of warranted asphalt pavements in Indiana. Transportation Research Record, 2573(1), 69-75.

Shahin, M. Y. (1994) Pavement management for airports, roads and parking lots. New York, Chapman & Hill.

Shrestha, P. P., O'Connor, J. T., & Gibson Jr, G. E. (2011). Performance comparison of large design-build and design-bid-build highway projects. Journal of Construction Engineering and Management, 138(1), 1-13.

Shuler, S., Aschenbrener, T., & DeDios, R. (2007). Effect of performance warranties on cost and quality of asphalt pavements. Transportation Research Record, 2040(1), 100-106.

Singh, P., Oh, J. E., Labi, S., & Sinha, K. C. (2007). Cost-effectiveness evaluation of warranty pavement projects. Journal of Construction Engineering and Management, 133(3), 217-224.

Thomas, F. (2004). Generating homogeneous road sections based on surface measurements: Available methods. Reprint from 2nd European Pavement and Asset Management Conference, 21-23 March 2004, Berlin Germany. (Paper no. 48). Statens väg-och transportforskningsinstitut., VTI särtryck 360A.

Thomas, O., & Sobanjo, J. (2012). Comparison of Markov chain and semi-Markov models for crack deterioration on flexible pavements. Journal of Infrastructure Systems, 19(2), 186-195.

Von Quintus, H. L., Yau, A., Witczak, M. W., Andrei, D., & Houston, W. N. (2001). Appendix OO-1: Background and preliminary smoothness prediction models for flexible pavements. Guide for mechanistic empirical design of new and rehabilitated pavement structures. National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

Warne, T. R. (2005). Design build contracting for highway projects: A performance assessment. Tom Warne & Associates, LLC.

Zhang, Z., & Damnjanovic, I. (2006). Quantification of risk cost associated with short-term warranty-based specifications for pavements. Transportation research record, 1946(1), 3-11.

Appendix 1: Average rutting vs. percentage exceeding the rutting requirement

Katrineholm - Valla, lanes heading east

Average RUT (mm) 14,8

	Number of of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12	342	87%
RUT requirement = 13	321	81%
RUT requirement = 14	273	69%
RUT requirement = 15	195	49%
Total no. of sections	395	

Katrineholm - Valla, lanes heading west

Average RUT(mm) 15,8

	Number of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12	373	95%
RUT requirement = 13	348	88%
RUT requirement = 14	321	81%
RUT requirement = 15	266	68%
Total no. of sections	394	

E4 Järna, lanes heading north

Average RUT (mm) 8,14

	Number of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12	94	17%
RUT requirement = 13	59	11%
RUT requirement = 14	18	3%
RUT requirement = 15	7	1%
Total no. of sections	561	

E4 Järna, lanes heading south

Average RUT(mm)	7,23		
		Number of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12		40	7%
RUT requirement = 13		29	5%
RUT requirement = 14		17	3%
RUT requirement = 15		6	1%
Total no. of sections		563	

Uppsala - Mehedeby, lanes heading north

Average RUT (mm)	7,28	
	Number of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12	8	1%
RUT requirement = 13	1	0%
RUT requirement = 14	0	0%
RUT requirement = 15	0	0%
Total no. of sections	1091	

Uppsala - Mehedeby, lanes heading south

Average RUT (mm)	7,28	
	Number of sections Exceeding	Percentage of road Exceeding
RUT requirement = 12	39	4%
RUT requirement = 13	16	1%
RUT requirement = 14	3	0%
RUT requirement = 15	0	0%
Total no. of sections	1091	

Uppsala - Mehedeby, lanes heading north

	Number of sections Exceeding	Percentage of road Exceeding
Average RUT(mm)	7,28	
RUT requirement = 12	8	1%
RUT requirement = 13	1	0%
RUT requirement = 14	0	0%
RUT requirement = 15	0	0%
Total no. of sections	1091	

Uppsala - Läby, lanes heading north

	Number of sections Exceeding	Percentage of road Exceeding
Average RUT (mm)	11,14	
RUT requirement = 12	219	38%
RUT requirement = 13	149	26%
RUT requirement = 14	84	15%
RUT requirement = 15	32	6%
Total no. of sections	572	

Uppsala - Läby, lanes heading south

	Number of sections Exceeding	Percentage of road Exceeding
Average RUT (mm)	11,20	
RUT requirement = 12	207	36%
RUT requirement = 13	123	22%
RUT requirement = 14	46	8%
RUT requirement = 15	11	2%
Total no. of sections	572	

ABOUT VTI

The Swedish National Road and Transport Research Institute (VTI), is an independent and internationally prominent research institute in the transport sector. Our principal task is to conduct research and development related to infrastructure, traffic and transport. We are dedicated to the continuous development of knowledge pertaining to the transport sector, and in this way contribute actively to the attainment of the goals of Swedish transport policy.

Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

VTI conducts commissioned research in an interdisciplinary organisation. Employees also conduct investigations, provide counseling and perform various services in measurement and testing. The institute has a wide range of advanced research equipment and world-class driving simulators. There are also laboratories for road material testing and crash safety testing.

In Sweden VTI cooperates with universities engaged in related research and education. We also participate continuously in international research projects, networks and alliances.

The Institute is an assignment-based authority under the Ministry of Infrastructure. The Institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Certain test methods used in our labs for crash safety testing and road materials testing are also certified by Swedac.

Swedish National Road and Transport Research Institute • www.vti.se • vti@vti.se • +46 (0)13–20 40 00