New York City Bridges: Expenditures, Conditions and Services

Bojidar Yanev[1]

Abstract

The paper discusses the fundamental bridge management problem of allocating expenditures in order to maximize services and minimize hazards, based on the knowledge of bridge conditions. In New York City, where numerous ageing transportation networks overlap and co-exist, this process cannot be rigorously optimized. Rather, "top-down", "ground-up", "network" and "project", "life-cycle" and "emergency" approaches to prioritisation and problem resolution are used to varying degrees. Examples from the experience of the Bridge Division at the New York City Department of Transportation are examined.

Introduction: Bridge Management Remains Disaster-Driven

On August 1, 2007 the steel deck truss bridge carrying Interstate-35W across the Mississippi River at Minneapolis collapsed, causing at least nine fatalities, numerous injuries and losses that have still to be assessed. While the forensic engineering investigations are progressing at their professional pace, public and political reactions are referring to the event as a "wake-up call" for better (funded) infrastructure management. Comparisons were drawn to earlier bridge failures, such as that of I-90 near Cleveland a decade earlier and, most notably, the collapse of the Silver Bridge across the Ohio River at Point Pleasant in 1967. Striking similarities and the differences between these events are emerging. The Silver Bridge failure is at the origin of contemporary bridge management in the United States because it triggered the Act of Congress which eventually produced the National Bridge Inventory (NBI). As a result, the failure of I-35 is being investigated from the standpoint of a well developed bridge condition database. Within hours, the NBI was scanned for structures similar to the failed one. Emergency measures, including inspections of potentially critical details were carried out within days. Refinements of the current procedures by the use of non-destructive testing and evaluation techniques were found to be already under consideration through several initiatives at the federal and local levels, most noteably inclding the Long-Term Bridge Health Monitoring Program, launched by the the Federal Highway Administration (FHWA). These improvements are to be expected, as the bridge at Minneapolis was constructed roughly when the one at Point Pleasant failed. Over the interim period of 40 years bridge management has been integrated into asset management, governed by life-cycle considerations. Nevertheless, bridge management nationwide is once again responding to a disaster. The conflict between long-term and emergency priorities remains central to management on the engineering, social, and political levels.

Executive Director, Bridge Inspection & Management, NYC DOT

Adjunct Professor, Columbia University, New York City

As all evolved professions, engineering must achieve its objectives under contradictory constraints. Design optimizes the balance between structural strength and weight. Infrastructure management maximizes quality and quantity of service at minimum cost. The short and long-term management of the infrastructure seeks a balance between technical and managerial considerations. Those considerations have grown increasingly divergent in the course of history. In earlier periods technicians provided services whereas management supplied resources in a bi-lateral relationship. Whatever their creative differences, builders and rulers of past eras concurred on the intended eternity of the products. The surviving monuments of building art satisfy that requirement even if they may not reflect the views of the majorities of their respective periods. Modern projects are launched through a complex interaction of political, economic, and technical considerations, as illustrated in Fig. 1. Expenditures, services, and physical assets are managed by experts with maximized knowledge in increasingly restricted domains. The process grows fragmented and discontinuous. The resulting products risk dissatisfying users and owners from the onset, becoming liabilities to future engineers and managers. New political and economic management teams justify their advent by "re-engineering" established management practices. Hence, planning horizons have narrowed down to election cycles. That tendency has affected the durability of infrastructure assets. The once eternal bridges are now designed for life spans of 75 years, recommended by the American Association of State Highway and Transportation Officials (AASHTO). Decks are frequently replaced after 35 years.

Catastrophic failures appear most effective in initiating revisions of established policies, with an impact proportional to the number of fatalities involved. At the annual AASHTO meeting (Sept. 27 – Oct. 1, 2007) it was pointed out that the Highway Trust Fund will be posting a $US 4.3 billion deficit in 2009. The Senate Finance Committee has approved adding $US 5 billion to the fund. A $US 25 billion bridge repair initiative over 3 years, funded by a 5 cents gasoline tax was proposed by a Representative of Minnesota and roundly rejected.

Top-down and Ground-up Management of Networks of Projects

Whereas disasters, such as the bridge collapse on Aug. 1, 2007 engage simultaneously all the levels of network and project management competence shown in Fig. 1, routine circumstances reverse that effect. As shown in Table 1, network management focuses on the process (e.g. transportation), whereas project management deals with the product (e.g. the engineered structures).

Table 1. Project and Network Methods, Output and Competence

Level	Method	Output	Management responsibility	Planning horizon	Model	Performance assessment
Network	Top-down	Process	Funding, data	Long-term	Statistical	Quality assurance
Project	Ground-up	Product	Structures, operations	Immediate	Physical	Quality control

The two spheres of responsibility have adopted *top-down* and *ground-up* methods, respectively. Originally, *top-down* and *ground-up* were intended to signify whether a given design is implemented according to a fully preconceived scheme or by incremental adjustments. The two terms are also associated with centralized and de-centralized government. In the case of a national transportation network, *top-down* decisions, such as budget allocation, determine, more or less directly, the purpose and magnitude of local projects over relatively long periods. *Ground-up* projects, in contrast, must adjust to the dynamic field conditions. Since the two are entirely interdependent, their methods must be compatible and complementary. The interaction is unavoidable in a large metropolitan center where network and project considerations are inseparable.

The management of a bridge network in an urban setting, such as that of New York City, must integrate a large number of projects into several overlapping infrastructure networks (e.g. vehicular and rail transport, energy, water supply, sanitation, and so on). The size, density and importance of the assets are comparable to those of other major metropolitan centers (as well as those of smaller states). In 2007 approximately 2200 bridges carry vehicular and train traffic over and between the five boroughs of the City. 787 are City-owned, and 600 are managed by the State. The Port Authority of New York and New Jersey operates the airports and several major facilities, including the George Washington and Bayonne Bridges. The Metropolitan Transit Authority is responsible for the subways and many bridges, the Verrazano, Whitestone, Throg's Neck and Triborough among them. The Authorities charge tolls. Both top-down and ground-up methods are abundantly required.

The Bridge Division was re-established at the City Department of Transportation (NYC DOT) in 1988 after the Williamsburg Bridge was temporarily closed and nearly scrapped. See for instance Yanev (2007, Example 3, p.54). The Office of Bridge Inspection and Management was formed within the Division a year later, after concrete spalled under the Franklin Roosevelt Drive (FDR) in Manhattan, killing a motorist. The Bridge Division manages capital rehabilitation contracts of up to $US 600 million and an expense budget of approximately $US 60 million, annually. Main priorities are the safety of the public and the condition of the bridge stock, assumed to be directly correlated with the quality of the provided service. None of these properties is uniquely defined. Management decision support is provided by the NBI and the New York State Department of Transportation (NYS DOT) databases .

Condition Assessments

Asset management relies on information about the state of the assets, the demands and the constraints. Al of these bliocks of information contain to to various degrees the three fundamental types of uncertainty, namely randomness, vagueness and ignorance. Recent efforts have concentrated on the integration of asset management over the entire system of infrastructure facilities, within the Asset Management Office at the U.S. Department of Transportation. Bridge management packages, such as PONTIS (sponsored by the FHWA) are enhanced with software for bridge lifecycle cost analysis (BLCCA), as in Hawk (2003), and multi-objective optimisation for bridge management systems, most recently in Patidar et al. (2007). These publications specifically identify the probabilistic methods they employ in treating the various uncertainties inherent in the network level management of infrastructure assets. They also point out the areas, particularly on the project level, where deterministic decisions are inevitable. Bridge managers are in a similar position. Although their information is incomplete and uncertain, their decisions must be definite and will determine the eventual outcomes. Consistently with Einstein's observation that statistics reflect better the behaviour of crouds than individuals, network management shows a preference for probabilistic methods, whereas project management prefers a deterministic approach. In order to satisfy all needs, condition assessments must be diverse and redundant, offering a variety of evaluations based on different criteria and obtained by (as much as possible) independent means. One example is the bridge condition database adopted by New York State Department of Transportation (NYS DOT), shown schematically in Fig. 2. The various condition assessments are briefly described.

Structural Condition Rating

Structural condition is rated on a scale of 0 (failed) to 9 (new) by the NBI, and 1(failed) to 7 (new) by NYS DOT. The evaluation is obtained by visual inspections. The final product is a single number for the entire bridge, however the NYS DOT system is *component and span-specific*. A weighted average formula combines the worst ratings of 13 key structural components throughout a bridge to obtain an overall condition rating. The NBI is *bridge-specific*. A varied rating system was more recently developed for the use of the federally supported Bridge Management System (BMS) PONTIS. It focuses on commonly recognized (CoRe) structural elements.

Rating-descriptive methods are not the only structural condition evaluations. Yanev (2007, Chapter 10.4) described the alternative *defect-action* approach, favored for example by the American Railroad Engineering and Maintenance Association (AREMA). In that method, conditions are described by the amount and urgency of the remedial work, recommended by the inspecting engineer. The latter method is better suited for a network in superior condition, allowing all actions to be taken as recommended. The *rating-descriptive* method must rely on other evaluations for recommending direct action.

Load Rating

Load rating is calculated based on the design of the structure and the reported departures from the as-built condition. NBI recognizes *inventory* and *operating* ratings, the former reflecting the regularly presumed structural capacity, the latter – its extreme capacity. In a well functioning system the qualitative condition ratings should inform about visible deterioration before the quantitative load ratings assess the structure as functionally deficient. AASHTO has recently approved load testing as a method of establishing the bridge capacity in addition to analytic evaluations, and is reviewing a new load-rating manual. Load rating is the principle condition assessment of railroad bridges where loads are more predictable.

Potential hazards

NYS DOT has designated potential hazards perceived as such during inspections as "flags". Flags can be structural or safety (where the former always implies the latter, but not vise versa). Their urgency can vary from requiring prompt interim action (PIA) within 24 hours to low priority (allowing for monitoring until the next regular inspection). Flags in New York City escalated from a steady 180 in 1987 to 739 in 1989 (following the Williamsburg Bridge closure), and to 3071 in 1992, after the fatal spalling under the FDR. As a result of the drastic expenditures quoted earlier, flags eventually abated to a steady 1200, at least half of which are previously documented ones of low priority. Yanev (2007, Appendix 46, pp. 630-637) obtained deterministic correlations between flag incidence and condition ratings of the most frequently flagged bridge elements, such as decks, primary members, railings, expansion joints and so on. Hazards related to traffic accidents and climatic changes occur at a relatively steady rate, whereas those caused by structural conditions increase predictably with deterioration. All potential hazards must be treated as emergencies and are therefore often remedied by temporary "stop-gap" measures. Overall structural conditions must be raised above the threshold of accelerated "flag" incidence before life-cycle and hence network management considerations can govern.

Serviceability rating

Serviceability is said to be appraised, rather than evaluated, however the federal rating is once again from 0 to 9. The quality of service is influenced by structural conditions, but depends also on factors, such as importance, obsolescence, and poor geometric alignment.

Vulnerability

This rating anticipates hazards, rather than react to them. Based on local demands, NYS DOT has recognized the following vulnerabilities: *hydraulic, seismic, collision, overload, steel details, concrete details, sabotage*. For each of these categories, the vulnerability of a bridge is determined first through a review of the inventory, and then confirmed by field inspections. The rating prioritizes the pre- and post event needs of the potentially vulnerable structures. Procedures for mitigating the conditions (for example by capital rehabilitation) and for responding to it in emergency mode are established.

Sufficiency rating

Sufficiency is an overall NBI rating combining structural (55%) and serviceability (30%) factors, weighted by importance (15%).

The described assessments resulting from field inspections and/or analysis inform the database and, through it, each other. Ground-up work on the project level (in this case, the individual bridges) must be specifically quantified. To various degrees quantification is provided by the reports of potential hazards, the load ratings, and the estimated deterioration of structural components. The latter must be span- and element-specific. Network level decisions on life-cycle strategies and investments rely on the more qualitative vulnerability and sufficiency ratings, and on estimates of deterioration rates over time.

All management is vulnerable to discontinuities in the process, as are individual structures. The condition assessment database shown in Fig. 2 is discontinuous since some of the information is obtained directly from the structure by inspections, whereas other, such as load rating is calculated. If the database of Fig. 2 is regarded as a section and viewed "in plan", Fig. 3 results. The plan view reveals the continuity of the structural lifecycle. It becomes evident that different types of assessment and different quality control & assurance are pertinent during the various stages of structural service, beginning with design and ending with replacement. It is also obvious how a tendency to reduce maintenance increases the demands for inspections and ultimately reduces the service life. In a safely functioning system, the network level assessments should be the more conservative ones, meaning that bridges should be decommissioned because of inadequate serviceability, rather than as a result of structural failures. Figure 4 confirms that the demand for better service, rather than structral failures is the main cause for bridge replacements in New York City. Other sources, notably Godart et al. (2005, Chapter 2) draw a similar conclusion.

A network-level model

The deterministic model illustrated in Fig. 5 assumes that citywide bridge-related activities maintain service, and hence, structural conditions at relatively constant (presumably optimal) levels. If bridge "conditions" are known and if they deteriorate linearly, the existing equilibrium can be expressed with the following notation.

A = deck area of the bridge stock
A_{Rec} = deck area under reconstruction
A_{Rep} = deck area under repair
R = average overall condition rating of bridges with aggregate deck area A
ΔR_{Rec} = average annual change of R of A_{Rec}
ΔR_{Rep} = average annual change of R of A_{Rep}
r = annual rate of negative change of R of $A - A_{Rec} - A_{Rep}$
C_C = reconstruction cost [$ US / unit of bridge deck area/ year]
C_R = repair cost [$ US / unit of bridge deck area / year]
C_M = maintenance cost [$ US / unit of bridge deck area / year]
C_{DA} = direct costs [$ US / unit of bridge deck area / year]
L = useful life [years]
L_0 = useful life at no maintenance [years]

R is an average of the overall bridge condition ratings R_{bridge} of the constitutive bridges, which New York State computes as follows:

$$R_{bridge} = \sum_{i=1}^{13} k_i R_i$$

where: R_i = (1,7) are the lowest condition ratings of thirteen critical bridge elements;
k_i are normalized weight factors.

A steady state equilibrium, such that R remains constant requires the following:

$$(A - A_{Rec} - A_{Rep})\, r = A_{Rec}\, \Delta R_{Rec} + A_{Rep}\, \Delta R_{Rep} \qquad (1)$$

Eq. (1) states that the bridge deck area restored by reconstruction and repair must compensate for the effects of steady deterioration. The direct annual costs for maintaining this steady state are:

$$C_{DA} = (A - A_{Rec})C_M + A_{Rec}C_C + A_{Rep}C_R \qquad (2)$$

The costs C_C, C_R and C_M reflect current established best design, construction and maintenance practices. They can vary significantly on the project level and produce durable or substandard results, depending on the quality of the ground-up execution and quality control. On the network level C_{DA} is perceived primarily as a function of A_{Rec} with some consideration of A_{Rep}. It is therefore essential to demonstrate that increases in maintenance, represented in Eq. (2) by their cost C_M , cost-effectively reduce A_{Rec}. For that purpose, C_M must be introduced into Eq. (1) . This can be achieved by assuming $r = f(C_M)$.

Yanev (2007, Examples 23 and 24) assumed linear relationships between each of the 15 maintenance tasks currently implemented on a network level by NYC DOT and each of the condition ratings of the 13 bridge components figuring in the "bridge condition" formula used by NYS DOT statewide. The relationship between r and C_M is therefore defined by a 13 X 15 matrix of factors, reflecting the effect of the tasks on the components. In the absence of data, these "sensitivity factors" must be assumed, based on some practical considerations. Fig. 5 reflects the assumption that a maintenance increase from $C_M = 0$ to $C_M > 0$ results in a deterioration rate $r < r_0$. On the network level the model can serve as a first approximation in determining long-term average needs. Recent cost estimates suggest an area of deck area under reconstruction A_{Rec} = \$US 7,000 /m^2. If projects are completed in 3.5 years on the average, the total reconstruction cost would amount to \$US 24,500 /m^2. The resulting improvement in the rating ΔR_{Rec} should be 5 points, to be achieved over the reconstruction period of 3.5 years (i.e. 5/3.5 annually). Given A = 1.5 million m^2 and $A_{rec} \approx 86{,}000$ m^2 (e.g. \$US 600 million / 7,000), Eq. (1) yields the following average annual rate of overall bridge deterioration (ignoring the effect of repairs):

$$r = A_{Rec}\, \Delta R_{Rec} \;/\; (A - A_{Rec}) = 0.087 \approx 0.09$$

Inspection reports independently obtain an average annual deterioration rate of approximately 0.1, represented by the middle graph on Fig. 6.

In summary, the bridge stock is represented in Fig. 5 as the totality of deck area A, near-normally distributed along the condition rating axis, well in agreement with condition rating data. The bridges receive preventive maintenance, quantified by its annual cost C_M . Portions of the stock, represented by A_{Rep} and A_{Rec}, are repaired and reconstructed at costs C_{Rep} and C_{Rec}, respectively. The model underscores the cost-effectiveness of the maintenance expenditure C_M, by relating it to the deterioration rate r, and hence, to the reduction of C_{Rep} and C_{Rec}. The numerical values of the actual annual expenditures corroborate the model. Equilibrium has been achieved since conditions and expenditures remain fairly steady. A comparison between different funding allocations would be highly effective, but no such data is available on the network level.

On the project level preventive maintenance and (re)construction are applied in part according to their cost-effectiveness, but to a considerable extent they depend on local engineering and administrative practices and habits. Whereas maintenance attempts to delay the deterioration r, reconstruction improves the condition R. The two methods of extending bridge service life compete for both funding and professional superiority on the network and project levels.

Project-level implementation

Table 2. Recommended Preventive Maintenance for New York City Bridges

Maintenance Task	Unit Cost c_j \$US/m^2	Recom. annual frequency f_j	Annual Cost [\$US 1999]
1	2	3	4
Debris Removal	*0.13*	*12(52*)*	*2,319,653*
Sweeping	*0.02*	*26*	*613,071*
Clean Drain	*0.33*	*2*	*863,804*
Clean Abut., Piers	*1.94*	*1*	*2,776,013*
Clean Grating	*0.40*	*1*	*55,490*
Clean Joints	*0.75*	*3(26*)*	*3,262,730*
Wash Deck,	*1.01*	*1*	*1,455,198*
Paint	*301.45*	*0.083*	*36,041,997*
Spot Paint	*66.44*	*0.25*	*23,743,128*
Sidewalk/ Cb. Repair	*3.72*	*0.25*	*1,328,182*
Pavement/Cb. Seal	*3.22*	*0.5*	*2,334,466*
Electric Maint.	*0.03*	*12*	*1,107,143*
Mech. Maint.	*0.03*	*12*	*1,010,502*
Wearing Surface	*4.85*	*0.2*	*1,390,305*
Wash Underside	*9.24*	*1*	*13,189,518*
Total			*91,491,200*

*East River Bridges

New York City adopted a maintenance program consisting of 15 tasks with specified frequencies of application as shown in Table 2. The cumulative deck area of the bridges is approximately 1.5 million m^2. Consequently the average unit annual cost of C_M is \$US 60/m^2. Full repainting of steel at a 12-year cycle and spot-painting every 3 to 4 years constitute 60% of C_M. That expenditure should reduce the rehabilitation needs by an appropriately cost-effective amount. Project-level implementation, however exposes certain vulnerabilities of this strategy.

On the project (i.e. bridge-specific) level the planning horizons are significantly narrower and needs tend to be immediate. Typically, the following difficulties arise:

- It is unlikely that an optimal "maintenance package" would be fully funded (if it were determined). Reduced funds must therefore be allocated to maintenance tasks in a prioritized manner, for example according to their cost-effectiveness. The cost of maintenance however does not represent its effectiveness with sufficient accuracy.

- Maintenance tasks are prioritized according to assumed life-cycle benefits. The network level model described in the previous section (Yanev, 2007, Examples 23, 24) derives the cost-effectiveness of maintenance tasks from assumed correlations between bridge component condition ratings and maintenance levels. The actual life-cycle benefits are not known and would not be identical at different sites.
- The bridge condition rating R is obtained by prescribed formulas from the condition ratings of components and elements, which, in turn reflect subjective visual assessments. The network-level model adopts an average linear bridge deterioration rate. Linear behaviour is to be expected of a large sample (nearly 800 bridges) normally distributed with respect to both condition ratings and age, as confirmed in Fig. 6. However, even after excluding known bridge improvements, the data contain effects of undocumented repairs. On the project level top priority is assigned to the worst cases, not the average ones. These cases consistently deteriorate at twice the average rate, as shown in Fig. 6. Their rating history behaves as if the sample were normally distributed with respect to condition ratings and uniformly distributed with respect to age.
- The effort to prioritize partial maintenance has suggested that some tasks are best managed as continuing operations at a prescribed schedule, whereas others should be contracted as discrete projects at optimal times. Dividing tasks among the two groups strongly depends on local practices. The typical regularly scheduled tasks include traffic-related operations, surface cleaning, drainage and joint maintenance, de-icing and snow removal. In contrast, painting, with its high cost, intensive logistical demands, and clearly defined life-cycle benefits, fully qualifies as a capital rehabilitation project. Painting contracts, including lead abatement, run in the hundreds of $US millions for large bridges ($US 167 million over 5 years at the Queensborough Bridge). The federal government shares this view and approves the funding of painting contracts from the capital improvement budget. The condition rating of paint (currently absent) should therefore be added to the formulas used in computing overall bridge condition. Painting as a task should be removed from maintenance and added to capital rehabilitation.

Bridge management costs

So long as networks are operated in terms of budgets, and projects are conducted in terms of deliverables, the common currency between the two levels of management will be the cost / time. It is therefore essential to identify differences in the way costs and time are perceived at the two levels. Several types of costs are likely to be incurred by a transportation network, including project (construction, rehabilitation), maintenance, emergency, and user. It is important to recognize that they cannot be assessed by similar methods because they are not measured in identical monies.

Project (first) costs

Project cost estimates (also known as first costs) cannot be reliably obtained from average network deterioration rates as was done in the model of Fig. 5. Fig. 6 shows a striking difference between average condition ratings (with respect to age), ratings excluding the improvements resulting from rehabilitation, and worst case ratings. The latter govern day-to-day project level needs. The glaring discrepancy illustrates why netwok needs estimates are always exceeded by project expenditures. Table 3 shows the evolution of the rehabilitation costs at the East River bridges in New York City. The escalation of the project costs shown in Table 3 can be interpreted as an example of poor initial estimates, however that view would be simplistic. Costs estimated based on average network level values, such as A_{Rec} do not apply to every project for a number of reasons, including the following.

Table 3. Rehabilitation cost estimates for the East River bridges [$US million]

Year of estimate	1990	1996	2000	2006	1990×1.04^{16}
Brooklyn Bridge	231.32	321.29	351.26	546.77	433.26
Manhattan Bridge	316.20	611.30	702.20	828.74	592.24
Williamsburg Bridge	398.53	697.21	748.51	1031.66	746.44
Queensboro Bridge	337.60	447.70	516.40	772.35	632.32

Projects extending over more than 20 years cannot be “scoped out” in advance with perfect accuracy. New conditions are discovered, the old ones change, the practice evolves and produces alternative options, service demands are upgraded, constraints (budget, environmental) are revisited. The last column of Table 3 shows that if the project costs estimated in 1990 were adjusted by 4% annually (say for inflation) over the elapsing 16 years, they would be comparable to the actually accrued ones.

Emergency and user costs

Emergency costs affect capital projects, continuing operations, the users and political management so dominantly that the top priority of infrastructure management occasionally appears to consist of avoiding them. The high level of uncertainty inherent in risk assessment however owes more to human subjectivity than it does to the randomness of events. The perceived likelihood of future emergencies strongly depends on the time following the previous ones. Separating the perceptions of public safety and quality of life creates more manageable groups of subjective constraints.

User costs are usually estimated based on traffic delays, however the outcomes are highly inaccurate. Alternate routes are not always availabvle, delays are unpredictable, accidents carry incalculable penalties. As a result these two costs which are absent altogether in Eq. (1) are of critical importance to management. Minimizing traffic disruptions during construction is a highest priority in an urban network, however user costs are not explicitly quantifiable to the degree of construction costs. Construction coordination under continuing traffic governs the scheduling of the project tasks. The projects shown in Table 3 were conducted concurrently and had to be staged for minimum traffic impact. As a result, their duration has exceeded two decades.

Life-cycle costs

The assessments of life-cycle costs, such as those incurred for maintenance and by the users, suffer from the opposite effect, namely that of discounting. The net value of these costs at the time of construction virtually annuls their significance beyond a period of roughly 30 years (depending on the assumed discount rate). The lowest first cost is misrepresented as the optimal one. It is not a coincidence that bridge life spans and maintenance contracts are converging to comparable durations. Minimizing maintenance expenses becomes even more attractive since they derive from local taxes, whereas reconstructions are funded by federal subsidies.

Management by diverse methods

The tasks of transportation management can always be condensed to minimizing costs and maximizing service. Over time the constraints have adjusted to the highest priorities of the moment, such as safety, quantity, and quality. The generally diverse, although not necessarily divergent top-down and ground-up management schools must optimize the cost/benefit equilibrium at both the network and project levels by reconciling a number of competing options, including the following.

Continuous tasks and discrete projects

Current management practices strongly favor "out-sourcing" work through capital contracts. Certain tasks, such as painting benefit from this trend. Other tasks, particularly the frequently performed (somewhat misleadingly labeled "routine") ones, such as oiling and cleaning of critical structural elements, are best performed by the bridge owner staff in a prescriptive manner. Such tasks are the first to suffer from the budget cuts and other austerity measures every administration periodically contemplates.

Prescriptive and performance based execution

Different incentives stimulate continuous tasks and discrete projects. If maintenance tasks are prescribed with their frequency and specifications, their implementation must be controlled (as all processes) by the approved tools of *quality assessment*. An incentive to maintain continuously could be created if the federal government were to subsidize bridge reconstruction proportionally to the years of service obtained from the replaced structure. Projects, in contrast allow latitude to the contractor within the predetermined budget and duration. The final product is evaluated by the methods of *quality control*. Timeliness is encouraged through incentive-disincentive clauses offering bonuses for early delivery and charging penalties for delays. Since this practice could affect the ultimate quality of the product, it is recommended to break down major contracts into staged smaller ones and evaluate each upon completion. The outcome could influence the awarding of later ones. Peer review is very effective as a method of quality assurance, but must continually reassert its presence against the demands to minimize first costs. It is noteworthy that new construction contracting methods are constantly emerging, including design-build, value engineering and so on, whereas maintenance performance management remains relatively obscure.

Minimal and intensive maintenance

Given the difficulties in implementing intensive maintenance, a logical engineering challenge is to design bridges requiring minimal maintenance and lending themselves to easy replacement. This alternative has been already adopted by other branches of engineering, for example the automotive industry. Whereas long-span bridges must be treated as irreplaceable, there are numerous single span ones, which can be easily prefabricated and replaced overnight. Thus maintenance is increasingly treated on a project-specific, as well as on a network level.

Projects can similarly be viewed as networks of elements. It is repeatedly noted that bridge deck expansion joints, drainage, and wearing surfaces are the most vulnerable to deterioration. Their re-design for better performance and for easier replacement (or, in the case of joints, elimination) can significantly extend bridge life. Traffic management, which is invariably a network concern, plays a unifying role in bridge-related decisions. Particularly the choice of de-icing salts or non-corrosive anti-icers has a defining effect on the deterioration rates shown in Fig. 6.

In contrast with regular maintenance, capital projects tangibly improve the infrastructure. By spending up to $US 600 million/year over a period of 15 years New York City eliminated nearly 100 bridges rated <3 on the NYS 7-grade condition rating system. In contrast, maintenance expenditures may cost-effectively reduce capital costs, but that effect is never apparent in the short term. Consequently, despite continuing reevaluations, the 10/1 (i.e. reconstruction/maintenance) annual expenditure ratio quoted herein is hard to modify. The result is a process consisting of projects, determined by expediency more than by long term cost/benefit optimisation.

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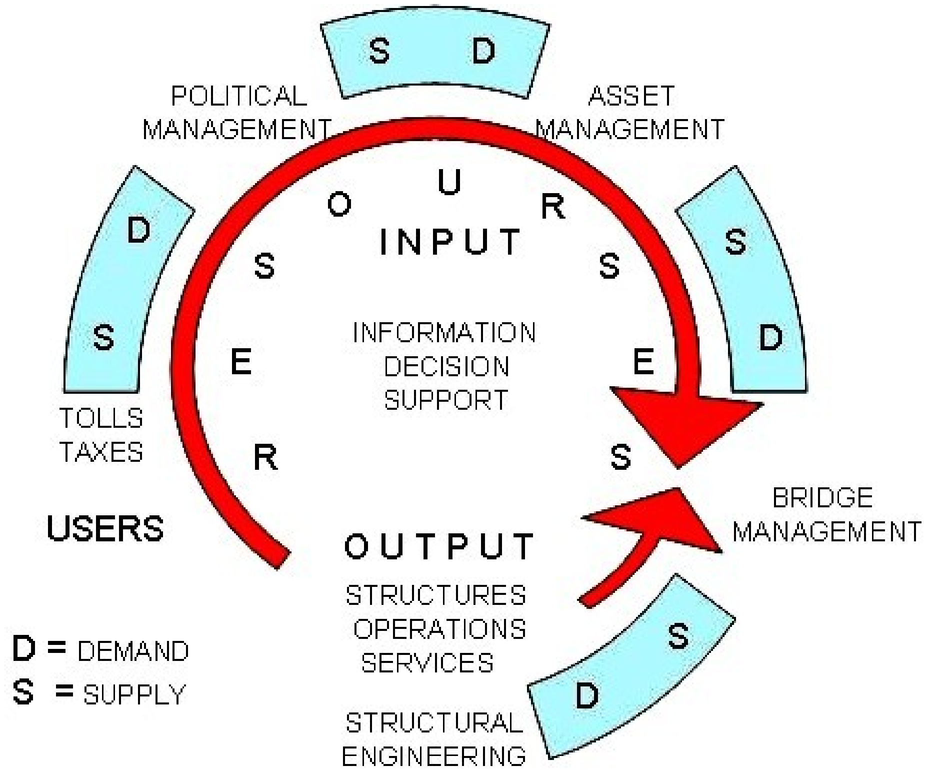


Figure 1. Multilayered Infrastructure Asset Management

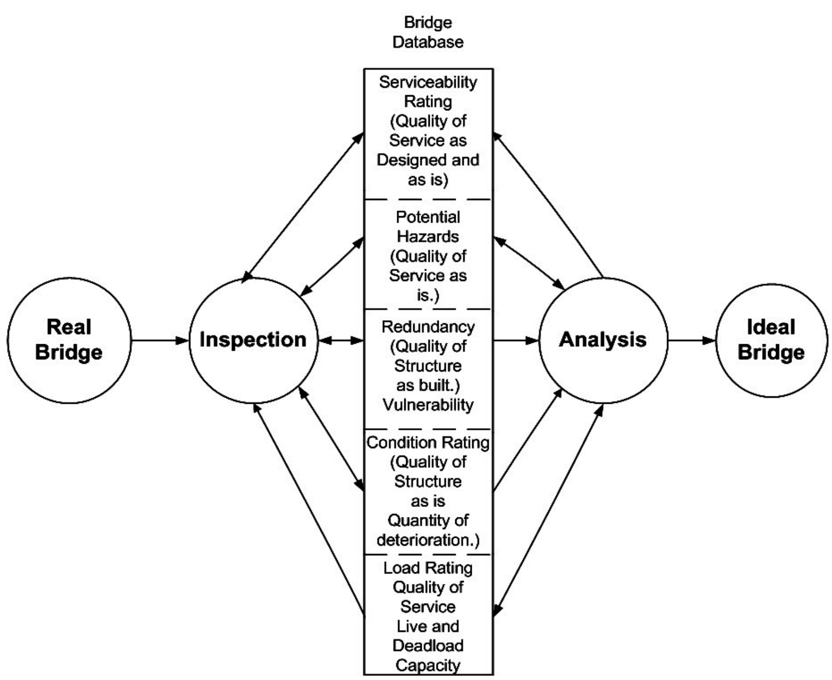


Figure 2. Various Bridge Condition Evaluations

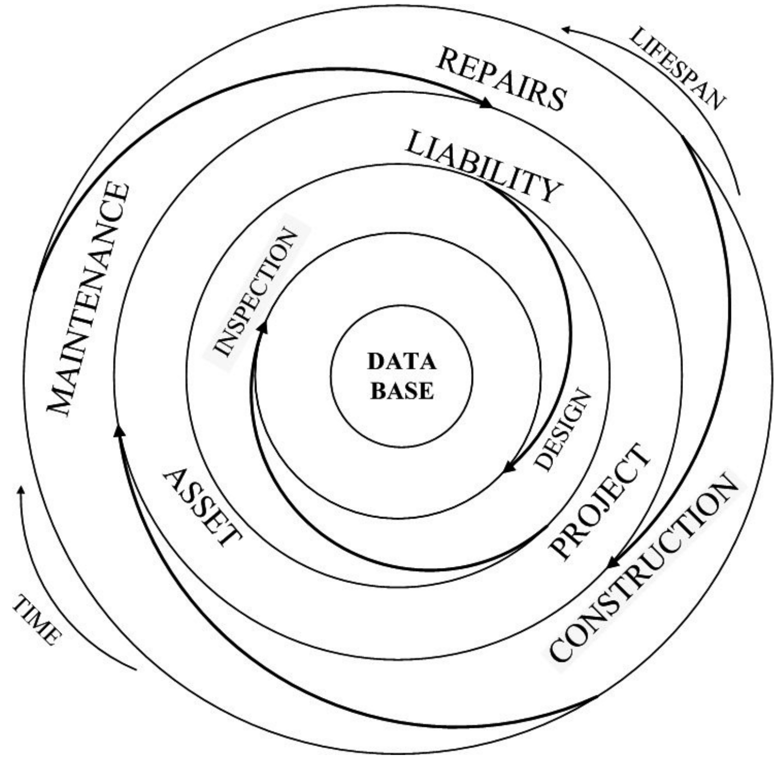


Figure 3. The Structural Lifecycle

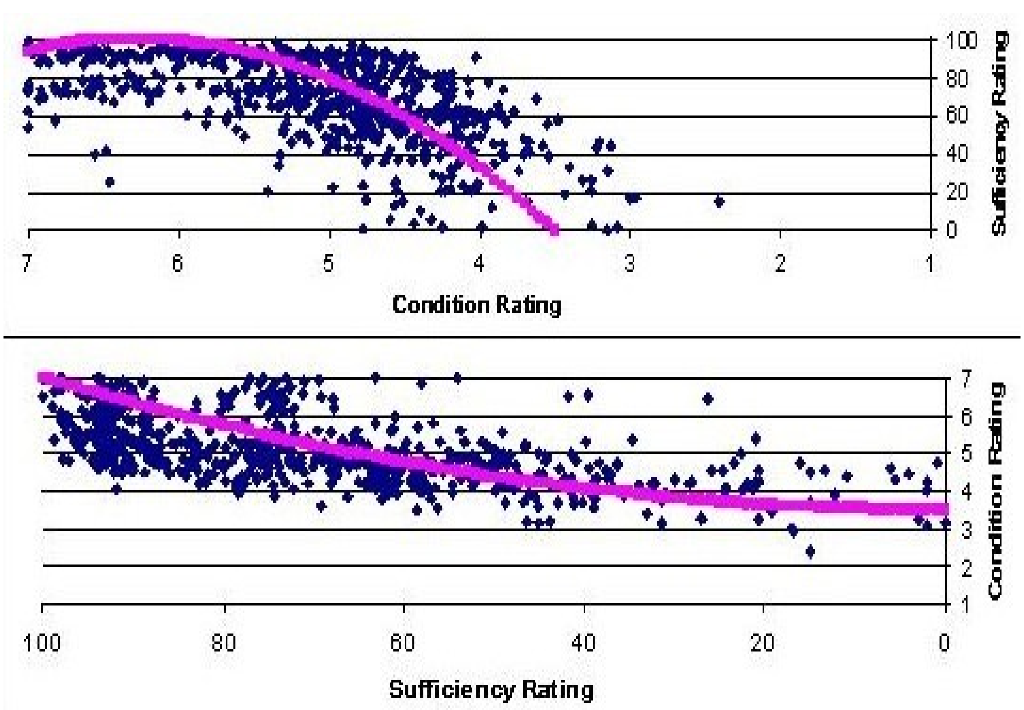


Figure 4. Condition and Sufficiency Ratings for 600 Vehicular Bridges, New York City

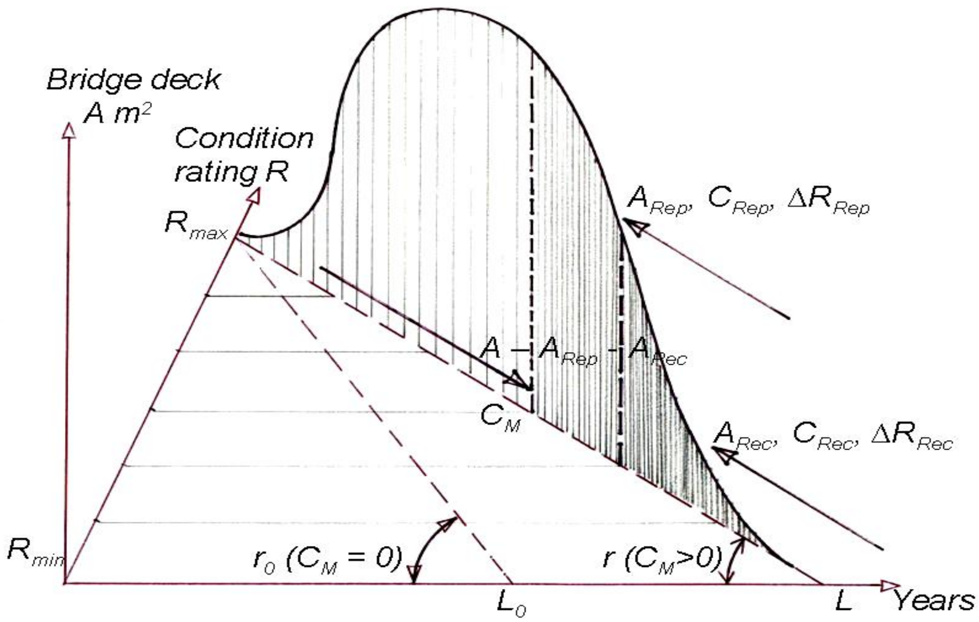
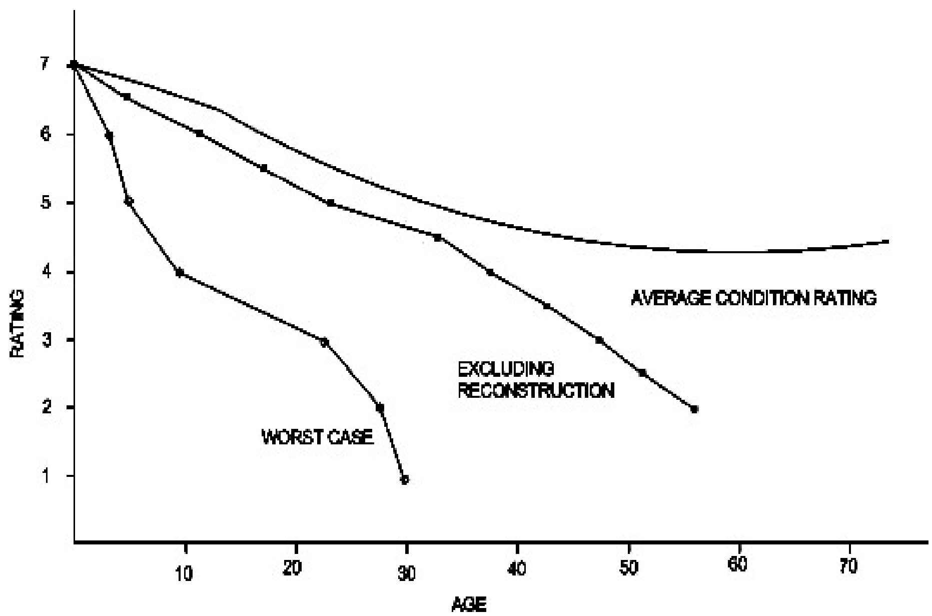


Figure 5. The Bridge Management "Steady State"



Figre 6. Average, Filtered and Worst Case Bridge Conditions, New York City