Data collection and monitoring strategies for asset management of New Zealand road bridges

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An important note for the reader

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Contents

Executive summary

This report comprises a review of road bridge asset management practices in New Zealand and overseas, a survey of the current New Zealand bridge asset management practice, and a strategy that will ensure that New Zealand bridge management practice is underpinned by sound principles and quality data. The review and local survey also covered the decision-making phases of the asset management cycle, as it is important to understand how collected data is used. The proposed strategy, however, focuses mainly on the data input to this process.

The research project was carried out between July 2008 and May 2011.

The review identified that bridge asset managers collect large amounts of data but do not link it appropriately to strategic decisions, and therefore do not obtain the maximum value from the collected data. For example, there was no clear link between technical measures (eg load-carrying capability) and network-level economic assessments set up by national or regional strategic service levels and performance targets. To overcome those issues, comprehensive performance frameworks are being developed in other countries such as Canada.

The strategy for New Zealand that is proposed in this report provides a clear and defined link and path between the operational management of bridges, comprising inspections and assessments, and the strategic outcomes. This is important if bridge asset managers are to concisely express and assert the importance of bridges to network functionality. This need has also been identified by the New Zealand Office of the Auditor General (NZOAG) (2004, 2010) in its recommendation that bridge asset managers should move to an advanced asset management approach, thereby providing users and stakeholders with quantifiable information about asset performance.

The need for enhanced practice in this area was further highlighted by this study's survey, which showed that many asset managers had a limited understanding of service levels for bridges, and considered these were restricted to performance levels as defined by technical standards. There is therefore a clear need to define the type of data that is recommended for collection, and how the data fits with strategic outcomes so that advanced asset management can be attained. This proposed strategy identifies the categories of data that will have to be collected to fully understand the performance of bridges, both at a bridge level and at a network level – inventory, maintenance, cost, environmental, network, safety, and condition and testing data.

In reviewing data collection methods, we found that bridge condition data was largely collated using visual inspections. However, these have been identified as often not providing consistent or reliable outcomes, or not always being able to detect critical problems. There is therefore a need to better integrate non-destructive evaluation (NDE) and structural health monitoring (SHM) into the data collection processes.

The survey of New Zealand practice also highlighted that few bridge managers had systematically integrated NDE, and virtually none had integrated SHM into the bridge asset management process. NDE can be used to more accurately define current issues or to assess long-term deterioration trends via one-off or periodic tests, whereas SHM can be used to monitor bridge performance, either in real time or as required.

We found that many countries used formalised condition-rating systems to provide a numerical assessment of condition, whereas New Zealand currently uses a defect approach that only catalogues specific issues for ongoing management. This is considered adequate for a core asset management approach, but provides little data for assessment of long-term deterioration trends. However, it is acknowledged that the NZ Transport Agency (NZTA) has embarked on a process that aims to close this gap and is starting to develop a condition data repository. This will aid the development of an advanced asset management approach characterised by the ability to predict asset performance and condition into the future.

The international best practice points out that data should be treated as an asset in its own right. This was generally not the case for bridges, both locally and internationally. A local example of good practice in that respect can be found in the roading sector, which undertakes regular verification and validation of the content of databases. It is recommended that quality assurance (QA) processes surrounding the storage, use and management of bridge data also must improve. It is recommended that bridge asset managers carry out checks of the data stored in their databases to ensure the inventory and other data is complete and correct.

The review identified that tiered methodologies have been used to provide a targeted approach to bridge management. These methodologies include:

- the use of core and advanced asset management techniques
- a five-point approach to optimising data collection so that the data is linked to the decision-making process
- a risk-based approach to data collection
- the use of a data premium that is dependent on data accuracy.

All of these approaches have been adopted in the proposed strategy and further extended to provide core, intermediate and advanced bridge management levels. The applicability of these levels to individual bridges is assessed, taking into account the bridge risk and criticality within a road network. The use of this strategy is considered to be a major change to current bridge management practices, which use a ‘one size fits all’ approach, irrespective of the bridges being managed.

Risk assessment is considered to be a function of the hazards facing the bridge, bridge vulnerabilities, failure consequences, the accuracy of data on these aspects, and risk assessment methods used. All of these factors are assessed for the key bridge risk factors – hydraulic and geotechnical safety, structural safety, maintenance and durability, and operational functionality. In the assessment of bridge criticality, wider, whole-network or regional-level consequences, including traffic delays, service interruption, loss of business, lowered community resilience to natural hazards, and even loss of heritage or iconic status assigned to the structure, are taken into account.

Using the risk and criticality assessment process, bridges can be categorised as requiring core, intermediate or advanced levels of asset management. Using this approach allows bridge asset managers to focus on those bridges that are central to network operation. It is intended that core-level bridges require only simple data collection techniques, and only collect data for key performance criteria (loading and safety). Intermediate- and advanced-level bridges require a broader range of performance data and increasingly accurate approaches to data collection (NDE and SHM). By adopting this tiered approach, more accurate data can be collected for structures that require it, improving the reliability of the decisions being made and accuracy of long-term planning.

It is recommended in the strategy that the visual inspection process should use variable inspection frequencies, based on the risk and criticality of the bridge, with a lower frequency (3–6 years) for core-level bridges, the current frequency (2–3 years) for intermediate-level bridges, and a high frequency (1–2 years) for advanced-level bridges. Furthermore, it is recommended that principal inspections should be removed from the regular inspection cycle and adopted as special inspections.

Visual inspections augmented with the use of NDE and SHM for intermediate- and advanced-level bridges provide an improved level of robustness in the data collection process by improving the reliability where it is required, and by removing unnecessary and low-value inspections on less critical and/or lower-risk bridges.

Adopting the variable visual inspection frequencies would generate savings that would allow bridge managers to redirect precious and limited time and budgetary resources towards the bridges that need them more. These savings would, however, depend on:

- the inspection contract form in place
- the number of bridges within the core, intermediate and advanced categories
- the local costs to undertake inspections.

The level of saving would however depend on the level of extra funding required to implement more advanced data collection techniques, so that improved levels of data accuracy can be achieved.

Abstract

This research was undertaken between July 2008 and May 2011 and brings together findings from a review of literature and a survey of New Zealand bridge asset management practices. The review and the survey identified that the type of data that is collected for bridges have to be improved if advanced bridge asset management is to be adopted. Also, techniques of data collection have to change to ensure data reliability.

To achieve these goals, a strategy is proposed that defines the data to be collected (inventory, cost, performance, safety and environmental, and risk) and how the data should be managed. The strategy also recommends changes to current New Zealand data collection practices, including improvements to the visual inspection regime, adoption of non-destructive evaluation and structural health monitoring, adoption of benchmarking data collection, implementation of condition rating, and improved inspector training courses.

The strategy also acknowledges that not all networks have the same requirements. A risk- and criticality-based approach is therefore promoted and outlined. The risk and criticality approach allows bridge asset managers to have flexibility to mould the strategy to their own needs and to maintain a cost-neutral data collection programme.

1 Introduction

Data collection on asset inventory, condition and performance appears at the earliest stage within an asset management cycle (Hughson et al 2006, Roads Liaison Group 2005) (see figure 1.1). It includes:

- appraisal of strategic goals
- understanding of level of service (LOS) delivery via condition assessment and definition of demand aspirations
- option identification via assessment of performance gaps and asset life cycle planning
- decision making, including optimisation and budgetary consideration and risk assessment
- service delivery via planning of forward works and their delivery.

At the end of the cycle, when reporting is undertaken, performance data again needs to be collected to identify any required improvement actions.

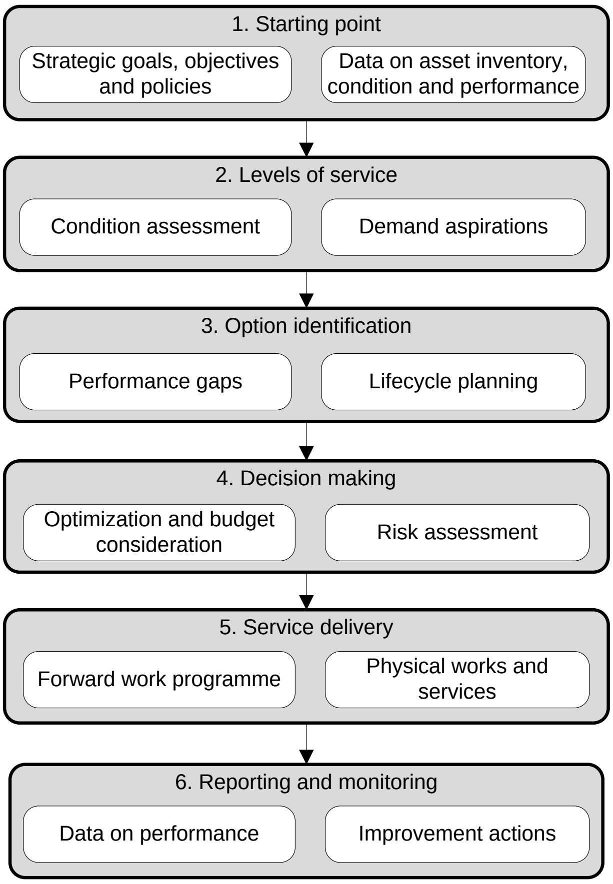
Clearly, the entire asset management cycle hinges on this data, which needs to be of the appropriate type, volume and quality.

This research project was carried out between July 2008 and May 2011, and focused on:

- the data required to meet the needs of the bridge asset management process
- the methods of collecting such data
- quality assurance (QA), validation and verification practices.

Collecting and maintaining such data will allow bridge asset managers to develop the information needed to understand whether and how they can deliver on policy objectives.

Figure 1.1 Asset management framework (Roads Liaison Group 2005)



1.1 Background to the research

During the period 2002–2003, the New Zealand Office of the Auditor General (NZOAG) produced its audit report on local government (NZOAG 2004), where it noted that almost all councils have management plans and basic information for the assets that are delivering essential services. However, the plans and accompanying information are, in general, relatively unrefined, with effort primarily concentrating on:

- identifying and quantifying the assets
- gathering information on their age and defects and/or condition
- developing information systems
- providing forecasts of cost elements, such as new capital investment, as well as renewals and operational expenditure.

Further, the audit report noted that virtually no council had reached an advanced level of asset management characterised by:

- a much higher level of knowledge of the assets held (thereby allowing predictions to be made about performance)
- a greater understanding of the desired LOS that the community wants the assets to provide
- a focus on addressing the risks associated with managing the infrastructure.

The need for improvements was further reinforced in the NZOAG audit of the New Zealand Transport Agency's (NZTA) asset management practices, which identified that bridge-related data needed to be improved (NZOAG 2010). The audit report observed that the NZTA did not have an effective model for monitoring the condition deterioration of bridges. Over-reliance on key asset management personnel's personal knowledge was exposing the NZTA to a high risk of losing institutional knowledge if those people moved on – especially critical for long-term planning. The situation regarding bridges was compared with road asset management, and the latter was found to be in a much better shape.

It is clear from the NZOAG audits that data gaps exist in the bridge asset management cycle, and these gaps have slowed the development towards an advanced approach. We therefore suggest that more data needs to be collected, thereby meeting the needs of the advanced asset management approach. This data, linked with improved decision-making practices, will go some way to meeting the needs of strategic decision makers. However, the collection of more data has to be balanced against funding limitations. A method of choosing which data to collect is therefore very important. Furthermore, not all bridges will require an advanced approach, so a method of selecting the bridges for data collection is also required.

Developing such a strategic and targeted approach to bridge data collection will help to close the gaps that have been identified by the NZOAG and put bridge asset management in New Zealand on a level comparable with road asset management. In the roading sector, good and robust data is collected, stored in well-maintained systems (RAMM Software Limited 2011), and audited by trained rating teams (NZTA 2009b). Further, the data is linked to the dTims modelling process (Deighton Associates Ltd 2010), which is widely used throughout New Zealand.

It is even more important that there are robust and defensible data collection practices for bridges, as they occur, on average, every 2.5km on the state highway network and every 5.2km nationally, and they have a critical role to play in the operation of the road network. Furthermore, the following characteristics of bridges mean they have to be managed effectively:

- Bridges are less easily repaired than roads, usually requiring special access, traffic closure etc for works to be carried out.
- Bridges are expected to perform for much longer than roads, with service lives in excess of 70 years and design lives of 100 years.
- Bridges cannot be easily upgraded to provide increased service-level requirements, such as increased traffic flow or increased truck weights.
- If bridges fail to provide the expected service, they will have a significant impact on the ability of the network to function efficiently.
- Bridge failure mechanisms are much more complex than those of roads and have less in-built redundancy against failure – as such, quality data is needed to understand and manage these mechanisms, so that bridge deterioration is managed and expected service lives are achieved.

1.2 Research objectives

To improve the current New Zealand practice in bridge asset management and move it closer to the standard of current international practice, the following research objectives were adopted:

- Provide a thorough understanding of international and local trends in bridge asset management, including the type of data that needs to be collected to fully meet the needs of the advanced asset management cycle.

- Provide an understanding of the current practices used by Territorial Local Authorities (TLAs) and NZTA bridge managers, as these reflect the policies followed by these organisations – this understanding would facilitate the development of a strategy to be used to answer the issues raised by the NZOAG.
- Develop a framework for the collection of bridge-related data, identifying the use to which the data would be put, and the accuracy levels that the data would need to achieve. This would align data collection and monitoring practices with the needs of the asset management cycle and strategic and operational needs.
- Develop an approach that prioritises bridges for data collection and monitoring, taking into account bridge risk and criticality in the transportation system (lifelines).
- Develop guidelines for optimal data collection and instrumentation, taking into account bridge type, design, material and condition, and existing data collection programmes (eg weigh-in-motion (WIM) systems operated by the NZTA), and flood, earthquake and other relevant data collected by third parties.
- Develop data collection guidelines that meet the varied needs of New Zealand road controlling authorities (RCAs), taking into account the range of transportation network complexities that are found in New Zealand, and addressing the range of asset management development levels that currently exist.

The strategy, based on a review of international and local practice and a survey of local practice, would identify good practice that could be adopted uniformly across the New Zealand bridge asset management arena, thereby disseminating the good practice that already exist in localised quarters.

The strategy would take into account the following important aspects of bridge asset management that personnel managing networks should ask themselves:

- What is the history of the data we have?
- In what system is the bridge data stored, and is it easily retrievable?
- Can the data be mined to provide information and knowledge of bridge performance?
- Are bridges appropriately classified, so that they receive the most appropriate management regime given their risk profile?
- Is the bridge management budget spent in the right areas, and are bridge maintenance and renewal outcomes optimal?
- Given that international and local practice are continually evolving, are my approaches aligning with good practice, and are therefore on par with peers?
- Where are improvements required to ensure the practices carried out align with good practice, and to ensure maximum value from carrying out those practices?
- Is the right data available to allow advanced asset management, as expected by NZOAG audits (NZOAG 2004, 2010)?

1.3 Research approach

To achieve the research objectives, a four-stage approach was used:

Stage 1 – a review of bridge asset management practice, which was used to define the current benchmark and to identify future directions

Stage 2 – a survey of the current New Zealand practice, which was used to understand the current national benchmark and, where required, to define the gaps, both positive and negative, between New Zealand and international practice

Stage 3 – development of a data collection and monitoring strategy to close the gaps that currently exist between international and New Zealand practice

Stage 4 – consideration of how the strategy could be implemented for a range of network and bridge types.

The first two stages of the approach provided the background to the strategic considerations, and the two final stages of the approach became the guiding sections of this report.

1.4 Report structure

Section 2 details the findings of the literature review, taking into account the need to collect strategic performance data, operational needs, data accuracy, and the end use of the data.

Sections 3–5 cover the aforementioned survey of the NZTA bridge managers and local authorities. A number of bridge managers were approached, including those from all the NZTA areas plus a range of local authorities, to ensure that large and small authorities were covered, as well as authorities with varying levels of asset management development. This range meant that the resulting strategy could be tailored to the varied needs of bridge asset managers in New Zealand.

Sections 6–8 provide details on the strategy, including recommendations on data collection requirements, changes to the inspection process, and integration and use of non-destructive evaluation (NDE) and structural health monitoring (SHM). As practice regarding how bridges are managed is changing, we reviewed the current state of practice in data collection techniques, taking on board the move towards full performance frameworks. The research also reviewed the monitoring regimes being used to manage bridges, including visual inspections, NDE and SHM.

Section 9 provides details of the strategy implementation framework, including examples of a risk- and criticality-based methodology for bridge prioritisation.

Finally, the recommendations and conclusions sections summarise the major changes proposed in the strategy and identify the directions of implementation and research efforts required in the future.

2 Review of bridge asset management

2.1 Introduction to the review

The focus of the review was to understand how the general asset management process, as outlined in figure 1.1, is applied to bridge management. A particular focus of the review was to understand how data collection and monitoring of road bridges is currently undertaken, and how the collected data is used in the decision-making process. The review covered international practice and compared it to New Zealand practice. The review topics were as follows:

- the asset management cycle and how it is defined
- how data collection is undertaken and how it can be improved, including the types of data collection methods
- the type of data that is collected, or needs to be collected, to optimally manage bridges
- the types of decision-making systems and how data is used in these systems
- how data is managed and stored, and how this can be improved so that asset management needs are met.

2.2 Main findings of the review

The literature review identified that a broad understanding of bridge performance, and the effect of bridge performance on the road network's performance, is important to strategic decision makers (NZOAG 2004, 2010, USGAO 2008).

We found that performance was considered to encompass the economic, social, environmental and safety benefits provided to society as a whole. In operational terms this equates to parameters such as load-carrying capability, economic outcomes, agency and project costs (efficiency), and environmental management. All of these needed to be linked through specifically developed performance measures. To achieve this goal it was recommended that bridge asset managers should align the data they collected with strategic outcomes, to ensure the required level of information and knowledge is developed. It was also found that the link between data and knowledge needs to be strengthened, even though work has been done in this area with the development of infrastructure performance frameworks (Félio and Lounis 2009*)*. This work mainly comprises greater understanding of the data that is needed to evaluate strategic performance.

We found that the data collected for bridges relied heavily on visual inspections, which did not always achieve the desired repeatability and accuracy and were often subjective (Moore et al 2001). An improved balance therefore should be sought between visual inspections, NDE and SHM. Data from these three techniques, together with inventory data, could be used for structural assessment; eg using the process of Structural Identification (St-Id) where an accurate structural model is developed and updated, reflecting the improved in-situ condition and operation of the bridge. The QA practices applied to bridge data were also identified as requiring strengthening (American Society of Civil Engineers, Structural Engineering Institute and American Association of State Highway and Transportation Officials 2009).

2.2.1 The asset management cycle and performance

To implement the asset management cycle, bridge managers must define service levels, agree on performance measures and set targets, collect data to understand where issues are occurring, and decide on whole-of-life solutions that meet the changing risk profiles of the network. Further to this, bridge managers should identify whether strategic goals are being met and how the network is being maintained and developed, such that it meets the needs of all of its users.

However, feedback from audits undertaken in both the US (USGAO 2008) and New Zealand (NZOAG 2008, 2010) showed that many bridge managers were failing to collect sufficient data or to generate information and knowledge on policy goals achievement, and were largely operating in a 'find-and-fix' paradigm of condition management and bridge replacement. Some countries were developing infrastructure performance frameworks (Félio and Lounis 2009), thereby moving away from a condition focus and towards a system of measures that could be used to inform strategic decision makers. To a lesser extent this has been carried out in New Zealand and is reflected in the New Zealand Transport Strategy[1] (NZTS) (MoT 2008) and the NZTA Statement of Intent (NZTA 2009c), both of which define performance measures for infrastructure. However, these documents do not develop performance measures to the level that direct assessment of operational delivery against government requirements can easily be achieved.

We found that many countries, even though they acknowledged the need to adhere to the asset management cycle, still followed the more traditional condition-data collection approach, with many of the policies surrounding bridge management based purely on inspections and basic performance assessment. This could be seen from much of the reviewed literature, which focused mostly on condition management and replacement. The associated bridge management models also focused on condition and maintenance optimisation. The by-product of this was a mounting maintenance deficit that could not be managed because of the lack of a full performance understanding. The impacts of bridge performance on network functionality were also not fully understood.

2.2.2 Data collection practices

Three processes are used to collect bridge data: visual inspections, NDE and SHM. This data can be used in a range of assessment processes such as St-Id, where a more accurate understanding of the as-built operational performance of a bridge is developed via creating and updating a bridge structural model.

We found that visual inspections were the most common form of inspection, with most countries carrying out general, detailed and special inspections, typically on 2-year and 6-year cycles (Bevc et al 1999). However, in some cases these cycles were altered according to bridge condition or failure risk (Kowalik 2009). While visual inspections were a simple form of data collection, a US study (Phares et al 2007) identified significant drawbacks to visual inspections, such as inability to identify the problem they were originally intended for, high outcome variability, lack of repeatability, and low accuracy. Those issues were deemed to be affected by aspects such as training, visual acuity, and the level of comfort (feeling of

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1 The NZTS was a non-statutory document released by the government of the day and has been largely superseded by subsequent policy decisions. So while the current government supports the overall intent of the NZTS 2008, the document is now less relevant as a practical guide to the issues facing the New Zealand transport sector in the immediate term. *Connecting New Zealand* (2011) is a summary of the current government's transport policy and intentions.

safety) of the inspector. Therefore, while visual inspections were the most common form of data collection, their use should be carefully monitored.

As visual inspections are not always able to identify problems, NDE and SHM have been implemented. These methods can be used to identify a range of problems, including chloride ingress, carbonation and material properties. SHM can also be used to identify other properties such as the load-carrying capabilities of structural elements. Monitoring is also useful as a network-level data-gathering tool (eg WIM, traffic counts, environmental conditions) and loads acting on the structure (eg hydrodynamic pressure from flood flows and seismic actions).

While SHM is more complex than NDE, it has the ability to more accurately define problems or to provide more accurate, up-to-date or real-time data. The already broad range of sensors that can be used is still growing. However, SHM still needs developing if it is to be used as an early-warning tool. This is primarily because a failure mechanism can occur anywhere in the structure, and in some cases have a similar signature to that of normal operation. SHM is also relatively expensive at this stage, and the level of training required is also significantly higher because of its complexity.

2.2.3 Decision making

A number of decision-making tools are available, ranging from simple risk assessments through to multi-criteria analysis and more complex stochastic modelling. The more advanced of these tools are beginning to take into account network functionality, as it is acknowledged that bridges are key nodes that affect road network operation. However, we found that decision making was largely condition-focused, unless new infrastructure was required, at which point economic evaluation methods were used. This would need to change if the wider network-level performance viewpoint was to be taken.

2.2.4 Data storage, usage and interrogation

Bridge asset managers store data in a bridge management system. These tools usually consist of an inventory, inspection-record area and decision-making tools (Curran et al 2002). Management systems that are expanded to include wider performance data (eg risk data, agency cost data, environmental data and economic data) have also been promoted. Bridge management tools range in complexity from purposely developed systems such as PONTIS (US Department of Transportation Federal Highways Administration 2008), through to simpler data-storage-focused systems such as RAMM (RAMM Software Limited 2011). Two areas for improvement that were noted in the literature review were:

- the need for QA with regards to the management of the data that is stored in these systems
- the need for a standardised inventory hierarchy for bridges, as this appears to vary between countries.

As databases grow larger, there will be an increased requirement for systems that perform data mining in order to access the relevant data and to make use of it in a way that information on, and knowledge about, the asset and its performance can be developed.

Recent international developments in bridge management have been predominantly in the area of condition-data collection, but further development will be needed if the wider performance frameworks are to be adopted, leading to a much-improved network-level understanding. An increase in performance frameworks will mean an increased requirement for data from bridge asset managers. In other countries this data was being collected using visual inspections, NDE and SHM, but there was only limited use of NDE and SHM in New Zealand.

2.3 The asset management process in detail

Asset management is a recognised process (Roads Liaison Group 2005, Kim et al 2010) (refer back to figure 1.1) that is used to ensure an asset (eg a bridge) operates in an optimal way that optimises the life of the asset and maintenance and management costs, and meets present and long-term demands. This is achieved by developing LOS and performance measures, setting targets, recording data on current performance, and assessing risk. Risk-based management plans are then developed and implemented. Furnishing the asset management process with the required data at the required level of accuracy is therefore the key to maximising the understanding of the asset and its performance.

With a view to standardising the asset management process, a number of countries have developed their own country-specific practice documents. These include PAS 55-1:2008: *Specification for the optimised management of physical asset*s (British Standards Institute 2008), *International infrastructure management manual* (IIMM) (Hughson et al 2006), and *Management of highway structures, a code of practice* (MHSCoP) (Roads Liaison Group 2005). While these documents are all industry-led, research input is occurring on specific aspects of the cycles noted in these documents, including advanced data collection and decision making, and setting of bridge-specific technical performance measures.

PAS 55-1: 2008 covers asset management, asset management policy, strategies, objectives and plans, enablers and controls, implementation, assessment and improvement, and management reviews – all areas that have to be taken into account when developing an asset management process. The document defines asset management as:

> *Systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan.*

Specific strategies detailed in the document and applicable to this research are:

- consideration of the life cycle management requirements of assets
- taking into account asset and asset-system-related risks and criticalities
- identification of function, performance and condition of existing assets and asset systems
- articulating the desired future function(s), performance and condition of existing and new assets and asset systems.

The IIMM (Hughson et al 2006) framework links LOS, performance measures, data collection, decision making and implementation to create a formalised asset management process that is internationally recognised. The manual promotes a stepped approach comprising core and advanced asset management levels. The core asset management provides a basic understanding of the asset and its needs; the advanced asset management provides an understanding of the relationship between LOS, performance, funding requirements, and the risks associated with not meeting the service levels. The stepped, core and advanced approach is applicable to the strategy under consideration in this report, as not all managers will require an advanced approach, especially for lower-risk and criticality bridges. However, according to the NZOAG comments (NZOAG 2004, 2010), development is still required in many cases to move from the core approach to the advanced approach. The identification and provision of data to meet the requirements of the advanced approach is an important step in realising this goal.

MHSCoP (Roads Liaison Group 2005) promotes the same ideals as PAS 55-1 and IIMM, but provides bridge-specific detail on data management, setting LOS, inventory, and financial management. Like IIMM, MHSCoP recognises that development is an incremental process and that not all authorities require complex management systems – an important consideration when developing a data collection strategy. In line with good asset management practice, four key performance measures – condition, availability, reliability and structures work-bank (total outstanding bridge management costs) – are promoted. The code is therefore one of the earliest documents to provide guidance on performance-related aspects of bridge asset management. These performance measures should be taken into account for the data collection strategy. However, the MHSCoP still fails to identify whether optimal and sustainable bridge management solutions are being promoted at a network level, as there is no clear link between network performance and the identified bridge maintenance/management issues. This observation again highlights the operational and strategic discontinuity identified by the NZOAG audits. A data collection strategy therefore has to help to close this gap.

More recently, Austroads have produced *Guide to asset management part 6: bridge performance*, which covers the performance of bridges with respect to the life cycle management (Maguire 2009). Like the MHSCoP, it provides details of good asset management of bridges and covers data collection, service levels, performance (ie structural capacity etc) and decision making. However, unlike other bridge management documents, it also recognises that bridges provide a network support function. The document considered asset management to be:

> *A comprehensive and structured approach to the long term provision and maintenance of physical road infrastructure using sound engineering, economic, business and environmental principles to facilitate the effective delivery of community benefits.*

In 2005, the US Federal Highway Authority (FHWA) carried out a review (Cambridge Systematics and Meyer 2007) of transportation asset management practices. The review found that asset management should be:

> *... guided by performance goals, cover an extended period of time, and draw on economics, as well as engineering; and at its most basic level should link together condition, performance, and availability with system management and investment strategies.*

Key findings from the study were as follows:

- The collection of data was seen as an important decision-support function, and data was considered as an asset in its own right that has to be managed appropriately.
- New technologies (eg NDE and SHM) have the potential of making data collection more cost-effective and efficient.
- Most successful strategies had moved away from making worst-first investment decisions towards a life cycle cost approach.
- There was little evidence of risk analysis techniques adopted in the asset management process.

Based on these descriptions, asset management has definable common principles including setting LOS, monitoring performance, risk management, whole-of-life analysis and performance optimisation. All of these have their own specific data needs and therefore need to be catered for in a data collection and monitoring strategy.

Further, it is clear that asset management is a process that evolves out of the need to more accurately understand critical aging infrastructure (Kim et al 2010). It is therefore essential to define and collect the data that can be used to understand the range of problems posed by constantly deteriorating infrastructure acting under constantly changing performance criteria.

2.4 LOS, performance measures and targets

A LOS is a defined service quality for a particular activity (Hughson et al 2006). It was developed by policy makers and tested through consultation with customers such as road users, freight managers, cyclists and pedestrians. Levels of service use measures to benchmark performance (Hughson et al 2006, Roberts et al 2006), and each performance measure has a target or range. In measuring performance, both customer and technically focused measures are used (Roberts et al 2006).

While performance measures were not the focus of our study, data collection was obviously a key stage of the performance assessment process, as both technical data and 'softer' stakeholder surveys were required. It was therefore important to understand the range of performance measures needed to describe the asset operation, and to match the data collection strategy to these measures.

2.4.1 Current performance management issues

In 2004, the USGAO recommended that bridge engineers should identify how the decisions they make not only ensure a functional and safe bridge asset but also, and equally importantly, identify how well they are delivering on national policy directives (USGAO 2008). At a similar point in time, the NZOAG reviewed service-level delivery across all assets, and found that many local authorities needed to create comprehensive frameworks, thereby allowing communities to understand the reason for each service and the level to which services were being achieved, including the associated value and costs of those services (NZOAG 2004, 2010). In light of the audit findings, NZOAG recommended the development of a framework that considered performance measures, was cognisant of the effects of time, and had a useful reporting structure, including commentary on strategies and uncertainties (NZOAG 2004).

According to the US and New Zealand audits, it is clear that bridge asset managers have not been meeting the criteria for acceptable bridge asset management, even though strategic measures existed to facilitate performance assessment – bridge asset managers therefore should be collecting data that would provide an understanding of their achievement. However, at the time of this research there was no clear link between the data that was collected and strategic performance measures.

Canada had already developed a framework for the management of core public assets (Félio and Lounis 2009) that included service levels relating to public safety, health, mobility, environmental quality, social equity, economy and public security, and linked strategic performance to operational measures. As an example, the public safety measures are outlined in table 2.1.

Table 2.1 Example of performance measures detailed in the Canadian framework (Félio and Lounis 2009)

Objectives	Performance indicator
Public safety	Condition rating of the asset
	Rated capacity versus maximum loads on the asset
	Load capacity of strength rating
	Bridge condition index
	Bridge width
	Reduction in number of fatalities and injuries
	Number of vehicle crashes
	Protection against climate change
	Number of truck or ship collisions with the bridge

2.4.2 LOS and performance measures

The New Zealand document defining the performance of all transportation-related assets is the NZTS (MoT 2008). With regards to state highways, this is further expanded in the NZTA Statement of Intent (2009c), which states that all national service levels have to be taken into account when collecting data to detail how they are being delivered. Examples of national service levels include the following:

- more efficient and reliable infrastructure
- improved transport safety
- improved transport access
- lower environmental impacts
- improved customer services.

The New Zealand Ministry of Transport (2010) indicators are as follows:

- access to the transport system
- environmental impact
- infrastructure investment
- network sustainability
- public health
- safety and security
- travel patterns
- transport indices
- transport volume.

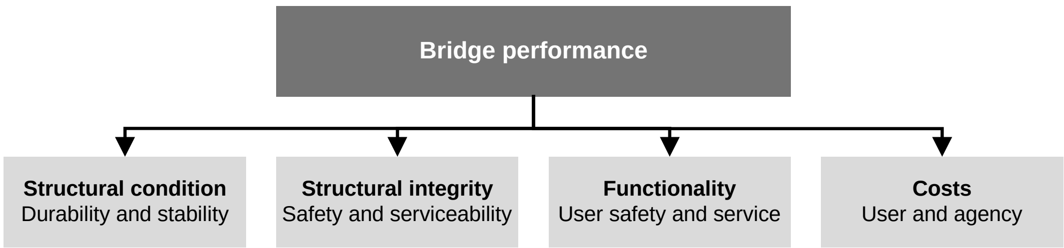
Our review revealed a wide range of national and international performance measures, and that a data collection and monitoring strategy has to be flexible enough to cope with the changing nature of those measures.

In developing an understanding of bridge-specific performance requirements, Ghasemi et al (2009) noted that the user community expected bridges to accomplish their purpose, or to perform in a satisfactory manner, as follows:

- Bridges should present a minimal hazard to users and minimal obstruction to the free flow of traffic during normal service.
- They should produce a minimal negative impact on the local and global environments during construction and maintenance.
- They should present an acceptable level of risk against catastrophic failure.
- They should have a pleasing appearance.
- All of this should be achieved with the minimum whole-of-life cost.

A summarised version of bridge performance issues is detailed in figure 2.1.

Figure 2.1 Bridge performance framework (Ghasemi et al 2009)



Ghasemi et al (2009) further developed specific performance data collection needs for bridges, as noted in table 2.2. If a holistic view of asset performance is to be achieved, bridge performance requirements as noted in figure 2.1 and table 2.2 need to be directly tied to strategic performance measures.

Table 2.2 High-priority bridge performance issues (Ghasemi et al 2009)

High-priority performance issues	
Category	**Issue**
Decks	Performance of untreated concrete bridge decks
	Performance of bridge deck treatments (membranes, overlays, coatings, sealers)
	Performance of precast reinforced concrete deck systems
	Influence of cracking on the sensitivity of high-performance concrete decks
Joints	Performance, maintenance and repair of bridge deck joints
	Performance or jointless structures
Steel bridges	Performance of coatings for steel superstructure elements
	Performance of weathering steels
Concrete bridges	Performance of bare or coated/sealed concrete superstructures and substructures (splash zone, soils, or exposed to deicer runoff)
	Performance of embedded or ducted prestressing wires and post-tensioning tendons
	Performance of prestressed concrete girders

High-priority performance issues	
Category	**Issue**
Bearings	Performance of bridge bearings
Foundations and scour	Direct, reliable, timely methods to measure scour
	Performance of scour countermeasures
	Unknown foundation types
	Structure foundation types
New construction	Performance of innovative materials and designs
Risk	Risk-based management approach
Functionality	Operational performance of functionally obsolete bridges

Maguire (2009) (table 2.3) identified nine areas specific to bridge management. These areas were further extended by Kadar (2009) to include environmental data and construction maintenance expenditure data. While Maguire included bridge historical data, only storage of defect data was recommended and not the long-term storage of condition data. Defect data in this report is understood as descriptions of the actual issues identified on a bridge, and condition data is the numerical representation of a condition state.

Table 2.3 Bridge data recommended for collection in Maguire (2009)

Key bridge data	
Inventory data	Stream/river flow
Inspection records	Traffic surveys
Maintenance history	Services
Design and construction	Cost-accounting data
Crash reporting	

An earlier Austroads document, *Bridge management systems: the state of the art* (Curran et al 2002) aimed to support consistency in Australia and New Zealand inventory and condition data for road bridges by developing a minimum set of inventory items, condition descriptors, inspection regimes, and indicators of condition and reliability for bridge structures. In this document, the data that should be collected was linked with the proposed database structure. However, while the literature review revealed a wide range of bridge systems and practices, it found no clear and definitive recommendations regarding the detailed data that should be collected, and only the data headings were mentioned. This report therefore provides a starting point for developing a data collection and monitoring strategy.

Data on condition is always specified by bridge management systems, but in reality condition data is an umbrella term for a wide range of deterioration processes including:

- corrosion of reinforcement
- corrosion of steel and pre-stressing tendons
- inadequacy/failure of waterproofing membrane
- freeze/thaw damage to parapet edge beams
- alkali silica reaction

- cracking and spalling of concrete cover
- scour of foundations and abutments (Daly 2001).

In bridge management systems, condition data is usually expressed as a numerical rating (Bevc et al 1999, Highways Agency (UK) 2007) that can be easily stored and later interrogated.

2.4.2.1 Benchmark data

In 2006, the Centre for Innovative Bridge Engineering submitted a report to the FHWA entitled *Development of a comprehensive plan for a long-term bridge performance program* (Chajes et al 2006). The programme's aim was to collect long-term data (over 20 years) that could be used to better understand the bridge deterioration process. Some 500 bridges, located throughout the US, were chosen for a larger sample set, with the testing programme using visual inspections and other NDE techniques to assess in detail the performance of seven representative bridges. The strategy included the collection of baseline data, regular inspection data and supplemental data.

The type of data collected as part of the baseline process included concrete cover, reinforcement location, concrete compressive strength, steel properties, coating types, bearing details and drainage information. This type of baseline data should also be collected in New Zealand. It would improve remaining-life and deterioration models by providing them with initial conditions.

The regular inspection data that was collected as part of the study focused on key areas of the bridge, including decks, superstructure (steel), superstructure (concrete) and substructure. The type of data collected included de-lamination details, voids, corrosion, spalling and scour.

The data collected between inspections included accident details, flood events, maintenance and rehabilitation actions and loading history. This data should also be collected in New Zealand to allow the improvement of models and the assessment of the effects of environmental factors and loading history.

According to Brownjohn et al (2004), collecting the above data would facilitate:

- tracking the long-term degradation of materials in critical structures
- enhancements to the effectiveness of resource utilisation as a construction deteriorates and its maintenance needs increase
- validation of modifications to an existing structure
- assessment of the safety performance of structures affected by external works
- feedback to the design process
- checks on new structural forms
- the move towards performance-based design philosophies, also underpinned by the use of SHM and NDE.

The performance of bridges is clearly a complex issue requiring significant amounts of data. A data collection strategy should therefore include the wider performance criteria and map them to specific data requirements. A data collection strategy should also be responsive and flexible enough to allow for change, as performance strategic objectives and targets are clearly linked to a nation's political direction at any one time.

2.4.3 Performance targets

Performance measures have associated targets that can be technical or customer-focused (Roberts et al 2006). Setting targets allows goals to be set and progress monitored.

Customer-focused targets are specific to individual networks and bridges and are outlined in an authority's asset management plan. Wider customer-focused data is not stored directly in the bridge asset management system, but is used to modify technical performance levels so that they align with customer and stakeholder expectations. However, bridge-specific customer data should be stored, or at the very least linked to, the bridge database (eg customer perceptions of bridge performance), especially for key links.

As noted in table 2.4, commonly recognised technical targets in New Zealand are defined by legislation including health and safety acts, environmental acts such as the Resource Management Act (New Zealand Government 1991), and design codes and guides covering geometric alignment, vehicle loadings (NZTA 2006), condition data collection (NZTA 2001), load-carrying capability (Standards New Zealand 2006a, b) and durability expectations, as noted in table 2.4. These documents provide the benchmark for managing bridges. Any gaps between the desired and current targets are considered to be a risk; these risks have to be assessed and managed, but not always mitigated. In some cases, the codified desirable limit may not be achievable; a safe working limit may therefore be decided (eg in the form of posting and rating of a bridge – NZTA 2006).

All applicable technical measures should be taken into account when assessing the performance of a bridge or bridge asset group, with data relating to the most important measures collected and stored in the bridge management system.

In cases where generalised targets are considered inappropriate, bridge-specific targets should be set, thereby allowing asset managers to operate a bridge up to a predefined acceptable safety limit, rather than the generalised limits defined by codes and standards. Research in this area has focused on developing reliability functions, where an improved statistical understanding of loads and material properties would allow a better understanding of bridge performance (O'Connor et al 2009, Casas 2011). This provides asset managers with the ability to work the asset harder and therefore to achieve higher operational efficiency.

Bridge reliability needs to be interpreted in the context of its effect on the entire network. At the time of this research, this was not the case for bridge asset management internationally, with only individual bridge performance being assessed. Such wider considerations are a requirement of strategic network-level performance models. This approach can also be applied to any system or problem that includes uncertainty (Liu and Frangopol 2006, Frangopol 1999), including cost data, deterioration rates and many other bridge-related parameters.

For example, in a power sector network, the reliability of an individual component and its effect on the network can be assessed (Fickler et al 2009). Even though such assessment is a requirement in strategic network-level performance models, it is currently not applied to bridge asset management. To achieve this, more accurate and strategically focused data collection would be required, and the use of collection techniques such as NDE and SHM. The development of the monitoring strategy also needs to take into account how data will be used in the decision-making cycle.

The review has shown that a broad range of data has to be collected and stored in order to efficiently manage bridges. This was further supported by Lee et al (2008), who noted that modern bridge management systems have only been in existence for approximately 20 years, and therefore only limited long-term condition data was available. However, the quality of the data could be strengthened by combining and relating data from many sources. Therefore we recommend a broad-ranging data collection approach.

Table 2.4 Formal documents defining technical performance targets

Focus	Documents detailing performance measures
Highway operation	*Land transport management act* (New Zealand Government 2003)
	Land transport management act (New Zealand Government 1998)
	Heavy motor vehicle regulations (New Zealand Government 1974) (axle and gross vehicle weights)
	Setting of speed limits rule (Rule 54001) (LTSA 2004)
	Traffic control devices rule (Rule 54002) (LTNZ 2005)
Society (safety)	*Building regulations* (Department of Building and Housing 1992)
	Occupational health and safety (OSH) regulations
	Working at height regulations
	Code of practice for temporary traffic management (COPTTM) (NZTA 2004a)
Environmental	*Resource management act* (New Zealand Government 1991)
	Regional standards pertaining to flood levels, sea-level rise and other specific environmental requirements that are relevant for bridges
Bridge-specific measures	*Bridge manual* (NZTA 2005)
	Design codes for concrete, steel, and timber structures
	Assessment codes for concrete, steel and timber bridges

2.5 Bridge data collection and monitoring practices

Data collection is the foundation of asset management (refer back to figure 1.1) – without it, it is impossible to understand how an asset is functioning. Yang et al (2011) advocated that accuracy in bridge maintenance management models could be achieved via better integration of qualitative and quantitative methodologies. Internationally, as mentioned earlier, data collection is carried out using a number of techniques including visual inspections, NDE and SHM. These techniques are discussed next, as well as St-Id, which is a paradigm that utilises data for structural assessment. By collecting data using both qualitative and quantitative techniques, it would be possible to extend the bridge maintenance management system philosophy proposed by Yang et al (ibid) to the data that enters the system.

2.5.1 Data collection using visual inspections

Two aspects of visual inspections are covered in this section: the issues relating to visual inspections, and a review of the processes used in New Zealand and internationally.

We found that the process of undertaking inspections was well-defined for many countries (Bevc et al 1999), but a US review of inspection practices identified the following:

> *Visual inspection by experienced professionals has been effective in identifying critical conditions affecting bridge safety but, in some cases, material defects and concealed elements do not lend themselves well for visual inspection and may need supplemental methods. NDE [SHM] and condition monitoring technologies have been developed in recent years that can, in some cases, assist in the effective condition assessment and monitoring of bridges. However, the application of these technologies continues to be a challenge, due to*

the complexity and accessibility of these technologies and a lack of effective guidance on the appropriate application of the technologies (American Society of Civil Engineers, Structural Engineering Institute and American Association of State Highway and Transportation Officials 2009).

The following specific issues were noted in the review:

- A more rational, risk-based approach to determining the appropriate inspection intervals for bridges is needed, as opposed to a set 24-month cycle for all bridges. This approach would consider factors such as the design, details, materials, age, and loading of specific bridges to determine the interval between inspections.
- New and more assertive types of quality control and assurance, such as performance testing of inspectors, could be used to encourage consistency of inspection practices.
- The consistency and effectiveness of inspections could be improved if inspector qualifications were matched to the bridge type, condition and complexity in a more uniform manner.
- A bridge inspection manual should be developed with expanded use of photographs, illustrations and detailed drawings indicating specific deterioration conditions, and methods of reporting deterioration.
- Close collaboration is needed between those responsible for the maintenance and repair of a bridge and those responsible for bridge inspection.
- The development and maintenance of a centralised system for documenting critical deterioration in bridges, as experienced by bridge owners, is needed to support the interchange of information and to provide a resource for bridge owners.
- Standardised procedures for special inspections involving NDE (eg pin inspections) should be developed to provide more guidance to bridge owners.
- Terms such as ‘structurally deficient’, ‘functionally obsolete’, and ‘fracture critical’ require accurate definitions in the public arena so that the public’s perception of bridge safety is consistent with the facts.

In contrast with data collection for roads, we found that there was no high-speed alternative for collecting data for bridges, and visual inspections remained the predominant method of collecting large amounts of condition data (Bevc et al 1999). However, a 2001 US study (Moore et al) identified the following acknowledged issues with the visual inspection process:

- Inspections have significant variability – 50% of inspectors vary in their condition ratings by one point on a 10-point rating system, and 5% of inspectors vary by at least two points in their assessments.
- Detailed inspections that solely use a visual-based approach are unlikely to detect or identify the specific types of defects for which the inspection is prescribed, and may not reveal deficiencies beyond those that could be noted during a general inspection.
- Accuracy can be affected by the perceived amount of time that is available to complete the inspection, comfort with access equipment and heights, structure complexity and accessibility, ability to view welds, flashlight use, and the number of inspections that have to be performed.
- Forty-eight percent of US state agencies and 55% of county managers use professional engineers between 0% and 20% of the time – ie professional engineers are not used on the majority of inspections.

- Visual acuity and other visual aspects are not tested by state bridge managers, and this affects inspection results.
- The main quality-control assurance measure used for state, county, and contractor reports is an office review of the inspection reports.
- The most common quality-control measures are re-inspection to spot-check reports, and occasional professional engineer attendance.

These findings indicate that a data collection and monitoring strategy should include visual acuity checks and improved training accreditation for inspectors and more formalised reviews of data. It is also clear that the use of visual inspections in a bridge management regime should be reviewed – because the data is the baseline from which maintenance decisions are made, data accuracy is essential. There needs to be a balance between the use of visual inspections and the improved accuracy achieved from NDE and SHM. In line with the original objectives of the research, this should be risk-based. Further, it is clear that a review of the inspection process should be undertaken and NDE and SHM should be used more.

New Zealand inspection policy, as defined by the NZTA's *Bridge inspection and maintenance manual* (2001), has been developed over a number of years, based on the 1983 UK Department of Transport (DoT) *Bridge inspection guide* (now superseded by the UK Highways Agency 2007 *Inspection manual for highway bridges*). Further, New Zealand has adopted an approach where condition assessment is not carried out – defects and recommended time to action are recorded in lieu of condition.[2] This provides an understanding of the defects found on the bridge, but not the prerequisite data required by condition-rating systems used for advanced asset management. As such, New Zealand inspection practices require alignment with current international practice, and the data collection strategy should therefore promote methods of carrying out condition rating.

The New Zealand *Bridge inspection and maintenance manual* (ibid) categorises inspections as 'superficial', 'general', 'detailed' and 'special' (now 'routine surveillance', 'general', 'principal' and 'special' inspections under the 2011 inspection policy (NZTA 2011)). General inspections follow a two-year cycle, and detailed inspections are carried out on a six-year cycle; the detailed inspections therefore replace the general inspection in the sixth year. Defects identified as part of the inspection process are recorded on Form 801 (see figure 2.2). (However, see the footnote for the recent changes to the condition data collection by the NZTA, replacing Form 801).

A 1999 review of bridge management in a number of countries, including Austria, Denmark, France, Germany, Norway, Slovenia and the UK, and also the US (Bevc et al 1999), studied practices used for the assessment of structural condition and the classification of defects. While this study is now relatively old, it provided a comprehensive view of inspection practices. Common themes included the following:

- Many countries use a risk-based approach to vary inspection cycles, with inputs based on current condition, age and importance.

2 At the time this report was in peer review, the NZTA formally adopted (NZTA 2011) the UK Highways Agency's updated bridge inspection practices (Highways Agency 2007). This approach uses condition rating. However, this report has retained the findings that were current at the time of the research. Where necessary, the changes to NZTA inspection practices have been noted.

- Inspection regimes tend to comprise superficial, general, detailed and special inspections, or combinations thereof.
- Many countries provide condition examples in catalogues or handbooks, including photographs and detailed descriptions of condition states.
- Most countries use a five-point rating system for condition, but this may be lowered to four or increased to 10.

The risk-based inspection cycles are considered to be relevant to this study, as not all New Zealand authorities have the required resources to undertake a detailed inspection programme. Arguably, based on Moore et al’s findings (2001), it is also questionable whether principal inspections provide significant value, compared with general inspections.

2.5.2 Data collection using non-destructive evaluation (NDE)

In the context of this report, NDE refers to the type of testing that:

- does not destroy the tested bridge element or component
- typically uses simple tools and techniques
- is short in duration
- can be carried without attaching sensors to the bridge for long time.

Some NDE approaches may use invasive techniques to obtain the required samples and data (Highways Agency (UK) 2006) and destroy small samples; however, in doing so they do not compromise the structure’s structural strength and integrity. Some examples of such tests are concrete core strength, steel tensile strength, or the carbonation test. Unlike SHM, NDE needs to be specifically arranged and carried out, and does not provide data or information on demand using automatic data-collecting systems.

Bar-Cohen (2000) showed that NDE had developed over a long period of time and was a technology that provided a great improvement over visual inspections. *BA86/06 Advice notes on non-destructive testing of highway structures* (Highways Agency (UK) 2006) outlines many of the processes that are recognised and currently used in the bridge inspection field. These include the concrete core compression test, Schmidt hammer, steel tensile test, chloride sampling, carbonation tests, half-cell potential test, cover-meter surveys, delamination surveys, and many others.

Figure 2.2 Extract from NZTA S/6 Inspection Form 801 (NZTA 2001)

NZ TRANSPORT AGENCY
WAKA KOTAHI

Bridge Inspection Report

Bridge Name: .... Highway: .... R.P: ....
Spans: .... Width Between Kerbs: .... Length: ....
Type of Bridge: .... Restrictions: ....
Inspected By: .... **Date**: / / **Reviewed By**: .... **Date**: / /
(Bridge Inspection Engineer)

Check List

General		
1	Appearance	
2	Approach adequacy	
3	Signs	
4	Vibration	
5	Bearings	
6	H.D Bolts and Linkages	
7	Expansion Joints	
8	Footways	
9	Road safety barriers and/or handrails	
10	Deck drainage	

Superstructure Concrete		**Deck**	**Main Member**	**Sec. Member**
11	Cracking			
12	Spalling			
13	Reinf. Corrosion			
14	Other defects			

Superstructure Steel		**Main Member**	**Sec. Member**
15	Condition of Paint		
16	Corrosion		
17	Joints		
18	Rivets and Bolts		
19	Other defects		

Superstructure Timber			
20	Decay		
21	Warping and Cracking		
22	Deck wear		
23	Bolts and Spikes		
24	Other defects		
25	Date of last boring		

Foundations and Substructure		
26	Settlement	
27	Cracking	
28	Spalling	
29	Abrasion	
30	Corrosion of Steel	
31	Other defects	

Scour and Waterway		
32	River aggrading	
33	River degrading	
34	Waterway adequate	
35	Erosion of abuts/ approaches	
36	Embedment of foundations	
37	Other erosion or scour risks	

Marking Code

Not inspected	0	Routine maintenance *(provide comment)*	3
Satisfactory	1	Structural maintenance *(provide comment)*	4
Monitor next inspection	2	Not Applicable	N

Remedial work recommended last inspection has been completed: **YES** **NO** *(comment overleaf if answer is NO)*

NZTA Database Changes Required **YES** **NO** *(describe change if answer is YES)*

(Continue over if required)

Comments and Recommendations for Maintenance/Repairs

Item	**Brief Description of Fault and Recommendations for Repair and Urgency**	**Cost Estimate**
	(Continue over if required)	

Comments and Recommendations Relating to Future Management (Transfer to Current Report)

Item	**Defect/Strategy**	**Person (Bridge Inspection Engineer)**	**Date**

A number of developing NDE technologies within the aircraft, composite and machine industries could be adopted and transferred to bridge asset management – for example, the Magneto-Optics Imager (Bar-Cohen 2000) has crack-detection applications. NDE is often employed in a reactive way to collect data on a defect or damage that has already occurred and been detected via visual inspection. However, NDE can also be used as a proactive tool to track changes and estimate future states – for example, the time to the initiation of corrosion of reinforcement, and the progress rate of corrosion based on measured levels of carbonation and chlorination.

Further discussion of NDE techniques that could be used for bridges are included in section 8.3.1 of this report.

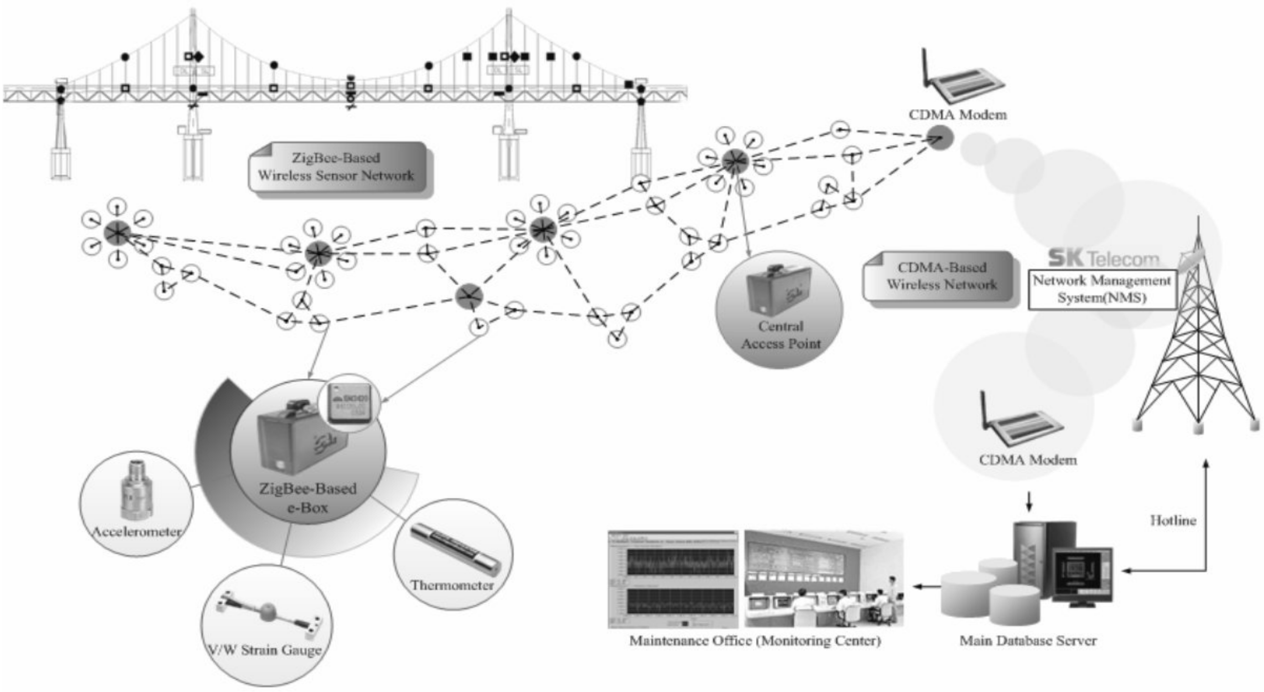
2.5.3 Data collection using structural health monitoring (SHM)

A significant amount of work has been, and continues to be, undertaken by the SHM community of researchers and practitioners, with two main focus areas being sensor development and data analysis techniques. This research is being undertaken all over the world, including the US, Europe and Asia (notably Korea, Japan and China). Most of the easily accessible information addressing more general approaches to the use of SHM (ie its integration into the structural assessment and wider bridge assessment and asset management) has been published in the US (American Society of Civil Engineers and Structural Engineering Institute 2011, Gastineau et al 2009, Glaser et al 2007, Khuzadi 2008) or Europe (Rücker et al 2006a, Rücker et al 2006b, Farrar and Worden 2007).

The notion of SHM adopted in this study defines it as a type of data collection that provides information (data) on demand about structural performance and any significant change or damage occurring in the structure. In the context of this strategy, SHM also comprises automatic data collection on wider network performance and environmental and operations factors affecting a bridge (eg traffic volumes, seismic excitation and river flows).

Figure 2.3 details an example of a wireless bridge management SHM system (Kim et al 2010) that includes bridge sensors, sensor control points, wireless communication routers, servers for data storage and end-user interfaces. This could be a much simpler arrangement if only a few sensors are used, or significantly more complex for a large number of sensors or for a large number of bridges located on a network. In New Zealand, consideration should be made of the availability of telephone signals, as coverage is not available everywhere (Telecom New Zealand 2010), a key consideration for remotely located critical bridges.

Figure 2.3 An example SHM arrangement used for bridge monitoring (Kim et al 2010)



Gastineau et al (2009) defined six key features of this SHM process as (1) real-time monitoring of (2) in-service structures using (3) an array or networks of sensors to collect data that can be used to (4) detect changes in the condition of a structure over time. The data is (5) communicated over a network, and (6) data-processing algorithms may be used, if possible, for damage localisation, classification and assessment, as well as residual life assessment.

To achieve the successful implementation of SHM, the following four-stage approach is usually adopted (Farrar and Worden 2007):

- operational evaluation
- data acquisition, normalisation and cleansing
- feature selection and information condensation
- statistical model development for feature discrimination.

Operational evaluation is the desktop-study phase to assess the reasoning behind the SHM strategy and includes life-safety and economic benefit justification, what damage/defect is to be monitored or is of most concern, what conditions the system should be monitored for, and what the limitations on acquiring data in the operational environment are. With a data collection perspective, data will be required to understand the economic benefit and the cost of implementing the system.

Data acquisition refers to the selection of the collection methods and sensors. Data will often be collected under varying environmental conditions, where environmental effects have to be separated from the damage effects that the system is trying to measure.

Feature selection and information condensation is the most studied phase, as is feature sample extraction and comparison between the damaged and undamaged structure. The most common approach used is the correlation of responses obtained from an SHM arrangement linked with observations of the system as it degrades. Data obtained from monitoring the bridge or network is linked to a number of sources spread across a number of bridge elements and a number of locations. Large amounts of data will be produced. Robust data-reduction techniques are therefore required, as asset managers need information, not just raw data (Brownjohn et al 2004). By helping to provide the information that an engineer needs to understand the structural action, data-reduction techniques aid the decision-making process (Farrar and Worden 2007).

Statistical model development for feature discrimination comprises statistical model development and includes the models that will be used to discriminate between the damaged and undamaged structure. There are many models available – for example, for the development of deterioration curves for bridges and elements, or for triggers so that outlier measurements cause specific management actions to occur.

One discipline that has had significant experience in the development of SHM systems is the aeronautical industry, as SHM is widely used on aircrafts to provide real-time feedback on operational parameters. The main recommendation that has arisen from research in this area is that it is essential that a top-down approach is employed in the development of health-monitoring systems. If a bottom-up approach is used, sensors may not cover all the intended areas and may not provide the level of feedback or the type of feedback that is required (Khuzadi 2008). The strategic aims of the SHM system therefore have to be understood before setting out on the development journey; this is especially relevant for bridges with high sensor numbers (Lynch 2007). On such bridges, the high costs associated with sensor installation can be justified if they are considered to be critical to the operation of the highway and therefore have a high level of importance.

Several applications of SHM were promoted by a US–China research programme (see table 2.5) (Glaser et al 2007). All of these are considered to be performance criteria that must be understood if asset appreciation at the strategic service level is to be developed. These applications are operationally focused, and therefore must be linked to the strategic decisions that are being made.

At the time of this research, Canada appeared to be the only country with a formalised SHM methodology that was being used by practising engineers (Rivera et al 2007). Their code covered the installation of fibre optic sensors, the type of conduits that could be used to protect them, and problems that could occur when sensors were installed. The code also covered methods to protect sensors and conduits during the installation phase. Other aspects covered included the choice of data acquisition units, and the use of specialised professionals for system installation. This code was especially relevant to our study, as it covered topics that were important for practising engineers who were planning the installation of SHM systems.

SHM is considered to be an important tool for bridge managers, as it can provide access to much more accurate data on an asset, and will therefore lead to a deeper understanding of performance, especially in the field of reliability. Further discussions about operations aspects of SHM techniques as applied to bridges are included in section 8.3.2.

Table 2.5 Systems and hazards identified by the US–China SHM programme

Target system that future SHM research should focus on	Areas for measurements that are associated with system
Signature bridges	Over-stressing, corrosion, wind/rain vibration, earthquake, intentional damage, uneven cable force distribution, breakage of cables, fatigue
Precast concrete girder bridges	Shear cracking, over-stressing, earthquake, intentional damage, corrosion, loss of pre-stress
Lifeline systems	Corrosion, leakage (pipes), wind, earthquake, intentional damage

2.5.4 Structural Identification (St-Id)

St-Id is an emerging paradigm that is used to understand the structural behaviour of a bridge. It uses bridge data to develop structural models that provide an improved understanding of the in-situ operation of the bridge under consideration. This has been seen as a step forward from the current approach, which generally uses the same assumptions to create those models as those that were used in the design process. St-Id is defined as:

> *The process of creating/updating a physics-based model of a structure (e.g., finite element model) based on its measured static and/or dynamic response which will be used for assessment of structures* (American Society of Civil Engineers and Structural Engineering Institute 2011).

The six stages of St-Id have been defined as follows:

- observation and conceptualisation of the structural system to understand relevant mechanisms of loading, deformations and load transfer, and critical structural details
- geometric measurements, visualisation and initial modelling
- experimentation – in-situ collection of static and/or dynamic data

- data processing and interpretation
- selection and calibration (updating) of structural models, such as FEM models, based on interpreted data
- utilisation of the structural models for structural assessment and decision making.

Because of its ability to more accurately describe a bridge's operational environment and capabilities, St-Id is a useful and important process for bridge asset management. For the bridge-engineering community, it is also attractive because it incorporates well-established and accepted approaches and tools such as FEM modelling. From the point of view of the data collection and monitoring strategy presented in this report, the above St-Id stages 1–3 are of direct importance. It is clear that these stages will overlap and use data supplied from inventory (eg bridge, element and component descriptions and drawings), visual inspections, NDE (eg in-situ concrete strength) and SHM (eg dynamic-response data). The choice of data collection technique will be directly related to the parameter identification requirements of the model. Furthermore, underlying the St-Id paradigm is the strong and logical connection between all its stages – in particular, the links between the collected data and its ultimate use are clearly articulated. Strictly speaking, data analysis, model updating and its use in simulations fall outside data collection as such – but these clear links make St-Id an attractive approach as it addresses the underlying philosophy of the strategy that all data should have a clear purpose.

Table 2.6 World Bank information quality levels (Paterson and Scullion 1990)

IQL[a]	Description	Applications	Data collection	Management function
I	Most detailed and comprehensive	Research, operations, advanced design, diagnosis	Short to limited lengths or isolated samples, using specialised equipment; slow except for advanced automation	Operations
II	Detailed	Design preparation, advanced programming, and advanced planning	Limited lengths using semi-automated methods; or full coverage using advanced automation at high speed	Operations and preparation
III	Summary details with categorisation of values	Programming, planning and basic design	Full sample using high-speed, low-accuracy, semi automated methods; or sample at slow speed; or processed from other data	Preparation and programming
IV	Most summarised	Sector/network statistics, simple planning and programming	Manual or semi-automated methods, processed or estimated	Programming and planning

a) Information quality level.

2.5.5 Data collection levels

The collection of data is both time consuming and expensive. In light of this, Paterson and Scullion (1990) promoted the four-tiered data collection approach described in table 2.6 above. Each level, defined as the 'information quality level' (IQL), relates to the end use of the data and the desired level of accuracy that is required for the decisions being made. While this process originated in pavement management, it is directly applicable to the management of road bridges, as different decisions require varying levels of data accuracy. The Paterson and Scullion model could therefore be used to further extend the current IIMM core/advanced model of asset management.

2.6 The decision-making process

Decision making occurs at the following three key stages:

- when the data is collected and the bridge asset manager makes a decision eg on the condition rating
- when the data that is collected is transformed into information (eg material strengths into assessment information)
- when the information is transformed into knowledge (eg the capacity of a bridge is used to understand network performance).

The decision-making process in asset management is characterised by three key stages:

- data analysis to understand the problem
- life cycle planning to understand the optimal solution
- optimised decision making so that strategic targets are met through the implementation of optimal solutions (Roberts et al 2004).

These three stages are discussed in detail in the following sections.

2.6.1 Data analysis

While many types of data can be collected, in its raw state the data will not be directly useable in the decision-making process (Brownjohn et al 2004). Data analysis is therefore required. Bridge-specific areas to be managed as part of the analysis process were noted by Ghasemi et al (2009). Data should be collected for all of these aspects. Wider performance data approaches, as detailed in the Canadian (Félio and Lounis 2009) and Austroads (Curran et al 2002) documents also form part of this process. Analysis of this data would result in the development of deterioration models, bridge assessment information, and cost models, all useful in the knowledge-development process.

The BRIME[3] study (Daly 2001) found that most countries used rules that attempted to correlate condition rating to bridge strength. A number of parameters and aspects were used to understand the impact of condition on strength, including:

- global condition factor
- reduced cross-sectional area
- modified properties of concrete/steel
- modified properties of bond
- modified structural behaviour
- additional stress.

In the Austroads document (Curran et al 2002) and the New Zealand Bridge Manual (NZTA 2006), the global condition factor is predominantly used. Daly noted in the BRIME study (2001) that most countries had developed methods of correlating bridge condition to bridge strength; however, they were heavily

3 Bridge Management in Europe

reliant on engineering judgement and were therefore imprecise and subjective. Daly also outlined NDE methods that could improve the assessment, but these tended to focus on localised features such as bond strength or delamination, or loss of reinforcement cross-section. Thus it was difficult to accurately correlate bridge condition to bridge strength.

One of the outcomes of the ongoing Long-term Bridge Performance Program (LTBPP) was to understand this relationship (FHWA 2011). In the LTBPP, the data that had been collected on the test bridges, using visual inspections, NDE and SHM, was used to update finite element models. As a part of this process, the deteriorated state of members was also accounted for. It was evident from the initial findings that the relationship between bridge strength and element condition was a function of the bridge structural system, and the importance of the element to structural integrity.

All of these inputs into wider bridge performance assessment practices were defined by Ghasemi et al (2009), the Canadian framework (Félio and Lounis 2009) and Austroads (Curran et al 2002). However, under current New Zealand inspection policy, only defect-related data is collected (NZTA 2001). This limits the development of these model forms.

In a wider context, bridge-specific factors were seen as only a small part of the analysis process. Models had to account for the relationship between bridge and network performance (Liu and Frangopol 2006, Bocchini and Frangopol 2011), and this had to be undertaken for the full range of performance criteria. However, the USGAO and NZOAG audits show that this was not being undertaken in New Zealand, and was considered to be the missing knowledge–information link that was causing a breakdown between operational analysis and strategic analysis. The data that is collected therefore has to link to the key decisions that are being made, and therefore to the performance measures that inform these decisions.

This process has been carried out for limited factors including seismicity, weather, and other transport-planning aspects (Wu et al 2009, Peterson and Church 2008, Dijkstraet al 2007, Sumalee et al 2011), but it will have to be developed further in order to directly relate operational bridge-specific decisions to strategic direction. Analysis will therefore have to be linked to performance criteria, both at bridge and network level.

2.6.2 Life cycle planning

Once the performance of the bridge has been assessed, the asset manager has to decide what maintenance actions should be carried out and the optimal way of doing this – usually using the Net Present Value Method, where options can be assessed and compared in monetary terms. In New Zealand, the *Economic evaluation manual* (EEM) (NZTA 2010a) describes this process and advocates for an assessment period of 30 years and a discount rate of 8.0%. Internationally, the assessment periods and discount rates varied depending on local policy – for example, the UK used a discount rate of 3.5% (HM Treasury 2003).

In order to understand life cycle issues, service lives of components and estimated costs of maintenance actions and components must be known. It is therefore important to store data on these, or to derive them from data that is already stored. Thus life cycle planning was seen as a tool to be used within the overall decision-making process, utilising maintenance costs, improvement costs, road-user costs and other costs, such as agency costs, along with performance and deterioration models (Frangopol 1999, Hawk 2009).

2.6.3 Decision making and optimisation

The way the data will be used in the decision-making process affects the type of data that is needed in the data collection framework. Within the decision-making process, optimisation is concerned with identifying and understanding problems and/or opportunities, and delivering interventions and improvements in a way that maximises the benefit/cost ratio – and this means sufficient data must be present. Previous research has noted a number of reasons for undertaking optimisation, including:

- providing sound justification for new investment and renewal decisions
- achieving efficiencies and reducing operational budgets
- the need to consider the full impacts (social, environmental, cultural and economic) of significant decisions
- resolving LOS gaps and managing risk
- meeting legislative requirements
- making better decisions across the organisation
- responding to political requests (Curran et al 2002, Roberts et al 2004).

To achieve the above objectives, the range of techniques that are available to authorities can vary in complexity. At one level, the process can be relatively straightforward, with decisions made using simple risk-based systems; at a higher development level, the process can be complex and use recognised mathematical optimisation techniques to offset opposing criteria, so that an optimal solution can be obtained.

Optimised decision making should be based on risk management, where risk is the combination of the probability of an event occurring, and the consequence of the event. Guidance on risk management is included in New Zealand Standards AS/NZS ISO 31000 (Standards New Zealand 2009) and AS/NZS 4360 (Standards New Zealand 2004), and in NZTA's *Risk management process manual (*2004b).

Moon et al (2009) promoted the consideration of hazards, vulnerabilities, exposures and uncertainty premiums, the latter being based on the assessment approach used to derive the bridge risk rating.

The risk assessment alone facilitates simple prioritisation of work actions. However, it does not facilitate assessment of the economic costs or benefits. This approach is appropriate for managing maintenance and project management problems on simple networks, but is not useful for assessing more complex bridge-failure or networks-level risks, or advanced asset management.

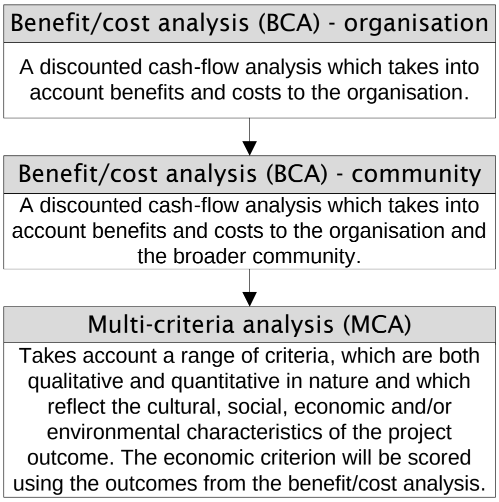
Risk is not the only important factor in network management. Criticality should also be assessed, as it is a measure of how important an asset is to the overall functionality of the network. O'Rourke (2007) expressed criticality in terms of infrastructure interdependency and asset resilience, where resilience was a factor of robustness, redundancy, resourcefulness and rapidity. Each of these factors contained four qualities – technical, organisational, social and economic. Thus, wider performance data was required to fully understand critically.

Liu and Frangopol (2006) promoted an approach that linked the functionality of bridges to network functionality. This approach was considered to be essential if infrastructure asset managers were to provide strategic-level knowledge about transportation network performance.

In order to carry out advanced asset management, it is important to understand the wider benefits that can be achieved from implementing a solution. Improvements on the basic decision-making approach are detailed in *Optimised decision making guidelines: a sustainable approach to managing infrastructure (ODM)* (Roberts et al 2004). The manual provides details on two optimisation techniques: benefit/cost analysis (BCA) and multi-criteria analysis (MCA) (see figure 2.4). BCA is divided into two levels, with the higher level taking into account the viewpoint of a wider community, as well as that of the organisation performing the analysis. The tools provided in the manual can be applied to the majority of authorities in New Zealand, but they may not be applicable to complex problems – eg network analysis or prioritisation of multi-objective problems in a complex system such as a large bridge.

Developing benefit and cost parameters uses recognised benefit/cost techniques to provide a notional dollar value for benefits such as environmental, social, cultural and economic impacts. In the case of roads-based projects, the EEM (NZTA 2010a) is used to quantify safety (eg accident costs), and economic impacts (eg travel-time savings and vehicle-operating cost reductions); however, it does not take into account the wider social and environmental impacts of the projects. The ODM manual provides advice on these aspects, and also provides advice on economic considerations that is less road-centric. The ODM details an MCA/BCA hierarchy to objectively assess and prioritise work actions, but more advanced approaches are required to objectively identify an optimal solution. Some of these include multi-attribute utility theory, the weighted-sum approach, compromise programming, the ε-constraint approach, and sequential optimisation (Liu and Frangopol 2006).

Figure 2.4 Optimised decision-making methods Roberts et al (2004), p2–9



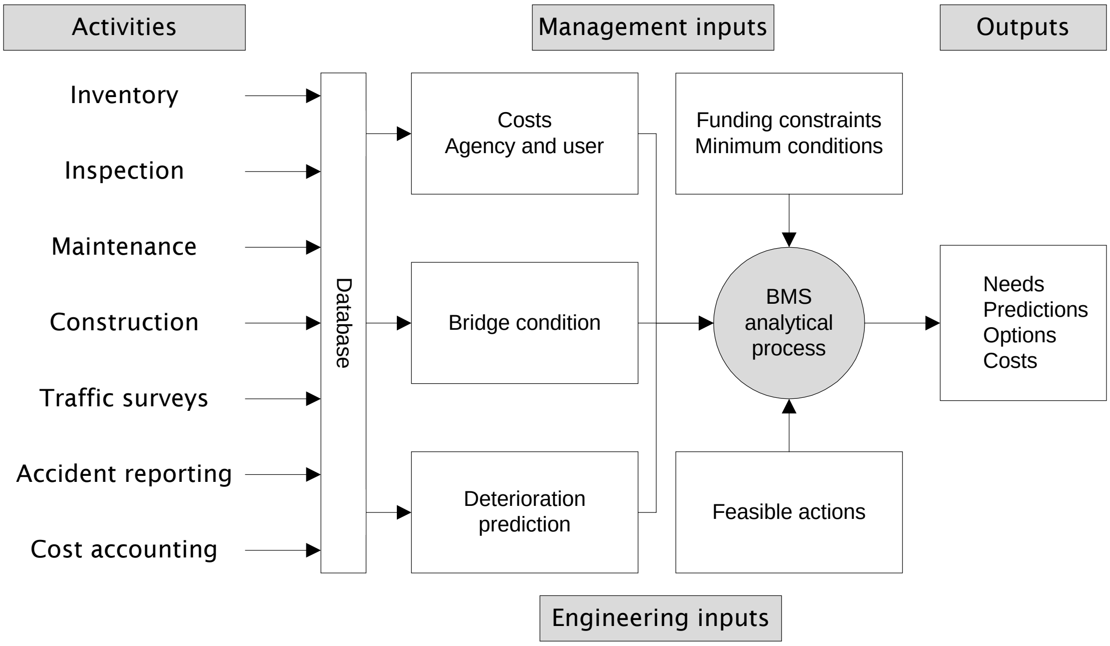
Many research papers have utilised complex advanced optimisation approaches in bridge asset management (O'Connor et al 2009, Frangopol 1999, Bocchini and Frangopol 2011, Frangopol and Neves 2008, Tsunokawa and Hiep 2008, Lounis 2005). However, virtually all of them looked at individual bridges or at groups of similar bridges, but none of the optimisation processes focused on bridges as parts of a network, including the effect of deteriorating bridge performance on whole-network performance. Nevertheless, Liu and Frangopol (2006) noted that the network-focused approach was starting to be adopted in bridge management. This would eventually lead to bridge managers linking asset improvement and management decisions to the network functionality and to the network-level policy outcomes. The network approach needed to be extended to take into account the full range of data collected under the promoted performance frameworks, and these techniques would also have to link operational and strategic decision making.

2.7 Bridge management systems

Advanced bridge management systems store a range of data relating to the management of bridges, including inventory and performance, and have modules enabling data modelling, interrogation and analysis, as well as decision-support tools. The Austroads documents *Bridge management systems – state of the art* (Curran et al 2002) and *Guidelines for bridge management – structure information* (Dowling and

Rummey 2004) provide a simplified example for a bridge management system shown in figure 2.5. As can be seen from this diagram, the data that is fed into the system underpins the whole decision-making process. The focus of these reports was, however, data collection with associated QA and storage, and hence those aspects received more attention.

Figure 2.5 Structure of a model bridge management system (Curran et al 2002, Dowling and Rummey 2004)



2.7.1 Overview of common bridge management systems

We found that all countries that used bridge management systems or stored any form of bridge data by default had developed an inventory list (asset list). However, there were myriad ways in which the data could be stored, including paper-based systems, spreadsheets, and informal/formal databases (Roads Liaison Group 2005). Inventory systems developed to store data about bridges included the US National Bridge Information System (NBIS) (Godart and Vassie 2001) and the UK Highways Agency's Structures Management Information System (SMIS) (Das 1999). In New Zealand, the main systems were the NZTA's Bridge Data System (BDS) (NZTA 2009a) and RAMM for Bridges (RAMM Software Limited 2011).

Further to these, technical descriptions of the most common bridge management systems have been included in *Overview of bridge management systems* (Adeyet al 2010), which was instigated by the International Association of Bridge Maintenance and Safety (IABMAS).

2.7.2 Bridge inventory data

Inventory data is core to the data collection and monitoring process, as all collected data (eg condition, capacity, deterioration) has to be tied to specific assets, and parts of assets. Commonalities between the bridge inventory systems (Curran et al 2002, Dowling and Rummey 2004, Godart and Vassie 2001, Adey et al 2010, Das 1999) were as follows:

- All systems stored specific bridge-level data such as bridge ID, location, type, age, basic geometrical data and number of spans.
- All systems stored element data such as spans, piers and abutments. Bearings and barriers were described, along with specific data relating to them, such as type, age and geometrical attributes.

- Component data about individual bearings, beams, decks and abutment sections was identified.

However, each country had adopted its own inventory categorisation, so there was no single common approach for bridges, probably because of the different needs for different environments. However, a commonly followed New Zealand approach should be developed, as the number of systems that are currently in operation can be confusing.

2.7.3 Other data relating to bridge management

In addition to the inventory data, the bridge management systems reviewed comprised financial management, condition management, and planning tools (Curran et al 2002, Mizusawa 2009, Das 1999, Godart and Vassie 2001). For example, the BDS stored rating information that was used in the overload assessment system, OPermit.

Further, data under this area included policy data, performance measures and performance targets. Performance data, as discussed in section 2.4, includes environmental data, economic data and technical performance data (eg bridge assessment data).

2.7.4 Third-party data

Not all data has to be collected and stored by the RCA, and in some cases such as seismic activity, flood, climate change, river levels and rainfall data, it has been more effective to link to third-party suppliers. In New Zealand these include the National Institute of Water and Atmospheric Research (NIWA) (NIWA 2010), the Institute of Geological and Nuclear Sciences (IGNS) (IGNS 2010), or regional authorities.

2.7.5 Data mining

The review found that data mining, sometimes called knowledge discovery, summarised data into useful forms so that correlations, patterns and trends could be identified among the data that was stored in the relational database (Frand 1996). In data mining, the following four types of relationship were sought:

- Classes: Stored data was used to locate data in predetermined groups – eg bridge type and typical problems being encountered could be grouped, so that appropriate actions could be taken for these issues.
- Clusters: Data items were grouped according to logical relationships – eg condition curves for bridge types.
- Associations: Data could be mined to identify associations.
- Sequential patterns: Data could be mined to anticipate patterns and trends – eg performance drop-off with increasing traffic growth.

The following data-mining analytical techniques and tools were available:

- Artificial neural networks – non-linear predictive models that learn through training.
- Genetic algorithms – optimisation techniques that use processes including genetic combination, mutation, and natural selection in a design based on the concepts of natural evolution.
- Decision trees – tree-shaped structures that represent rules for the classification of a dataset.
- Nearest-neighbour methods – each record in a dataset being classified according to a combination of the classes records most similar to it in a historical dataset.
- Rule induction – the extraction of useful 'if/then rules' from data based on statistical significance.

Data mining should form a part of the advanced data analysis, and raising awareness of the available techniques needs to be improved. As the data stored for bridges will be numerous, effective formalised interrogation techniques will be needed to draw conclusions.

3 Survey of current New Zealand road bridge asset management practices

3.1 Introduction to the survey

The survey was undertaken to understand the asset management practices used by New Zealand bridge managers and more specifically, the data collection and monitoring approaches that they used to manage bridges. The wider asset management context was also assessed, in order to understand how the collected data was used. To that end, a representative sample of RCAs, including both NZTA regions and local authorities, was selected. A paper-based survey sheet (see appendix A) was developed and mailed to bridge asset managers. A system was used to convert quantitative responses to quantitative scores so that the level of asset management development could be assessed.

The following specific topics were covered in the survey:

- data collection: inventory – network-specific data
- data collection: inventory – general bridge data
- data collection: condition data
- data collection: structural health monitoring
- performance: risk, LOS, deterioration and cost models
- optimisation/prioritisation: budget management, risk management
- systems tools and QA.

The survey areas were aligned with the asset management framework (refer back to figure 1.1). As the strategy we were developing was oriented towards data collection, these areas received considerably more attention in the survey. Questions were asked about the type of bridge and network data that was stored, as this forms the basis of inventory data. Condition data was also covered, as this is considered to be one of the inputs into an advanced asset management approach.

The methods of collecting data included visual inspections, NDE and SHM, which allowed us to see whether the current data collection practice in New Zealand was aligned with the international practice found in the literature review. Data collected via NDE and SHM is considered essential for the accurate long-term planning involved with advanced asset management. Some questions aimed to gather information on how bridge asset managers used the data to understand and manage risk. Questions gathering information about how and what data was stored, and how it was managed, were included because the literature review noted that data is an asset in its own right.

3.2 Sample set identification and survey returns

The survey used the NZTA's categorisations for local authorities ('very large', 'large', 'medium', 'small', and 'very small'), with the category based on the number of people resident within the authority's area (LTNZ 2008). In the NZTA categories, very large authorities cover larger cities, and small authorities cover rural towns. However, for this survey the very large and large, and very small and small, authorities were combined. Asset management development levels were also a key factor in choice of local authority and were therefore taken into account when developing the sample set. In total, the survey was submitted to all 14 NZTA regions and 20 local authority areas. It should be noted that some NZTA regions are combined, resulting in a total of 9 survey submissions. The following returns were received:

- 6 NZTA areas (67% of NZTA regions surveyed)
- 9 local authorities (45% of local authorities surveyed).

Table 3.1 summarises the sample set and survey return distribution amongst local authorities.

Table 3.1 Local authority sample set and survey returns

Size category	Development level	Number of surveys	
		Sent	Returned
Very large	Good	2	2
	Moderate	2	2
	Poor	1	1
Large	Good	1	
	Moderate	2	
	Poor		
Medium	Good		
	Moderate	2	
	Poor	1	1
Small	Good	1	
	Moderate	2	
	Poor	2	2
Very small	Good		
	Moderate	2	1
	Poor	2	
Total		**20**	**9**

These returns show that while there was a range of asset management plan development levels, there was some bias towards moderate and poor ratings (2 ‘Good’, 3 ‘Moderate’, and 4 ‘Poor’). As well, only one medium-sized authority returned the survey (and 5 ‘Large’ and 3 ‘Small’). This imbalance may have affected our understanding of bridge asset management development for the medium-sized authorities.

The total returns covered 3224 bridges, which is approximately 17.4% of the national bridge stock (18,500 bridges = 14,000 local authority and 4500 NZTA bridges) (NZTA 2010b). Given the range of asset management development levels and the number of NZTA and local authority areas that replied, this was considered to be a representative sample of bridge management practices in New Zealand.

3.3 Survey marking

The survey data was analysed using two approaches.

1 Collate the comments provided by each returnee, to develop an understanding of the approaches used by bridge managers.

2 Rank each bridge management area out of 3 (with 1 signifying poor practice, 2 medium, and 3 good), in order to compare the assessed operational development levels against best international practice and good practice.

We acknowledge that scoring the qualitative returnees' comments is, to an extent, arbitrary, but it helped provide an important insight into the gaps between the New Zealand and international best practice and good practice.

Full details about the scoring methodology can be found in appendix B. In the following sections, the methodology is explained in general terms, using the third survey topic (data collection: condition data) as an example.

3.3.1 Scoring questions

Each survey topic contained a number of questions, and key questions were used to define the overall topic rating (ie some questions were not ranked, as they provided only supplementary information). In the example in table 3.2 below, (data collection: condition data):

- 3.1a was used to understand compliance with the typical regime of general, detailed, and special inspections
- 3.2a was used to understand the alignment with best practice relating to coverage of inspections (ie defect description condition rating, cost data)
- 3.3a–3.3d were used to understand how QA was aligned with best practice
- 3.4a–3.4b were concerned with planned improvements and their anticipated effects (ie not current practice).

Table 3.2 Questions on the topic 'condition data'

ID	Questions for the topic 'data collection: condition data'
3.1a	Please outline the type of inspections that you carry out, along with the frequency of inspection for each of the identified inspections (ie fixed or variable cycle).
3.1b	Are there any specific triggers for these inspections?
3.1c	What standards, policies or best-practice documents do you follow?
3.2a	When you carry out inspections, what type of data do you collect (eg defects, condition, extent of defect, severity)?
3.2b	What reports do you produce with the data (eg general, detailed, special, safety), and how detailed are the reports (eg defects lists, estimated costs, recommended actions, photographs etc)?
3.3a	How do you ensure consistency between each individual inspection and inspector (eg formal training, specific basic qualifications, use of manual process and procedures)?
3.3b	Do you carry out checks to ensure consistency between inspections and inspectors?
3.3c	If so, how, and on how many bridges?
3.3d	Do you follow any validation/verification standards?
3.4a	Are there any improvements you are planning or implementing as part of the visual inspection process?
3.4b	What benefits do you feel the identified improvements would bring?

All findings were compared against the international best-practice benchmark we identified, and the gaps were noted. In all cases, best practice was considered to be the process that should be undertaken, even if it wasn't currently being undertaken internationally. For example, best practice for QA demands that a representative sample of inspections is reviewed, including the actual inspection and the report; however, actual current international practice indicated that only limited QA is carried out for inspections. Good practice was considered to be the level to which New Zealand should ideally aspire, given the local context and resources available. Good practice could be lower than, or equal to, best practice.

3.3.2 Scoring topics

To provide an overall ranking for each topic area, each question within the topic area was weighted according to its perceived importance by multiplying the question score by a weighting factor. The final weighted topic score was then normalised in order to fit the overall topic score within the 1–3 system. Table 3.3 provides an example of the normalisation process.

Table 3.3 Example of the process used to score questions

Topic area	Question	Question weighting		Example question score	Weighted question score
		Initial	Normalised		
Topic area 3	3.1b	1	0.33	3	1
	3.2a	1	0.33	2	0.66
	3.3a–3.3d	1	0.33	2	0.66
Topic rank (sum of question scores)					2.33

3.3.3 Setting scoring limits

As the overall topic score needed to be a discrete value between 1 and 3, the outcome was further processed. An upper and lower bound was set for each topic area; if the weighted topic score was above the upper limit it scored a 3, if it was below the lower limit it scored a 1, and scores in between those limits were rounded to 2.

To derive an overall score, an expectation range was developed for each question. For example, for question 3.1a the expected upper value would be 3.0 if authorities were complying with international practice of detailed, general and special inspections. Table 3.4 shows that to achieve an overall topic rating of 3, a score greater than 2.66 has to be achieved, and for an overall score of 1, less than 1.32 has to be achieved.

Table 3.4 Setting Limits for each outcome (condition)

Topic area	Question	Expectation limit		Weighting	Normalised upper limit	Normalised lower limit
		Upper	Lower			
Topic area 3	3.1b	3.0	2.0	0.33	1	0.66
	3.2a	3.0	1.0	0.33	1	0.33
	3.3a–3.3d	2.0	1.0	0.33	0.66	0.33
Outcome limit					2.66	1.32

3.3.4 Overall ranking

The overall survey score was the combined score of all questions. This was considered to be an overall asset management practice rating. This rating was obtained using the same limit-setting process detailed above.

3.4 Benchmarking

Network-specific data from the responses to topic area one ('Network-specific inventory') was used to develop a complexity rating. The complexity rating was used in the benchmarking process to assess any development gaps.

The following factors were used in the assessment:

- length of network (related to bridge spacing)
- urban/rural mix (related to management complexities – ie, bridges on rural networks tend to be more accessible because of lower traffic volume)
- specific network issues (used to reflect the special circumstances affecting the risk profile of each network – eg lifeline routes or susceptibility to flooding or land slips)
- number of bridges (indicates the degree of effort that has to be applied to management)
- number of strategic bridges (indicates the number of bridges that may require special attention).

For example, a network with a score of 3 was considered to be complex, with many risk issues, including a high number of strategic bridges, relatively large numbers of bridges in the stock, long network lengths and a high urban content.

We envisaged that a network-complexity assessment process could be used as an important factor when developing a network-specific bridge management process. The complexity assessment would then be updated and changed to reflect the outcomes of the more rigorous risk management strategy that is outlined in section 9.

3.4.1 Example

An authority scores 1 for network length, 1 for urban/rural mix, 2 for number of bridges, 1 for complexity, and 3 for strategic risks. It is considered to have an overall weighted rating of 2.0. The gap between the complexity factor (2) and the topic area rating (2) is zero. The authority is therefore considered to be providing the required level of data collection and asset management, given the issues that are being faced.

3.5 Gap analysis assessment

The approach that was used for the assessment and ranking of topics was also followed for gap analysis. The gap was defined as variations (both positive and negative) between best international practice and current New Zealand practice, and between current practice and New Zealand good practice. These gaps have been addressed by the proposed strategy so that New Zealand practice aligns with international best practice and more importantly, so that authorities develop an appropriate level of bridge asset management approaches relative to New Zealand good practice.

4 Survey analysis

4.1 Introduction to the survey analysis

Using the survey assessment methodology, each topic and each question was assessed. These findings, combined with the literature review, form the primary inputs into the gap analysis and the strategy development process.

In this chapter, the main findings of the survey analysis are highlighted first, followed by detailed analysis of the survey topic areas and questions. In tables 4.1– 4.10, a score of 3 is considered to be high and a score of 1 is considered to be low.

To obtain the relative development rating, each returnee was assessed against a network complexity benchmark. The benchmark included a number of factors such as the number of strategic bridges, total number of bridges, number of network issues noted by the bridge manager (eg lifeline roads), urban/rural mix, and network length (see appendix B for details). A gap of 0, as defined in the overall rating, identified that an authority was in accordance with best practice. A score of +/-1 indicated that an authority was above (+1) or below (-1) best practice, and a score of +/-2 indicated a significant deviation from the best-practice benchmark.

This chapter concludes with a series of recommendations to inform the development of data collection and monitoring strategy.

4.2 Main findings of the survey analysis

Of those authorities that were surveyed, there were a range of bridge asset management development levels, with some authorities scoring lower levels than required by their assessed needs.

With regards to inventory collection, a good level of data was collected by all areas and this was generally in keeping with network needs. However, the data collected by each area was inconsistent, probably because the best-practice advice and standardisation guidance available in New Zealand was limited.

With regards to inspection practices, most of the areas surveyed were generally in line with the current New Zealand recommendations. However, if New Zealand is to align with international best practice, these recommendations will need to be changed – eg to include condition rating. As New Zealand good practice regarding the type and frequency of inspections was generally being followed, there was a good correlation with the international community. However, New Zealand practice had, in some cases, been modified to meet local needs – eg omitting detailed/principal inspections. Also, little if any formalised QA was being carried out for inspections – eg checking inspector's findings.

Feedback on testing and monitoring aspects such as NDE identified that many bridge managers were carrying out, or had carried out, some form of testing. This appeared to be reactive and not used in a strategic manner, other than providing greater data on already-known defects. There were one or two examples where testing was well integrated and was being used in a proactive manner, which constitutes good practice for New Zealand.

SHM had been considered by some authorities and had been deemed too expensive, reflecting a limited understanding of its true capabilities. Some positive examples of SHM were noted – eg flood data triggered investigation into scour issues, and strong-motion data triggered post-earthquake examination, again good practice. Overall, we found that a greater understanding of the benefits of SHM was needed amongst New Zealand bridge managers, and the limited general awareness of SHM indicated that standardised documentation should be introduced.

In general, there was a reasonable level of development with regards to data collection, but some improvements were required to align the rating for some authorities with the needs of their networks.

With regards to decision making and optimisation, and forward works programme (FWP) development, there tended to be a good understanding of the risks facing the networks, but most of the outcomes manifested themselves as maintenance actions. As such, there was little information provided on wider performance issues such as strength, clearance, side impact, scour and fatigue. In some areas, the wider network impacts were studied, which is good practice in New Zealand. However, the international lack of understanding of performance definitions was also seen in New Zealand practice.

There was little evidence that long-term planning was taking place, and limited or no evidence of condition or performance models being utilised. This had resulted in limited understanding of what was required regarding optimal funding amounts.

Most managers were using the RAMM database or other bespoke systems for data storage. However, if the changes, such as storage of condition data, are to be implemented, these need to be modified, as most are currently unable to absorb condition rating.

4.3 Question 1: Network-specific inventory

4.3.1 Survey analysis

The targeted outcome for this section was the provision of data that could be used to benchmark each individual network against the level of bridge asset management development as assessed in the remaining sections of the survey.

In many cases, bridges were not the majority asset being managed – one authority was managing 5685 other structures, with 668 retaining walls, 96 sea walls, and 4907 other non-defined structures. In many other areas, bridges, large culverts and retaining walls formed the majority of stock managed by the RCA. Structures were considered to be:

- bridges, large culverts and deep drainage pits
- tunnels
- high masts, gantries and gantry poles
- vehicle, pedestrian and stock underpasses
- retaining walls and sea walls
- wharves
- cattle stops.

In accordance with the ranking process, the larger urban networks ranked as more complex; however, some of the more rural networks were moderately complex, owing to specific features such as lifeline services to remote rural communities (see table 4.1 – 3 indicates a complex network, 2 a moderate network, and 1 a simple network, and blank indicates that data was not available).

4.3.2 Common themes

In general, managers of state highway networks had a good understanding of the number and type of structures they had and their construction forms. The information that was stored was also consistent between all areas, as one system – the Bridge Data System (BDS) – was being used (NZTA 2009a).

This contrasted with local authorities, which generally stored differing data types, and to differing levels of detail. Also, in some cases authorities either had a less developed understanding of their stock, or were unable to easily obtain the data from the systems they were using – eg the total number of bridges listed for the network did not equal the total number of bridges listed for material or construction types. We concluded that a review of the wider inventory classification process should be carried out, as many authorities seemed to store data in a format that failed to allow easy access, which means their systems would have to be improved to allow data mining.

Table 4.1 Network-specific inventory rankings

Returnee ID	Question 1: Network specific inventory					
	Network length (percentile score)	Rural/urban (reviewer-rated)	No. of bridges (percentile score)	Perceived complexity (reviewer-rated)	Strategic bridges (reviewer-rated)	Overall complexity rating
1	1	1	2	1	3	2
2	2	1	3	2	3	3
3	1	1	2	3	3	3
4	1	1	2	2	3	2
5	2	1	3	2	1	2
6	3	1	3	1	1	2
7	3	3	1	2	3	3
8	1	3	1	3	3	3
9	2	2	1	1	1	1
10	3	1	3	1	2	2
11	3	1	3	1	2	2
12						
13	2	1		1	2	1
14	3	1	3	1	2	2
15	2	2	2	1	2	2

4.3.3 Analysis outcomes to be incorporated into the strategy

It is recommended that the following should be included in the strategy:

- Structural inventories need to be classified and categorised consistently.
- Inventory collection requirements need to be formally outlined.
- Network complexity needs to be accurately identified.
- Inventories should include a wider range of data – not only asset description, but also drawings, photographs and reports.

4.4 Question 2: General bridge inventory information

4.4.1 Survey analysis

It was clear from the literature review that no commonly adopted structure existed for the storage of bridge data. It was also important to understand the type of data that was collected across New Zealand, so that a consistent approach could be adopted. The targeted outcome from this section was therefore to understand what data is collected in New Zealand, and how this compares with international practice.

All the answers for inventory data collection generally had New Zealand and international practice in alignment (see table 4.2). However, there were numerous naming methods for bridge construction and material types. Overall, the NZTA regions collected a considerable amount of data, as noted in table 4.3.

Generally, inventory collection was carried out to a high standard across network and bridge data, but it was less well developed for element data, and poorly developed for component data. The component aspect aligned well with international practice. Overall, the development level was slightly lower than international practice, as denoted by scores of 2.

Table 4.2 Inventory: general bridge information rankings

Returnee ID	Question 2: General bridge information							
	Network level data	Bridge level data	Element level data	Component level data	Extra data collection	Data collection improvements	Overall inventory collection rating	Inventory vs. complexity
1	3	3	1	1	3	1	2	0
2	2	3	3	2	3	3	2	-1
3	3	3	3	2	3	2	3	0
4	3	3	3	1	2	1	2	0
5	3	3	3	1	3	3	3	1
6	3	3	1	1	3	3	2	0
7	2	3	3	2	3	3	2	-1
8	3	3	1	1	1	2	1	-2

9	2	3	3	1	1	2	1	0
10	3	3	3	1	2	3	2	0
11	3	3	3	1	3	1	3	1
12								
13	3	3	3	1	2	1	2	1
14	3	3	1	1	3	1	2	0
15	1	3	2	1	3	3	1	-1

4.4.2 Common themes

In general, the NZTA and local authorities collected data for bridges and their elements. Neither the NZTA nor local authorities routinely collected component-level data (eg data specific to items such as a specific bearing or beam), although a number of respondents noted that they highlighted specific components if problems were occurring on the component. The registering of defects at component level allowed targeted maintenance to be carried out. This approach aligned well with international practice. However, while data was collected for bridges and their elements, there was general confusion about terminology – eg bridge data, element data and component data. There was also confusion in terminology with regards to materials and construction forms. This was further exacerbated by the fact the defect and the condition were thought to be the same thing; however, defects are considered to be actual effects noted on the bridge, and condition data is considered to be a numerical representation of the defect.

Extra data that was collected and stored included:

- as-built drawings of the bridges
- risk assessments for bridges
- photographic information
- studies and reports including feasibility studies and ongoing inspection reports
- bridge files with overload assessment and posting information.

Information considered useful, but not stored electronically by local authorities, included posting and rating data, and assessment details such as load capacity and seismic capacity. The NZTA stores a version of load assessment data for structures carrying state highways, as this is used in the OPermit system. This type of data is considered to be performance related, and should be stored.

Table 4.3 Bridge data system fields

Inventory area	Coverage description
Structure ID	Structure Identification (ID) – unique identifier, bridge structural number (based on location)
Road data	State highway number, road section, displacement, direction
Location data	Territorial region, network area, Start N, Start E, Start location (N/E), End location (N/E), RCA
Name	Name of bridge

Inventory area	Coverage description
Drawings	Drawing numbers, drawing reference and titles, plus storage location
Highway details	Increasing lanes marked, decreasing lanes marked, traffic-control devices
Structure details	Structure type, cross section of superstructure, long section of superstructure beam type, deck material, superstructure material, expansion joint type, bearing type, foundations, pier type, wearing surface on deck, central median barrier, guardrails, handrails
Geometrical data	Overall length, span no., span length, pier height, waterway area, fill depth, kerb, guardrail height, road width between kerbs, footway width (left & right), height of handrails, width between handrails, vertical clearance, curvature, radius of horizontal curve, k value of vertical curve, gradient of deck
Utilities	Lighting on bridge, emergency phones, flushing pipes, gas pipes, irrigation pipes, phone fibre optic cables, power wires, cables, sewer pipes, sign gantries, water supply pipes, other utilities
Capacity	Action recommended, work status, alternative route, amended date, gross weight limit, axle weight limit, stresses gross limit, stresses axle limit, restriction date, failure mode, analysis method, overweight analysis (y/n), condition, speed limit, slow central
Posting	Bypass type, bypass description, speed limit, posting, width, critical span, critical moment, bridge class, last data calculated, deck capacity factor (DCF), restrict X (increasing), restrict X (decreasing), comments
OPermit data	Specific data for the deck , influence line, beam, VBeam, timber deck, transom, models
General	Ownership, valuation, cost, design loading, year constructed, drawings, number of drawings, drawings comment, structure amended, widened (y/n), hazards

4.4.3 Improvements identified by bridge managers

Bridge managers identified the need for the following specific improvements:

- the storage of valuation data and associated remaining-life estimates
- the development of structures risk assessment processes
- storing data by bridge, rather than by project.

4.4.4 Analysis outcomes to be incorporated into the strategy

- Define inventory storage needs to ensure consistency in terminology and use.
- Recommend varying development levels to suit varying network complexity.
- Include performance data such as load capacities, scour and risk.
- Include valuation data and associated remaining-life estimates in inventory data.

4.5 Question 3: Collection of condition data

4.5.1 Survey analysis

Condition data is a result of the assessment of the extent of defects or deterioration, and/or their severity, using a numerical scale. At the time of the survey, New Zealand practice focused on the recording and managing of defects without assessing condition as such. The targeted output from this section was to understand general compliance with current practice and to identify any new practices. Since this survey, the NZTA have been implementing the UK Highways Agency Bridge Inspection Standards (Highways Agency (UK) 2007); some of the findings in this section will therefore have changed since our research.

All NZTA regions were following best practice and the inspection guidance (table 4.4) as defined by the *Bridge inspection and maintenance* manual (NZTA 2001), and local authorities had also largely followed this philosophy, resulting in a high number of 2 and 3 ratings for inspection-type compliance.

Table 4.4 Overall inspection practice rankings

Returnee ID	**Question 3: Condition data collection**				
	Inspection type compliance with best practice	Data coverage alignment with best practice	Perceived inspection quality assurance level	Overall inspection rating	Inspection vs. complexity
1	3	2	1	2	0
2	3	3	2	3	0
3	3	2	2	2	-1
4	1	2	1	1	-1
5	3	2	2	2	0
6	3	3	3	3	1
7	3	2	2	2	-1
8	3	2	3	3	0
9	2	2	3	2	1
10	2	2	1	1	-1
11	2	2	1	1	-1
12	3	2	3	3	
13	2	2	2	2	1
14	1	2	1	1	-1
15	2	2	2	2	0

Authorities did not collect condition data – only defect data was available. There appeared to be confusion amongst many authorities on what constituted condition rating, with many reporting they used s/6 and form 801/802 to collect condition-related data. However, this form has no focus on condition, as noted in the literature review. Some authorities had added condition rating, but no formal system was noted, such as the *Inspection manual for highway structures* (Highways Agency (UK) 2007) or the *Bridge condition indicators* (Roads Liaison Group 2004).

In one case, the bridge team had developed a specific manual based on photographic evidence, to aid inspectors in categorising problems that they found. This follows international practice carried out in countries such as the UK and France. However, since this survey was undertaken, the NZTA has introduced condition rating, as defined by the latest update of the UK Highways Agency's *Inspection manual for highway structures* (2007). It is thought that the introduction of this standard will help to differentiate between condition rating and defect data.

Most authorities undertook general and detailed inspections. In the majority of cases, local authorities were aligned with the traditional inspection cycle, but some had moved away from the six-yearly detailed inspections and were only carrying out two-yearly general inspections. In one case, the frequency of general inspections had been extended to three years. No reason was provided for omitting the detailed inspections, but it was assumed to be cost-related, as there is much more time and set-up required for detailed inspections, and many local authorities do not have sufficient funds for these.

Three of the local authorities noted that they carried out annual inspections. In one case, this was to review bridges after an earthquake measuring 6.5 on the Richter scale. In another case, it was to specifically inspect timber bridges. The third authority noted the use of superficial inspections. It was assumed that the superficial inspection was likely to be a relatively high-level inspection to ensure integrity, rather than to assess overall condition. The earthquake trigger was evidence that some authorities were starting to use third-party SHM data, with actions based on environmental triggers.

With regards to QA, bridge inspectors' field reports tended to be checked in the office for consistency after submission, and that consistency was further promoted through the long-term use of the same inspector or through use of the HZHIT training course (NZIHT 2010). Only one authority noted that they carried out specific audits on bridges, and retaining-wall inspections; this was considered to be on par with international best practice, but better than typical actual international practice. Two other authorities noted that reviews were carried out, but this was only a follow-up on trainee inspectors and did not form a part of a regular review process. Given the importance of the data to the asset management process, it is expected that, as a minimum, ad-hoc audits would be used to identify issues in the bridge inspection process.

4.5.2 Common themes

Common themes identified included local authorities moving away from the standardised inspection timings, and the adoption of condition rating by some authorities. A general omission of inspection QA was also noted, but this is also lacking in international practice.

4.5.3 Improvements identified by bridge managers

Bridge managers identified the need for the following specific improvements:

- Conduct risk assessments for each structure.
- Use specialist inspectors for steel structures.
- Change the inspection records database to suit current needs.
- Move away from a paper-based system and start to use a recognised database (RAMM).
- Include condition-data collection (now covered by the NZTA's adoption of the UK Highways Agency's *Inspection manual for highway structures*).

- Use minicomputers to collect data, to minimise double-handling of data.

4.5.4 Analysis outcomes to be incorporated into the strategy

- Include condition-rating recommendations to improve reporting and consistency.
- Allow for variable inspection timings based on risk.
- Include details of QA and data checking.
- Include the improvements identified by bridge managers (in the previous section).

4.6 Question 4: Structural health monitoring (SHM)

4.6.1 Survey analysis

It is understood that SHM is widely used in the US, Europe and Asia to monitor bridges, to more accurately understand their performance. The targeted output for this question was to understand how well developed New Zealand practice is with regards to advanced data collection practices via NDE and SHM.

The majority of bridge managers carried out some form of additional testing and monitoring, usually NDE. However, there were a few authorities that carried out extensive testing. With regards to full integration of NDE into the data collection regime, there tended to be a split between not carrying it out, and partial/full integration into the inspection system, as denoted by the 3 and 1 rankings in table 4.5. However, even in cases of full integration, NDE was generally used in a reactive manner, with only one authority noting that proactive sampling was being undertaken.

Understanding of SHM tended to be limited, with one returnee noting that it was too expensive and therefore not used. No managers stated that they were using it as a monitoring tool; in many cases it was not integrated with the visual inspection process, and as such was not being used to carry out extra condition-data collection. SHM has been used in the past on a number of bridges (Andersen 2000a, b, c). It is thought that SHM would be a more utilised form of bridge monitoring as it enables automated, cost-efficient data collection on remote bridges, which are often of concern to many asset managers.

Table 4.5 Data collection: SHM rankings

Returnee ID	Question 4: Data collection: SHM				
	NDT use/awareness	Use of NDT as a monitoring tool	SHM awareness/use	Overall testing rating	Testing vs. complexity
1	2	2	1	2	0
2	3	3	2	3	0
3	3	3	1	2	-1
4	1	1	1	1	-1
5	3	3	2	3	1
6	3	3	2	3	1
7	2	2	1	2	-1
8	2	3	1	2	-1
9	2	3	2	2	1
10	2	1	2	2	0
11	2	2	2	2	0
12	2	3	3	3	
13	2	1	1	1	0
14	2	1	1	1	-1
15	2	1	1	1	-1

According to the survey returns, most bridge managers had carried out extra NDE to supplement the basic visual inspection process. Reasons for testing included:

- joint deterioration
- poor condition of concrete
- scour
- assessments of concrete and steel strength
- traffic loadings on narrow bridges
- chloride ingress and carbonation and its effects

- timber coring for strength assessment
- fatigue of steel structures/deck suffering from fatigue/deck slab failure
- to assess options available, maintenance time frame, and to estimate budget
- prediction of remaining life.

Types of testing included:

- chloride sampling
- crack monitoring
- timber testing
- crack width monitoring.

The above tests were then used to quantify a specific problem and to identify solutions. In some cases, such as chloride testing, the test was carried out to proactively identify issues at bridge-stock level, with bridges near coastal environments being targeted. While there were a range of tests, as noted above, these could be mainly categorised as providing data on changes in the bridge element or components state through deterioration.

Uses of SHM practices included:

- monitoring river flows for scour
- monitoring earthquakes to trigger special inspections
- strain gauging older bridge slabs to assess performance (not currently used).

4.6.2 Common themes

The following common themes were noted with regards to ongoing testing and monitoring of structures:

- testing used for specific problems that had already been identified (reactive)
- good understanding of NDE, but generally in only one or two areas, and not by all authorities
- generally limited integration of testing into the decision-making process
- limited use of SHM
- limited understanding of the full capabilities of SHM.

4.6.3 Analysis outcomes to be incorporated into the strategy

- Provide recommendations on the use of NDE and its integration into the inspection process.
- Provide recommendations on the use of SHM and its integration into the inspection process.

4.7 Question 5: Performance management

4.7.1 Survey analysis

As identified in the review, data is collected for the specific task of managing bridge performance to ensure that structures provide the required LOS in terms of strength, traffic flow capacity, river flow capacity and resilience, and thereby allow the network to deliver the required LOS to the road user. The targeted output for this question was to understand the performance management practices used by bridge managers and how well they understood risk, both at bridge level and at network level (ie the bridge impact on network performance).

At the network and bridge level, managers had a good understanding of the risks affecting their asset, as many had awareness of lifeline assessments that had been carried out in their areas and understood network-level risks and bridge-specific risks such as scour, seismicity and loading. However, based on the returnees' comments, overall performance knowledge was considered to be moderate to low (see table 4.6).

The following were highlighted as common risks facing bridge managers:

- ownership of structures (mainly retaining walls)
- seismic impacts, scour and excessive loading
- management of Civil Transport routes during emergencies
- managing network lifelines.

Table 4.6 Performance management rankings

Returnee ID	Question 5: Performance management							
	Network-level risk appreciation	Bridge-level risk appreciation	Setting levels of service	Performance assessment	Gap analysis	Long-term planning	Overall performance knowledge	Performance vs. complexity
1	3	3	1	1	2	1	2	0
2	3	3	1	2	3	2	3	0
3	3	3	3	3	3	1	3	0
4	1	3	1	1	1	1	1	-1
5	2	3	1	3	1	1	2	0
6	2	3	1	2	3	2	2	0
7	2	3	1	3	2	2	2	-1
8	2	2	1	1	2	1	1	-2
9	2	2	1	1	1	2	1	0
10	3	2	1	1	1	1	1	-1
11	3	3	3	2	2	1	3	1
12	3	1	2	2	3	3	2	
13	3	1	1	1	1	1	1	0
14	3	2	1	3	1	2	2	0
15	1	1	1	1	1	1	1	-1

There was generally a poor understanding of service levels – where they came from, how they were measured, and when and how to react to them. In many cases, LOS were related to technical documents such as the *Bridge manual* (NZTA 2006). In an asset management context, technical documents identify how LOS will be met – they are therefore considered to be performance assessment tools and not LOS definitions in their own right. This level of understanding mirrors international bridge asset management practice, where a poor understanding of delivery of strategic goals can be observed (USGAO 2008).

Localised areas had a good understanding of performance, and used screening processes to manage high-risk bridges. The main risks that were noted were seismicity, scour and excessive loading.

Long-term estimates were mainly defect-focused, and this is a reflection of the fact that many bridge management contracts required that. Defect management is the pervading paradigm currently used by New Zealand bridge asset managers. While this is good practice for short-term management, it will inevitably break down for long-term planning. For long-term planning, condition management is recommended, with a numerical score applied to the defects. By collecting condition data, long-term trends can be understood and used to model gradual deterioration. This is considered essential if advanced asset management approaches are to be adopted, along with adequate decision-making techniques.

4.7.2 Common themes

A number of common themes were identified, including typical risks that authorities have to manage and specific issues relating to the asset management process:

- good understanding of network and bridge risks at element and bridge level, but no mention of how bridge risk transposed to network-level risk management
- the need for an improved understanding of bridge performance, including loading, scour and seismic performance
- limited long-term forward-planning development, with planning tending to be maintenance-related
- little understanding of LOS with regards to bridge management, which in turn is linked to a limited understanding of the performance gap
- no collection of cost information.

4.7.3 Analysis outcomes to be incorporated into the strategy

- Provide detail on bridge LOS and performance measures.
- Include performance-related aspects in the planning process.
- Identify long-term planning aspects.
- Incorporate lifelines management ideas.
- Ensure all the data that is stored is used in the decision-making process.
- Collect risk data for bridges and networks.

4.8 Question 6: Optimisation and prioritisation

4.8.1 Survey analysis

Delivering the required LOS must take available budgets into account. It is therefore necessary to prioritise and optimise interventions, such as repair, strengthening or replacement, so that they deliver desired improvements to the LOS while maximising the benefit/cost ratio. Optimisation takes place at bridge level (optimising bridge-specific improvements), and at network level (optimising which bridges to improve). By optimising and prioritising interventions, the bridge asset manager will be able to demonstrate why specific decisions have been made, linking budgetary expenditure to specific LOS outcomes as defined by key performance indicators. The targeted output for this question was to understand the types of tools used to undertake prioritisation and optimisation, and whether there was a correlation between these tools and the level of development with regards to optimal funding needed to manage the stock.

Many of the respondents had a moderately well-developed approach to prioritising the works identified as part of the inspection process, including:

- the use of manager's informal knowledge of the asset
- the use of the NZTA funding process requirements

- a risk-based approach
- a condition- and performance-based approach, with low-ranking structures receiving treatment first
- an asset safety-based approach.

However, no formally recognised methodologies, as used internationally, were noted. The only formal methodology noted was benefit/cost analysis, but this was only used for major capital projects such as seismic improvements. In some cases, bridge asset managers noted they knew the network well enough to undertake optimisation using their own judgement. This was likely a fair comment for a defect-management approach on simple networks (ie short-term planning – see section 4.7.1), but would be difficult to adopt for a condition-based approach, or for more advanced approaches that review network demand. This resulted in low development levels, as shown in table 4.7.

Most managers had little understanding of funding needs, and what would constitute an optimal amount for their network – most based it on historical expenditure, funding of depreciation, or relating it to a fixed percentage of the asset value. Of those managers questioned, nine provided financial data regarding asset management of bridges. This data identified that there was a broad range of funding with respect to asset value. The mean was 2% and the 95th percentile was 7.2%. This generally aligned well with anecdotal evidence that nominated 2.5% as the typical spend. When the bridge funding was compared with the total road budget, the mean was 6.4% and a 95th percentile 11.4%. Bridges can therefore be seen to receive significantly less funding than roads.

Some of the improvement actions nominated included management of backlog, implementing risk assessment reviews into the overall process, and life cycle assessments based on condition curves. With regards to understanding backlog, this was not considered to be possible at present, as only defect data was collected, and there was no understanding of the levels of service that were required.

Table 4.7 Optimisation and prioritisation rankings

Returnee ID	Question 6: Prioritisation/optimisation				
	Work prioritisation/decision-making development	Funding need appreciation	Improvement actions	Overall decision-making development	Decision making vs. complexity
1	1	1	2	1	-1
2	2	2	3	2	-1
3	2	1	3	1	-2
4	1	1	1	1	-1
5	2	2	1	2	0
6	3	2	1	3	1
7	3	1	3	2	-1
8	2	1	1	1	-2
9	2	1	1	1	0
10	2	1	2	1	-1
11	1	2	2	1	-1
12	2	1	3	1	
13	1	1	1	1	0
14	2	1	1	1	-1
15	2	1	1	1	-1

Overall, the lack of understanding of funding needs, combined with moderate to poor adoption of prioritisation tools, had led to low overall development in this area, with only four authorities having moderate development levels.

4.8.2 Common themes

Common themes identified as part of the analysis process were:

- a reasonable level of prioritisation for simple tasks, primarily based on engineering judgment – no mention of formal decision-making tools being used
- no clear link between the risk data and performance and the work-bank that was generated

- poor understanding of optimal funding needs
- decision making not always commensurate with network complexity.

4.8.3 Analysis outcomes to be incorporated into the strategy

The outcomes decision-making process identified that there needs to be more robust decision making and greater linkage to the stored data. However, this falls outside the remit of this project. The following was therefore the only outcome to be taken forward to the strategy:

- Ensure all data is linked directly to the decision-making process.

4.9 Question 7: System tools and quality assurance (QA)

4.9.1 Survey analysis

Because large amounts of money are spent collecting bridge data, it is important to store the data and manage it using appropriate QA practices. The outcomes targeted by this question were the types of systems used to store data, and the level of QA development used in the management of the data.

The majority of bridge managers were using RAMM to store their inspection data, with only a few using specially developed in-house systems, as indicated by the level 3 rankings in table 4.8. Some networks were using spreadsheets and paper-based systems (a ranking of 2 or 1). This was for inventory data only. This implied that bridge management systems had not been fully adopted and/or that bridge management tools did not meet the full needs of bridge asset managers. However, as only the inventory development level was reviewed, it was difficult to identify whether the systems were carrying out their tasks adequately. According to evidence from earlier questions and comments from bridge managers, some systems, even the formal ones, needed changes to meet the needs of bridge managers. These changes included storage of valuation, risk and condition data. Also, the returns provided by some authorities indicated that some of the formal databases were difficult to use, as searches on the same stock provided different outcomes for materials, construction form and total structures numbers. Other important data, such as reports, tended to be stored on bridge files, which indicated that this data was not easily accessible by all the parties that needed it.

Table 4.8 Data storage rankings

Returnee ID	Question 7: Data storage & management				
	Storage development level	Database/data management	Other important data storage	Overall storage development	Data storage vs. complexity
1	1	3	1	1	-1
2	3	3	1	2	-1
3	2	2	1	1	-2
4	3	1	1	1	-1
5	2	2	2	2	0
6	3	3	3	3	1
7	3	1	1	1	-2
8	1	1	1	1	-2
9	3	1	1	1	0
10	3	3	1	2	0
11	3	3	1	2	0
12	3	3	1	2	
13	3	1	1	1	0
14	3	1	1	1	-1
15	3	1	1	1	-1

Most of the bridge managers questioned had poor data management processes in place, with the best using formal reviews of the data, and the majority not carrying out any reviews of the data. This is an important issue, as data is essential to the decision-making process and poor-quality data drastically impairs the decisions that can be made with it.

Overall, there was only a low/moderate development level with regard to data storage and data management, with the outcome affected by poor data management practices. However, overall data storage and management tended to be appropriate for most bridge managers, as noted by the zero data storage and complexity gaps. Even so, while this may be appropriate for maintenance management, a significant change is required to meet the advanced asset management approach required by the audit office, as New Zealand systems are significantly behind with regards to decision-making tools and forward-planning models.

4.9.2 Common themes

Common themes identified as part of the analysis process were:

- a good level of development for data storage systems (inventory)
- formal data management carried out on an ad-hoc basis
- limited decision-making tools, as none noted under the optimisation section
- limited risk data stored.

4.9.3 Analysis outcomes to be incorporated into the strategy

- Ensure formal data management is included.
- Identify the type of data that should be stored and linked to the decision-making process.
- Store more risk-related data.
- Ensure the asset management process is used to develop data collection, use, and data storage strategies.

4.10 Overall data collection and asset management practices

When the overall data collection practices were reviewed (topic areas 4–6), it was identified that 40% of authorities were commensurate with their benchmark complexity rating (see table 4.9).

On review of the overall asset management cycle (ie the outcomes from all questions), it was found that most areas required some level of improvement, mainly in the later stages, which comprise decision making and bridge management systems (table 4.10). To move towards an advanced asset management approach, a significant amount of work is required in the performance assessment areas and the development of decision-making tools.

Table 4.9 Summary of data collection practices rankings

Returnee ID	Data collection rating				
	Q2 outcome (inventory practices)	Q3 outcome (inspection practices)	Q4 outcome (testing practices)	Development (Q2-Q4) of overall data collection practices	Overall data collection vs. complexity
1	2	2	2	2	0
2	2	3	3	2	-1
3	3	2	2	2	-1
4	2	1	1	1	-1
5	3	2	3	2	0
6	2	3	3	2	0
7	2	2	2	2	-1
8	1	3	2	2	-1
9	1	2	2	1	0
10	2	1	2	1	-1
11	3	1	2	2	0
12		3	3		
13	2	2	1	1	0
14	2	1	1	1	-1
15	1	2	1	1	-1

Table 4.10 Summary of asset management practices rankings

Returnee ID	Asset management rating					
	Data collection development	Performance knowledge	Decision making	Data storage and management	Overall bridge asset management development	Asset management development vs. complexity
1	2	2	1	1	1	-1
2	2	3	2	2	2	-1
3	2	3	1	1	1	-2
4	1	1	1	1	1	-1
5	2	2	2	2	2	0
6	2	2	3	3	2	0
7	2	2	2	1	1	-2
8	2	1	1	1	1	-2
9	1	1	1	1	1	0
10	1	1	1	2	1	-1
11	2	3	1	2	2	0
12		2	1	2		
13	1	1	1	1	1	0
14	1	2	1	1	1	-1
15	1	1	1	1	3	1

4.11 Summary of survey findings

Table 4.11 shows the combined list of outcomes that should be incorporated into a data collection and monitoring strategy. Including these suggestions will align New Zealand bridge management practice with international practice.

Table 4.11 Summary of the outcomes to be incorporated into the strategy

Question number	**Outcomes to be incorporated into the strategy.**
1	Consistently classify and categorise structural inventories.
	Formally outline inventory collection requirements.
	Accurately identify network complexity.
	Include a wider range of data in inventories – not only asset description, but also drawings, photographs and reports.
2	Define inventory storage to ensure consistency in terminology and use.
	Recommend varying development levels for varying network complexity.
	Include performance data such as load capacities, scour and risk.
	Include valuation data and associated remaining-life estimates in inventory data.
3	Include condition-rating recommendations to improve reporting and consistency (now covered by the NZTA's adoption of the UK Highways Agency's *Inspection manual for highway structures* (2007).
	Allow for variable inspection timings based on risk.
	Include details of QA and data checking.
	Include improvements identified by bridge managers (see section 4.5.3).
4	Provide recommendations on the use of NDE and its integration into the inspection process.
	Provide recommendations on the use of SHM and its integration into the inspection process.
5	Provide detail on bridge LOS and performance measures.
	Include performance-related aspects in the planning process.
	Identify long-term planning aspects.
	Incorporate lifelines management ideas.
	Ensure all the data that is stored is used in the decision-making process.
	Collect risk data for bridges and networks.
6	Ensure all data is linked directly to the decision-making process
7	Ensure formal data management is included.
	Identify the type of data that should be stored and linked to the decision-making process.
	Store more risk-related data.
	Ensure the asset management process is used to develop data collection, use and data storage strategies.

5 Benchmarking New Zealand bridge management practice

5.1 Introduction to the benchmarking of New Zealand bridge management practice

This section highlights the gaps between international practice and New Zealand practice and covers:

- where current international bridge management practice does not align with international best practice
- where New Zealand practice does not meet the standards of international practice
- where current operator practice does not meet the required level of good New Zealand practice.

5.2 International practice improvements

The literature review revealed that the key gap affecting bridge asset management was the formal agreement on bridge performance measures. This is a key requirement to understanding strategic goal delivery. As this is a high-level gap, it affects the whole asset management cycle, and more specifically data collection practices and decision-making tools.

It also revealed that visual inspections, and the processes and procedures surrounding them, have flaws that result in outcome variability and inadequate inspection repeatability. As such, these issues should be addressed in a data collection and monitoring strategy. Further, to limit the variability and repeatability issues, it was also recommended that there should be increased use of NDE and SHM in inspection practices.

5.3 Comparing New Zealand and international practice

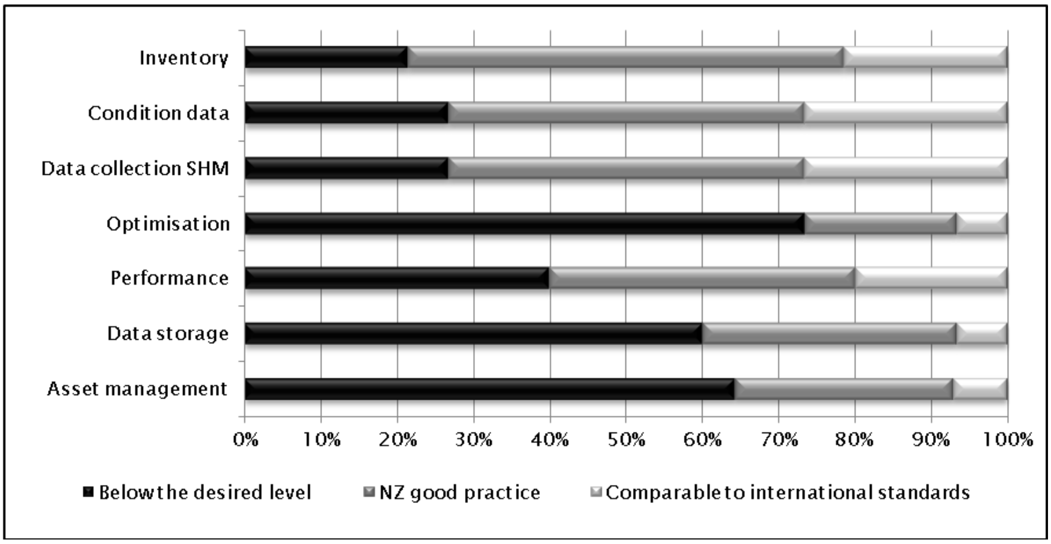
The review comparing New Zealand practice to international practice was carried out as it was deemed important to understand what improvements were required in the data collection strategy.

Overall, New Zealand compared well to international practice for many of the data collection aspects, but fared less well in the optimisation and decision-making area. The main improvements needed were the collection and storage of condition-related data, the storage of performance data, and the standardisation of inventory terminology. While the collection of condition data is now covered by the updated NZTA inspection practice, systems will have to be configured to reflect these changes in type of data collected.

It was also clear that New Zealand bridge asset management practice relied too heavily on visual inspections, with only limited NDE carried out and very limited SHM used on bridges. There was also little awareness of the existence of SHM and the benefits it can bring.

In assessing the development level for each question (figure 5.1), a ranking of 3 was assumed to be comparable to international practice, a ranking of 2 was considered to be good practice, and a ranking of 1 was considered to be below the desired good-practice level. These findings showed a low overall development level for bridge asset management, with over 60% of authorities rating lower than a good-practice standard.

Figure 5.1 Rankings compared to international practice



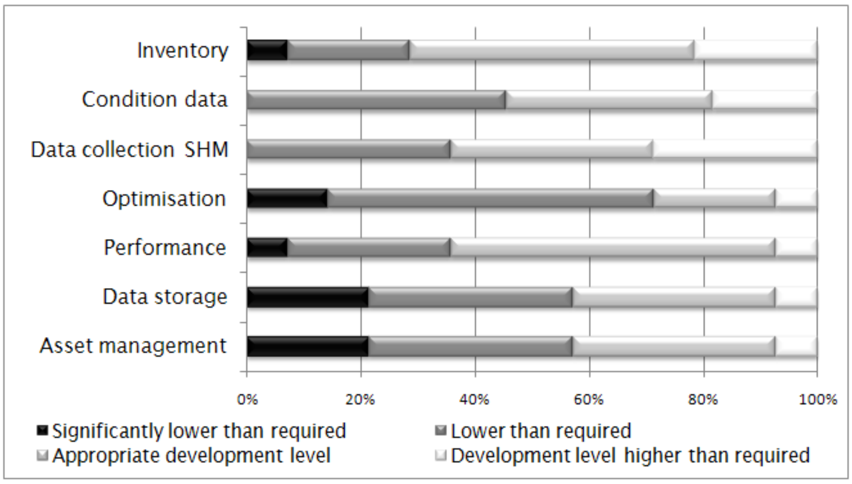
5.3.1 Comparing New Zealand practice to network complexity

Best international asset management practice may, in some cases, be out of balance with New Zealand's needs, as many networks are less complex than those overseas and therefore require less-advanced asset management approaches. However, this does not mean an advanced approach should not be used – rather, that internationally recognised systems and process may not be directly applicable. To better understand local practice requirements, network complexity was compared to the development level assessed for each question and topic area (figure 5.2).

For this assessment, a difference of 2 was considered to be a level significantly higher than required and -2 was considered to be significantly lower than required. A difference of ±1 was considered to be moderately higher or lower than required. A difference of zero was considered to be appropriate to the needs of the network.

It can be seen (figure 5.2) that while New Zealand does not necessarily align well with international practice, it is generally carrying out adequate processes for data collection when network complexity is taken into account – but even so, development is still required for decision-making aspects.

Figure 5.2 Topic rankings compared to network complexity



5.3.2 Overall comments

Even though inventory is well developed, when compared against good practice, there are still inconsistencies in terminology and the range and type of data that is collected.

While defect management can be considered as an optimal level for simpler networks, lifting the standard to include condition data collection, and therefore adopting condition-based management, would improve the long-term planning required for the later asset management stages related to decision making and work optimisation.

The main specific points identified as part of the analysis process are as follows:

- The recognised asset management cycle is currently used in an ad-hoc way, with a focus on inventory storage and defect management. There is therefore a need for a well-defined bridge management process, thereby moving away from a find-and-fix approach.
- Inventory data is inconsistent between many bridge managers, who need to more accurately define inventory categories.
- The stored data needs to be increased to include performance data, over and above loading data and other records, including drawings and reports.
- Maintenance is currently the main focus of bridge management – the wider performance management context also needs to be included.
- Maintenance management is currently focused on defect management, which is a reactionary approach, and it needs to be more oriented towards condition management. Formalised condition-rating standards need to be used (this is now covered by the changes to the NZTA inspection practice, which is based on the 2007 UK Highways Agency's *Inspection manual for highway structures* (2007).
- Awareness of SHM needs to increase, and NDE needs to be integrated, where appropriate, into the bridge inspection process.
- Best practice for QA needs to be defined, both for the inspection process and inventory and condition-data management.
- The linkage between collected data and its use for decision making is not clear; however, risk is used to identify large problems.

6 Data collection and monitoring strategy

6.1 Introduction to the data collection and monitoring strategy

A formalised approach needs to be taken to data collection and monitoring of road bridges, as bridges are long-life assets with expected design lives of 100 years. They are typically expensive and difficult to replace without affecting the operation of the network, especially in heavily congested areas. It is therefore important to understand how a bridge is performing in situ, so that its service life can be maximised and the risk of bridge failure minimised within budgetary constraints. However, it was identified from the survey of New Zealand bridge asset managers that a number of changes should be made to align current local practice with that carried out internationally. These changes include the following:

- Bridge asset managers need to ensure the collected data is better linked to the decision-making process and to strategic outcomes.
- The type of data collected for bridges needs modification, ensuring that sufficient data is collected for advanced asset management.
- The full range of data collection techniques should be adopted, including visual inspections, NDE and SHM, thereby supplementing visual inspections and ensuring more accurate data is available for long-term planning.
- Data needs to be treated with the same respect as the asset itself, and formal data management should be undertaken, as it is for roads.
- Not all bridges or networks require an advanced asset management approach, and a risk-based approach to data collection should be developed so that practices can be tailored to the needs of specific networks.

To meet these requirements, the strategy is divided into four sections, with specific good-practice requirements detailed for each section, and recommendations on improvement actions based on the identified gaps. The specific sections are as follows:

- Section 6: Data collection framework (the underlying structure)
- Section 7: Data required for bridge asset management
- Section 8: Changes to New Zealand inspection practices for improved data collection
- Section 9: Implementation of the strategy within a risk- and criticality-based framework.

Adopting and implementing this strategy will ensure the data required to meet advanced asset management needs (Hughson et al 2006) is available and can be linked to strategic outcomes. This is because there will be more data with which to undertake the advanced asset management decision-making process. This will move the bridge management process away from defect management to service-level management, with improved performance measures and targets developed. By developing these measures it will be possible to link operational and strategic outcomes. This is important if long-term planning and proactive asset management of the bridge stock is to be achieved.

In developing these recommendations, it is the aim of this document to provide a prescriptive framework, but one that still provides, where required, sufficient space for bridge asset managers to develop innovative and network-specific approaches to bridge management. The approach therefore provides a risk-based framework for the categorisation of bridges, where acceptable risk levels can be set according to risk tolerance and available budgets. However, once these have been decided, there are specific recommendations with regards to the type and ways in which data should be collected. By developing this approach, it is hoped that bridge asset managers will more readily adopt the recommended changes, as they will be flexible enough to cope with most network needs.

6.2 The underlying structure of the strategy: core, intermediate and advanced approaches to data collection and monitoring

In New Zealand there are approximately 18,000 bridges, with bridges on local-authority roads having an average span length of 17m, and state highway bridges having an average span length of 35m (see table 6.1) (NZTA 2010b). It can be concluded that an 'average' New Zealand bridge has one or two spans. Further to this, 42% of the stock are single-lane bridges and 5% of the stock are timber bridges (ie bridges having one or more timber elements, not including decks (ibid). However, the current New Zealand and Australian practice (Curran et al 2002, Maguire 2009) details a uniform approach to the management of the entire bridge stock, irrespective of the differences in their risk profiles. The review of international practice and New Zealand practice identified that many countries and areas in New Zealand are carrying out this uniform approach. To facilitate the implementation of a new risk-based approach, there need to be changes to the current data collection and monitoring practice. Before this can happen, an underlying strategic structure has to be developed. This is outlined in this section.

Table 6.1 New Zealand bridge statistics (NZTA 2010b)

	Total number	Total length	Average length
State highways	4027	142,190	35
Local roads	13,912	237,719	17
Total	17,939	379,909	-

The literature review identified that many asset management practices are based on a tiered approach. For example, IIMM (Hughson et al 2006) promotes the core and advanced asset management approach, and Paterson and Scullion (1990) use four data collection levels in the management of roads. The survey also showed that not all bridge networks require the same level of development with regards to asset management. This is because of different network complexities and that fact that not all bridges present the same risk or have the same criticality for network functionality. This philosophy has been adopted and further extended for the data collection and monitoring strategy, with three levels of bridge management – core, intermediate and advanced. Each of these levels is applicable depending on an individual bridge's criticality and risk. These aspects determine how the bridge is inspected and the type of data that is collected. Adopting this tiered approach will move bridge inspection and data collection away from a 'one size fits all' approach to an approach where the bridge's importance to the network, and its operational needs, are taken into account. This will allow bridge managers to focus their efforts on those bridges that require it, and will allow a more effective balancing of the funds and resources used to inspect and manage bridges.

The asset management process is usually differentiated into the core asset management and the advanced asset management. The advanced asset management is characterised by two capabilities:

- the ability to forecast the condition or risk over time
- the ability for long-term investment optimisation.

In table 6.2, the core and advanced asset management levels are juxtaposed with the proposed data collection needs and levels. While only two asset management process, core and advanced, are envisaged, an extra layer of sophistication of data collection was added, since there seemed to be a need for more detailed investigation and analysis of the most-critical or at-risk structures. This allows bridge asset managers to adapt their data collection regimes depending on what the data is ultimately used for in the asset management decision-making processes, and according to the specific information needs for a particular bridge, based on its risk and criticality assessment. For the advanced asset management process, appropriate data is sourced from an intermediate or advanced data collection level. However, advanced data collection is required when more detailed analyses, such as diagnostics at the bridge component level, is to be undertaken. Explicitly linking the asset management approaches to data collection regimes will ensure that for high-risk and critical bridges, appropriate data will be available to implement the required advanced approach to their management. On the other hand, for less at-risk or critical structures, where core asset management is appropriate, data collection can be simplified. The use of three data collection levels also allows bridge asset managers more freedom in developing bridge-specific approaches that can be used to ensure cost neutrality is maintained.

Table 6.2 Correspondence of asset management and data collection levels

<table>
<tr><th rowspan="2">Data collection and monitoring level</th><th colspan="2">Asset management level</th></tr>
<tr><th>Core</th><th>Advanced</th></tr>
<tr><td>Core</td><td rowspan="3">Basic functionality of asset management can be achieved, including valuations and prioritisation of annual budget expenditure.</td><td>Core data may not be sufficient for advanced asset management processes.</td></tr>
<tr><td>Intermediate</td><td rowspan="2">Advanced asset management processes, including network-level analysis, forecasting condition/risk and investment-level scenario analysis can be achieved using intermediate data.
Advanced data is utilised for further analyses at a more detailed level (eg project level) such as diagnostics and more accurate intervention needs and costs.</td></tr>
<tr><td>Advanced</td></tr>
</table>

The boxed text Action 1 (see below) summarises the core recommendations discussed in this section. Other action text boxes are used for the similar purpose in the subsequent sections of the report.

Action 1: Categorise bridges as core, intermediate and advanced, linking the ranking to the risk and criticality rating of the bridge (see section 9). This will allow asset managers to focus their effort towards bridges that most require it and are central to the network service-level provision and functionality. It will also allow bridge asset managers to justify why an advanced asset management approach has not been adopted for all bridges, thereby addressing comments raised by the NZOAG (2004, 2010) (see section 1.1).

6.2.1 The core approach

The core level is the lowest development level. ‘Core’ bridges will have a low criticality rating and a low risk rating. These bridges will therefore require a lower level of management, with the practices focusing on core asset management.

A core asset management approach is considered appropriate for these bridges as they will be generally in good condition, will have a limited impact on the network if the service level is reduced, and will be operating well within their operational capabilities. These bridges will also have structural systems of high redundancy, reducing the risk of failure. Based on this, only limited performance data will be collected, focusing mainly on known key risks. Collecting this data will facilitate core asset management and the development of a prioritised work programme.

The primary method of data collection for these bridges will be visual inspections, with NDE used in a limited way to manage issues raised during the inspection programme. Visual inspections will provide key data such as condition ratings, defect descriptions, defect risk ratings, maintenance action recommendations and cost estimates. While visual inspections provide a less accurate understanding, it is considered that the approach is appropriate for core bridges.

If culverts, retaining walls and gantries are used as a sample set for core bridges/structures, they account for 47% of all the assets that were listed by the 15 returning authorities. While these structures may be intermediate, this identifies that a large proportion of structures could have a reduced requirement for data collection. By reducing the data development for these bridges, the data collection burden for bridge asset managers will be lower, allowing energy and funds to be refocused.

6.2.2 The intermediate approach

If the criticality and/or risk ratings increase, the bridge changes from ‘core’ to ‘intermediate’. Intermediate bridges have an increased impact on network performance if they fail, are in a poorer operational state, or are operating close to their performance envelope. Their structural systems may have little or no redundancy, increasing the risk of failure. Intermediate bridges will therefore require a broader understanding of their performance risks, and a more accurate data collection approach, if performance risks are to be adequately managed.

The data collected for the intermediate development level is expected to provide sufficient data to allow advanced asset management to be carried out, such that forward planning and optimisation can be undertaken. Data for these bridges will typically be collected using visual inspections and also NDE, which should be used to achieve the greater level of accuracy that is required for advanced asset management.

Further to this, network-level data such as annual average daily traffic (AADT), truck weights, and flood and seismic data should be collected, to enable advanced decision making. It is expected that this data will be collected from third parties or as part of regional/national programmes, and is likely to be collected using SHM.

If footbridges, large culverts, highway bridges, and rail overbridges are used as a sample set for intermediate bridges, 47% of all structures nominated by the survey returnees fell into this category. Therefore there are feasibly 47% of structures where data collection, inspection and evaluation practices should be improved to provide the required level of accuracy and data needed to undertake advanced asset management.

6.2.3 The advanced approach

The advanced level is only for the most critical or high-risk bridges. These bridges will have a pivotal role in the operation of the network, will be in a poor state of repair, or operating very close to (or even beyond) their performance limits. Their structural systems may lack redundancy. As such, more accurate data has to be collected if the risks are to be managed appropriately. It will also be cost-beneficial to use more advanced techniques to collect the data. Because of these facts, data will be collected to a level where critical components can be understood and using more advanced approaches to ensure the required level of accuracy is achieved.

The investigation approach for advanced bridges will include the full range of evaluation and monitoring techniques, including visual inspections, NDE and SHM. The use of SHM will allow bridge asset managers to adopt a proactive approach to bridge management, unlike the visual inspection and NDE approaches used for intermediate and core bridges, which can only be used to detect bridge defects once they have occurred. The advanced approach therefore provides the most developed bridge management process, allowing accurate long-term planning to be undertaken. This will result in improved management of the bridge and therefore improved network functionality.

Examples of critical structures on the state highway network are SH1 Auckland Harbour Bridge, SH5 Mohaka Bridge and SH6 Kawarau Gorge Bridge. All these are key bridges with specific management approaches required for critical components. Given the type of bridges considered and the costs involved, it is likely that only the most critical of New Zealand’s bridges will require the advanced approach.

7 Data requirements for bridge asset management

7.1 Introduction to data requirements for bridge asset management

It was clear from the survey of current practice that bridge asset managers tend to focus towards managing bridge strength and condition (via managing defects). Some work is also done, but not always stored, on addressing scour and seismic vulnerability. However, the review of international practice made it clear that many countries are moving towards a more holistic approach to bridge performance management that addresses the whole range of performance indicators. It is important that a greater breadth of data is collected if bridge management is to take a LOS view point as required by the NZOAG (2004, 2010).

In developing a new data collection framework, the Austroads bridge data recommendations (Curran et al 2002, Maguire 2009), the Canadian core infrastructure framework (Rivera et al 2007) and current BDS data collection practices have been combined to provide a more complete picture of the data needed to deliver full performance management.

In this section, specific data collection expectations have been identified for inventory, condition, asset history, planned work, cost and performance data. As data is an asset in its own right, data management techniques are also detailed.

7.2 Aligning data and strategic outcomes

Understanding the links between the data that is collected, the information derived from it and the knowledge that is developed is considered critical. The NZOAG (2004) and USGAO (2008) audits emphasised that that bridge managers need to provide not just data, but information that can be used to understand whether national strategic objectives are being delivered. Figure 7.1 provides a viewpoint of this, showing how data (fifth layer) is developed into information (fourth and third layers), and information into knowledge (second and first layers).

To assist in this process, collected data needs to be mapped to performance measures and strategic service levels. At present this process is not carried out. If done, it will help bridge asset managers to understand what data is needed to carry out strategic asset management and operational tasks, and what data can be considered as only supplementary. Figure 7.2 outlines an example of a data chain related to the efficient-travel-performance measure noted in the NZTA Statement of Intent (2009c).

Figure 7.1 Data requirements for use with performance frameworks

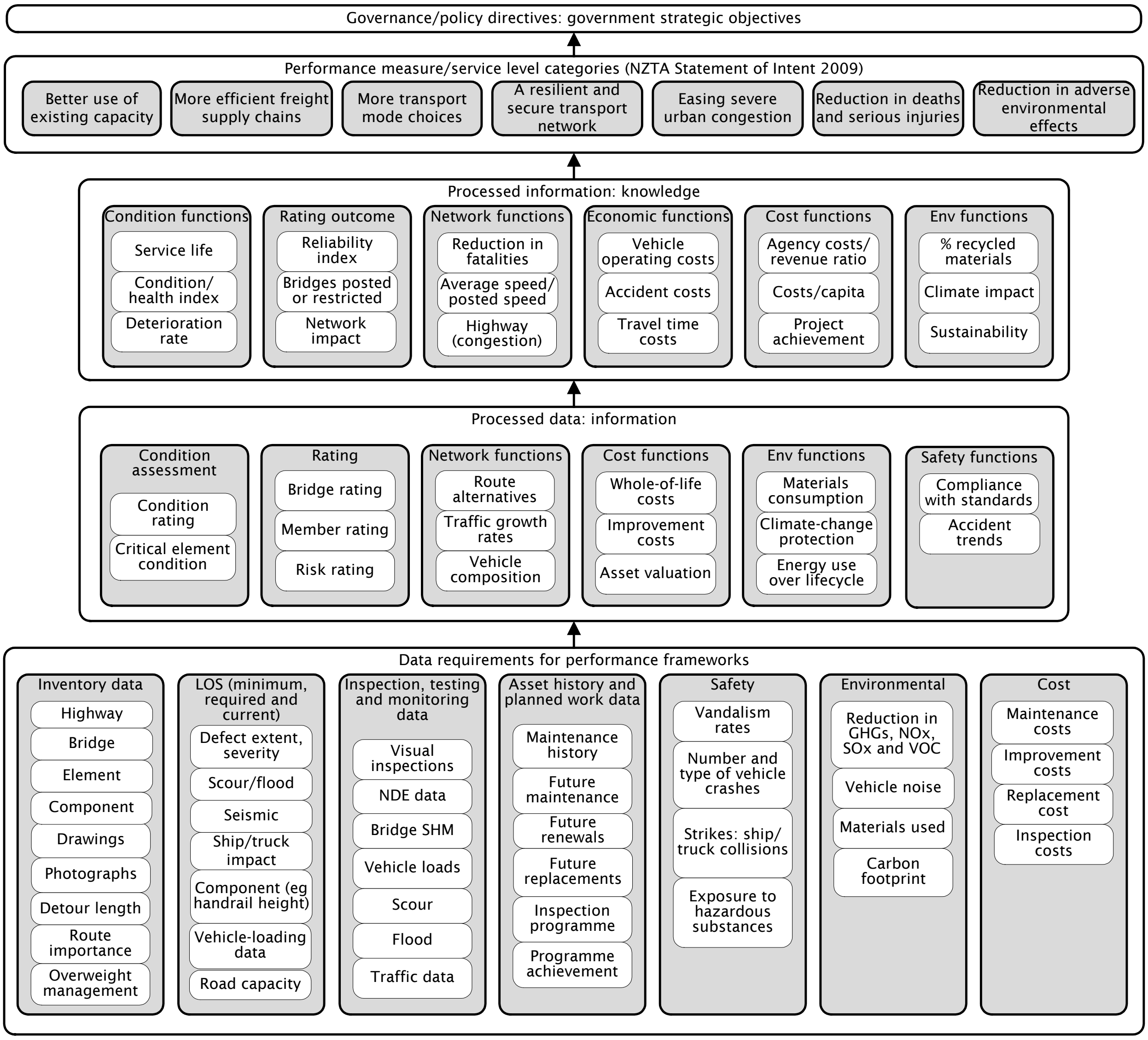
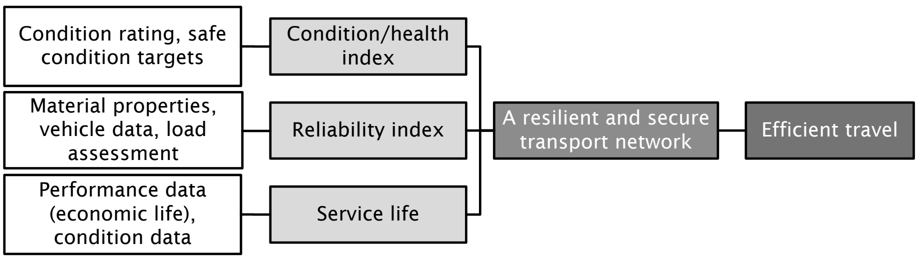


Figure 7.2 Data chains linking strategic and operational data



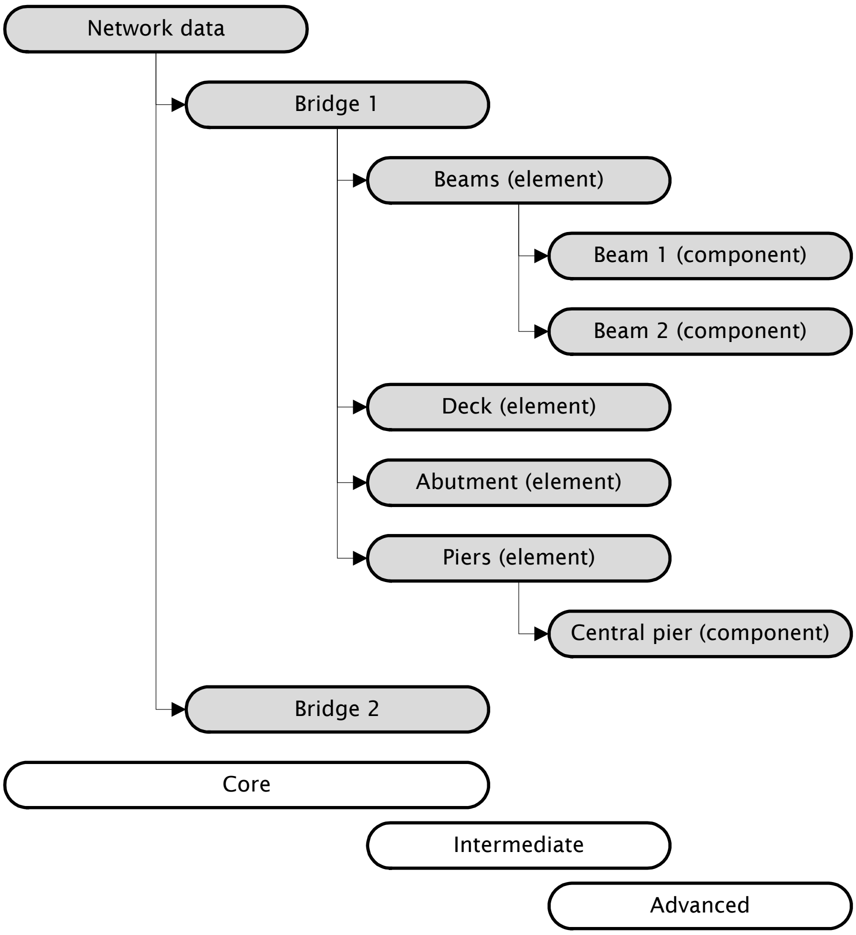
Action 2: Bridge asset managers must link operational activities and related data to strategic outcomes, identifying how the operational activities underpin achieving strategic outcomes as defined by performance measures.

7.3 Inventory data

The literature review identified that internationally, bridges are not consistently categorised in terms of network data, bridge data, element data and component data. This issue was further identified in the survey of New Zealand bridge managers, many of whom were using different terminology for element and bridge types. This section provides details of inventory data to be collected, and its hierarchy.

Bridge inventory comprises four levels – network, bridge, element, and component data (see figure 7.3). Network data relates to the route or corridor section that the asset is located on; bridge data defines the individual bridge as an entity; element data provides more detail on bridge elements such as deck, bridge beams or bearings; and component data provides specific details on areas such as single bearings or bridge beams.

Figure 7.3 Inventory hierarchy



Network-level and whole-bridge-level inventory data needs be collected for the core approach. This will then be augmented by element-level data for the intermediate approach, and will be further expanded to component-level data for the advanced approach. Therefore, for an increasing level of criticality and/or risk there will be an increased understanding of the bridge – from an identification and management point of view, it is important to store data with greater resolution (down to element and component level) on the bridges that are most important to the network's functionality.

7.3.1 Network inventory data

Network inventory data (table 7.1) covers all collection levels and provides details on the route the bridge is located on and the route's importance. Further data that may be collected includes road section ID, to allow it to be tied to the RAMM pavement sections and thus provide a more detailed understanding of the carriageway that the bridge supports. Aspects such as roughness can also be factored into bridge performance – eg approach roughness and its impact on bridge expansion joint life.

Table 7.1 Network inventory data

Data item	Description and comment	Development level		
		Core	Int	Adv
Road name/road no.	Road name or number	x	x	x
Road designation	Road of national significance, arterial	x	x	x
RAMM section ID	Allows the bridge and pavement databases to be interfaced	x	x	x

7.3.2 Bridge inventory data

Bridge data, in line with Austroads (Curran et al 2002), is considered to be 'sets of descriptive data that define [the] bridge[s] as physical assets and are used in the management and administration of bridges'. Bridge data therefore identifies the type of asset, what is it made from, when it was constructed, and where it is located, along with basic dimensional details (see table 7.2). This differs from some inventory databases used in New Zealand, which list defects under inventory – eg damage due to alkali/silica reaction, or scour. This approach is not considered appropriate, as inventory should describe the asset; condition and defect should describe defect issues affecting the bridge; and the rating should describe the severity and extent of the issue.

Core inventory data provides sufficient information to identify the type of asset, what is it made from, when it was constructed, and where it is located, along with basic dimensional details (table 7.2). The data requirements listed in table 7.2 are based on BDS.

Intermediate data defines bridge elements. By collecting element-level data it will be possible to tie specific defects, condition ratings and performance assessments to each element. It is also important to understand structural redundancy of the bridge and consider the possible failure modes. This will determine which elements require more accurate inventory description. Collecting element data will lead to improvements in optimisation of maintenance and improved levels of performance management, which are key for advanced asset management. The intermediate approach is intended for moderately critical and/or at-risk bridges.

Advanced data (table 7.3) will not be required for the majority of structures, and it will focus solely on high-criticality and/or high-risk bridges that require an improved level of detail to understand key component issues, contributing to more advanced decision making. This again needs to be linked to structural redundancy to determine which components require more accurate description.

Table 7.2 Core and intermediate bridge inventory data

Data item	Description and comment	Development level		
		Core	Int	Adv
Structure number/structure ID	Unique identifier assigned to the bridge	x	x	x
Structure location (grid ref)	6-figure grid reference	x	x	x
Structure location GPS	A unique GPS location point	x	x	x
Displacement	Distance along the road section	x	x	x
Obstacle crossed	Eg river, highway	x	x	x
Structure name	Name used to identify the bridge	x	x	x
Route position/location	Location position on the route	x	x	x
Construction year	Overall age of the bridge	x	x	x
Structure type	Description of structure form	x	x	x
Construction material	General description	x	x	x
Overall length	Overall length of bridge or structure	x	x	x
Width data	Bridge width from footways, carriageway	x	x	x
Element type	Name of the element group	x	x	x
Element name	Name of the element eg handrails, bearings, joints, foundations, piers, barriers, guardrails	x	x	x
Importance weighting	Used to assign risk ratings for condition or performance	x	x	x
Geometrical data current	Dimensional data eg kerb or guardrail height, road width between kerb or guardrail, height of handrails, pier height, barrier heights	x	x	x
Geometrical data required	As defined by design standards (eg guardrail heights) used to assess compliance	x	x	x
Element materials	Construction material	x	x	x
Age (linked to change history)	Age of the element	x	x	x
Approach alignment	Defines the alignment to the bridge	x	x	x
Clearance (min and max)	Min. clearance to the obstacle crossed	x	x	x
Obstacle crossed	Eg road, river, stream, railway	x	x	x
Number of spans and lengths	Individual span lengths	x	x	x
Number of lanes	Number of lanes crossing the bridge	x	x	x
Ownership	Who is responsible for bridge management	x	x	x
Utilities	Lighting, emergency phones, flushing/gas/irrigation pipes, phone fibre-optic cables, power wires cables, sewer pipes, sign gantries, water-supply pipes, other utilities	x	x	x

Table 7.3 Advanced bridge inventory data

Data item	Description and comment	Development Level		
		Core	Int	Adv
Component name	Specific component within a group			x
Component type	Specific name given to the component			x
Importance weighting	Used to assign risk ratings for condition or performance			x
Geometrical data	Dimensional data			x
Component materials	Material the component is made from			x
Age (linked to change history)	Age of the component			x

Action 3: Set up a structured hierarchy for bridge inventory data comprising network data, bridge data, element data and component data. Categorise materials, bridge forms and elements using consistent terminology. This will improve the ability to accurately mine data for analyses. Do not store defect data in the inventory section – eg scour data or alkali/silica reaction data (as is the current practice); this is because in line with Austroads (Curren et al 2002), inventory data should only refer to the asset and not its defects.

7.4 Bridge condition data

The review of New Zealand practice made it clear that defect data (ie a description of the specific problems found on the bridge) is often understood, wrongly, to be condition data. However, in international practice, condition data is an assessment of the extent of defect or deterioration and/or its severity, using a numerical scale (Curren et al 2002, Roads Liaison Group 2004). It is therefore important to define the condition data that should be collected and stored. In carrying out this task there are two types of data: firstly, the raw data that is created via visual inspections and testing programmes; and secondly, the data entered into the bridge management system as a numerical rating.

Inspection, evaluation and monitoring data comprises results from visual inspections, NDE and SHM. This data will be used in forward-planning models and the decision-making process. Data collected via visual inspections, NDE and SHM programme includes:

- condition-rating data
- raw NDE and SHM data
- benchmark data.

7.4.1 Condition-rating data

Condition-rating data is collected through visual inspections, NDE and SHM. Core and intermediate condition data is stored at element level, and advanced condition data is stored at component level. By collecting condition data for elements and components, it is possible to determine those elements or components that may have an elevated risk of failure.

Developing improved knowledge at element and component levels will facilitate improved optimisation and advanced asset management approaches.

Table 7.4 Condition-rating data

Data item	Comment	Development level		
		Core	Int	Adv
Condition ratings (severity and extent)	Bridge (overall weighted average for bridge)	x		
	Element (severity and extent of defect on inspected element)		x	
	Component (severity and extent of defect on inspected component)			x
Collection methodology	Noted as collected by visual inspection, NDE or SHM	x	x	x
Actions	Stored as planned work	x	x	x
Condition models	See performance data		x	x
Programme	Inspection programme	x	x	x

7.4.2 Raw NDE and SHM data

Storage of raw data collected as part of NDE and SHM programmes is considered to be optional. However, it is recommended, as alternative conclusions may be made than those already drawn, and further, it may be useful at some later stage.

Table 7.5 Raw NDE/SHM data

Data item	Comment	Development level		
		Core	Int	Adv
Raw data	Raw NDE and/or SHM systems outputs	x	x	X

7.4.3 Benchmark data

Many of the current deterioration models have no starting reference. Therefore, in accordance with suggested best international practice, it is recommended that at the time of commissioning, benchmark data is collected (see table 7.6). This should be collected for intermediate and advanced bridges, as these are the ones that require more advanced asset management approaches, and hence it will be beneficial to track trends throughout the life of the bridge.

Table 7.6 Benchmark data for inspection, testing and monitoring strategies

Data item	Comment	Development level		
		Core	Int	Adv
Cover levels	All used as added information when developing deterioration models. Other data to be stored as required by the specific bridge manager		x	x
Chloride levels			x	x
Environment description			x	x
Paint thickness			x	x
Concrete core strengths			x	x
Reinforcement strengths			x	x
Steel strength			x	x
Critical element stresses				x
Timber grade			x	x
Timber treatment level			x	x
Timber type			x	x

Action 4: Store numerical condition data to facilitate the development of long-term condition models. This data should be time-stamped and kept permanently, to allow an understanding of bridge-specific deterioration rates.

Benchmark condition data should be stored at the construction of the bridge to record 'Day 1' parameters. This data should be updated as required to better understand specific bridge performance and to update bridge-specific models.

7.5 Asset history and planned work data

Austroads (Curren et al 2002) recommends the collection of asset history data, as it not only provides a history of an individual bridge but also, when collectively analysed, can lead to an understanding of common maintenance problems. It is intended that asset history (table 7.7) and planned work data (table 7.8) will be used to improve forward-planning estimates, understand typical maintenance costs, identify bridges with higher maintenance rates, and will help to develop whole-of-life-cost models that can be used to optimise maintenance.

Including this data will allow the assessment of component lives and typical maintenance cycles (which improves long-term planning processes and asset valuations), as a truer picture of replacement cycles can be developed. It will also be possible to understand economic lives, an alternative age assessment tool, which is as important in asset valuation and replacement programme development as the condition rating. To facilitate this process, inventory updates and associated cost data will be time-stamped and will not be over-written with new data fields.

7.5.1 Asset history data

All development levels will store asset history data (table 7.7). However, only basic data will be stored for the core level. For intermediate bridges, it will be stored at element level; however, it may be recorded at bridge level for more major works. This allows general maintenance and upgrade trends to be derived at element and bridge level.

All work is recorded at component level for the advanced development level; however it may also be recorded at element or bridge level for certain broad-ranging tasks. This allows general maintenance and upgrade trends to be derived at the component, element and bridge level. The advanced approach is more likely to be used when tracking or managing specific component changes. It should, however, be noted that because of the risk posed by a specific element or component, core or intermediate bridges may require more detailed asset maintenance histories. This is because the risk assessment may have identified a critical component or set of circumstances that require a greater level of vigilance.

It is important that greater data resolution is supplied for the intermediate and advanced approaches, as the data is intended for use in advanced asset management. Collecting data at the element and component levels facilitates a finer level of decision making.

Table 7.7 Asset history data

Data item	Comment	Development level		
		Core	Int	Adv
Bridge data	Amendment history at bridge level – eg work carried out and date completed	x		
Element data	Amendment history at element level – eg work carried out and date completed		x	
Component data	Amendment history at component level – eg work carried out and date completed			x

7.5.2 Planned work data

It is intended that planned work data (table 7.8) is stored at all development levels, the only difference being the accuracy of the FWP. For the core asset management approach, the programme is likely to be prioritised using a risk-based process. For the advanced asset management approach, it is likely to use an optimisation process using wider network, asset history and cost data.

Table 7.8 Planned-work data

Data item	Comment	Development level		
		Core	Int	Adv
Work ID/bridge ID	Stored in roads database	x	x	x
Work description	Amendment history at element level – eg work carried out and date completed, and cost of work (see Cost, below)		x	
Programme	Estimated commencement date	x	x	x
Programme development process	Prioritisation, simple optimisation, complex optimisation	x	x	x
Cost	Cost of the planned work			x
Bridge	Level at which the data is linked	x		
Element			x	
Component				x

Action 5: Collect and store asset maintenance data (work history) and asset maintenance programme data in the bridge asset management system. This will help to develop a high-level understanding of typical problems that occur. The data can also be used in the development of whole-of-life-cost models, and as an important input into the advanced asset management process.

7.6 Cost data

Austroads (Curren et al 2002) defines cost data as economic costs and agency costs (table 7.9). All of this data is important, as it facilities an understanding of network performance both in terms of how much it costs to maintain and improve the bridge stock (agency cost), and the benefits that the bridge provides in terms of, for example, lowered vehicle-operating costs and lowered travel times (economic cost) as a result of the bridge providing a shorter route.

Table 7.9 Cost data collection for core, intermediate and advanced strategies

Data category	Data item	Comment	Development level		
			Core	Int	Adv
Valuation data	Replacement cost	As detailed in the valuation	x	x	x
	Annual depreciation	A function of condition/remaining-life model, or age	x	x	x
	Depreciated replacement cost	Linked to remaining-life and/or condition models	x	x	x
Maintenance cost data	Initial estimates	Include all costs including design, procurement, construction, and construction management. It is recommended that these are stored such that a time variant is added – eg maintenance undertaken now may be relatively inexpensive; however, if deferred this could escalate to a more major issue. Short-, medium- and long-term solutions should therefore be accounted for. This will improve the risk planning process.		x	x
	Planning estimates			x	x
	Construction estimates			x	x
	Construction costs		x	x	x
Improvement cost data	Initial estimates	Include all costs including design, procurement, construction, and construction management (linked to the historical and planned work database)		x	x
	Planning estimates			x	x
	Construction estimates			x	x
	Construction costs		x	x	x
Other costs	Studies	Other costs that are incurred as part of the bridge management process, and stored at bridge level		x	x
	Inspections			x	x
	Miscellaneous costs			x	x
Economic data	Vehicle-operating cost	Provides the basic input data to undertake economic analysis – eg an assessment of the benefits gained from widening a bridge and allowing more traffic to flow, thereby lowering journey times		x	x
	Travel-time costs			x	x
	Safety costs			x	x

Action 6: Along with condition and inventory data, store cost data relating to agency costs and economic costs. This will facilitate the development of economic models to be used for long-term planning, an important part of advanced asset management. In carrying out advanced asset management, it will then be possible to link operational bridge outcomes to strategic outcomes, as required by NZOAG (2004, 2010).

7.7 Bridge performance data

Bridge performance data is data stored on any performance aspect deemed to be important to the bridge. This will be directly related to the severity of risks facing the bridge; therefore lower-risk bridges will have core performance data collected, and high-risk bridges will have a greater amount of risk data collected. Performance data should be stored such that desired and current performance levels can be assessed, with performance assessments based on codes, standards and best-practice documentation. The technical performance assessments will be used to develop an understanding of the risks the asset is facing, and when combined with cost models and other data, will be used to deliver an advanced asset management approach. Key aspects of performance data are considered to be loading, overweight system, safety, environmental and risk data. When storing performance data it is intended that core bridges use more simplified assessments and only store data for high-risk issues. Intermediate bridges will store more accurate data and for a wider range of risks. Advanced bridges will store the most accurate data at the highest level.

7.7.1 Load-carrying capacity assessment data

Loading data (table 7.10) is not solely related to the performance level of a bridge, but is also considered, especially for state highway bridges, to be the overweight-load assessment data. As such, the OPermit data is recorded in table 7.11.

Table 7.10 Assessment data

Data item	Comment	Development level		
		Core	Int	Adv
Assessment date	When the assessment was undertaken	x	x	x
Assessor	Who carried out the assessment	x	x	x
Vehicle load design standard	The design loading used by the highway authority	x	x	x
Current vehicle load capacity (gross weight and axle limit)	Loading limit at bridge level (critical element noted)	x		
	Loading capacity at element level		x	
	Loading capacity at component level			x
Posting data	Restricted Y/N, restriction (speed limit, mass limit)	x	x	x
Seismic design standard	Assessed capacity relative to design loading		x	x
Current seismic capacity	Elements noted that limit capacity		x	x
Over-height impact design standard	The design loading used by the highway authority		x	x
Current over-height capacity	Assessed capacity relative to design loading (rating)		x	x
Pier impact design standard	The design loading used by the highway authority		x	x
Foundation design standard	The design load		x	x
Foundation capacity	Current capacity compared to required capacity		x	x
Current pier impact capacity	Assessed capacity relative to design loading (rating)		x	x
Barrier capacity design standard	The design loading used by the highway authority		x	x
Current barrier capacity	Assessed capacity relative to design loading (rating)		x	x
Other performance data	Other performance data as required by strategic, national or regional programmes		x	x

Table 7.11 OPermit: permitting system data

Data item	Comment	Development level		
		Core	Int	Adv
Permitting system data	Influence line, beam, V-beam, timber deck, and transom, models, deck capacity factor (DCF), restrict X (increasing), restrict X (decreasing), comments		x	x
Assessor	Who carried out the assessment		x	x
Data updated	When the assessment was undertaken		x	x

7.7.2 Traffic data

Traffic data will be used to understand the network parameters that the bridge affects. This is important in understanding how well the bridge is performing in a network context, and for assessing the success of bridge improvements. As the intermediate and advanced approaches both use optimisation for performance assessment, it is considered that a greater level of data is required – as such, more network data is stored, including traffic figures, vehicle weights, and bridge-performance capacity with regards to traffic levels. As the core level of bridge management only uses prioritisation, only basic data needs to be collected in order to assess risks.

Table 7.12 Traffic data

Data item	Comment	Development level		
		Core	Int	Adv
AADT over the bridge	Economic assessment and risk management – also used in network-level modelling	x	x	x
Heavy vehicle %		x	x	x
Site-specific traffic count data	Lane counts, vehicle types, used in bridge-specific loading development			x
Traffic growth rate	Stored in RAMM database	x	x	x
Traffic capacity	Used to assess performance gap		x	x
Current capacity	Based on number of lanes		x	x
WIM data	Used to understand truck configurations		x	x

7.7.3 Safety and environmental data

Safety and environmental data (tables 7.13 and 7.14) contains events occurring on the network and in the vicinity of the bridge – eg flood levels at a bridge, or numbers of crashes occurring at a specific location. In accordance with identified strategic measures, it may also be used to store data on typical noxious gas levels at a location, or the percentage of recycled materials used in the bridge. Tracking the data will facilitate understanding of how strategies that have been implemented have affected the recorded statistics.

Table 7.13 Safety data

Data item	Comment	Development level		
		Core	Int	Adv
Crash statistics	Stored to assess economic impact and to identify black spots	x	x	x
Over-height strikes/impacts	Number of vehicles impacting the bridge		x	x

At the core level, it is expected that sufficient data will be collected to facilitate understanding of aspects such as crash numbers. At the intermediate and advanced levels, it is expected that a much wider range of data will be stored, in order to allow trends such as over-height strikes to be assessed. This in turn will allow strategies to be developed that can minimise specific safety-related aspects. This data may be collected by the asset manager or from third-party databases.

Table 7.14 Environmental data

Data item	Comment	Development level		
		Core	Int	Adv
Flood/sea-level clearance	Assesses the gaps identified (recommended and achieved)		x	x
Sustainability data	Use of recycled material (recommended and achieved)		x	x
Noxious gas levels	Used to assess environmental impact (recommended and achieved)		x	x
Noise (network and sites)	Noise compliance of vehicles on the network and site compliance (recommended and achieved)		x	x

7.7.4 Risk information

Risk Information (table 7.15) is higher-level data defined by assessing the gaps between recommended and achieved levels. This information will be calculated from inventory and performance data stored in the system.

Core data for risk is considered to be data that covers key bridge asset management issues, which are considered to relate to user safety and load-carrying capability. Intermediate and advanced risk data are considered to cover the wider range or risks facing the bridge, including lifeline-related issues, flood or scour, vehicle impact, clearances or barrier performance. This is also related to the degree of redundancy in the structure, as the level to which this data is collected (ie bridge, element or component) will depend on redundancy and identified failure modes. By understanding the risks it will be possible to develop strategies that can be implemented to manage each of the identified issues. These strategies will form part of the long-term work programme.

Table 7.15 Lifeline assessments/network risk data

Data item	Comment	Development level		
		Core	Int	Adv
Compliance	Safety and environmental compliance	x	x	x
Loading	General bridge compliance	x		
	Specifically identified element risks		x	
	Specifically identified component risks			x
Flood/scour	Based on assessment: for core bridges, desktop and document review; for intermediate/advanced bridges, assessment based on additional data (eg NDE/SHM)		x	x
Tsunami	Based on assessment: for core bridges, desktop and document review; for intermediate/advanced bridges, assessment based on additional data (eg NDE/SHM)		x	x
Volcanic	Based on assessment: for core bridges, desktop and document review; for intermediate/advanced bridges, assessment based on additional data (eg NDE/SHM)		x	x
Assessor	Who carried out the assessment	x	x	x
Data updated	When the assessment was undertaken	x	x	x

Action 7: Store the full range of bridge performance data (load-carrying capacity assessment, traffic, safety, environmental and risk) in the bridge management system, as it will facilitate the development of advanced asset management approaches.

7.8 Other data requirements

Other data (table 7.16) is any record that is associated with bridge management. Other data can be stored as hardcopy records or electronically within the system.

Table 7.16 Other data stored for bridges

Data item	Comment	Development level		
		Core	Int	Adv
Photographs	Inspection photographs	x	x	x
Reports	Any report written regarding the bridge	x	x	x
Construction reports/site records	Details of work carried out on the bridge	x	x	x
Drawings	Drawing numbers, drawing names, drawing locations, drawing coverage description	x	x	x

Action 8: Store other data such as photographs, construction and site reports and drawings in the bridge asset management system.

7.9 Storing and managing bridge-related data

This section describes how the data that is collected by bridge asset managers should be stored, and how it should be managed. Both aspects, as identified in section 2.7, are important to the operation of a bridge asset management system.

It has been identified that data is an asset in its own right; therefore, like any other asset, it should be managed appropriately. To do this it has to be stored in an appropriate system and has to be managed using appropriate quality management techniques. The survey of New Zealand practice identified a number of shortcomings to the data QA. The NZTA's *State highway database operations manual* (2009b) has been used as a basis for the recommendations included in this section.

7.9.1 Data quality assurance (QA)

It was identified as part of the literature review that QA is an issue to be considered in data collection and data management, and QA checks of all data used in the decision-making process should be carried out. The data that is required as part of this process is outlined in table 7.17 – it applies to all levels of development, as core, intermediate and advanced levels have the same data quality requirements.

Table 7.17 Data QA

Data item	Comment	Development level		
		Core	Int	Adv
Updated by	Name of person loading the data	x	x	x
Generated by	The person generating the data	x	x	x
Assessor's name	The name of the data reviewer	x	x	x
Date added	The date the data was added	x	x	x

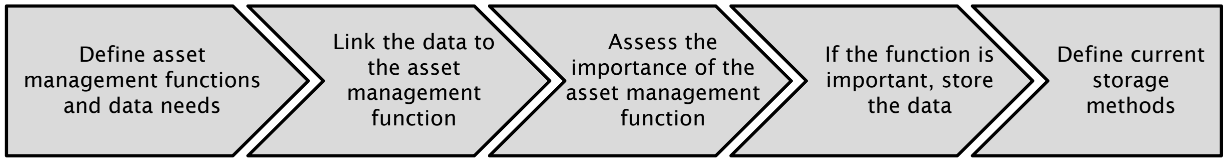
7.9.2 Understanding the data storage needs

Collecting bridge data is important, but it is also important to store the data in a readily available format that can be used by the asset management team. It is also important that the data is up to date and is a fair reflection of reality, as this has a direct bearing on the quality of the asset management decisions and the management of network risks. Key considerations when developing an asset system, and storing and managing data, are outlined below.

Asset management systems should be representative of the network that is being managed; the tools used may therefore range from a spreadsheet through to a fully integrated bespoke asset management database. However, at the time of this research, most New Zealand bridge management systems focused on data storage, and as such were asset lists with little decision-making functionality. It is recommended that these systems should be modified to include the data requirements noted in earlier sections, and also further developed to include decision-making tools.

It is acknowledged that it would be impractical to store all bridge-related data in one system. It is therefore important to understand the type of data that is collected, and to assess which aspects of the data are relevant to the overall asset management decision-making process. Once this is known, a decision can be made on what to store. The five key stages to understanding data storage requirements are noted in figure 7.4.

Figure 7.4 Data assessment process used to understand data storage needs



Once the range of data is understood, a priority assessment can be carried out regarding the data that should be stored. The assessment should rate the data by how important it is to the decision-making process, and should therefore prioritise the strategic outcomes that are the most important to report on.

When considering the range of data to store, the data with the highest priority should be data that can be mapped to important asset management functions. Data with moderate or low importance may be stored in the system depending on the case specifics. In any case, a register of the data and its location should be maintained so that it can be tracked. Once the data list has been developed, it is recommended that the bridge asset manager should identify how the data is currently stored, and how this may be adapted and transferred to the central storage system once it has been developed. This may require the development of data management protocols.

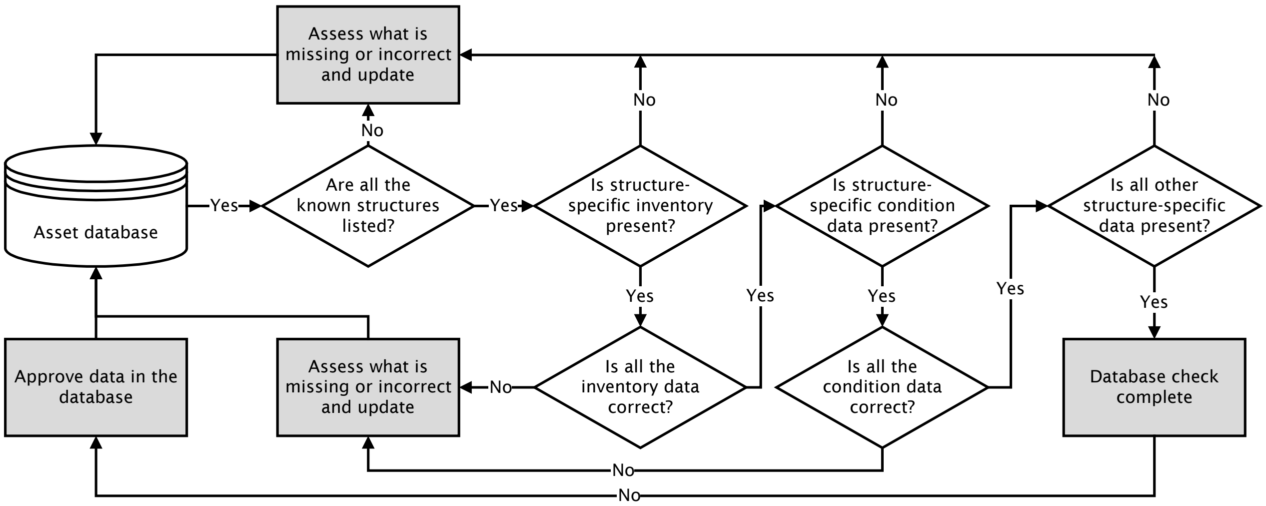
7.9.3 Data management

As data is important to the asset management process, it should be managed like the asset, with appropriate techniques used to ensure it is robust and reliable. It is important that quality control of inspections and all data-related aspects is carried out, as all asset management decisions stem from the data that is collected and stored in the system. Missing or incorrect data impairs the asset management process, leading to reduced decision-making accuracy and outcome confidence, and suboptimal results. Good practice requires that the data management process is audited, and an assessment is made of the input data and the data stored in the system (NZTA 2009b) – this is known as data validation. It also recommends that verification is carried out to ensure consistency of results and to ensure the data is a fair reflection of reality. Adopting these approaches would place bridge data management on a par with road data management.

Asset validation is carried out to ensure all bridges, bridge elements and components are recorded in their respective databases. If assets no longer exist or new ones have been vested to the road controlling authority, the database should be updated to reflect this. Future assessments will comprise a check of new or changed data only. In some cases, an asset check may require a complete network drive-over to ensure all assets are present within the system.

Data validation is used to ensure that data used in the decision-making process is up to date. It is also a check that the data has no obvious errors – eg zero lengths, or incorrect asset descriptions within the bridge management system. Unlike the detailed data check carried out when inputting the data, validation checks are high level and are carried out to ensure the asset database is maintained correctly and has the data needed by the bridge asset manager. The data validation process, as developed for this strategy, is detailed in figure 7.5.

Figure 7.5 Data validation process



To ensure data validation is undertaken regularly, the asset manager should create a validation audit schedule, preferably on an annual basis. Missing data can then be specifically requested in the following inspections.

Field verification tests should be carried out to ensure the data collected by the inspectors and inputted into the system is a fair reflection of reality. Verification can also be used to assess and review dimensions and other inventory data. As verification is a random sampling exercise, only a representative portion of the database needs to be checked.

In many cases algorithms could be developed to identify blank areas within the database, aged data, or even highly used data. This would allow simple audits to be carried out to see where improvements are required in the system.

7.9.4 Implementation of data changes

At the time of this research, a wide range of systems were being used, including RAMM for bridges (local authorities) and BDS (NZTA). All of these had specific issues and would need changes to adopt the proposed strategy. For example, BDS did not store all bridges in the order they occur on the network (ie if searched for, overbridges and underpasses appeared on different lists); RAMM did not have any consistency regarding the storage of bridge-specific inventory data (eg construction type and materials). We recommend that the *State highway database and operations manual* (NZTA 2009b) should be updated to classify bridge elements and provide recommendations on how bridge databases should be set up and managed. This would bring bridge database management in line with road asset database management. It would also ensure that systems store comparable data.

Action 9: Data should be managed via regular checks, and gaps filled in as required. These processes will increase confidence in the data as well as the quality of the decisions made using the data.

8 Changes to New Zealand bridge data collection practices

8.1 Introduction to changes to New Zealand bridge data collection practices

Visual inspections are the main type of data collection, especially for condition and defect data. However, as frequently noted in literature, this technique is not altogether reliable. We have therefore developed a strategy to enhance visual inspection practice, and also suggest the following improvements:

- Enhancement of the bridge visual inspection practice including:
  - the adoption of risk and criticality-based inspection timings
  - the adoption of condition rating, and changes to the inspection and maintenance manual
  - medical check-ups of inspectors to ensure ongoing inspection quality
  - the use of benchmark inspections to collect data that can be used to improve bridge management models.
- The wider adoption of techniques supplementing visual inspections, including NDE and SHM.

We recommend that the aspects covered below should be further developed, and the *Bridge inspection and maintenance manual* (NZTA 2001) should be updated to ensure the wide distribution that is required to raise the awareness of bridge asset managers (the manual is used both by NZTA and local authority bridge managers).

8.2 Changes to the bridge inspection regime

8.2.1 Bridge inspection timings

To date, a 'one size fits all' approach has been adopted for bridge inspections. Under this new strategy, it is proposed that the criticality and failure risk of the bridge are taken into account. Therefore, bridges with higher risk and/or criticality ratings will have inspections carried out on a more frequent basis than bridges with lower criticality and/or risk.

Table 8.1 outlines the proposed inspection cycles for New Zealand bridges. In developing an altered inspection programme, the asset manager may account for the need to have a 'common denominator' for all inspection cycles, so that all the stock is inspected within that time duration. For example, if four years were chosen for the core bridge inspections frequency, a cycle of two years would be appropriate for intermediate bridge inspections.

In the current *Bridges and other highway structures inspection policy* (NZTA 2011), bridge inspections comprise routine surveillance inspections (formally superficial), general Inspections, principal inspections (formally detailed) and special inspections. Routine surveillance inspections are intended to identify any obvious defects that may affect the safety of highway users or anything else needing urgent attention – eg vehicle impact damage or build-up of flood debris. It is proposed that principal inspections should be removed from the baseline cycle of inspections, now comprising only general inspections, as for most bridges they provide little improvement in accuracy when compared with general inspections (Phares et al 2007). Former principal inspections will therefore be incorporated into special inspections as their visual component and programmed as required – eg for bridges with special access conditions or where critical components or elements need close examination. This is considered to be appropriate, as the general inspection process will be augmented with NDE for intermediate bridges and with SHM for advanced bridges, therefore offsetting the risk associated with omitting principal inspections of critical elements and components. Special inspections will comprise:

- special visual inspections, including principal inspections or large or complex structures
- monitoring and testing inspections, likely undertaken by specialist contractors (eg specialist testing of steel bridges)
- posting/loading assessments
- overload damage inspections
- Bailey bridge inspections
- post-earthquake event inspections
- post-flood event inspections.

It is considered that known vulnerable structures, previously managed using vulnerable bridges inspections, would be managed by the recommended risk assessment process. As such they would be classified as either intermediate or advanced bridges and would therefore have increased data collection, monitoring and management requirements.

The timing of general inspections has also been modified to reflect the risk-based approach, with the frequency reduced for core bridges and increased for advanced bridges. Indicative timings are identified in table 8.1.

Table 8.1 Proposed bridge inspection regime for New Zealand road bridges

Development level	Baseline inspection approach	Inspection frequency		
		General inspections	Special inspections	Routine surveillance inspections
Core	Routine surveillance inspections, general inspections, programmed special inspections, reactive NDE	3–6 years	As identified during general inspection process or as planned by the bridge asset manager	As required by contractual arrangement
Intermediate	Routine surveillance inspections, general inspections, programmed special inspections, reactive and proactive NDE, network SHM	2–3 years		
Advanced	Routine surveillance inspections, general inspections, programmed special inspections, reactive and proactive NDE, network SHM and bridge-specific SHM	1–2 years		

As core bridges are considered to have low criticality and risk, their inspection frequency can be decreased to between one and two inspections in the six-year cycle. This is considered to be appropriate, as general inspections are supported by routine surveillance inspections and special inspections after a recognised event (eg flood, storm surge, seismic activity) or for a specific issue such as a posting assessment. In line with current practice, should anything be identified during the general inspection, testing would be undertaken to better understand the issue. This testing may be a special visual inspection or NDE. The bridge is therefore looked at:

- annually to ensure safe operation is maintained
- between three and six years to understand condition
- when defects are identified or after an event.

Thus there is a full and balanced inspection regime for core bridges.

For intermediate bridges, which are considered to be more important to network function or are operating close to performance limitations, the inspection cycle should follow the current New Zealand guidelines, with general inspections undertaken every two years. However, this may be modified to three years for new bridges or bridges with a lower level of risk – typically, bridges that have performance levels comparable to current design standards. These inspections would be supported by reactive NDE in order to understand issues identified as part of the ongoing general inspection process, and by proactive NDE. Proactive NDE is testing that is carried out in a strategic manner and provides either improved data for a bridge (eg cover meter survey to identify steel locations) or improved data for a set of bridges (eg chloride tests for deterioration rates). Depending on the outcome of the testing, the bridge(s) could remain at the intermediate level, or be moved to the advanced or the core level. Under the intermediate strategy, it is also proposed that third-party or network-level SHM data should be collected, thereby providing extra data for the decision-making process. As with core bridge inspections, intermediate bridge inspections would also be supported by special inspections and routine surveillance inspections.

Advanced-level bridges are visually inspected every one or two years. This will also be augmented by NDE to understand ongoing or newly identified issues, and to develop strategic-planning models (eg for paint lives). Further to the use of NDE, it is also expected that advanced-level bridges will have in place some form of SHM, thereby allowing bridge managers to understand the day-to-day performance of these high-risk, high-criticality bridges. Using SHM will allow more proactive management so that advanced bridges can be reliably managed up to better-defined performance limits. This will ensure the lives of advanced bridges are optimised. As with core and intermediate bridge inspections, advanced inspections will also be supported by special inspections (eg for critical elements or components) and routine surveillance inspections.

Action 10: Adopt risk- and criticality-based inspection timings, so that bridges with a greater level of risk or higher criticality have increased inspection frequencies. This allows the bridge asset manager to focus on bridges that require an increased level of attention and service.

8.2.2 Condition inspections

As the later version of the 1983 Department of Transport inspection manual is out of print, the NZTA has recently adopted the UK Highways Agency's *Inspection manual for highway structures* (Highways Agency 2007). This system integrates well with current New Zealand practice and also provides an overall condition rating for a bridge, so that trigger values for action can be set. Using this system will provide an improved view of the bridge stock and the works that are required to bring the stock up to a minimum condition level to ensure safety. However, we consider there are better systems available internationally, such as the County Surveyors Society's *Bridge condition indicators* (Roads Liaison Group 2004), which further extends the information provided by the UK Highways Agency manual by reporting on the condition of critical structural members. This is considered to be important for a condition-rating system, as data resolution is lost when ratings are averaged at the bridge level. The areas that should be included in a bridge condition system are as follows:

- Critical member condition: The *Bridge condition indicators* (ibid) utilises a general rating for most condition systems, and more usefully, it also identifies the critical rating. This is considered to be important to a rating system, as the 'average condition' can be highly misleading – in some cases, critical elements are not identified by the system and are therefore missed from risk assessment and management processes. This also needs to be linked to the degree of redundancy in the structure and its failure modes, in order to understand the critical elements or components. Understanding condition for both critical and non-critical elements and components makes it possible to develop deterioration rate models, a key part of whole-of-life costing, valuations and optimisation.
- Condition-rating systems: These vary, depending on specific country requirements, but most use either a 5-point or a 10-point system. However, a 10-point system has been shown to be too refined, as in practice, inspectors have trouble differentiating between adjacent condition scores (Phares et al 2007). A 5-point system is therefore recommended.
- Defect severity: This is the degree of deterioration affecting the element or component under consideration – eg a significant loss of section would be a high rating, and a 1 would be a low rating. This is linked with the defect extent to describe the condition of the element or component.
- Defect extent: The recommended approach is to estimate and record the percentage of bridge or elements at a particular condition state. This allows an improved picture of deterioration, plus an improved understanding of the general condition make-up of the structure – both key inputs into developing an understanding of bridge health.
- Cost data: Visual inspection data should also include the typical cost to repair, an important part of the prioritisation and optimisation process.
- Element weighting: Through its application, this leads to the development of a weighted average-condition rating for the bridge. However, because this can lead to critical elements being missed, it is recommended that two weightings are developed – one that focuses solely on critical elements that are key to the safety and functionality of the bridge, and a second rating that provides an overall picture of bridge condition.
- It is also recommended that a bridge is given a network criticality rating to allow more important bridges to be identified.

An expert panel should be developed when developing member weightings for bridges, to ensure appropriate outcomes are achieved. Members of a panel should have an awareness of the issues facing differing structural forms.

While the 2007 UK Highways Agency's *Inspection manual for highway structures* has recently been adopted by the NZTA, with the inspection forms updated to reflect this, it still lacks the 'critical' and 'general' rating included in the *Bridge condition indicators* (Roads Liaison Group 2004). 'Critical' ratings provide details on the worst condition found at an element, and the 'general' rating provides details of the overall condition of the element. If the general rating is used in isolation, it could feasibly mask localised areas of poor condition. This is especially important if decision making is to be automated – for example, the system may 'miss' one bridge beam that is less than adequate, as the set of beams will generally be in good condition.

Action 11: Formally adopt condition rating, where defects are recorded and their extent and/or severity is assed using a numerical scale for component, element and whole bridge. Over the long term, this will facilitate the development of bridge condition-deterioration models and improve long-term maintenance planning and whole-of-life management.

Also ensure the condition-rating system reports the general condition and the critical/worst condition, as this facilitates the identification of localised condition-related risks.

8.2.3 Changes to training standards and inspector evaluation

As a greater use of NDE and SHM is promoted, the training associated with inspection practices must be improved. Our survey also identified that some bridge asset managers had little appreciation of the abilities of SHM and NDE. To address this problem, two approaches are detailed below: the first is the updating of the basic bridge inspection course, and the second is the development of a more advanced, specialist course. While there will only be limited number of personnel required to pass the higher level of training, this is considered important for the long-term management of the steadily aging bridge stock.

The training currently carried out by the New Zealand Institute of Highway Technicians (NZIHT) (2010) for the bridge inspection process covers the following areas:

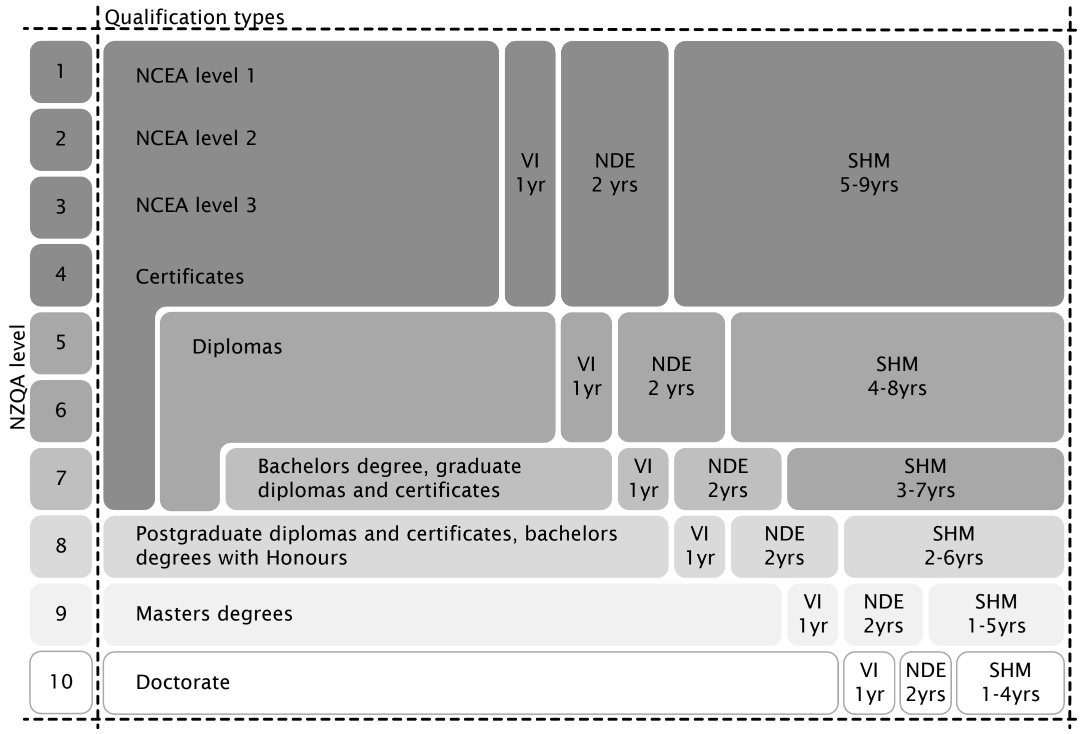
- asset management systems
- the inspection procedure
- condition assessment for common bridge materials
- repair procedures
- coatings for steel structures
- economic evaluation
- durability and maintenance of bridging materials
- maintenance requirements
- waterway, drainage and seismic damage.

It is considered that this is a good introductory course that, when linked with ongoing professional training, adequately covers the bridge visual inspection process. Even so, it is considered that some changes could be made to this course, especially as wide variability of results is usually seen in the bridge inspection process (Moore et al 2001, Phares et al 2007). It is therefore recommended that the bridge inspector training course progresses from largely theoretical, to include a significant practical phase. In the practical phase inspectors will be tested on pre-inspected bridges and their evaluations compared to those that were predetermined. This process adopts a similar approach to that used in the US visual inspection accuracy study (Phares et al 2007), where the proficiency of inspectors was formally recorded for study purposes. This approach also reflects the practice for higher-level traffic management courses, where both theoretical and practical assessment is undertaken. Inspectors should achieve the desired benchmark before passing the course.

As the NZIHT course focuses on visual inspections, it is recommended that more formalised instruction on NDE and SHM should be included, particularly as the general awareness of the benefits delivered by these tools is limited. Training should also be structured so that it relates to the data collection development level – lower-ranking core bridges would have a lower training requirement than higher-ranking intermediate and advanced bridges. This process mirrors the process already in place in the US.

In figure 8.1, the existing New Zealand Qualification Authority (NZQA) (2010) training levels are compared with post-qualification training requirements. The expected time frames for visual inspection, NDE and SHM training are also indicated. The figure shows that it is assumed that it can take one year, on average, to become familiar with visual inspections, NDE assessment take two years, and SHM takes a variable time period depending on the initial qualification – the higher the level of initial qualification, the shorter overall time to become proficient in SHM. These timelines are indicative only at this stage, but highlight the significant training time required by more advanced techniques. It is envisaged that specific training courses would be developed for levels 1–7 and 8–10, where these courses focus on inspections for core, intermediate and advanced bridges, and take into account visual inspection, NDE and SHM training.

Figure 8.1 Recommended training levels of each data collection development level (NZQA 2010)



The basic bridge inspection and maintenance course (NZIHT 2010) needs to be updated and expanded. The basic course should provide a general overview of bridge inspection and maintenance, and explore in-depth inspections and management of core bridges. It should also encompass an introduction to the types of NDE and SHM that are available, how these techniques can be used to collect more accurate data, and the benefits of this. The basic course should be further supported by more advanced learning for intermediate and advanced bridges. The advanced course should also provide more specialist instruction on NDE and SHM, reflecting the complexity of the bridges being inspected. Thus bridges with intermediate or advanced development levels would require a higher degree of certification than core bridges.

Action 12: Alter training courses to include aspects on NDE and SHM, indicating the importance of these tools in the bridge data collection process.

8.2.4 Benchmark inspections

Understanding relative changes in bridge performance throughout the bridge's life is an important aspect of bridge management and is essential to advanced asset management. To that end, and to provide a performance baseline, benchmark inspections are utilised in the 20-year US bridge performance programme (Chajes et al 2006). As understanding the relative changes in bridge performance is very beneficial, benchmark inspections have also been included in our proposed strategy.

Benchmark inspections or surveys should be carried out at the point of commissioning a structure. It is not intended that benchmarking will be used on every bridge, but as in the US long-term bridge performance programme, it will be used on typical bridges. At this stage, it is envisaged that testing of key components or elements will be undertaken to understand load-carrying performance. Benchmark inspections will comprise visual inspections, NDE and SHM of the bridge, such that chloride levels, depth of cover, concrete strength, and other factors that are likely to be used in the assessment and performance management process are known and stored.

Examples of where benchmark testing has proved useful are described in the FHA's *Long-term bridge performance program: pilot study* (Cousins et al 2011), which identified, through the use of SHM, that as-built actions were not the same as the idealised models used for design, especially around support location. In these locations, idealised free-end movement was, in reality, partially fixed. The use of SHM also allowed the bridge engineers and asset managers to more accurately model bridge performance. More specifically, the modelling provided an improved understanding of the relationship between performance and deterioration.

With the adoption of a risk- and criticality-based approach, budgets could be reprioritised towards the use of benchmark tests. This would improve models, such as those for deterioration, used in advanced asset management.

Data that may be tracked includes:

- chloride levels, delamination, carbonation, fatigue
- load-carrying capability and member in-service characteristics
- vehicle loads and numbers
- data on high-risk or high-consequence factors affecting a bridge.

Action 13: Undertake benchmark inspections to improve the accuracy of data on how representative bridges are performing. This data will be useful for the long-term management of the bridge stocks and can be used in developing more accurate condition and performance models, both of which are important to advanced asset management and long-term planning.

8.2.5 Visual acuity checks

The review of practice identified that visual acuity was a key factor in data collection accuracy. Given this finding, it is recommended that inspectors should be tested on a regular basis to ensure that an appropriate level of visual acuity is maintained.

8.3 Increasing the role of testing and monitoring in bridge management

The survey of New Zealand bridge practice identified that NDE is not widely used, and SHM is either not well known or has had limited use as a tool for data collection. It is acknowledged that visual inspections have a pivotal role to play in the bridge data collection process, but as they do not always adequately identify many deterioration mechanisms and are prone to inaccuracies (Phares et al 2007), we highly recommend that they are supplemented with NDE or SHM.

NDE and SHM data can be analysed on its own, or it can be used as part of the St-Id process that develops improved bridge models, such as FEM models, to be later used for structural assessment in the decision-making stages of the bridge asset management cycle. NDE, SHM and St-Id are recommended because they can help to more accurately define the in-situ operational performance and capabilities of a bridge, and lead to a longer service life. More accurate understanding of bridge performance parameters, such as load-carrying capability, or susceptibility of element or components to deterioration, facilitates the development of advanced asset management strategies that can be used to maximise the in-service potential of a bridge.

8.3.1 Uses of non-destructive evaluation for data collection

The survey process identified that NDE was being used in New Zealand, but not to its full potential. As visual inspections do not adequately identify most deterioration mechanisms (Phares et al 2007), we highly recommend that visual inspection data is supplemented with testing data obtained through NDE or SHM. As noted in the strategy, NDE is only recommended for intermediate and advanced bridges, because these are the only bridges that are considered to have a criticality and risk profile appropriate to the expenditure that is usually incurred in carrying out NDE.

A significant amount of work has been carried out internationally on the topic of NDE and its use in bridge management. A recommended text regarding the use of NDE is BA86/06 *Advice notes on the non-destructive testing of highway structures* (Highways Agency (UK) 2006), which is produced as part of the Highways Agency's design manual for roads and bridges. Figure 8.2 details the documents, coverage and examples and applications of NDE, as it relates to bridges. Note, however, that this text lacks any detail on timber bridge management. Any improvements to the NZTA's *Bridge inspection and maintenance manual* (2001) should reflect the findings in BA86/06 and should include guidance on NDE applications to timber structures.

Outlined in table 8.2 shows details of typical NDE types and the applications to which they may be put. It should be noted that this is not an exhaustive list and new techniques are being adopted all the time. For less well-known problems, we recommend that the bridge asset manager should carry out a desktop study of available techniques, or consult with a recognised expert when developing an NDE strategy.

Figure 8.2 BA86/06 format of advice notes (Highways Agency (UK) 2006)

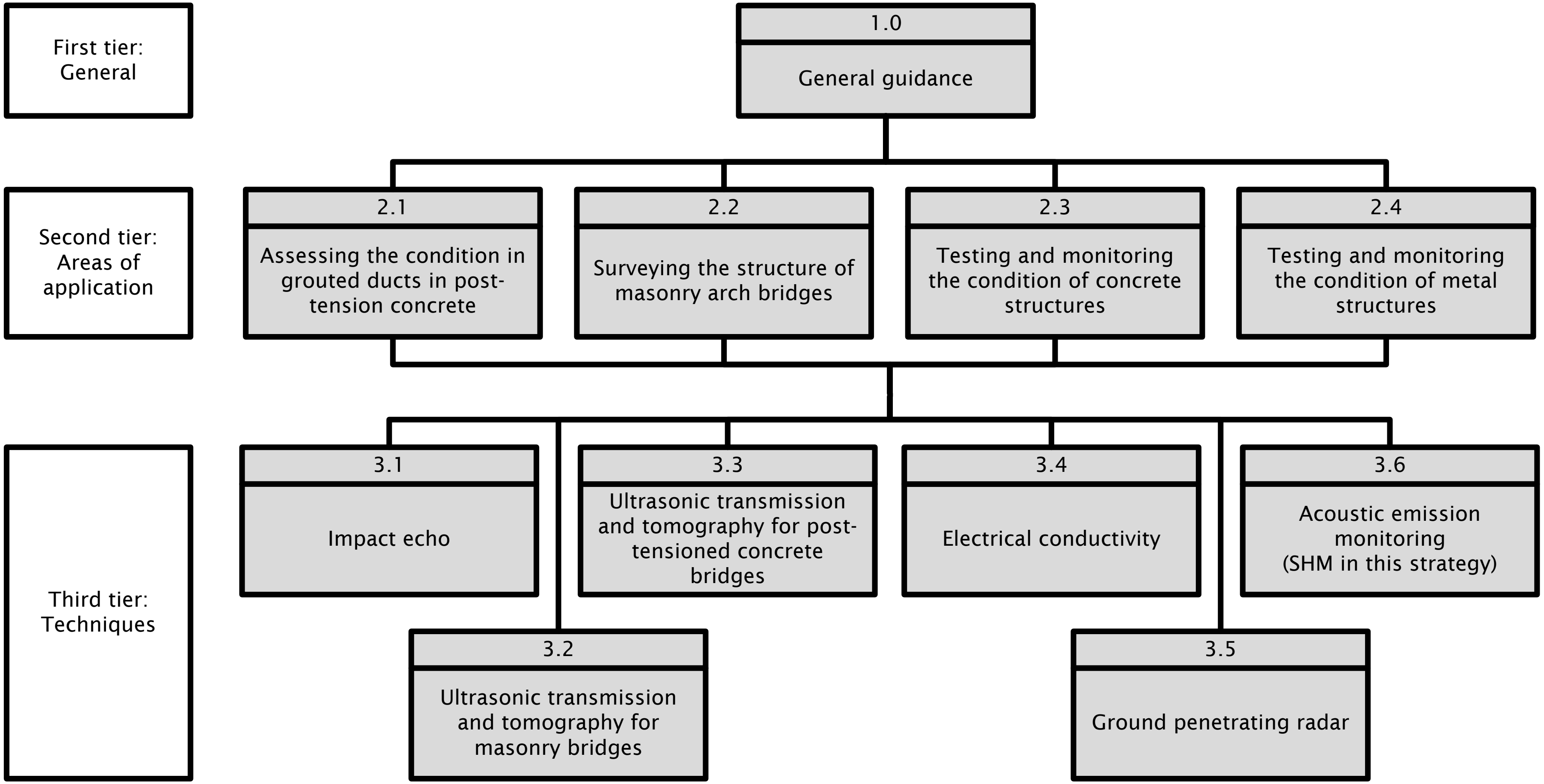


Table 8.2 Types and uses of NDE

NDE test	**Possible applications**
Concrete compression tests	Used to identify the strength of concrete – with a number of tests, statistical models can be developed for the stock or bridge-specific strengths identified, which is useful for performance assessments.
Schmidt hammer	A rebound test that is a measure of hardness, and can be used to understand material strength eg the compressive strength of concrete.
Steel tensile tests	Similar to concrete compression tests; can be carried out on reinforcement or steel sections, with a view to understanding stock or bridge performance.
Chloride sampling	Used to understand the penetration level of chloride ions, which is an indication of the possibility of corrosion. Can be used to understand maintenance actions that are required, such as concrete replacement or cathodic protection.
Carbonation tests	Usually carried out with chloride tests, and can be used to understand the probability of corrosion occurring.
Half-cell potential tests	Usually carried out with chloride and carbonation tests as alternatives, to understand corrosion probability.
Cover meter survey	Used to identify reinforcement location and cover depth – considered essential for bridges with no records, as it aids the assessment process. Depth to reinforcement can provide an indication of the time to onset of corrosion, taking into account factors such as the environment, concrete compaction, and concrete strength.
Delamination survey	Carried out with a hammer – delamination indicated by hollowness in the concrete, as sound concrete provides a ringing return. A useful test for identifying areas that require repair. Also useful in performance assessments, as delaminated areas may be an indication of loss of bond strength, which may affect member capacity.
Mortar patches or tell-tales	Mortar patches are the older version of tell-tales, but both are used to understand the rate of any ongoing movement that has manifested itself as a crack. May be used to understand the crack mechanics before repair is undertaken.
Steel section loss measurement	By measuring the loss of section it is possible to understand the loss of capacity and therefore the overall effect on the bridge.
Decay/damage/ weathering/ delamination	Used to understand section loss and strength loss in timber bridges through rotting, fire damage and ongoing weathering.
Infestation (timber)	Used to understand section loss and strength loss in timber bridges.
Contamination (timber)	Used to understand strength and remaining life of the member.

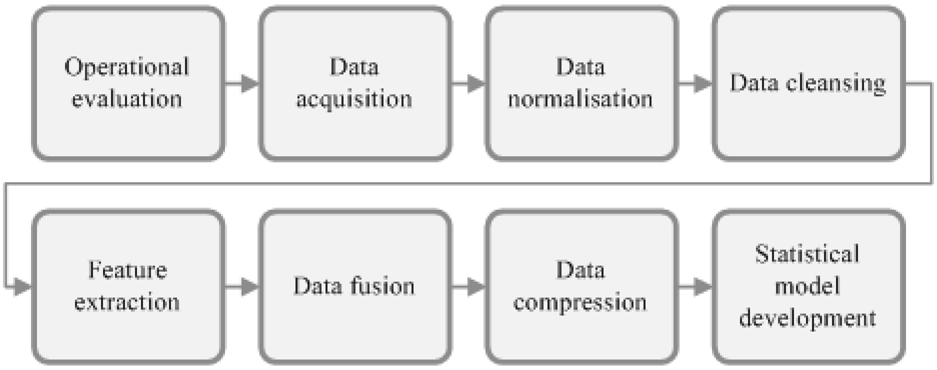
8.3.2 Use of structural health monitoring (SHM) for data collection

In general, New Zealand bridge asset managers appear to have a limited appreciation of SHM. However, SHM is considered to be the only appropriate tool when a proactive asset management approach is required – eg where a bridge is to be managed up to specified performance limit, or where real-time feedback is required (eg flood flows). It is also considered that SHM is the only appropriate tool for collecting wide-scale network-level data, including WIM or traffic data. However, while it is known that SHM is being undertaken on some high-risk and high-criticality bridges, such as the Auckland Harbour Bridge, these represent a very limited number of cases.

We therefore recommend that more literature regarding SHM should be made available to New Zealand bridge managers. As with NDE, we recommend that SHM should be outlined in an update of the *Bridge inspection and maintenance manual* (NZTA 2001). Wide adoption of SHM will improve the reliability and accuracy of data for critically rated and/or high-risk bridges and will improve long-term planning and management.

When updating the *Bridge inspection and maintenance manual* (ibid), we recommend that the SHM development cycle should be fully discussed. The cycle comprises eight key stages (Farrar and Worden 2007), as discussed below (also see figure 8.3). The early stages require that the asset manager understands the problem; the middle stages cover solution implementation; and the final stages involve modelling to understand performance of the bridge and how the collected data relates to performance.

Figure 8.3 SHM cycle



When carrying out operational evaluation, key areas for consideration include system design, monitoring time frames, spatial scale of the project, and more specifically, the data to be collected (general metrics, concrete metrics, steel metrics, timber metrics, third-party or network data).

Khuzadi (2008) notes that the development of an SHM system should take into account a top-down and bottom-up design approach. The top-down approach focuses on the strategic outcomes that are required from the SHM programme, and the bottom-up approach focuses on the types of sensors and sensor locations that are needed to address the strategic outcomes. Without using both, an SHM system might not be able to be used to its full potential.

As discussed in *Bridge health monitoring and inspection systems: a survey of methods* (Gastineau et al 2009), the time frame (table 8.3) of the project is an important part of developing an SHM system, as it will affect the SHM approach that is used.

Table 8.3 SHM time frames

Time frame	Description
Irregular	Used to notify the asset manager when predetermined parameters are exceeded. Examples include storm surge, bridge impact, or bridge overload.
Short-term	Monitoring to obtain bridge response information. Examples include load rating, tracking short-term fatigue growth, or monitoring for a permitted vehicle.
Long-term	Monitoring of a new, retrofitted, or structurally deficient bridge to track its response, usually over a year or more.
Regular cyclical	Monitoring to assess condition as part of an inspection programme. Likely to follow same cycle as the programme eg every two years.

Spatial scale (see table 8.4) is an important aspect to factor into the process, as it will have a major impact on the approach that is carried out. International examples exist where thousands of sensors have been placed on bridges, both for research purposes and to collect real-time damage and performance data to be used in the management of the bridge. Further, undertaking optimisation of the system is important as it ensures the required data is collected using the minimum number of sensors.

Table 8.4 SHM spatial scales

Time frame	Description
Local	Focuses on a specific location within a bridge.
Member	Focuses on a specific member or member-sized area. Examples include deflections of a member, or strain distributions.
Global	Focuses on the overall health of a bridge. Examples may include bridge deflections, natural frequencies and temperature distributions.

Monitoring metrics (tables 8.5– 8.7, and table 8.8) refer to the parameters to be measured as part of the SHM system and include general metrics, concrete metrics, steel metrics, timber metrics, and network metrics. Metrics are considered to be specific aspects that are being measured on the bridge to derive an understanding of bridge performance. The following metrics are based on *Bridge health monitoring and inspection systems: a survey of methods* (Gastineau et al 2009).

By using general metrics (table 8.5), network- and bridge-specific data is collected such that the performance of each can be understood. As noted earlier, it is important to collect network data, as it forms a key part of advanced asset management. Network data, when linked with bridge data, allows both the loading action and the effect of the load action on the bridge to be understood.

Concrete metrics (table 8.6) provide details of the typical metrics that are likely to be measured on concrete bridges, such that performance can be understood. These metrics may be collected through the use of NDE or SHM, depending on which is considered most appropriate for the bridge and the time frame under consideration.

Steel metrics (table 8.7) refer to the typical properties that are measured on steel bridges. By measuring these properties the performance of the bridge can be assessed, where performance may relate to deterioration rates or load-carrying capability.

No timber metrics were proposed in Gastineau et al’s 2009 study. Given the asset value associated with many timber road bridges, it is more likely that NDE would be used, and as such have been covered under NDE. However, for large bridges, such as those found on the rail system, SHM could be used to understand performance characteristics such as strains in members, or maximum load-carrying capability.

While data can be collected specifically for the bridge, there are also a number of sources in New Zealand from which network-level data is available without the bridge manager having to collect it. This data can be useful in developing network-risk models or understanding network functionality. Table 8.8 provides some examples of environmental condition and other network data. This third-party data is typically network metrics data.

Table 8.5 General metrics

Parameter	Parameter description
Scour	Refers to scour around a bridge, based on bed movement
Seismic	Seismic data referring to earthquake intensity
Traffic load	The actual/total load of vehicles using the bridge; measured using WIM stations
Acceleration	Acceleration data can be used to assess whether deterioration or damage has occurred
Curvature	The rate of change of curvature along a flexing member can be used to understand increase in live load effects, or induced bending from vehicles
Displacements	The movement of the bridge under specific loads
Tilt/slope	Angular changes; used to measure distortion in a bridge

Table 8.6 Concrete metrics

Parameter	Parameter description
Corrosion	Defines corrosion rate/total corrosion amount. Used to understand remediation actions for chloride contamination, or strength loss through section loss
Cracking	Possible to detect cracks through acoustic emission sensors. It is also possible to monitor cracks using strain gauges. This will generally apply to larger cracks, as some cracking is expected in concrete sections. See also NDE and crack gauges/tell-tales
Reinforcement position	This function is likely to be carried out using a cover meter survey, where a cover meter survey is considered to be NDE
Strain	Under normal service loads, strain can be used to understand the stresses being developed in specific sections. This can be useful when run in conjunction with WIM data – capacity can be understood, and therefore the loading-capacity margin for the member being measured
Strength	Strength of concrete can be assessed using Schmidt Trigger or through compression strength tests – both are considered to be NDE
Tension	Applicable to pre-stressed, pre-tensioned and post-tensioned bridges, as tension in the tendons is directly related to strength. Used to understand the capacity of the member

Table 8.7 Steel metrics

Parameter	Parameter description
Corrosion	Measured as a function of loss of section over time – considered to be NDE in this strategy
Cracking/crack growth	Useful in understanding the fatigue effects on steel bridges, especially for active cracks.
Strain	See concrete metrics strain (table 8.6)
Tension	Useful for understanding the actual tension loads – eg on tied arches; especially useful if an element/component is operating close to its design load

Table 8.8 Third-party data used for network metrics

Organisation	Available SHM data types
NIWA	River flow, sea level, air quality, climate change
IGNS	Natural hazard data including seismic, tsunami, volcanic activity, geological
Regional authorities	Rainfall, river levels and flows, regional traffic growth
NZTA/TLA	WIM data, state highway traffic count data

In the middle stage of the SHM development process, data collection has to be considered. Consideration of how the data will be collected, stored and presented should therefore be made. For example, will all of the data be sent via wireless connections/phone lines to be stored on a server; will it be processed at the site and only cleansed data sent on; or will all the data remain at the point of measurement and be collected by the bridge inspector? This has to be considered, as bridges can be spread widely on remote networks, phone lines may not be available, and wireless connections may be an issue because of signal strength, network availability or transmission costs.

When the modelling phase is reached, we recommend that specialists in this area are consulted, as they will have a greater understanding of the models that should be developed for SHM.

Action 14: Integrate NDE and SHM into the data collection and decision-making process, using it *reactively* to understand problems identified in visual inspections, and *proactively* to collect data on network and bridge performance. Collecting NDE and SHM data proactively will improve asset management and will lead to improved models used as an essential part of an advanced asset management process.

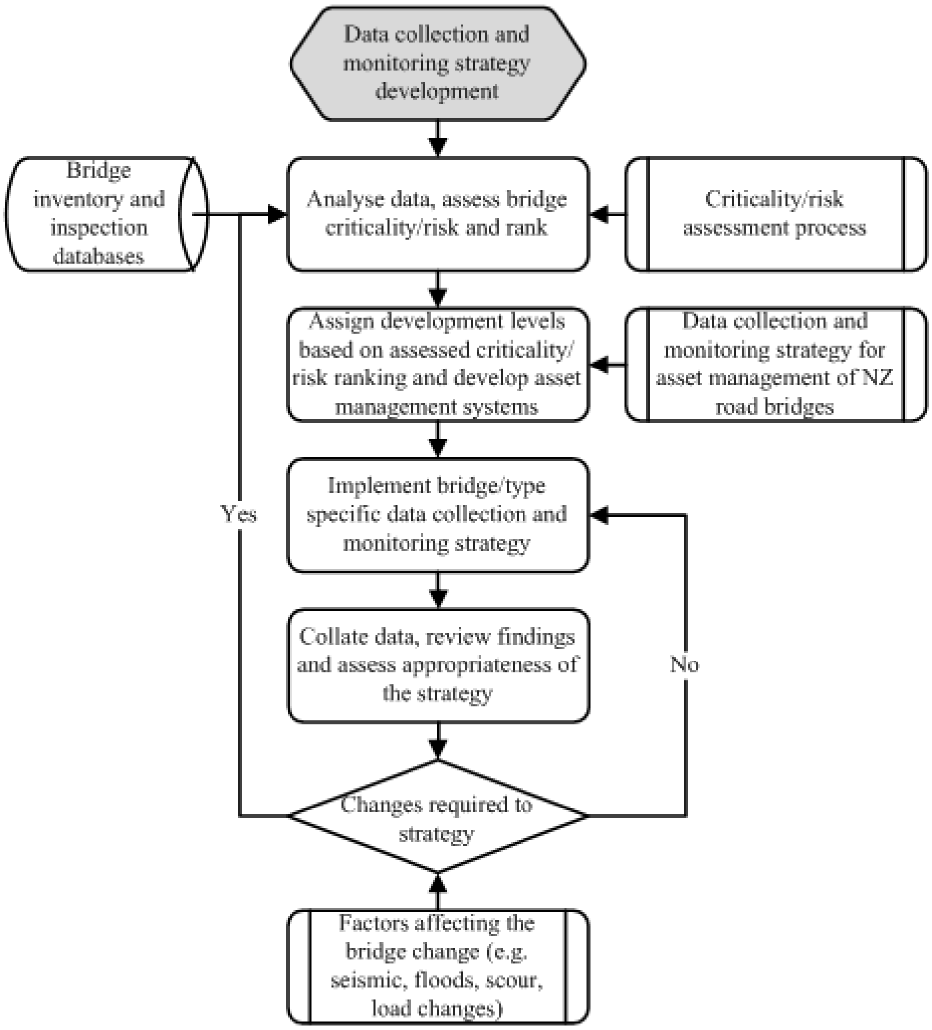
9 Strategy implementation

9.1 Introduction to strategy implementation

This section provides two examples of the implementation of the data collection and monitoring strategy. The first worked example discusses the risk and criticality assessment used to assign data collection levels for four bridges – a small culvert, a typical single-span highway bridge, and two large bridges. The second worked example is included to show how cost savings made from the changes in the bridge inspection programme can be redirected to collecting data through improved methods, where these are required.

The strategy implementation process is detailed in figure 9.1. As explained in section 6, knowledge of the bridge inventory, the risks affecting the bridge (eg scour, deterioration, loading-related issues, and accidents), the network operation and bridge replacement costs are all needed to carry out the risk and criticality assessment. Once this is done the core, intermediate or advanced data collection strategy can be assigned to the structure. Note that the implementation process is dynamic, as changes to risk and criticality may require corresponding adjustments to the ways the bridge is managed.

Figure 9.1 Data collection strategy development and review protocol



9.2 Bridge risk and criticality assessment

The international best practice review identified that risk-based practices are being used to tailor bridge management practices to the specific needs of individual networks and bridges. Given that a risk-based approach provides a level of flexibility that is not currently available to New Zealand bridge asset managers, we recommend that it should be adopted. This section provides details of a recommended risk- and criticality-based management approach.

Outlined below is a methodology for assessing and quantifying risk and criticality. It should be noted that there are many processes and systems that could be used – the proposed process is therefore one of many alternatives.

The commonly adopted definition of risk, also used in this study, quantifies risk by multiplying the probability of bridge failure with overall consequence or impact of the failure. Here 'failure' is understood broadly as any situation where a bridge does not fulfil its performance expectations. This may, in extreme and rare cases, be the same as structural collapse or damage, but it also includes non-catastrophic failures where, for example, vehicle load or speed are restricted to manage structural element fatigue or because of bridge functional deficiency. It is useful to break the overall consequences of failure into:

- direct consequences, including bridge maintenance, repair or replacement costs
- wider, whole-network or regional-level consequences, including traffic delays, service interruption, loss of business, lowered community resilience to natural hazards, and even the loss of heritage or iconic status enjoyed by the structure.

From the point of view of risk perception, events of low probability and high consequences prove to be a challenge for risk assessment and risk-based decision making, as in such cases risk is a small number multiplied by a large number with a somewhat arbitrary result (Stewart and Melchers 1997). However, events with large consequences or impacts warrant a special treatment, as the public's tolerance of risk decreases as the consequences increase, irrespective of the probabilities of failure occurrence involved (Faber and Stewart 2003). In the context of transportation networks and bridge asset management, bridges with large failure consequences will be herein referred to as 'critical'. It is traditionally assumed in road asset management that criticality assessment takes into account only the wider, network- and regional-level consequences (Theoharidou et al 2009), and a similar approach is also adopted in this study.

It can be seen that risk and criticality are both important factors to fully appreciate risks in bridge asset management. Furthermore, risk and criticality will dictate the type of data to collect and the collection regime. It is therefore important to understand the environmental and loading factors affecting the bridge under consideration, and how the bridge resists these actions – including an understanding of critical details and mechanism, such as those resulting in low structural redundancy. Therefore to undertake a preliminary risk assessment, sufficient basic data on loads, capacity and condition must be available.

9.2.1 Risk and criticality assessment and quantification

In this research, the method proposed by Moon et al (2009) for risk assessment and relative quantification is used. Risk is calculated as:

$$R = H \times V \times C \times U \qquad \textbf{(Equation 9.1)}$$

where

H = probability of a hazard

V = vulnerability to a given hazard

C = consequences resulting from a failure to perform adequately

U = uncertainty premium.

For each bridge, risks related to four broadly defined performance criteria – hydraulic/geotechnical safety, structural safety, serviceability (durability and maintenance), and functionality – which are calculated separately (table 9.1).

Table 9.1 Risk assessment framework (Moon et al 2009)

Performance limits	Hazards	Vulnerabilities	Exposures
Safety: geotechnical/hydraulic	• Flowing water • Debris and ice • Seismic load • Vessel collision • Flood	• Scour/undermining • Loss of support • Soil liquefaction • Unseating of superstructure • Settlement • Overtopping	• Loss of human life • Replacement and repair costs • Impact of removal from service related to: - safety (lifeline) - economic - social (mobility) - defence
Safety: structural	• Seismic load • Repeated loads • Trucks and overloads • Vehicle collision • Fire	• Lack of ductility and redundancy • Fatigue and fracture • Overloads • Details and bearings	
Serviceability, durability and maintenance	• Winter maintenance practices • Climate • Intrinsic loads • Impact (vertical) • Environment	• Corrosion • Cracking/spalling • Excessive deflections/ vibrations • Chemical attack/reaction • Difficulty of maintenance	• User costs • Maintenance costs - direct - indirect (delays, congestion, etc)
Functionality and cost	• Traffic • Special traffic and freight demands	• Network redundancy and adequacy • Geometry and roadway alignment	• Loss of human life and property (accidents) • Economic and social impacts of congestion

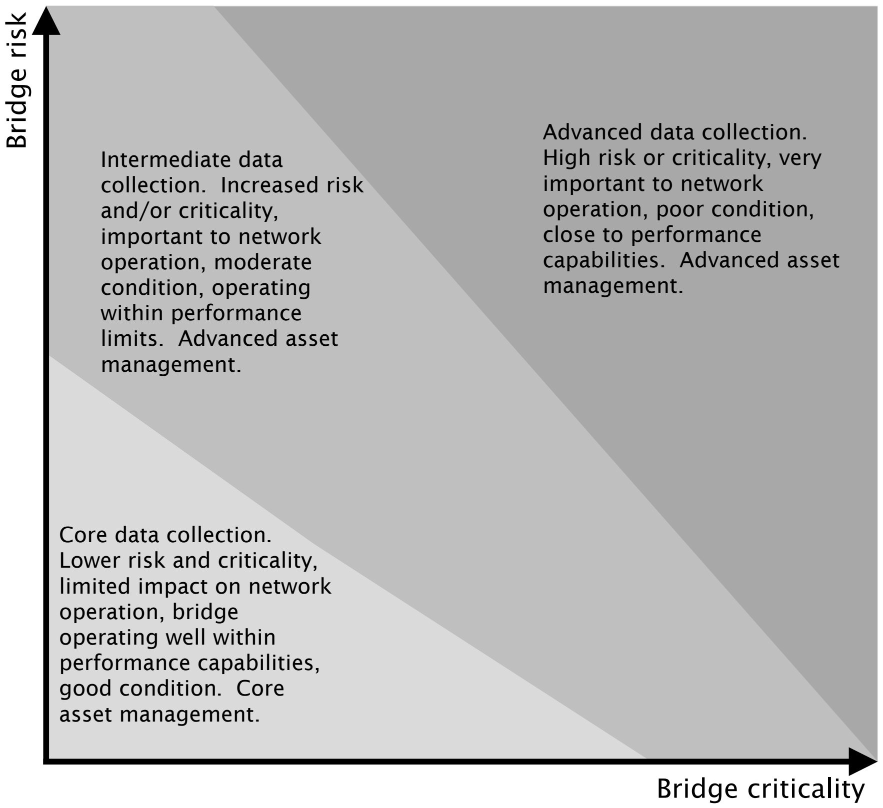
Detailed tables that cover each risk aspect listed in table 9.1 and enable determination of the factors in the above risk equation are provided in Moon et al (ibid). Through the use of the tables, relative scores ranging between 1 and 3 for the first three factors (ie *H*, *V* and *C*) are derived. For example, the score for hydraulic/geotechnical hazard probability depends on the design flood-return period at the bridge location, seismic design category, distance from the coast, possibility of vessel impact, scour potential, and history of hazard occurrence. The uncertainty premium *U* takes into account the accuracy of the data available and approaches used for risk analysis and quality-control measures employed. Five different uncertainty values are proposed, ranging from 2.5 for assessments based on minimum standard visual inspections and document review, to 1.0 when best-practice visual inspections and document review are used together with best-practice NDE and SHM. This risk assessment method is useful for proposed data collection and monitoring strategy.

To obtain an aggregate bridge-level risk, the root mean square (RMS) of the individual performance criterion risks is calculated. This ensures that greater emphasis is placed on specific performance issues that contribute more to the aggregated risk. This is considered important, as in many cases it is likely that one key risk will be driving the outcome. However, for bridges with heightened overall risk (ie high risk ratings in a number of categories), we recommend that individual performance risks should also be examined to understand their relative importance and to aid in the development of risk-specific mitigation measures, which may comprise the full range of available techniques. It is likely that an enhanced approach will be applied to specific failure-critical areas, components and elements. This mirrors current practice, which uses special inspections to monitor high-risk components.

Bridge criticality is measured by the wider consequences to the network functionality and regional economy resulting from a failure. Separately reporting on criticality ensures that the bridge asset manager takes into account those bridges that have a significant impact on network functionality, but because of their low probability of failure, might not receive the same recognition if only a risk-based approach is used. The overall bridge criticality score was assumed as the maximum criticality score for the individual performance criteria. As with the overall risk score, for highly critical bridges we recommend that the individual scores should be examined.

Using this method, bridges on a given network will be assessed for their risk and criticality. Based on this assessment, bridges will be prioritised for a core, intermediate or advanced data collection regime. However, intermediate and advanced data collection regimes are likely to be more costly than current approaches, and it is expected that the required changes in data collection need to be cost neutral. Thus, each asset manager will have the choice of drawing the core/intermediate and intermediate/advanced boundaries to suit their particular budgetary circumstances and risk tolerance (figure 9.2).

Figure 9.2 Core, intermediate and advanced development levels



9.3 Implementation examples

9.3.1 Example 1: Bridge risk and criticality assessment

Four bridges have been used in this example – a small corrugated-steel culvert, a single-span highway bridge, the Auckland Harbour Bridge (AHB), and the replacement Newmarket Viaduct. These bridges were chosen as representative of some of the challenges that are faced by New Zealand asset managers. All inventory data referring to the bridges was taken from the NZTA BDS. All details for the four bridges are provided in table 9.2.

Table 9.2 Description of bridges used in the risk and criticality assessment example

Bridge	Photograph of the bridge	Description
Corrugated-steel culvert		• 4m diameter corrugated-steel culvert supports a state highway of national strategic importance • Overall good condition; only minor corrosion to the barrel; no scour • Replacement cost low; AADT >50,000 vehicles; heavy commercial vehicles 5%; reasonable LOS could be restored within a few days; temporary measures quickly available; alternative routes available with only minor reductions to service level • Data collected via regular minimum-standard visual inspections
Single-span timber bridge		• 12m span timber bridge carrying a road of local importance over a small river • Designed to outdated load standards; overall moderate condition • Replacement cost moderate – between NZ$100K and NZ$1m; AADT is 1000 • Service can be returned after several days, with a temporary bridge installed to cross the river • Data collected via regular minimum-standard visual inspections
Auckland Harbour Bridge (AHB)		• Key link across a harbour, supporting a state highway of national strategic importance at the heart of the major economic centre of New Zealand; complex truss bridge with 'clip-on' extensions on both sides • Navigable shipping channel; coastal environment • Known fatigue issues in extensions (heavy vehicles prohibited on extensions); extensions recently strengthened but only limited service life expected • Replacement cost very high >NZ$750M; AADT for extensions >38,000, centre truss >80,000; major service would take >1 year to restore; a detour available for long routes, but nothing available locally; failure will cause significant delays in the region and impact heavily on local, regional, and inter-regional commerce; a national icon • Individual management plan implemented, including best-practice visual inspections, NDE and SHM

Bridge	Photograph of the bridge	Description
Newmarket Viaduct		• Key link supporting a state highway of national strategic importance at the heart of the major economic centre of New Zealand; completed in 2011; twin post-tensioned bridges with 12 spans, ~60 m each • Replacement cost very high >NZ$200M; AADT >160,000; service would take >1 year to restore; detours available but failure will cause significant delays in the region and impact heavily on local, regional, and inter-regional commerce • Data collected via best-practice visual inspections and technical analyses conducted; a university-operated SHM system that could be integrated into management plan is in place

Using the risk and criticality assessment and scoring method outlined in section 6, the results for the four bridges are shown in table 9.3. Individual risk and criticality scores are provided and overall risk and criticality scores computed. At the bottom of the table, each bridge is assigned to a data collection regime and asset management level. Those assignments are indicative only, as the decision to which regime and level a bridge will be eventually assigned should take into account budgetary constraints and risk tolerance. This requires conducting risk and criticality assessment (at least) for the majority of bridges in a particular stock. For example, while it can be argued that the AHB is certain to receive special attention, whether or not the culvert will be a subject of advanced approaches will be a decision for the asset manager to make.

Table 9.3 Risk and criticality assessment of analysed bridges

Performance criteria	Culvert		Timber bridge		AHB		Newmarket Viaduct	
	Risk	Cons.	Risk	Cons.	Risk	Cons.	Risk	Cons.
Structural safety	10.0	2	7.5	1	27.0	3	11.3	3
Hydraulic/geotech safety	10.0		5.0		22.5		3.8	
Serviceability	5.0	1	5.0	1	12.0	2	7.5	2
Functionality	15.0	2	5.0	1	18.0	2	7.5	2
Aggregate: risk (RMS)/criticality (max cons.)	10.6	2	5.7	1	20.6	3	8.0	3
Data collection regime (indicative)	Intermediate		Core		Advanced		Advanced	
Asset management level (indicative)	Advanced		Core		Advanced		Advanced	

It can be seen from table 9.3 that the AHB and Newmarket Viaduct, while having very different risk scores, both have the same criticality rating, which could be anticipated given their importance. The proposed strategy indicates that:

- both bridges should be managed using an advanced asset management process
- data should be collected on the full range of performance criteria
- the data should be collected using the most accurate techniques.

At the time of this research, the AHB was being managed using an up-to-date data collection and asset management processes, with SHM and a WIM system used to understand structural performance; the bridge was also being visually inspected annually. It is also worth noting that using these best-practice approaches to data collection reduces the overall bridge risk by a factor of 2.5, using the adopted uncertainty premium scores given by Moon et al (2009). However, given the comparable criticality of Newmarket Viaduct, we recommend that for this bridge, a detailed understanding of its reliability should be developed. The asset manager may then decide to defer an advanced data collection regime, but the review should at least be undertaken and a proactive management plan put in place.

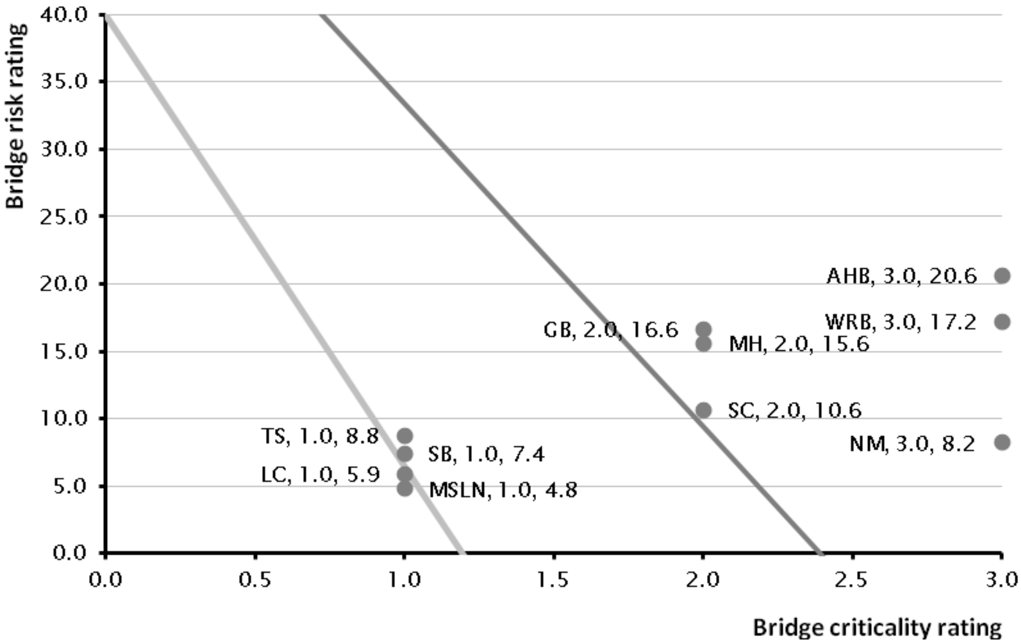
Another important conclusion was that the corrugated-steel culvert, while being a relatively simple structure in good condition, still had a high-criticality rating – we therefore suggest it should be managed using an advanced asset management approach. A greater data quality will then have to be ensured, probably with the help of techniques, such as NDE, that provide an improved level of data accuracy and precision. Based on more traditional bridge management practices, the culvert would not be managed using an advanced asset management approach, as many asset managers would believe it required only limited investigations.

This procedure may now be extended by considering bridges on a network. A set of 10 different structures representative of those found in New Zealand is assessed for risk and criticality in table 9.4. Based on this assessment, bridges can be prioritised for a core, intermediate or advanced data collection regime. Intermediate and advanced data collection regimes are likely to be costlier than current approaches and it is expected that the required changes in data collection need to be cost neutral. Thus, each asset manager will have the choice of drawing the core/intermediate and intermediate/advanced boundaries to suit their particular budgetary circumstances and risk tolerance (see figure 9.3).

Table 9.4 Risk and criticality assessment of a number of bridges

			Structural					Geotechnical					Serviceability					Functionality				
Asset description	**Bridge criticality**	**Bridge risk**	**Hazard**	**Vulnerability**	**Exposure**	**Uncertainty**	**Structural**	**Hazard**	**Vulnerability**	**Exposure**	**Uncertainty**	**Geotechnical**	**Hazard**	**Vulnerability**	**Exposure**	**Uncertainty**	**Serviceability**	**Hazard**	**Vulnerability**	**Exposure**	**Uncertainty**	**Operations**
Auckland Harbour Bridge (AHB): strategic route, good condition, operating close to load limits	3.0	20.6	3.0	2.0	3.0	1.5	27.0	3.0	2.0	3.0	1.3	22.5	2.0	2.0	2.0	1.5	12.0	3.0	3.0	2.0	1.0	18.0
Newmarket (NM) Viaduct: strategic route, new design standards	3.0	8.2	2.0	2.0	3.0	1.0	12.0	1.0	1.0	3.0	1.3	3.8	3.0	1.0	2.0	1.3	7.5	3.0	1.0	2.0	1.3	7.5
Small culvert (SC): strategic route, good condition, well within load limit	2.0	10.6	1.0	2.0	2.0	2.5	10.0	1.0	2.0	2.0	2.5	10.0	1.0	2.0	1.0	2.5	5.0	3.0	1.0	2.0	2.5	15.0
Mohaka (MH) River Bridge: strategic route, operating close to load limit	2.0	15.6	3.0	3.0	2.0	1.3	22.5	2.0	1.0	2.0	2.0	8.0	1.0	3.0	2.0	2.0	12.0	2.0	2.0	2.0	2.0	16.0
Grafton Bridge (GB): non-strategic route, good condition, close to load limit	2.0	16.6	3.0	3.0	1.0	2.5	22.5	2.0	2.0	1.0	2.5	10.0	2.0	2.0	2.0	2.5	20.0	2.0	2.0	1.0	2.5	10.0
Waimakariri River Bridge (WRB): strategic route, at load limits, moderate condition	3.0	17.2	3.0	3.0	3.0	1.0	27.0	3.0	3.0	2.0	1.0	18.0	2.0	2.0	2.0	1.0	8.0	2.0	2.0	2.0	1.0	8.0
Medium sized local network (MSLN) bridge: poor condition, close to load limit	1.0	4.8	2.0	3.0	1.0	1.0	6.0	1.0	2.0	1.0	1.0	2.0	2.0	3.0	1.0	1.0	6.0	2.0	2.0	1.0	1.0	4.0
Twin-span (TS) bridge: non-strategic route on state highway, good condition, operating well within limit	1.0	8.8	2.0	2.0	1.0	2.5	10.0	2.0	2.0	1.0	2.5	10.0	1.0	1.0	1.0	2.5	2.5	2.0	2.0	1.0	2.5	10.0
Large culvert (LC): non-strategic state highway, good condition	1.0	5.9	1.0	1.0	1.0	2.5	2.5	1.0	2.0	1.0	2.5	5.0	1.0	1.0	1.0	2.5	2.5	2.0	2.0	1.0	2.5	10.0
Small bridge (SB): non-strategic state highway, poor condition	1.0	7.4	2.0	3.0	1.0	1.5	9.0	1.0	3.0	1.0	1.5	4.5	2.0	3.0	1.0	1.5	9.0	2.0	2.0	1.0	1.5	6.0

Figure 9.3 Example of a network-level risk and criticality domain



9.3.2 Example 2: Assessment of strategy implementation cost for a network

A wide range of bridge inspection contract forms currently exist both within the NZTA and TLAs. For example, some NZTA contracts have a greater number of detailed/principal inspections than others, and some also only include general inspections, with detailed/principal inspections undertaken as special inspections. There is also a wide range of bridge stock types managed throughout New Zealand. It is therefore difficult to provide exact forecasts of the costs involved in implementing the proposed strategy across all NZTA regions and TLAs.

When undertaking an assessment of likely costs, we recommend that the following are taken into account:

- contractual requirements specific to the network
- the number of core, intermediate and advanced bridges
- the costs of carrying out the current inspection regime on core, intermediate and advanced bridges
- the number of bridges that require special access requirements for principal inspections, and the breakdown of access costs for core, intermediate and advanced bridges
- the altered inspection cycle for the proposed regime, following the removal of principal inspections
- extra travel costs resulting from more-frequent advanced bridge inspections (ie travelling annually).

An example is provided in table 9.5. This example methodology may also serve as a template for assessing individual networks. The following assumptions have been made while producing this cost estimate:

- All travel costs are included in the rates.
- Under the current regime, all bridges have two general and one detailed inspection in a six-year period.

- Principal inspection costs are the same as general inspection costs, other than access charges (for the current regime only).
- No principal inspections are undertaken in the proposed regime.
- For the proposed regime, two core general inspections, three intermediate and six advanced inspections are undertaken in a six-year period for bridges falling into each respective risk and criticality categories.

The estimates show that savings can be made. The calculated estimate is approximately $60,000 (table 9.5). However, the amount of saving will depend on network size, number of bridges and current contract requirements. These savings are a result of the smaller number of core inspections (assumed to follow a three-year inspection cycle) and the removal of all detailed inspections. The savings could be reinvested into NDE or SHM data collection.

Table 9.5 Estimate of strategy implementation cost

Data collection and monitoring estimate							
Structure numbers	Bridges & large culverts	Culverts	Stock under-passes	Retaining walls	Sea walls	Deep drainage pits	Calculation
	177	133	31	40	2	52	a
Estimated proportion of structure type (%)							
Core	40%	90%	90%	50%	50%	90%	b
Intermediate	55%	10%	10%	50%	50%	10%	c
Advanced	5%	0%	0%	0%	0%	0%	d
Estimated percentage of core, intermediate or advanced structures requiring special access							
Core	10%	10%	10%	10%	10%	90%	e
Intermediate	40%	40%	10%	20%	20%	90%	f
Advanced	90%	0%	0%	0%	0%	0%	g
Estimated general inspection costs (no access costs)							
Core	$200	$100	$200	$100	$100	$100	h
Intermediate	$500	$200	$300	$300	$300	$200	i
Advanced	$1000	$500	$500	$500	$500	$300	j
Estimated principal inspection access costs							
Core	$200	$200	$200	$200	$200	$200	k
Intermediate	$500	$500	$500	$500	$500	$300	l
Advanced	$1000	$1000	$500	$500	$500	$500	m
Current visual inspection cycle							
Number of general inspections in cycle	2	2	2	2	2	2	n
Number of detailed/ principal inspections in cycle	1	1	1	1	1	1	p

Current regime costs							
Core costs general	$28,320	$23,940	$1160	$4000	$200	$9360	a*b*h*n
Intermediate costs general	$97,350	$5320	$1860	$12,000	$600	$2080	a*c*i*n
Advanced costs general	$17,700	-	-	-	-	-	a*d*j*n
Core costs detailed	$15,576	$14,364	$6138	$2400	$120	$13,104	a*b*h*p + a*b*e*k*p
Intermediate costs detailed	$68,145	$5320	$1085	$8000	$400	$2444	a*c*i*p + a*c*f*l*p
Advanced costs detailed	$16,815	-	-	-	-	-	a*d*g*p + a*d*j*m*p
Total visual inspection costs for one cycle of current regime						$367,801	
Proposed general visual inspection cycle (general only)							
Number of inspections in core cycle	2	2	2	2	2	2	q
Number of inspections in intermediate cycle	3	3	3	3	3	3	r
Number of inspections in advanced cycle	6	6	6	6	6	6	s
Proposed visual inspection regime costs							
Core general inspection costs	$28,320	$23,940	$11,160	$4000	$200	$9360	a*b*h*q
Intermediate general inspection costs	$146,025	$7980	$2790	$18,000	$900	$3120	a*c*i*r
Advanced general inspection costs	$53,100	-	-	-	-	-	a*d*j*s
Total visual inspection costs for one cycle of proposed regime						$308,895	
Difference between current and proposed regime						$58,906	

10 Conclusions

In this report, a risk- and criticality-based data collection and monitoring strategy has been developed. The strategy provides guidance on the type of data to collect and the inspection, evaluation and monitoring techniques that are most appropriate to collect it, given the specific requirements of the bridge and its risk profile within a network. Changes are also recommended to the current data collection and monitoring practices used in New Zealand.

Through the development of this strategy, the original objectives of this project have been achieved, as the data collection and monitoring strategies are linked to bridge risk and criticality; the data to be collected has been defined and linked to strategic outcomes; and a methodology for optimising the type of data collected and the method of collection has been promoted. The overall outcome is a strategy that can be used to reshape the data collection and inspection practices used for bridges, and thus an enhanced approach will be adopted for data collection and monitoring.

The literature review identified that understanding bridge performance and its effect on network performance is important to strategic decision makers. There is therefore a need to align the data with strategic outcomes, so that the required level of information and knowledge is developed. This requires the link between data and knowledge to be further strengthened (even though work has been done in this area) with the development of infrastructure performance frameworks. Further, an improved balance in data collection is sought between visual inspections, NDE and SHM. QA practices applied to bridge data also need strengthening, as data is generally not accorded the level of importance it should have. These findings align well with the original objectives, which required data collection and monitoring strategies to be linked to bridge risk and criticality, and alignment of collected data with strategic outcomes.

In the strategy, risk and criticality scores are used to assign to a given bridge one of three data collection development levels – core, intermediate and advanced. Using these levels, bridge-specific data collection and monitoring regimes ensure that an appropriate level of data is collected using appropriate inspection, evaluation and monitoring techniques. Using this approach will provide for the varied needs of road controlling authorities, as the complexities and risks associated with the individual road networks and bridges are taken into account.

Six key data collection categories were identified – inventory, performance, condition, cost, asset history, and planned work data. However, as asset history and planned work data both identify tasks that are to be undertaken or have been undertaken, these can be considered as a single data collection set, thereby reducing the set to five overall. Each collection category provides data specifically required for the asset management process – eg inventory data provides details of the physical asset; performance data provides information on risk and environmental and safety compliance; and condition data provides details of the extent and severity of maintenance defects identified through the inspection process. Collecting data under these categories means that information and knowledge can be developed on the asset, so that optimal asset management regimes can be put into place. It is acknowledged that not all bridges have the same management requirements and therefore do not require the same level of data collection. Therefore the data collected under each category is linked to the bridge risk and criticality rating. This ensures that an improved level of knowledge is developed for those bridges that are important to network functionality, are close to their operating capabilities, or are in poor condition.

The review identified that visual inspections, NDE and SHM were the three data collection options currently used for bridges. NDE and SHM can provide an enhanced level of accuracy and repeatability, compared with visual inspections. SHM also provides a level of proactiveness that is not available from visual inspections or NDE, as these generally only detect defects once they have occurred. However, there is a cost increase associated with the use of NDE and SHM, and this increase has to be balanced with the level of accuracy that is required. To achieve this, the risk and criticality scores were used with data collection strategies and then aligned to the core, intermediate and advanced development levels. Using this approach, we recommend that the bridges assessed to be in need of an advanced data collection regime (ie they are critical to network functionality and/or are in poor condition or operating close to, or beyond, their performance capability) should utilise the full range of inspection, evaluation and monitoring techniques. This will ensure bridges with the highest risk and/or criticality profile have the most accurate data collected, thereby improving the reliability and confidence of the decisions being made. The application of the strategy therefore provides a process that can be used to optimise the data collection methods used for bridges.

Risk- and criticality-based visual inspection timings have been proposed, with core bridges having the lowest frequency of visual inspections, and advanced bridges having the highest frequency. With this strategy, the introduction of risk- and criticality-based inspection timings means that savings can be made, and these savings can be reinvested in more advanced data collection practices for bridges in the intermediate and advanced categories. However, the size of saving will be variable and will depend on specific contract requirements, numbers of bridges in a particular category and the local costs of undertaking inspections.

The LTBPP that is currently underway in the US is using benchmark surveys to collect condition and performance data for bridges. This will lead to improvements being made to bridge asset management models and an improved level of performance information gathering. It is also the intent of the programme to use these models to understand the impact of time-based deterioration on bridge performance. Given that baselines are important when developing such models (eg load and condition models), benchmark surveys have been included in our strategy. This will help bridge asset managers to more accurately understand the in-situ performance characteristics of bridges, and to more accurately manage their bridge stocks. The relationship between condition and performance can also be assessed – this is important, as it can be used in the development of optimal management and replacement strategies. It can also be used to understand the relationship between deteriorating bridge performance and network performance, an important factor for prioritising bridge maintenance and improvement strategies.

The survey of New Zealand practice identified that there was only limited use of NDE and a limited understanding of SHM. It is considered that to manage the higher-risk and/or criticality bridges more appropriately, a greater range of NDE and SHM methods needs be included in the bridge inspection and maintenance programme. To do this, a greater awareness of NDE and SHM has to be developed. One method of achieving this is via training and alignment of the bridge inspection and maintenance course with international practice.

Data is considered to be an asset in its own right; however, the review of New Zealand and international practice showed that data is not accorded the required level of importance, with only limited QA undertaken. Providing only limited data QA can have a detrimental effect on the quality of decisions, possibly leading to suboptimal results. The strategy therefore uses data validations (checking of stored data), and data verification (checking of inspection data) to ensure the data that is used in the decision-making process is accurate and up to date.

Through the development of this strategy, two future research areas have been identified. These include the development of a comprehensive set of performance measures for bridges, and a bridge asset management system/algorithm that uses the data to understand bridge and network performance and develop optimal management strategies.

It was identified that strategic decision makers want to understand how the money they invest results in achieving the strategic outcomes that have been agreed. To do this, the data has to be used to create information on the performance of bridges, and this information has to be further used to create strategic knowledge. It is considered that the first link is happening, but at the time of this research, it was not occurring in any formalised manner. Further, it is considered that strengthening the relationship between information and knowledge needs significant work, with the USGAO and the NZOAG both calling for bridge asset managers to report on the effectiveness of their strategies and to move away from the limited condition/safety/functionality paradigm that is being used. This will require robust performance frameworks and linking the data used in the frameworks to the required information on strategic outcome achievement. Doing this will create a level of accountability and auditability that is not currently present. It will also ensure engineers and strategic decision makers liaise to understand the measurability of proposed performance criteria, and which measures are important.

A second area that requires further attention is the long-term planning of bridge maintenance and improvements. While long-term planning models are being used internationally, at the time of this research they were not in use in New Zealand. It is therefore considered that an understanding of optimal maintenance and performance needs is not being achieved. This is evident by the broad range of desired funding levels that were identified in the survey as optimal.

Developing the performance measures and the bridge decision-making tools will lever the maximum value from the data that is collected and will directly link the data to the decision-making process. It will also add a level of importance to the data that is not currently present.

The adoption of this strategy will help to move bridge asset management in New Zealand to a new good-practice benchmark, thereby placing it on a comparable level with the current international practice. It will also ensure the data that is needed for the proposed performance frameworks and bridge management models is available.

11 Recommendations for improving bridge data collection and monitoring practices

Comparing the findings of the literature review and the New Zealand practice survey identified that three areas required changes if New Zealand practice was to align with international practice. The recommended changes cover the type of data that is collected for bridges, the methods used to collect bridge data, and the systems and processes used to manage the data. A number of specific recommendations have been identified for each of these areas, as outlined below:

1. Bridge asset management should use a risk- and criticality-based approach, assigning bridges asset management approaches based on priority (see also Action 1, section 6.2).
2. Bridge asset managers need to strengthen the link between the data that is collected and the strategic performance measures that use the data (see also Action 2, section 7.2).
3. Asset managers should store the data important to the decision-making process (including inventory, condition, condition benchmark, work history and planned works, cost, wider performance (load-carrying capacity assessment, safety, traffic, environmental, risk) and other data such as photographs, reports and drawings (see also Action 3, section 7.3; Action 4, section 7.4; Action 5, section 7.5; Action 6, section 7.6; Action 7, section 7.7; and Action 8, section 7.8).
4. Data is an asset in its own right and should therefore be managed accordingly. Therefore data management and inspection QA practices should be improved (see also Action 9, section 7.9).
5. Bridge inspection cycles should be varied according to risk-criticality ratings (see also Action 10, section 8.2.1).
6. New Zealand bridge inspection practices should include condition rating (see also Action 11, section 8.2.2).
7. Bridge management and inspection training courses should cover NDE and SHM, thereby providing a greater awareness of these techniques (see also Action 12, section 8.2.3).
8. Performance of representative bridge types need to be understood and benchmark data collected for those. To meet this requirement, benchmark inspections should be undertaken (see also Action 13, section 8.2.4).
9. The data collection process should support visual inspections with NDE and SHM (see also Action 14, section 8.3).
10. The bridge inspection and maintenance manual should be updated to reflect current bridge asset management thinking and recommendations put forward in this strategy.

To take into account the fact that not all networks or bridges have the same complexities and risk profiles, it is recommended that risk and criticality assessment is used when developing bridge asset management strategies (see section 9.2). This approach defines the type of data to be collected for bridges, how accurate the data needs to be, how frequently the bridges are inspected, and the level of training required to manage and inspect the bridges. Adopting the risk and criticality approach means the bridges can be prioritised, and core, intermediate and advanced management strategies applied (see section 6.2). It is considered that the adoption of the tiered approach will provide a level of flexibility that is currently missing from New Zealand bridge management practice.

It was identified that the link between the data that bridge asset managers collect and the strategic performance measures used to assess service delivery needs to be strengthened. It is therefore recommended that asset managers make an assessment of the data needed to develop knowledge of strategic outcomes. One process that could be used is data chains (see section 7.2); these require bridge asset managers to map the data onto tactical performance measures and then onto strategic outcomes, thereby ensuring the data is turned into strategic knowledge.

It is recommended that an assessment of the data that needs to be stored in the bridge management system is carried out (see section 7.2), with data only being stored if it links to the decision-making process. This is important, as collecting and managing the data is expensive and time consuming. The data areas that are recommended for collection, and ones that are considered to link to the decision-making process, are inventory, condition, condition benchmark, work history and planned works, cost, wider performance (load-carrying capacity assessment, safety, traffic, environmental, risk), and other data such as photographs, reports and drawings (see section 7). Even though specific data headings are provided, the amount of data collected for each area and the accuracy of the data should be varied according to bridge criticality and risk. This will allow bridge management practice to be tailored to the specific requirements of individual bridges.

Throughout the world, the data collected for bridges is managed using varying degrees of QA. In light of this, it is recommended that QA for bridge data in New Zealand should be improved, as the data is an asset in its own right. It is therefore recommended that formalised data management practices are put into place for bridges (see section 7.9.3) to improve the accuracy of the data and the confidence in the decisions being made with it. This process will also place bridge management on a par with road data management, which uses formalised techniques to manage stored data.

In many countries, bridge inspection regimes are modified according to the risk of failure (see section 2.5.1). It is recommended that this approach is adopted in New Zealand and that the risk and criticality framework is used as the process for deciding on inspection cycles. Lower frequencies of general inspections (3–6 years) should be used for core bridges; standard general inspection frequencies (2–3 years) should be used for intermediate bridges; and higher general inspection frequency (1–2 years) should be used for advanced bridges. For intermediate and advanced bridges, the data collection process should be augmented by NDE and SHM. Therefore time and effort can be focused on the bridges that have higher risk and/or criticality profiles, and the expenditure that is saved on core and/or intermediate bridges (see section 9.3.2) can be redirected to more accurate data collection techniques.

It was found that New Zealand currently manages bridges using a defect-based approach, and condition rating is not undertaken. While it is understood that the NZTA is addressing this issue, we recommend that the system that is adopted should reflect the approach used by the bridge condition indicators systems. The bridge condition indicators systems provide ratings for general condition and for critical members within a bridge, unlike the proposed UK Highways Agency's approach, which only provides general condition ratings (see section 8.2.2).

The survey of New Zealand bridge managers identified that there is little use of NDE in this country, and, in some cases, little understanding of SHM (see section 4.6). One method of improving the general awareness of these techniques will be through training. It is therefore recommended that the bridge inspection and maintenance training programme be updated. The basic course would provide a general overview of bridge inspection and maintenance, and would cover in-depth management and inspection of core bridges. It would also encompass an introduction to the types of NDE and SHM that are available; how these techniques could be used to collect more accurate data; and the benefits that could be achieved from collecting more accurate data. The basic course should be further supported by more advanced learning related to the management and data collection of intermediate and advanced bridges. The advanced course would also provide more specialist instruction on NDE and SHM, reflecting the complexity of the bridges being inspected. As such, bridges categorised as intermediate or advanced would require a higher degree of certification than core bridges.

In the US, the LTBPP is using benchmark surveys to understand the operational performance of the bridges in the trial (see section 2.5). It is recommended that such surveys should be used in this country for newly constructed bridges in the intermediate to advanced range, or for older bridges where an understanding of performance is required to develop appropriate management strategies. Collecting the data will provide a point of reference that can be used to understand baseline performance, and also help bridge asset managers to improve models, as start parameters will be known. These models may include an estimate of deterioration rates or loading performance models. The main expected outcome from this process is improved long-term planning as an enhanced level of bridge stock performance knowledge develops.

It was identified that visual bridge inspections do not identify the issue that they were originally intended for, and that condition rating is subjective and suffers from variability. It was also found that principal inspections provide little extra benefit over and above general inspections. It is therefore recommended that the weakness in visual inspections is managed using a risk- and criticality-based approach to data collection, with high-risk and -criticality bridges requiring improved data collection techniques (see section 6.2). The general recommendation is that visual inspections should be used for core bridges; a combination of visual inspections and NDE for intermediate bridges; and the full range of techniques, including visual inspections, NDE and SHM, for advanced bridges. Further, it is recommended that principal inspections should be moved to the special inspection category and only carried out when a closer visual inspection is required – eg if an issue is raised during a general inspection, or if a critical component or element requires a close inspection.

The main document used to inform New Zealand bridge asset managers about the bridge inspection and management benchmark, both for state highway networks and local roads, is the NZTA's *Bridge inspection and maintenance manual* (2001). It is therefore recommended that this manual should be updated to include the findings of this study. The update should include information about:

- risk- and criticality-based inspections
- condition data collection and its role in bridge asset management
- the use and application of NDE and SHM in bridge asset management.

It is also recommended that the training required to inspect core, intermediate and advanced bridges should be outlined, and the data management practices that would ensure quality data is maintained are covered. As the manual is the industry standard, it has the ability to set a new benchmark in bridge asset management by providing information on the proposed new bridge inspection and maintenance policies.

It is considered that adopting the outlined changes will help to develop a good-practice benchmark for New Zealand, which in turn will help to strengthen bridge asset management practice and place New Zealand on a comparable level with its international peers.

It has been the aim of this document to provide a prescriptive framework, but one that still provides, where required, sufficient space for bridge asset managers to develop network-specific approaches to bridge management. The strategy therefore provides a risk- and criticality-based framework for the categorisation of bridges that is flexible enough to enable acceptable risk levels to be set according to tolerance. However, once these have been decided, specific recommendations have been provided about the types and ways in which data should be collected. It is hoped that this approach can be easily adopted by bridge asset managers, so they can target improvements in a cost-neutral way.

11.1 Further work

At the beginning of this project, we anticipated that these guidelines would be much more focused on the operational aspects of data collection. However, we realised that the major limitation of both international and New Zealand practice was the lack of a strategic and systems approach to the data collection. The focus of this document therefore centred on establishing the data collection framework and principles for determining the appropriate data collection level (ie level of detail, accuracy, collection method and frequency).

This, however, leaves a number of further tasks to assist in the implementation of the framework presented in this report, including the following:

- A 'how to do this' guideline, based on the recommended strategic approach, should be released.
- As the data collection framework will have a significant impact on bridge databases and repositories currently being used in New Zealand, a software functionality specification based on this work should be developed.
- Policy should be developed that determines which of the various manuals relating to bridge asset management that are currently used in New Zealand are the most appropriate for New Zealand conditions and the intended framework – eg the Austroads guidelines (Curran et al 2002), *Guide to asset management* (Maguire 2009, Kadar 2009), and *Guidelines for bridge management* (Dowling and Rummey 2004).

Ultimately, the new data collection strategy will assist with the need to obtain more robust data. However, the value of the data will ultimately be determined by how effectively authorities are able to use the data. There is still significant development work to be done to build on this strategic framework. Most of this work needs to aim towards establishing a decision-making framework for bridges, including a forecasting capability.

This development work should include:

- deterioration and risk forecasting based on the most significant factors that influence bridge decay
- cost models that can take into account the bridge condition and required remedial interventions
- work-effect models that forecast improvement in condition or failure risk as a result of the remedial work
- a decision algorithm combined with an optimisation routine that will return the most optimal options for a set of constraints and objectives.

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Appendix A Survey question sheet

Section One: Data Collection (Inventory - Network Specific Data)

All networks are different and have different issues facing them. This section is aimed at understanding your network and will allow us to compare and benchmark equivalent networks. We have therefore asked questions on rural/urban mix, and funding allocations. If you feel that there is any other information that would allow us to further understand your network please add the data in the last box.

1.1a	What is the length of your road network and ratio of rural to urban roads on your network?	
1.1b	In your own words please tell us about your road network, e.g. traffic levels, key issues, route types etc.	
1.2a	How many structures (e.g. retaining walls, culverts, bridges, high masts, gantries etc) and bridges are on your network? Please state actual numbers of bridges and structures.	
1.2b	What is the make up of the bridges you manage (e.g. arch, viaducts, overbridges, underbridges etc)? Please state actual numbers of bridges for each type.	
1.2c	What are the typical construction materials (e.g. prestressed, insitu concrete, timber)? Please state actual numbers of bridges.	
1.2d	Do you have any significant/strategic bridges? If so please detail the bridges and outline the reason they are significant.	
1.3a	Is there any other network specific or asset management related information that you feel would be useful for this survey?	

Section Two: Data Collection (Inventory - General Bridge Information)

This section aims to find out what type of data you collect and store for the bridges that you manage, and to what level of detail that you collect the data. It is acknowledged that this will vary depending on the criticality of the bridge in question and the complexity of the bridge.

2.1a	Inventory data can be collected at a range of levels, what network level bridge data do you collect (e.g. location, route importance, AADT etc, risk/criticality)?	
2.1b	What bridge level data do you collect (e.g. bridge type, bridge length/height, overall bridge age, rating/posting, obstacle crossed, photographs)?	
2.1c	What element level data do you collect (e.g. number of specific components, specific material of components, ages)?	
2.1d	Do you collect data on individual components, e.g. individual bearings? If so what data do you collect?	
2.2a	Is there any other data or information that you collect and/or store for bridges? Types of data may include drawings, specific investigation reports, special inspection reports, or specific studies such as seismic assessment, loading assessments etc.	
2.3a	Is there any other inventory data or bridge related information that you would like to collect or you feel would improve your decision making?	
2.4a	Are you currently making any changes to close the gaps between the data that you would like to collect and the data that you currently collect? Please identify what these are and how they will help the decision making process (e.g. items in your asset management plan/improvement	

Section Three: Data Collection (Condition Data)

Visual inspections may be carried out in accordance with New Zealand, Austroads and other international standards, they are also generally carried out at regular intervals to develop an understanding of the current defects and in some cases to understand the rate of deterioration of structural components and the structure as a whole. Our aim is to find out what inspections you carry out, what data you collect and how detailed the information you collect is. The aim of the question is also to find out what standards you use, what type of inspections you carry out (safety inspections, general inspections, detailed inspections) and what triggers the inspections that you do.

3.1a	Please outline the type of inspections that you carry out, along with the frequency of inspection for each of the identified inspections (i.e. fixed or variable cycle).	
3.1b	Are there any specific triggers for these inspections?	
3.1c	What standards, policies or best practice documents do you follow?	
3.2a	When you carry out inspections what type of data do you collect (e.g. defects, condition, extent of defect, severity)?	
3.2b	What reports do you produce with the data, e.g. general, detailed, special, safety? How detailed are the reports (e.g. defects lists, estimated costs, recommended actions, photographs etc)?	
3.3a	How do you ensure consistency between each individual inspection and inspector (e.g. formal training, specific basic qualifications, use of manual process and procedures)?	
3.3b	Do you carry out checks to ensure consistency between inspections and inspectors?	
3.3c	If so how and on how many bridges?	
3.3d	Do you follow any validation/verification standards?	
3.4a	Are there any improvements you are planning or implementing as part of the visual inspection process?	
3.4b	What benefits do you feel the identified improvements would bring?	

Section Four: Data Collection (Structures Health Monitoring (SHM))

Visual inspections are one form of data collection, other forms include Non-Destructive Testing (NDT) and Destructive Testing (DT); testing may include chloride samples, half cell potential and a range of other testing aspects such as stress/strain monitoring. Testing may also include long-term specific testing such that requires the installation of monitoring sensors. The questions below aim to find out the type of testing that you currently carry out on your bridge stock, and whether structural health monitoring would be useful for you.

4.1a	Are there any bridge defect problems (such as deteriorated bridge elements) that have required you to carry out more specialist testing and sampling?	
4.1b	Please describe what you have done and what triggered the need for the work.	
4.1c	How was the data used in the asset management/decision making process?	
4.2a	Are there any bridges where you are collecting on-going data to supplement the visual inspection process?	
4.2b	If so what data are you collecting and how is it used in the asset management/decision making process?	
4.3a	Have you ever considered structures health monitoring for your network? If so please discuss.	
4.3b	Are there any bridges on your network where SHM would be beneficial to the management of your network e.g. weight management (stress, strain) of posted bridges, flood warnings, scour etc?	

Section Five: Performance (Risk Identification, Level of Service, Deterioration and Cost Models)

Once the condition or defect data has been collected it feeds into a greater decision making process. The questions below aim to find out what these processes are and how they are used to develop a forward works programme that manages the identified network issues?

5.1a	What risk have been identified at network level, i.e. transportation lifelines risk influencing specific bridges?	
5.1b	What risk have been identified at bridge level, e.g. seismic, scour, overweight? Please detail specific bridges and issues.	
5.2a	How do you set the levels of service for your bridges (e.g. standards, best practice)?	
5.2b	How do you assess whether the bridges comply?	
5.2c	Are there any minimum triggers that you use to ensure timely action?	
5.4a	How do you use your condition or defects data that you collect from the inspections?	
5.4b	Do you have any minimum triggers for action?	
5.5a	Do you use performance models (e.g. condition, risk) or would models help in the planning process? If so please state how.	
5.6a	Do you use cost data to assess current improvement, upgrade or maintenance actions? If so how is this data developed?	
5.7a	Is there any other information that you would like to provide that may add to this section?	

Section Six: Optimisation/Prioritisation (Budget Management, Risk Management)

Once list of works is known there it has to be matched to the current funding allocation. This section focuses on the process of developing the forward works programme.

6.1a	How do you develop your prioritised forward works programme from your list of identified actions (i.e. manage your identified risks)?	
6.1b	Do you use any optimisation techniques to ensure a balance between identified risks, level of service and cost? If so please discuss (e.g. approach, standards used etc). If not please explain current practice.	
6.2a	What structures funding (dollar values) is detailed in your asset management plan for the next 10 years (e.g. maintenance, renewal, replacement, upgrading)?	
6.2b	How does the structures allocation compare to the overall allocation for roads and structures (dollar values)?	
6.2c	How does the bridge allocation compare to the overall structures allocation (dollar values)?	
6.2d	What is the Asset value of your bridges and structures?	
6.2e	What would be an optimal maintenance budget for you network?	
6.3a	Are there any strategies or approaches you have identified in you AMP improvement plan, or would like to introduce? What benefits would these bring to the asset management process and what information/data do you need to implement them?	

Section Seven: Systems Tools and Quality Assurance

There are a range of ways of storing data and managing data and the asset management process. This question aims to find out the type of systems that you use to help you manage your assets, and how you manage each of the individual systems.

7.1a	How do you store your inventory/condition information?	No formal system		Paper system		A spreadsheet		In-house database		Recognized system	
7.1b	Please describe your system and how you ensure it is verified and validated, and how frequently you carry out this process.										
7.1c	What standards do you use?										
7.2a	Question 2.2a asks if extra data is collected. How do you store this?	No formal system		Paper system		A spreadsheet		In-house database		Recognized system	
7.2b	If there is a range of methods please outline what is used for each and why.										
7.3a	Do you use any other formal or informal data management systems? Please list.										
7.3b	Please detail their level of sophistication. Please rank in accordance with the same system used in 7.1a and 7.2a.										
7.3c	How do they help in the decision making process?										
7.4a	Do you carry out any formal validation and verification of the data that you store? Validation is check for data completeness, and verification is an on-site check of correctness/accuracy.										
7.4b	Do you audit you asset management process, if so how regularly is this done?										
7.4c	How do you take into account any findings?										
7.5a	Are there any other systems, tools or quality assurance processes that you would like to cover?										

Appendix B Survey scoring methodology

B1 Scoring methodology introduction

This section provides greater detail on the scoring methodologies that were used for each of the survey questions. It explains the following:

- the aim of each question
- what constituted international practice for benchmarking responses
- the ranking system that was used to score each question
- the relative weightings applied to each sub-question and how the scores were normalised to fit within the three-point rating system.

B2 Question 1: Network-specific inventory

Network data was used to gain an understanding of the complexity of each network. The complexity rating was used to benchmark the topic rankings and overall asset management, in order to assess any development gaps that may have been present. The following areas were used to assess network complexity:

- network data (length and urban/rural mix)
- structure numbers and structures breakdown, including bridge numbers
- strategic structures numbers and reason for inclusion
- other factors perceived to bear on network complexity (eg traffic numbers, other topics covered by the authority).

Perception of complexity was included, as it allowed a fairer assessment of complexity, as each network had its own specific issues.

B2.1 Relative importance weightings

Relative importance weightings were focused towards bridge-specific issues, as the overall process was focused towards bridge data collection and monitoring strategies. Numbers of structures/bridges, and numbers of strategic bridge issues were considered to be the main factors. The perceived issue category was also treated equally, as it gave authorities an opportunity to describe the specific problems on their own networks. Network length and rural mix were considered to be important, as they create management problems in the own right; however, they were considered to be less important than the bridge-specific issues.

B2.2 Survey marking

Score definitions were set for each of the individual assessment areas; these are shown in table B1.

Network length was set such that longer networks, ranking 3, comprised the top 33rd percentile length (1350km), and the lower ranking comprised the lower 33rd percentile length (790km).

Table B1 Question 1: Rating network complexity

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
1.1a(1)	Length of network	Long – greater than 1350km	3	0.25	0.0625
		Medium	2		
		Short – less than 760km	1		
1.1a(2)	Urban/rural mix	High – greater than 80%	3	0.75	0.1875
		Medium	2		
		Low – less than 20%	1		
1.1b	Specific network issues	High – large number of issues	3	1	0.25
		Medium	2		
		Low – low number of issues	1		
1.2b	Number of bridges	High – greater than 220	3	1	0.25
		Medium	2		
		Low – less than 110	1		
1.2d	Number of strategic bridges	Complex – 5 or more bridges	3	1	0.25
		Medium	2		
		Simple – 2 (or fewer) bridges	1		

Urban/rural mix was set so that cities with very high urban percentages were considered to be of higher ranking. The boundary was therefore set at 80% for the upper ranking. Higher urban mix was assumed to add to complexity, as working in urban areas provides its own planning issues (eg traffic management arrangements). The boundary for the lower ranking was set at 80% rural (20% urban).

Specific network issues were addressed through the open question used in this section. The upper ranking was based on subjective assessment, with assessment criteria focusing on traffic numbers in the area, general descriptions of road types and issues, and topography of the areas (which affects working practices), along with any specific issues such as strategic routes or lifeline issues. Those areas with a range of network issues were ranked as 3, and those with generally few or no issues were ranked as 1.

Number of bridges was considered to be an important factor when assessing the overall complexity of the bridging network. The upper boundary was set so that the top 33rd percentile bridge count (more than 220) was ranked as 3, and the lower boundary was set so that the lower 33rd percentile bridge count (less than 110) was ranked as 1.

Number of strategic bridges was subjectively rated, but based on numbers of bridges noted, or the complexity or impact of failure of the strategic bridges being noted. High numbers, high complexity or high impact of failure was considered to be a ranking of 3; two or fewer significant or strategic bridges were considered to be a ranking of 1.

B2.3 Outcome boundary

The upper ranking boundary for complexity was set so that known complex authorities achieved a ranking of 3, and known simple authorities achieved a ranking of 1. Those close to the boundary were assessed based on knowledge of the areas, and the boundaries adjusted so that they were included within an appropriate ranking.

B3 Question 2: General bridge inventory information

While question 1 sought to understand typical network characteristics, question 2 aimed to understand the level of data collected for bridges, including network-level data, bridge-level data, and data on specific areas such as bridge elements and bridge components. It also sought to understand the wider range of bridge information collected by authorities.

B3.1 International practice definition

Internationally, there is a wide range of inventory data collection practices, with each country collecting their own specific data. However, generally best practice is considered to comprise collection of data in the following areas:

- network/route data (ie name, location and structure type)
- bridge data (ie bridge age, dimensional details, number of spans, construction form and materials)
- element data (ie age, specific descriptions on decks, abutments, beams, parapets, and other component groups such as bearings)
- component data (ie descriptions of specific beams, bearings, joints, etc).

B3.2 Ranking

Internationally, data is collected for network, bridge and element, but less data is collected on components. However, the international practice review indicated that component data is required, especially for SHM and the monitoring of critical components. The bridge condition indicators are an example of where component-level data is used (Roads Liaison Group 2004).

While good data collection was rated as 2, practices commensurate with international practice received a score of 3. The following were used to rank the bridge inventory data collection outcomes for network, bridge, element and component:

- Ranking 3: Good range of data collected
- Ranking 2: Moderate range of data collected
- Ranking 1: Poor range of data collected/no data collected.

Other information was considered to be drawings, feasibility studies, inspection reports, assessment reports, and any other information that added to the overall understanding of the bridge or network. This information was considered to be used in either long-term planning or the management of bridge-specific issues.

Ranking for other data followed the same format as the rankings used for the inventory collection: a range of useful information collected was ranked as 3, through to 1 for no or little extra data collected (table B2).

Table B2 Question 2: Weighting and rating for bridge inventory collection

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
2.1a	Network data	High – a good level of data	3	3	0.273
		Medium	2		
		Low – limited or no data	1		
2.1b	Bridge data	High – a good level of data	3	3	0.273
		Medium	2		
		Low – limited or no data	1		
2.1c	Element data	High – a good level of data	3	2	0.182
		Medium	2		
		Low – limited or no data	1		
2.1d	Component data	High – a good level of data	3	1	0.091
		Medium	2		
		Low – limited or no data	1		
2.2a	Other data collection	High – a good level of data	3	2	0.182
		Medium	2		
		Low – limited or no data	1		

B3.3 Relative importance weightings

The relative importance for inventory collection ranking (table B2) was focused towards bridge-level data, with a secondary focus on network-level data and element-level data, and a tertiary focus on component-level data. This ensured network- and bridge-specific data would be collected, so an authority would know where the bridge was and what types of bridges they had. Element-level data were considered to be of lower importance than bridge data, but these areas were important for maintenance-planning tasks, as condition data tended to be stored at this level. Component-level data was considered to be of the lowest importance, as it was rarely used for specific purposes.

B3.4 Outcome assessment

The upper limit (see table B3), was based on the findings of the literature review, which found that network-level data was stored – therefore 3 was considered commensurate with international practice. Bridge data was also well developed for most countries, and therefore 3 is again the upper limit. The same is also true for element-level data, but as most countries do not collect component data, 2 is therefore the limit. Extra data such as drawings was also noted – therefore 3 is the limit in this case.

Core asset management practice (good practice) was assumed to require network- and bridge-level data (3 and 3). The lower limit for element and component data is 1 and 1, respectively, as both are required but not always used. Other data collection is expected for good practice – 3 was therefore the limit.

Network- and bridge-level data were considered to be more important than element-level data, which was considered to be more important than component-level data. Other data was considered to be as important as element-level data.

Table B3 Inventory data ranking boundaries

	Network	Bridge	Element	Component	Other data
Upper boundary	3	3	3	1	3
Lower boundary	3	3	1	1	3

B4 Question 3: Condition data collection

Condition data collection seeks to understand the type of visual inspection data that is collected for bridges, the typical inspections that are undertaken, the cycles that these inspections follow, and the QA processes, such as training and audits, which are used to ensure long-term consistency and the quality of the inspection outputs.

B4.1 International practice definition

Internationally, a wide range of techniques and inspection processes are used to collect defect and condition data for bridges and structures. International practice for visual inspections comprises:

- inspections following defined guidelines and practices
- inspections that include frequent less-detailed general inspections, less-frequent detailed inspections, and other more specific special inspections
- inspections carried out on a regular and fixed cycle basis, typically two and six years, but in some countries varying according to structure type and risks (where inspection cycles are altered, risks should be nominated and assessed)
- inspections that collect data on defect severity and extent, and record these as a condition rating – also record mitigation actions, rough order cost to repair, time to action
- audits of the inspection process and audits of reports, both for content and consistency between inspectors (ie a review at bridge level).

Best practice for QA is considered to be:

- training of inspectors
- reviews of the inspection reports
- reviews of inspections, and bridges reinspected to ensure consistency between findings
- audits of the overall inspection process, to identify improvements or changes.

B4.2 Ranking

Ranking was based on general compliance with good practice, and covered alignment to inspection types, inspection coverage, and QA processes. The review considered general alignment with types of inspection undertaken and the typical time periods between inspections. Coverage reviewed the type of data collected, including extent, severity, whether mitigation actions and associated costs were noted, and whether an estimated time to action was included.

The following ranking criteria were used:

- Ranking 3: General, detailed and special inspections being carried out on a predefined cycle of two and six years, and as nominated for special inspections

- Ranking 2: General special inspections/general and detailed inspections being undertaken on their predefined cycle
- Ranking 1: General inspections only on a predefined or ad-hoc cycle.

The following inspection coverage ranking criteria were used:

- Ranking 3: Collection of severity, extent and defect description
- Ranking 2: Two out of three noted from description, severity and extent
- Ranking 1: One out of three noted from description, severity and extent.

The following ranking criteria were used to assess QA development and compliance with good practice:

- Ranking 3: Formal audits carried out, reviews of all deliverables undertaken, and training of inspectors apparent
- Ranking 2: Some of the above carried out
- Ranking 3: Limited or no QA apparent.

B4.3 Relative weightings

The relative weightings (B4) were considered to be equal across all areas, as the types of inspection undertaken, frequency and QA are all important parts of the inspection process.

Table B4 Question 3: Weighting and rating for condition data collection

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
3.1a	Inspection type alignment with best practice	High – good alignment	3	1	0.333
		Medium	2		
		Low – poor alignment	1		
3.2a	Inspection coverage	High – good alignment	3	1	0.333
		Medium	2		
		Low – limited data	1		
3.3a–3.3d	Perceived QA development	High – good practice	3	1	0.333
		Medium	2		
		Low – limited data	1		

B4.4 Outcome assessment

International practice (table B5) comprised general, detailed and special inspections – hence a ranking of 3 was assumed as the upper limit. Inspection coverage generally included costs estimates, condition, extent, defect description and time to action. This was considered to be the upper limit – hence compliance with it constituted a ranking of 3. Some QA was carried out internationally, but as identified in other studies, it was not as rigorous as it should have been (American Society of Civil Engineers, Structural Engineering Institute, and American Association of State Highway and Transportation Officials 2009). Therefore a limit of 2 was set.

For the lower limits, 3 was set for compliance, as New Zealand practice tended towards international practice, with policy defining general, detailed and special inspections. However, as no condition data was collected, 2 was set as the lower limit for data coverage. The QA lower limit was set as 1, as most authorities undertook some QA.

Table B5 Condition data development ranking boundaries

	Alignment	Coverage	Quality
Upper boundary	3	3	2
Lower boundary	2	1	2

B5 Question 4: Structural health monitoring (SHM)

SHM is a relatively new process used in civil engineering. It has been adopted in only a small number of countries, and generally only for critical or larger bridges. The intention of this section was to find out whether New Zealand bridge asset managers regularly used NDE to supplement their visual inspection process, whether they were familiar with more complex techniques such as SHM, and whether it would be desirable or appropriate for the bridges they managed.

B5.1 International practice definition of NDE and SHM

International practice for NDE is considered to be active use of NDE, both to provide extra data on issues that have already surfaced, and also to provide data on possible future issues such as chloride ingress or carbonation. Best international practice is further defined by the use of SHM and its integration into the data collection and decision-making process. Our survey covered awareness of SHM – ie whether it had been used, whether bridge asset managers were aware of it, or planned to use it.

B5.2 Ranking for NDE and SHM

The following ranking criteria (table B6) were used to assess development regarding the awareness and use of NDE and SHM:

- Ranking 3: NDE well understood and widely used, or used in the past or planned for the future
- Ranking 2: Reasonable understanding of NDE, and some use of NDE
- Ranking 1: Virtually no use or awareness of NDE.

The following were used to assess how well NDE was integrated into the data collection and monitoring processes:

- Ranking 3: NDE well used, with defined problems being managed
- Ranking 2: NDE used ad hoc, with no planned approach
- Ranking 1: Virtually no use of NDE.

The SHM ranking criteria used were as follows:

- Ranking 3: SHM used in the decision-making process or to trigger other actions
- Ranking 2: Awareness of SHM, but not used
- Ranking 1: No awareness and no use of SHM.

B5.3 Relative weightings

Weightings were focused towards NDE, as it was considered to be more important than SHM for the majority of networks and the majority of bridges.

Table B6 Question 4: Testing and SHM weighting and ranking

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
4.1a–4.1c	NDE coverage (types of test and reason for testing)	High – good coverage	3	2	0.333
		Medium	2		
		Low – poor coverage	1		
4.2a–4.2b	NDE integration with inspection process	High – good integration	3	2	0.333
		Medium – ad-hoc integration	2		
		Low – poor/no coverage	1		
4.3a–4.3b	SHM awareness	High – integrated	3	2	0.333
		Medium – awareness	2		
		Low – limited awareness	1		

B5.4 Outcome boundaries

NDE was well appreciated and understood by international bridge engineers – hence a ranking of 3 (table B7) was set as the upper limit. NDE was also well used for finding issues on bridges – therefore 3 was set as the upper limit. As SHM was widely appreciated and understood, but was not used in all cases, 2 was used for the upper limit.

Good practice for New Zealand's use of NDE was defined as an appreciation of NDE, resulting in a lower limit of 2. It was also expected that an ad-hoc use of NDE would be carried out, so a ranking of 1 was set as a lower limit. It was expected that there would be a lower-than-average appreciation of SHM, because of the nature of bridges in New Zealand – therefore the lower boundary for good practice was 1.

Table B7 Monitoring and testing outcome boundaries

	NDE awareness	NDE used as a monitoring tool	SHM
Upper boundary	3	3	2
Lower boundary	2	2	1

B6 Question 5: Performance management

The USGAO report on bridge performance (USGAO 2008) identified that performance measures have to be used to understand how policy and government-defined service levels are being delivered. Question 5 aimed to gain information about this process through an assessment of:

- failure-risk knowledge, both network and bridge risks
- setting and measuring LOS

- understanding performance
- understanding the gaps between current and future performance.

B6.1 International practice definition

International practice for bridge performance measurement is not well developed, with most documents focusing on condition and technical performance measurement aspects such as load-carrying capacity. This has resulted in a relatively poor understanding of bridge performance and a poor understanding of bridge and strategic LOS.

Lifeline studies have been carried out locally (Auckland Engineering Lifelines Group 2007) and internationally (Werner and Taylor 2004), so there was a good understanding of the risks facing networks. Risks facing bridges were also well understood, and numerous bridge-risk management papers have been written (eg Kowalik 2009, Moon et al 2009).

The use of models to assess long-term maintenance needs and work prioritisation tools was limited.

B6.2 Ranking definition

The international practice benchmark for decision making was considered to comprise good understanding of network and bridge failure risks, understanding of the desired outcomes through LOS adoption, understanding of performance gaps, and evidence of long-term modelling.

Table B8 Question 5: Criticality, risk and performance management

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
5.1a	Network-level risk appreciation	High – good understanding	3	3	0.273
		Medium – some understanding	2		
		Low – no understanding	1		
5.1b	Bridge-level risk appreciation	High – good understanding	3	3	0.273
		Medium– some understanding	2		
		Low – no understanding	1		
5.2a–5.2c	LOS understanding and compliance	High – good understanding	3	2	0.182
		Medium – some understanding	2		
		Low – no understanding	1		
5.4a–5.4b	Gap analysis and understanding of the process	High – good understanding	3	2	0.182
		Medium – some understanding	2		
		Low – no understanding	1		
5.5a	Performance management and long-term planning	High – evident and used	3	1	0.091
		Medium – understood but not used	2		
		Low – not evident	1		

The following rankings were used for network- and bridge-level risk aspects:

- Ranking 3: A good understanding of the risks

- Ranking 2: Some understanding of the risks
- Ranking 1: Little or no understanding of the risks.

LOS development and understanding was ranked as follows:

- Ranking 3: A good understanding and development of LOS
- Ranking 2: Some understanding of LOS
- Ranking 1: Little or no understanding of LOS.

The following were used when assessing gap analysis development:

- Ranking 3: A good understanding of the performance gaps and triggers for action
- Ranking 2: A moderate understanding of the performance gaps and triggers for action
- Ranking 1: Little or no understanding of the performance gaps or triggers for action.

When assessing long-term planning development, the following rankings were used:

- Ranking 3: Advanced forward planning evident through the use of models
- Ranking 2: Forward planning evident
- Ranking 1: No forward planning evident.

B6.3 Relative weightings

Relative weightings were mostly focused towards risk appreciation, and moderately towards LOS and performance and gap understanding, as these were considered to be core asset management functions that have to be carried out in order to ensure safe and reliable networks and bridges. Long-term planning, through the use of models, was considered to be less important and a function of advanced asset management, as it was considered that knowing the risks was the first objective. Table B8 provides details of the ratings used and the weightings.

B6.4 Outcome assessment

Internationally, there was a good understanding of network-level risk, including lifelines issues (table B9) and this was reflected in New Zealand practice; therefore the limit for this aspect was set at 3. However, bridge-risk understanding tended to be more developed internationally than in New Zealand, with numerous papers on the subject – hence a ranking of 3 for the upper limit and 2 for the lower limit.

Internationally, bridge service levels tended to be technically focused; an upper and lower limit of 1 was therefore set. Internationally, models, mainly for condition, were used to develop an understanding of forward work need. However, no performance or network-level service models were used – hence the upper limit was set at 2 and the lower limit at 1. The lower limit of 1 reflected feedback from engineers and asset managers, who reported using their judgement to optimise maintenance. Therefore good practice was considered to be anything above this, as it would provide an auditable trial.

Table B9 Performance ranking boundaries

	Network risk	Bridge risk	LOS	Performance	Gap analysis	Planning
Upper boundary	3	3	1	2	2	3
Lower boundary	3	3	1	1	1	1

B7 Question 6: Optimisation and prioritisation

Asset management is a function of the data that is collected, the decisions that are made with it, and the programmes that are developed from it. Developing these programmes makes it possible to ensure the risks and needs of the network and customer are met and that LOS are fulfilled. Prioritisation and optimisation leads to a FWP that meets the needs of the network and the bridges on the network in an optimal fashion so that the impact of key drivers is taken into account and managed. The areas covered by this question included:

- development of the prioritised FWP and the use of associated optimisation techniques
- appreciation of funding need, ie whether the asset manager was able to provide good reasoning for the budget that was needed to optimally manage the stock.

B7.1 International practice definition

International practice is considered to be the use of prioritisation tools to ensure budgets are spent appropriately. It is also considered to be a good understanding of the budgets needed to manage the bridge stock. At the time of this research, prioritisation only focused on maintenance management, and did not actively store and assess data relating to performance.

B7.2 Ranking

Ranking definitions (table B10) are detailed below for work prioritisation and budget-spending needs appreciation. Work prioritisation development level was ranked as follows:

- Ranking 3: Prioritisation tools are used to manage the budget allocations and identified action lists; these tend to be formalised tools such as multi-objective analysis
- Ranking 2: Prioritisation is carried out, but using simple or less formal tools
- Ranking 1: No prioritisation is carried out and only informal judgement is used.

The following rankings were used for budget-spending appreciation:

- Ranking 3: Optimal budget discussed along with detailed reasoning
- Ranking 2: Optimal budget noted, but no proof of detailed reasoning provided
- Ranking 1: No appreciation of optimal budgets.

Table B10 Question 6: FWP development

<table>
<tr><th>Question</th><th>Description</th><th>Rating criteria</th><th>Ranking</th><th>Relative importance</th><th>Normalised ranking</th></tr>
<tr><td rowspan="3">6.1a–6.1b</td><td rowspan="3">Work prioritisation and decision-making development</td><td>High – formal tools</td><td>3</td><td rowspan="3">1</td><td rowspan="3">0.500</td></tr>
<tr><td>Medium – informal tools</td><td>2</td></tr>
<tr><td>Low – no evidence/tools</td><td>1</td></tr>
<tr><td rowspan="5">6.2a–6.2c</td><td rowspan="5">Funding need appreciation</td><td>High – proof of need and reasoning for need</td><td>3</td><td rowspan="5">1</td><td rowspan="5">0.500</td></tr>
<tr><td>Medium – appreciation, but no reasoning for need</td><td>2</td></tr>
<tr><td>Low – no understanding</td><td>1</td></tr>
<tr><td>Medium</td><td>2</td></tr>
<tr><td>Low – limited improvements</td><td>1</td></tr>
</table>

B7.3 Relative weightings

Work prioritisation and optimisation, and funding appreciation, were considered to be equally important, as there was a need to understand what had to be spent, where and when, and what the optimal network funding needs were.

B7.4 Outcome assessment

Internationally, prioritisation was well developed, but it tended to be maintenance focused with little link to LOS – hence a ranking of 3 for prioritisation. Funding appreciation was mainly maintenance focused – therefore a score of 2 was defined.

New Zealand practice was used to set the lower boundary. It was expected that in New Zealand, prioritisation would be less well developed as we do not have the same issues as countries such as the US; however, it was expected that some formalised decision-making tools would be used – therefore a lower limit of 2 was set. Funding appreciation was similar to international practice in being mainly condition- and functionality-based, so the same level was chosen. Table B11 details the boundaries used in the assessment process.

Table B11 Prioritisation/optimisation ranking boundaries

	Prioritisation	Funding
Upper boundary	3	2
Lower boundary	2	2

B8 Question 7: System tools and QA

System tools are important for asset managers, and it is important to have a system that is appropriate for the type of network that is to be managed. It is also important to validate the data that is stored within the systems, as this is directly proportional to the quality of the decisions being made and the quality of the outcomes. To meet these needs, many organisations have developed or use recognised data management systems and other tools to manage their asset. This question aimed to gather information that would facilitate understanding of the type of inventory systems and QA systems that bridge managers use to maintain the data they store.

The topics covered included:

- storage of condition and inventory data
- management of the main inventory and condition data
- storage of other information used in the decision-making process.

B8.1 International practice definition

International practice is considered to be the adoption of a formal system of data storage, such as a bespoke or a widely used system. The system comprises a number of elements including inventory and condition data storage, and decision-making and forward-planning tools.

With regards to the storage of other information, best practice is considered to be storage in electronic form for main items such as as-built drawings or key reports.

QA is considered to comprise a full regime of data management and review, such as the one defined locally by the *State highway database operations manual* (NZTA 2009b).

B8.2 Scoring definitions

Data storage development rankings (table B12) were considered to be as follows:

- Ranking 3: Use of a formally recognised system or in-house bespoke system
- Ranking 2: Use of spreadsheets
- Ranking 1: No data storage system, or paper records only.

Other information storage was ranked using the same criteria as above.

Storage management rankings were based on the following criteria:

- Ranking 3: Fully developed data QA programme
- Ranking 2: An ad-hoc QA approach
- Ranking 1: No data QA.

Table B12 Question 7: Data systems weightings and ranking limits

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
7.1a	Storage development level	High – recognised system	3	1	0.333
		Medium – in-house database	2		
		Low – spreadsheet/paper	1		
7.1b	Database data management	High – full QA developed	3	1	0.333
		Medium – some QA – ad hoc	2		
		Low – no QA	1		
7.3a–7.3c	Storage of other important Information	High – recognised system	3	1	0.333
		Medium –in-house database	2		
		Low – spreadsheet/paper	1		

B8.3 Relative weightings

The weightings were all considered to be 1, as all the aspects under consideration were considered equally important. As can be seen, outcome provides a focus towards storage and management of the main decision-making data (0.66 databases, and 0.33 other data).

B8.4 Outcome assessment

The upper ranking boundary (table B13) assumed that some form of bespoke or recognised system was being used to manage inventory and other data needs (eg condition), and that the data was well managed, as this aligns well with international practice. Management of the data was also well defined. Other data was less well developed.

Table B13 Data systems ranking boundaries

	Storage	Management	Other Data
Upper boundary	3	3	2
Lower boundary	2	2	2

Lower limits assumed there was a more formally developed system – either a simple database or a spreadsheet – so 2 was set as the limit of good practice. It was also expected that some level of data management would be undertaken, especially given the importance attached to the data; 2 was also set for this limit.

B9 Overall data collection development

For overall data collection development, a score was developed that combined the outcomes of Questions 2 (inventory), 3 (inspection practice) and 4 (monitoring and testing). Combining these questions meant it was possible to review overall development levels for data collection.

B9.1 International practice definition

Limits were set as 3 for international practice, 2 for moderate practice, and 1 for less-developed practices. The upper-limits boundary was therefore set as 3, and the lower-limit boundary as 2.

B9.2 Weightings

All aspects, as detailed in table B14, were assumed to be equally important and weightings of 1 were used.

Table B14 Overall data collection development

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
2	Inventory data collection practices	High – best practice (see Q2)	3	1	0.333
		Medium	2		
		Low	1		
3	Inspection practices	High – best practice (see Q3)	3	1	0.333
		Medium	2		
		Low	1		
4	Testing and monitoring	High – best practice (see Q4)	3	1	0.333
		Medium	2		
		Low	1		

B10 Overall asset management development

Overall asset management development was assessed to understand the relative ranking of each surveyed authority and to understand how New Zealand compared with international development levels. The assessment was based on the outcomes of Questions 2–7.

B10.1 International practice definition

As good-practice limits have already been set, good practice was assumed to be represented by 3, moderate practice by 2, and less-developed practices by 1. The lower limits were therefore set as 2.

B10.2 Relative weightings

All aspects were assumed to be equally important – therefore weightings of 1 were used for each. The specific details are noted in table B15.

Table B15 Overall asset management development

Question	Description	Rating criteria	Ranking	Relative importance	Normalised ranking
2-4	Overall data collection	High	3	1	0.273
		Medium	2		
		Low	1		
5	Performance management	High	3	1	0.273
		Medium	2		
		Low	1		
6	Optimisation/prioritisation	High	3	1	0.182
		Medium	2		
		Low	1		
7	Data storage and management	High	3	1	0.273
		Medium	2		
		Low	1		

B10.3 Outcome assessment

The upper boundary (table B16) was set such that best practice had to be achieved in all areas, and the lower boundary was set such that moderate practice had to be achieved across all areas.

Table B16 Asset management ranking boundaries

	Collection	Performance	Prioritisation	Storage
Upper boundary	3	3	3	3
Lower boundary	2	2	2	2

Appendix C Abbreviations, acronyms and terms

C.1 Abbreviations and acronyms

AADT	annual average daily traffic
BDS	bridge data system
FHWA	Federal Highway Authority
FWP	forward works programme
GPS	Government Policy Statement
IGNS	Institute of Geological and Nuclear Sciences
IIMM	International Infrastructure Management Manual
LOS	level of service
LTBPP	Long-term Bridge Performance Program
NDE	non-destructive evaluation
NIWA	National Institute of Water and Atmospheric Research
NZOAG	New Zealand Office of the Auditor General
NZTA	New Zealand Transport Agency
NZTS	New Zealand Transport Strategy
RCA	road controlling authority
SHM	structural health monitoring
St-Id	structural identification
TLA	Territorial Local Authority
USGAO	United States Government Accountability Office

C.2 Terms used

- Advanced asset management:

  Asset management which employs predictive modelling, risk management and optimised decision-making techniques to establish asset lifecycle treatment options and related long-term cash flow predictions (Hughson et al 2006)

- Best practice: A desired performance level that may or may not be attained by the current management practices
- Bridge: The whole bridge asset, including deck, beams, abutments, foundations, handrails and surfacing
- Bridge inventory: A physical description of the bridge

- Component: A single entity that forms an element of the bridge – eg a specific joint, bearing or bridge beam
- Condition data: An assessment of defect or deterioration extent and/or severity, using a numerical scale
- Core asset management:

  Asset management which relies primarily on the use of an asset register, maintenance management systems, job/resource management, inventory control, condition assessment, simple risk assessment and defined levels of service in order to establish alternative treatment options and long-term cash flow predictions (Hughson et al 2006)

- Criticality:

  The degree of impact that a requirement, module, error, fault, failure, or other item has on the development or operation of a system (Webster Online Dictionary 2011)

- Critical assets:

  Systems and assets, whether physical or virtual, so vital … that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters (Moteff and Parfomak 2004)

- Damage:

  [An] unfavourable change in the condition of a structure that can affect structural performance (International Society for Structural Health Monitoring of Intelligent Infrastructure 2010)

- Data:

  Numbers, words, symbols, pictures etc without context or meaning (Roads Liaison Group 2005)

- Defect data: Details of defects found during the inspection process, including defect description and proposed mitigation actions
- Element: A structural or functional section of the bridge – eg deck, bearings, beams, abutments, foundations
- Good practice: A performance level that is deemed appropriate taking into account time, budgetary, and operational constraints
- Information:

  A collection of numbers, words, symbols, and pictures that have meaning, ie information is data with context (Roads Liaison Group 2005)

- Knowledge:

  The understanding of information through assessment and analysis that provides a basis for the decisions to be made (Roads Liaison Group 2005)

- Network complexity: A qualitative assessment of how complicated the network is – takes into account network length, urban/rural mix, number of issues that may pose a high risk, the total number of bridges managed and the number of strategic bridges located on the network

- Network functionality: The level to which a network delivers on the expected LOS criteria, as measured using a series of key performance indicators
- Non-destructive evaluation (NDE): The type of testing that does not destroy the test object, typically uses simple tools and techniques, is short in duration, and can be carried out without attaching sensors to the bridge for a long time. NDE needs to be specifically arranged and carried out, and does not provide data or information on demand using automatic data-collecting systems. Typical examples include Schmidt hammer, chloride sampling and cover meter surveys. NDE also includes tests, such as concrete core strength, steel tensile strength or carbonation test, that destroy small samples extracted from the structure but do not destroy the bridge or any of its elements or components.
- Optimisation: Optimisation takes place at two levels, comprising bridge and network level. At bridge level it involves the development and delivery of lowest whole-of-life-cost solutions. At network level it involves the development and implementation of programmes of work that have the most positive effect on network functionality, as measured by key performance measures, at the least cost.
- Performance data: Data as measured against defined assessment criteria, relating to the operation of the bridge and its impact on network functionality – includes condition assessment, loading assessment, seismic assessment, scour assessment and other similar data.
- Risk:

  The chance of something occurring that will have an impact on objectives, measured in terms of a combination of the consequences of an event and their likelihood (Standards New Zealand 2009)

- Structural Health Monitoring: A type of data collection that provides data (information) on demand about structural performance and any significant change or damage occurring in the structure. In the context of this strategy, SHM also comprises automatic data collection on wider network performance and environmental and operations factors affecting a bridge (eg traffic volumes, seismic excitation and river flows)
- Structural identification:

  The process of creating/updating a physics-based model of a structure (eg finite element model) based on measured static and/or dynamic responses to be used for structural assessment (American Society of Civil Engineers and Structural Engineering Institute 2011)

- Validation: An exercise carried out to ensure an asset database is maintained correctly and has all data up to date and free of obvious errors
- Verification: A random sampling exercise carried out to confirm the results from an inspection and to assess the accuracy of the data that is held in the bridge inventory database
- Visual inspection:

  ... the process of examination and evaluation of systems and components by the use of the human sensory systems aided only by such mechanical enhancements to sensory inputs as magnifiers, dental picks, stethoscopes, and the like (Spencer 1996)