Framework of Performance Indicators for Managing Road Infrastructure and Pavements

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Performance measures are the basic input to a variety of decision processes and activities in infrastructure management. These include charting progress toward achieving operational, sectoral, and policy objectives; assessing whether users are receiving services that they want at the level of quality that they are willing to pay for; and comparing competing or alternative service producers to determine the most efficient provision arrangement for infrastructure services. A framework is presented for defining consistent measures of infrastructure performance, particularly for roads and pavements. The framework identifies relevant indicators and the linkages between them. Because there are changes over time in information needs and in the types of agencies using performance indicators as well as in their relationships to one another, a framework is needed to maintain consistency in the information bases used and to update the indicators to ensure relevance. Performance is measured at five major levels: (*a*) service quality and reliability from a user's point of view; (*b*) network size and condition from a facility's point of view; (*c*) operational efficiency and productivity from a service provider's perspective; (*d*) sectoral performance measures such as investment, pricing, and provision arrangements; and (*e*) institutional performance indicators such as the effectiveness of the expenditure program, enforcement of vehicle weights and dimensions, and so forth. These are applied to the management of pavements with a listing of all the road network and user indicators but defining the measures and data quality only for the pavement component.

A number of changes in the past decade with respect to customer demand, regulation, technology, competition, and resource availability have created a focus on the performance of all infrastructure systems. Road infrastructure must increasingly be viewed in its macro context, from both an economic and an institutional perspective. Changes in ways of providing road infrastructure,—including, for example, the provision of roads and toll roads by developers—as well as a general decline in resources available for investments in road infrastructure—have made it necessary to allocate resources more efficiently across competing alternatives. Such efficiency can be achieved only if the nature of performance information used for determining the allocation strategies is consistent across the competing alternatives, which requires aggregating data from different sources and various spatial and time phases. These requirements present a need and an opportunity to reconsider the definition of performance and to develop a framework that allows integrated consideration of functional, environmental, technical, financial, and institutional issues.

Performance Measures: Objectives, Users, and Uses

Performance measures serve the following objectives:

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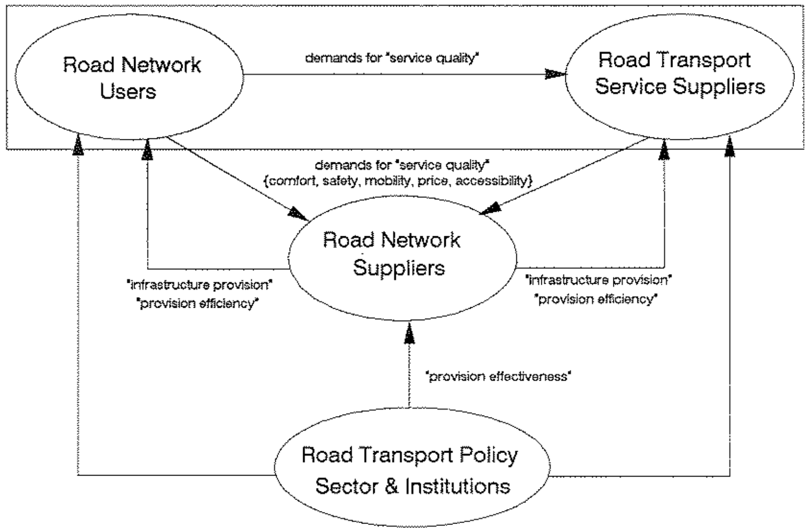

FIGURE 1 Users of road sector performance indicators.

- As a management decision-making tool they provide inputs for managerial decisions that address issues such as investment levels, maintenance expenditures, and frequencies and for day-to-day operating decisions on matters such as traffic management (*1,2*).
- As a diagnostic tool they provide an early warning system that can identify critical locations for investment and allow actions to prevent undesirable outcomes, such as accelerated deterioration of pavements (*3*).
- As a tracking and monitoring tool they help assess the adequacy of government and managerial policies by providing measures of effectiveness and mechanisms for charting the success of predefined policy objectives (*4*).
- As a signaling system they provide information to users (e.g., communities monitoring the effectiveness of municipal roads and streets) from the suppliers of infrastructure services, and they also provide information to suppliers (e.g., about safety targets at intersections) from policy makers in order to guide action toward desired outcomes (*5*).
- As a resource allocation tool they support the efficient distribution and control of public resources by quantifying relative efficiency of investments across competing alternatives [see, for example, work by Dole and Barnhart (*6*), who use performance data as an input to resource allocation ratios across states and local governments].
- As information systems they track construction costs and other data of relevance for constructing and managing infrastructure (*7,8*).

Which particular performance indicators are of interest depends very strongly on the view of the party involved in the uses of the indicators. These parties include road users, transportation service suppliers, road network suppliers, and regulating agencies, as shown in Figure 1. For example,

- Private users of road networks, such as passenger cars and pedestrians, demand a high quality of services from road transportation service suppliers (trucking and bus transportation agencies) as well as comfort, safety, mobility, affordability, accessibility, and a good driving environment.
- Commercial road transportation service suppliers are concerned with the service qualities of the road network and the impacts of policy decisions on transportation operations.
- Road network providers (owners and investors), roadway service suppliers (managers and operators), and producers of materials and services used in the supply of roads are concerned with efficiency, productivity, and effectiveness in satisfying user demands.
- Road transportation policy institutions (including regulators and enforcers) are concerned with the efficiency of investment allocation to various road agencies, with pricing and cost recovery for road-related use (e.g., fuel prices, tolls) and with compliance with road laws and regulations (e.g., safety and vehicle weights and dimensions).

Current practice in assembling performance information has several limitations. First, the data are collected by a variety of agencies, with or without formal performance-monitoring frameworks and systems, and they are collected for a variety of purposes. Second, the performance data collected often differ in nature. For example, there might be differences in (*a*) the type of data collected; (*b*) the level of detail, precision, and reliability with which they are collected; (*c*) the frequency in space and time at which they are collected, processed, and published; and (*d*) the frequency with which the various data items are updated as well as the currency of existing data types. Third, the consistency in performance data collection is

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variable across time, and hence the relationships between different forms of data collected across agencies are not easily established. Because of these factors, existing performance data do not lend themselves to easy aggregation. Furthermore, with increasing focus on performance, the various uses and users of performance information increasingly need to be integrated, which means that a common and consistent framework for defining, collecting, and aggregating performance information is needed.

Framework of Performance Measures

The appropriate identification of performance indicators is crucial to allow proper management and monitoring of a network of infrastructure and the flow of services generated by such a network. The set of indicators selected should measure the following:

- Whether operational, sectoral, and policy objectives are being met;
- Whether user demands are being met and to what degree the users of the provided services are satisfied;
- Whether the service providers are performing as efficiently as expected; and
- Whether the actions desired by policy makers (e.g., regulators) are being carried out and whether policy makers' actions are creating bottlenecks for service producers.

A subset of indicators that captured multiple effects and covered more than one of these four dimensions would be ideal. To satisfy these needs, performance can be viewed from five perspectives, namely, infrastructure provision, service quality, provision efficiency, provision effectiveness in sectoral aspects, and provision effectiveness in institutional aspects.

The perspective of infrastructure provision, in the case of roads, includes indicators relating to the characteristics of the road system and network such as the size, value, and distribution of the network; it also represents the performance of the facility in meeting demand for availability and access to road transportation users. The perspective is that of government and the owners of the facility considering the size, value, utilization, and appropriateness of the road stock.

The service quality indicators reflect the user's perspective, which can be measured in two ways. The first of these is in terms of the end product to the user—for example, whether the user actually receives the services desired and whether there has been an alteration, cessation, or total loss of service. This category of indicator relates more to expected than to actual quality of service. The second way of measuring service quality relates to how the services have been delivered—for example, the integrity of suppliers with respect to tolling, charging users, handling user queries, and responding to reports of incidents (e.g., accidents and slipperiness) and requests for service improvements, as measured by time required or promptness of response. This category of indicator relates more to realized than to expected quality of service.

The indicators of provision efficiency measure characteristics of the infrastructure providers and the level and efficiency of supply. Generic indicators include measures of productivity and efficiency, quantity of works delivered, and resources required per unit of output (such as employment and expenditures).

Provision effectiveness is measured in terms of achievement with respect to a goal or policy objective. At the sectoral level, effectiveness concerns measures of the overall adequacy of infrastructure provision and quality from economic, social, technical, and environmental perspectives. At the institutional level, relevant issues include the effectiveness of long-term supply strategies (maintenance backlog), the economic returns of investments in infrastructure, the ability to recover costs, and the functioning of the regulatory and enforcement bodies.

Application to Management of Road Systems and Pavements

In this section, the framework is defined for the management of road systems and in particular for road pavements. By simple extension it could also be applied to other infrastructure pavements such as airfields and industrial pavements.

The performance indicators are identified in Tables 1 through 5, one for each performance perspective, by aspect, level of detail, and unit of measurement. Under aspects, related indicators are grouped together. For example, in the case of infrastructure provision, the aspects relate to road system size, asset value of the road system, users of the system, demographic and macroeconomic environment, availability of the road system to users, and utilization of the road system.

The indicators are organized around two levels of detail. The first is general, providing the macrolevel indicators that would be used in public statistics. These indicators are readily understandable without a specialist's knowledge, but each has an objective definition and is derived from a reproducible base. The indicators provide sufficient information to chart progress toward the various performance objectives and to generate the type of information necessary for performing cross-national, cross-state, or cross-interest-group comparative studies.

The second level of detail in the tables is more comprehensive, providing the objective, detailed information on which the first level is based. Generally, this level comprises the data that would actually be measured or retrieved from a data base, and it includes the subdivision of the indicator data into smaller subunits likely to be relevant to particular applications or user groups.

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The tables also present the preferred units of measurement for each of the indicators, as well as the method of reporting and aggregating the data collected. In some cases concurrence is yet to be reached on the standardization of units. In these cases the units shown are the authors' recommendations, based on their experience in international-sector studies and cross-national evaluations. In the performance perspective tables that follow, the aspects presented are somewhat selective for reasons of space; they are not exhaustive.

Infrastructure Provision

The indicators for the provision of road infrastructure characterize the size and value of the asset, the user environment, and the connection between these. They are used in tracking the amount of the largely public asset, the size of demand, and the adequacy of the road system for the demand environment. In Table 1 these uses are met by identifying the indicators within the following six aspects.

Network Size

The network size must be defined in terms of the primary elements of the publicly used road network. Road length is the total length that can be traveled by users; it is frequently subdivided at the secondary level by administrative, functional, technical, and subsectoral categories. Road space, defined here in terms of lane kilometers, is a measure of the space available for occupancy by vehicles and of the expansion of the network. The lane-kilometer unit defines space in a more meaningful way than would a unit of pure area (say, square meters); it directly translates into average number of lanes (for any road group) when compared with road length; and it is a more effective base for estimating maintenance costs than is simple road length.

Road structures should be grouped and measured in number at the primary level, that is, bridges and tunnels, and distinguished by type and class at a secondary level measured in both total length and number. Road-ferry and missing or unclassified links should be grouped as extramodal links. Road reserve area, in area units such as hectares, is a measure of land ownership and utilization.

Asset Value

The value of infrastructure assets (roads, bridges, tunnels, and road furniture) is an important measure of the capital invested and at risk in a road system; it generally constitutes from 2 to 17 percent of gross national product (GNP). It is best quantified in terms of current replacement value, which is the cost of reinstating existing structures to the as-new condition of existing standards.

Road Users

The user population is characterized by the indicators vehicle fleet and motorization. Detailed fleet data (second level) would include the composition in various categories. The present vehicle classifications extant in many countries need to be rationalized or summarized in the light of policy needs and new traffic-sensing technology. The level of motorization is one of the important indicators of the potential for growth in vehicle ownership and hence traffic growth; it can be sensitive to vehicle pricing policies.

Demography and Macroeconomy

The demographic and macroeconomic environment is an important determinant of demand and utilization of capacity, sustainability and revenue generation, and the costs of provision. The primary indicators are total population, country area, urbanization, and GNP.

Availability

The availability of the road network for consumers is typified by the network density (in kilometers per 100 square kilometers) and road-space availability per capita. The availability for producers and the economic sustainability of the network are characterized by road space per unit GNP, termed road-space sustainability.

Utilization

Utilization reflects the realized demand from users, which is sensitive to service quality, economic factors, and regulatory policies. It is a strong determinant of total energy consumption and total vehicle emissions. The prevalent indicator is vehicle travel, colloquially known as VKT (vehicle kilometers traveled per year), or VMT (vehicle miles traveled). Secondary indicators are transportation-oriented aspects such as heavy vehicle travel, passenger travel, and freight travel, which are useful adjuncts distinguishing the main user types for policy purposes. The traffic volume level on the network is the mean traffic volume, calculated from the vehicle travel divided by the road length.

Service Quality

The quality of service sought by users consciously or subconsciously relates to perceptions of (*a*) quality of the surface and functionality of the facility, (*b*) safety risk, (*c*) ease of using the facility in terms of the quality of mobility and the risks of delay and access denial, (*d*) costs of usage and particularly the avoidable vehicle operating

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TABLE 1 Indicators of Infrastructure Provision

ASPECT	INDICATOR	UNITS[1]	NOTES & SOME SECOND-LEVEL INDICATORS
NETWORK SIZE	Road Length	km	Lengths: by road class, jurisdiction, function, technology, (surface type), subsector (interurban, urban, rural)
	Road Space	lane-km	Total and by road category (access-controlled, primary, secondary, tertiary)
	Bridges and Tunnels	m *number*	Bridge and tunnel categories.
	Extra-modal Links	m number	Road-ferry and Road-rail links, etc.
	Road reserve area	ha	
ASSET VALUE	Replacement value	$M	Current replacement value by component (roads, structures, furniture, facilities, land area)
USERS	Vehicle fleet size	Mveh.	Vehicle fleet, i) by category, heavy, light; ii) class: articulated trucks, trucks, buses, lights, cars, other motorized.
	Motorization	veh/1000 inhab.	Licensed drivers (licensees per 1000 inha.)
DEMOGRAPHY & MACROECONOMY	Total population Area of country Urbanization Gross National Product	inhabitants km^2 % I$M	II: Climate range, topography, etc.
AVAILABILITY	Network density Road-space availability Road-space sustainability	$km/100km^2$ lane-km/M inhab lane-km/$M(GDP)	
UTILIZATION	Vehicle travel Traffic density Passenger travel Freight travel	G.veh-km/yr veh/lane-day psg-km/yr tonne-km/yr	Vehicle Travel by road class and vehicle class.

Note:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

costs, and (*e*) judgments by users and nonusers on the usage environment of air quality and noise. The indicators proposed for these various aspects are defined in Table 2 and discussed in the following.

Road Surface

The primary performance characteristics demanded of the pavement surface by road users are riding quality, tracking quality (that the surface be free from bias by ruts, grooves, uneven crossfall, or excessive crossfall), friction quality (having sufficient skid resistance, dependent on demand, and minimal potential for hydroplaning), minimal spray and splash, and acceptably low surface noise levels.

It is proposed that all the service quality characteristics demanded of the road surface be summarized in just two new indicators, one representing all aspects of ride and tracking (because these all relate to profile and demand for 100 percent of travel time) and one representing all aspects relating to the safety supplied by the road surface (which is in varying demand, depending on location and time). The indicator dimension should be the incidence of *adequate, tolerable, and inadequate* levels of service, and the relevant weighting is by vehicle travel, because that is the appropriate dimension of exposure and demand.

The ride and tracking quality would combine measures of longitudinal unevenness, transverse unevenness, and interior noise ratings. Preferably the indicator should be defined as a quantitative function of objective measures, for example, roughness/unevenness [using the international roughness index (IRI) in meters per kilometer], rut depth mean divided by rut depth standard deviation, macrotexture and megatexture depths, and normalized with respect to the nominal traffic speed or the standard for the given road class. Some effort is required to formulate and gain consensus on this indicator.

The Surface Safety Adequacy would combine a measure of the skid resistance and hydroplaning potential relative to demand. A good model for this is the British two-level classification of adequate or investigatory friction determined from sideways force coefficient (SFC) values relative to standard values for 13 categories of road site (*9*). Similar demand levels could be set using other measures, such as skid number, or the new international friction index expected to emerge from the recent international experiment (*10*). A similar approach to classifying hydroplaning potential would involve the parameters of

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TABLE 2 Indicators of Service Quality for Roads and Pavements

ASPECT	INDICATOR	UNITS[1, 2]	NOTES & SOME SECOND-LEVEL INDICATORS[3]
ROAD SURFACE	Ride and Tracking Quality	Incidence (% VKT) [A/T/I]	Surface profile measures = {IRI, RDM/RDS, TX2, Vnom}
	Surface Safety Adequacy	Incidence (% VKT) [A/T/I]	Skid resistance relative to demand, hydro-planing potential
ROAD CORRIDOR	Geometric Standard	Incidence (% km) [A/T/I]	{Curvature, Gradient, Width, Shoulders, Sight Distance}
	Driver Guidance	Incidence (% VKT) [A/T/I]	Road markings, signage, message
	Collision Mitigation	Incidence (% VKT) [A/T/I]	Barriers, obstacles, distractions
USER SAFETY RISK	Fatality risk exposure	fatalities/100k. veh-km	
	Injury risk exposure	injuries/100k. veh-km	
	Accident risk exposure	accidents/100k. veh-km	
MOBILITY QUALITY	Total Vehicle Delay	veh-hrs	{Nominal speed, Avg. travel speed, VKT}
	Incidence of Congested Flow	incidence (% VKT) [A/T/I]	Ranges of V/C, incidence adjusted for time and length by VKT.
	Average travel speed	km/h	Average speeds by road class, adjusted by VKT.
ACCESSIBILITY QUALITY	Link closure incidence	No. link-days	Number of days a link is impassable (washout, flooding, blockage, etc.) annually summed overall links.
ROAD USER COST	Average VOC/veh-km	I$/veh-km	
	Avoidable VOC	I$/veh-km	[Program Total VOC - Optimal Program Total VOC]/Total VKT
ENVIRONMENT	Emissions incidence	% km [A/T/U]	Time subject to elevated levels, location of areas
	Noise incidence	% km [A/T/U]	Time subject to elevated levels, location of areas

Notes:
1. Code for compliance categories: A = Adequate; T = Tolerable; I = Inadequate.
2. Units: I$ = Reference Currency (US$, ECU, etc) indexed to normative year's value. $ = Reference currency in nominal (current) value.
3. VKT = veh.km/yr travelled; RDM = rut depth mean, RDS = rut depth standard deviation; TX2 = macrotexture TMS depth, mean; Vnom = nominal (design or posted) speed; V/C = volume-capacity ratio; VOC = vehicle operating costs; [] = expression; {} = function.

macrotexture, permeability, crossfall, road width, superelevation transition, and gradient, or simply a median value of surface water-film thickness.

User Safety Risk

The user safety aspect of performance is the extant levels of bodily risk to which the user is exposed through use of the road facilities; this involves many more factors than the surface characteristics. The appropriate indicator is the extant risk relative to the level of exposure, namely the fatality, injury, and accident risk exposures, determined from the annual rates relative to vehicle travel, that is, per 100 000 VKT.

Mobility Quality

Mobility needs are experienced through the amount of delay in travel times, the uniformity and level of traffic flow, and the overall travel time required to make a trip. Indicators of the quality of service are difficult to measure and rare in practice but sorely needed. Those suggested include total vehicle delays, in vehicle hours; delay risk, defined by the spatial incidence of encountering acceptable, tolerable, or inadequate traffic flow; and average travel speed, most usefully separated into interurban travel speed and urban travel speed.

Accessibility Quality

The quality of the access to road space is dependent on how often the road space is not available because of impassability, closure, blockage (by debris or snow), washout, flooding, and so forth. The duration of impassability is, in turn, an indication of the responsiveness of the maintenance agency. Since closure affects the utility of the entire link, the indicator is the link-closure incidence, in units of link days closed per year.

Road User Cost

The costs of vehicle operation (VOC) in the system are an indication of how well the benefits of the road expenditures are transferred to the user. The key element relevant to service quality is the level of avoidable user costs, which is the difference between the extant costs and optimal user costs. The most appropriate measure is relative, such as percentage of the optimal cost, which avoids currency units. Ideally the base optimal VOC should be the unconstrained optimum, because both underspending and budgetary constraints are restrictions on the service quality delivered to users. The extant VOC is the total VOC calculated for the network under current conditions at the beginning of the program year. The base total optimal VOC is that calculated for the theoretically optimal pro-

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gram of works and expenditures, without budgetary constraint. Calculation of the optimal VOCs must rely on the use of a life-cycle simulation analysis [such as HDM-III (*10*) or a similar model].

Provision Efficiency

The efficiency indicators address the productivity and efficiency of the agency providing the inputs into the road system. The productivity is the measure of the resource throughput (quantity of works, amount of expenditures, number of staff, equipment, etc.) during the defined period. The efficiency is the measure of how much resource was required to produce a unit of output.

Table 3 presents certain aspects and indicators of provision efficiency. The aspects relevant to pavement management include expenditure productivity, output productivity (works, operations, etc.), output efficiency (output per unit of resource, such as expenditure or employee), and provision mode (use of public and private providers). Omitted here for brevity's sake, for example, is a description of the service providers (financiers, constructors, owners, managers and operators, manufacturers) and their respective modes of provision (private contract, own account, etc.).

Expenditure Productivity

Statistics of expenditures are commonly used, fulfilling a general auditing type of function. For primary performance indicators, the expenditures should be aggregated and summarized in ways that relate to the major purposes of funding. The four categories recommended as suitable for universal use, which avoid the diverse uses of financial terms such as capital, investment, and recurrent, or work categories such as construction and maintenance, are the following:

- Adjustment expenditures: expenditures for all works of extension (new construction, new roads and structures, etc.), betterment (upgrading of surface or functional standard, realignment, minor widening), and expansion (additional lanes, highways, etc.) to the road networks, inclusive of pro rata administrative costs when these works are executed by public agency staff (i.e., realistic overhead costs).
- Preservation expenditures: expenditures for all other works on the existing system (pavement, structures, furniture) such as rehabilitation, resurfacing, restoration, routine maintenance, emergency maintenance, and so forth, inclusive of pro rata administrative costs when these works are executed by public agency staff (i.e., realistic overhead costs).
- Operations expenditures: expenditures for all traffic management (traffic control, control equipment, staffing), safety management (enforcement of safety measures, vehicle weights and dimensions, incident response, etc.).
- Administrative expenditures: expenditures on policy development, regulation, the preparation of expenditure plans and work programs, supervision of contracts and agencies, monitoring of road system conditions.

Output Productivity

The indicators for output productivity are the quantities of service provided during the period. For works, the as-

TABLE 3 Indicators of Provision Efficiency for Roads and Pavements

ASPECTS	INDICATORS	UNITS[1]	NOTES & SOME SECOND-LEVEL INDICATORS
EXPENDITURE PRODUCTIVITY	Total Expenditures	I$	Civil works expenditures, total and allocation by works category.
	Adjustment Expenditures	I$	All extension, betterment and expansion works expenditures
	Preservation Expenditures	I$	All other works expenditures on the road system
	Operations Expenditures	I$	Traffic and safety management expenditures
	Administration Expenditures	I$	Preparation and supervision of policies, plans, programs, etc.
OUTPUT PRODUCTIVITY	Adjustment Works	lane-km	
	Preservation Works	lane-km	
	Operations Works	veh-km	
OUTPUT EFFICIENCY	Average Preservation Cost	I$/lane-km	(Civil works expenditures/VKT: Total, and by works category.
	Average Operations Cost	I$/veh-km	Operations includes traffic management, enforcement, emergency support, etc.
	Expenditure-staff ratio	I$/employee	Total expenditures/total agency staff.
	Employment-Output Ratio	p-yrs/veh-km	Total agency staff/Annual Vehicle Travel
PROVISION MODE	Private Supply Participation	%	Contract expenditures/Total expenditures.
	Contract: Force Account Expenditure ratio	%	Contract expenditures/Agency force account expenditures.

Note:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

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pects are similar to those for expenditures, that is, adjustment works measured in road space (lane kilometers), with subsets of space added, upgraded, or bettered; preservation works measured in road space when presented in aggregate or in subsets of road space for pavement rehabilitation and resurfacing, number of structures for structures works, and road length for routine maintenance. Fairly typically, agencies would report the subsets within each aspect since the distinctions are of interest, but those should be considered as second-level indicators.

For operations, the relevant indicators would be vehicle travel, number of incidents, and so on. For administration, the indicators would comprise, for example, number of projects, road space monitored, and so forth.

Output Efficiency

The output efficiency indicators provide summary measures of the unit costs of delivering the output services. The average preservation cost, in expenditures per unit of length, and average operations cost, in expenditures per unit of vehicle travel (vehicle kilometers per year), will indicate over time how well the agency is managing to contain or reduce costs of preserving and operating the existing road system. The adjustment works cost is the expenditure per unit of road space provided, that is, constant currency per lane kilometer.

Useful indicators for human resources are the expenditure-staff ratio, indicating the total expenditures disbursed per staff employed, and employment-output ratio, being the total person years involved per unit of output (for an aggregate indicator the unit of output should be vehicle travel, but in subsets the unit of output should be road space for works and vehicle travel for operations). As the institutional efficiency rises and as more services are supplied under contract, this indicator should decrease significantly.

Provision Mode

The extent to which the private sector is involved in the supply of services is indicated by the private supply participation, being the proportion of expenditures implemented through the private sector. The contract volume, measured in terms of funds and number, is a second-level indicators.

Sectoral Effectiveness

The sectoral effectiveness perspective of provision concerns how closely the condition and operation of the road facilities match the optimal state. These are the technical and functional qualities as evidenced by the physical condition of the facilities and the quality of service provided to road users. The primary aspects of relevance to pavement and road management are presented in Table 4.

Roadway Function

Roadway function assesses the provision, in technical dimensions, of those components that affect service quality to the user. Being viewed from the sectoral rather than the service perspective, the indicators measure the spatial incidence of adequate standards achieved by the provider or providers.

TABLE 4 Indicators of Sectoral Effectiveness

ASPECTS	INDICATORS	UNITS[1, 2]	NOTES & SECOND-LEVEL INDICATORS
ROADWAY FUNCTION	Evenness Adequacy	% lane-km [A/T/I]	{Roughness incidence (km x IRI-level)}
	Friction Adequacy	% lane-km [A/IV]	Incidence of skid resistance not at investigatory level.
	Blackspot Incidence	No./1000 km	
	Traffic Flow Adequacy	% lane-km [A/T/I]	Thresholds of average travel speed or volume/capacity ratio.
	Environmental Adequacy	% km [A/T/I]	Thresholds of adequate noise, vibration and exhaust emissions.
PRESERVATION EFFECTIVENESS	Pavement Condition	% lane-km [G/F/P]	{Roughness (IRI), Residual Capacity, Surface Distress (SDI)}
	Sideworks Condition	% units [G/F/P]	Sidework components (sidedrains, signs, barriers, culverts, etc.)
	Structures Condition	% units [G/F/P]	{Bridge, tunnel condition scores: incidence by structure class}
ROAD SAFETY	Total fatalities	persons	
	Total injuries	persons	
	Total cost of accidents	I$M	
	Number of accidents	Number	

Notes:
1. Code for compliance categories: A = Adequate; T = Tolerable; I = Inadequate; G = Good; F = Fair; P = Poor; FD = Functionally Deficient; IV = Investigatory.
2. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

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Ride quality concerns can be assessed from evenness adequacy, which is the incidence of road space where road roughness is better than the adequate and tolerable thresholds defined from an economic optimization analysis. This yields thresholds that become progressively tighter as traffic volumes and speeds reach higher levels. The roughness and thresholds are best defined in terms of a standard unit such as the IRI.

Safety concerns can be assessed from friction adequacy, which is the incidence of adequate road surface friction where the friction available has not dropped to investigatory levels (*9*). The blackspot incidence, in number of blackspots per 1000 km of road length, is another indicator that is useful when blackspot is defined.

The provision of capacity and management of congestion is assessible by traffic flow adequacy, which reflects the spatial incidence of adequate capacity and road geometry. To cover this range, the most objective measure of adequate flow is one such as this: "The average travel speed exceeds 0.8 of the general posted speed for at least 90 percent of the time." Finally, environmental adequacy would indicate the road length over which noise, load vibration, and exhaust emissions met applicable standards.

Preservation Effectiveness

The aspect preservation effectiveness assesses the adequacy of response to preserving the condition and integrity of the infrastructure asset. Here, the indicators measure those factors affecting the physical condition rather than function of the facility. These would include indicators for each of the major components of a road facility, such as pavement condition, sideworks condition, and structures condition. Condition is represented by a composite indicator, normalized by thresholds depending on the technology, environment, and use. Incidence would be expressed in terms of road space for pavements, road length for sideworks, and length for structures.

Pavement condition has three elements that would be distinguished at a secondary level. There are: (*a*) pavement residual capacity, a structural measure of the remaining life of the pavement in terms of structural capacity for the traffic load being carried; (*b*) roughness (or unevenness), the surface profile element measured in IRI units; and (*c*) pavement distress index, the surface integrity element, which could be an index such as the pavement condition index (PCI) (e.g., ASTM D5340-93), or preferably another distress index that distinguishes between maintenance inputs and pavement distress. The combination of these into a single indicator, condition, can be done using one of a number of existing indexs and defined values of good, fair, poor, and bad.

Sideworks condition measures the defects in the sideworks components (comprising surface drains, culverts, verge, signs, barriers, etc.). An effectiveness indicator for sideworks could be based, for example, on the quantitative ratings given in an Organization for Economic Cooperation and Development manual (*11*).

Road Safety

The road safety aspect assesses impacts on life and property through the indicators of total fatalities, injuries, accident costs, and number of accidents.

Institutional Effectiveness

The performance of the institution on behalf of the public and road users can be defined by its effectiveness in identifying the necessary programs and budgets needed to optimize the total costs of the road system and to meet institutional goals. Recommended indicators are shown in Table 5. The resource lag and the economic return are two aspects of the most relevance to pavement management. They measure the effectiveness of long-term infrastructure supply strategies. Cost recovery covers the ability to recover costs in terms of revenue-to-expenditure ratios, expenditure-to-investment ratios, and maintenance–to–capital expenditure ratios. Regulatory goals cover the effectiveness of regulations and enforcement, such as the incidence and level of overloading, and road safety targets. More aspects could be added—for example, investments in research and training and choice of appropriate technology.

Resource Lag

The backlog comprises the works that could not be included or accomplished in the previous year's authorized program of works but that had been identified as economically feasible for some time up to that year in the long-run (e.g., 5-year) optimal program. Because the program is often being adjusted if it is a "rolling program," the most practical definition of backlog is "the sum of works were economically feasible in the previous year but were not included or achieved under the authorized program." The indicators represent this in physical terms of lane kilometers (usually for each main budget category of works) and as a percentage of the current budget. Shortfall is the amount of additional funding that would have been needed in the current year in order to accomplish all the works in the backlog.

Economic Return

Economic return is a measure of the economic return on the investment of funds in the road system, limited in this paper to meaning expenditures on the road pavements. To determine economic indicators, the program analysis in

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TABLE 5 Indicators of Institutional Provision Effectiveness

ASPECTS	INDICATORS	UNITS[1]	NOTES & SECOND-LEVEL INDICATORS[2]
RESOURCE LAG	Backlog Value Backlog Road-space Annual shortfall	% (budget) lane-km % (budget)	Backlog ($) by budget works category Backlog (lane-km) by budget works category
ECONOMIC RETURN FOR PAVEMENTS	Program Benefit: Cost ratio	fraction	Yearly total program net benefit (NPV)/Program total expenditure (may be limited to civil works)
	Average NPV/km Rate of return Network Depreciation	$/km % %	Yearly total program NPV/Network length. Summary statistics of project EIRRs (Minimum, Median). Depreciated value/Replacement value of network
USER SAVINGS	Net Usage Savings	$/veh-km	[(Base total VOC -Program total VOC)/Total VKT]
COST RECOVERY	Revenues Revenue/Expenditure ratio Revenue/Maint. Expenditure	I$M % % (Maint.Exp)	Revenue breakdown (fuel tax, user charges, appropriation)
SAFETY GOALS	Fatalities reduction Injuries reduction Accident cost reduction	% % %	By composition (type of accident, impacted parties, etc)
RESEARCH & TRAINING	Expenditures	%	Research and training funds/total road expenditure (%)
TECHNOLOGY CHOICE	Employment generation	Total Workforce (public and private)	

Notes:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.
2. NPV = Net Present Value (economic); EIRR = economic internal rate of return.

the management system must generate cost time-streams of total road costs comprising road works expenditures, road user costs (VOCs and accident costs), and other costs and benefits, all expressed as economic costs, that is, net of taxes and subsidies. The indicators are based on project-level statistics for (*a*) the net present value (NPV) of the project relative to the base case (usually "do minimum" maintenance strategy), computed at the appropriate discount rate (opportunity cost of capital), and (*b*) the economic internal rate of return (EIRR).

The works program benefit, which is the aggregate economic benefit of all projects on the network, is compared with the works expenditures in the program benefit–cost ratio, and the average NPV per kilometer. The recommended indicator for the rate of return for a program is to cite the minimum and median project EIRR values, because the EIRR is not strictly additive across projects. Finally, an indicator that proves highly valuable when justifying road user charges is the net usage savings derived from the program—this is the works program benefit divided by total vehicle travel. Normalizing the net usage savings as a percentage of total VOCs may be found more appropriate than a currency value.

Producing Pavement-Related Information

The data required for generating the performance indicators discussed here need to be included under the regular monitoring procedures used for the planning and management of road expenditures, for reasons of efficiency and to avoid duplication and discrepancies. Thus, it is important to identify the necessary and sufficient data for calculating the performance indicators and to develop guidance on the amount of detail and accuracy required and the norms to be followed in the calculation.

For the information specifically relating to road pavements, traffic, and their impact on users, most of the indicators are likely to be developed by aggregation from data collected on a link- or section-specific basis, which would be maintained in the data base of a road or pavement management system, if these exist. Such data vary considerably in amount of detail, depending on the system and on the originally intended usage. A classification of the level of detail, based on the number of attributes used to describe a particular item of information, has been defined first by Paterson and Scullion (*12*) and is being developed further.

The options for determination of the performance indicators, therefore, fall in three categories: namely, detailed data collection and aggregation, sampling and projection, and the processing of bulk or aggregate statistics. The relative use of these methods varies with circumstances, but the trend is toward greater use of detailed collection and aggregation as information technology has improved the ease of collection, storage, and processing of data.

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Conclusions and Future Work

The framework presented here for defining performance indicators for the road sector was developed in the broader context of the modern trend to monitor performance and increase the accountability of those who provide services and are responsible for public expenditures. In the specific context of the task of managing pavements, the framework is particularly apposite. The indicators identified here are of relevance and interest to the various transport groups involved, namely, private and commercial road users, policy makers and regulators, and the many groups of providers (including highway agencies for planning, programming, budgeting, and implementation services; consulting service agencies for design, supervision, and so forth; suppliers of goods and materials; and funding or financing agencies).

The paper has identified a number of specific performance indicators to satisfy these goals and defined these sufficiently to indicate the information that is needed. However, it has stopped short of defining all of these quantitatively and unambiguously, partly because this work is still in progress but also because of the need for consultation in the sector to reach consensus. In some cases the measures currently available from pavement management systems are adequate or can be made so with little recomputation. In several instances, though, the paper indicates a need to rethink and redefine some old parameters in a more relevant way.

Particular efforts are in progress to define the indicators of service quality and provision effectiveness, because the physical measures now becoming available from modern road and traffic monitoring technology make the performance indicator goals more capable of being realized. Several national, international, and standards agencies are active in these aspects. One objective is to define an improved set of statistics on the highway sector to be used worldwide in the reporting and analysis of highway and infrastructure data.

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