HDM-4 BASED PROCEDURE FOR REVIEWING CONDITION PERFORMANCE TARGETS IN THE MEXICAN ROAD NETWORK

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ABSTRACT

Agencies of the Mexican government responsible for managing the federal road network use the International Roughness Index (IRI) as the main indicator for rating road performance, set intervention thresholds and define performance targets. Although the IRI standards currently employed reflect somehow the international practice and the historical availability of resources, the actual approach followed for selecting those standards has been essentially empirical. In this context, some stakeholders are requiring the adoption of lower IRI limits, forcing responsible agencies to assess the affordability of such a change. Considering the above, a HDM-4 based procedure for analyzing the effects of a given IRI standard on budget requirements and road performance has been developed. This procedure can be summarized as follows: a) Define an IRI standard; b) Using a HDM-4 strategy analysis, obtain an unconstrained work program for a 10-year analysis period; c) Adjust the above program for a given set of restricted budget scenarios; d) Assess the feasibility of each scenario and determine the performance targets that can be achieved. HDM-4 has been used by Mexican road agencies for several years to prepare investment programs, so it has been deemed appropriate to use this tool in developing the proposed procedure.

1. BACKGROUND

The performance of a road network is a key input for modern asset management as it provides the information necessary for determining if the objectives of a road agency are being met. Road performance comprises various attributes used to rate the service provided through the network, including safety, serviceability, sustainability, mobility, reliability and economic aspects.

In fact, monitoring road performance has become an increasing concern worldwide, leading to initiatives such as the one launched by the US government in 2012 through the MAP-21 act. In this legislation, states are required to define specific targets for a set of performance measures and describe how program and project selection will help achieve those targets [1].

Performance management is the systematic process of setting goals and regularly checking progress towards achieving them [2]. This requires the development of a performance management framework, which should include components such as [3]:

- Levels of service or agency objectives. Broad statements that describe road performance in terms readily comprehensible for road transport stakeholders (users, government agencies, legislators, professional associations, contractors, financial institutions, etc.)

- Performance measures. Indicators used to determine whether responsible agencies are meeting the established levels of service and report on actual performance.
- Performance targets. Describe the performance the agency is pursuing to achieve.

Even though Mexican road agencies have not adopted an asset management approach yet, elements of a performance management framework are present to various extents in their resource allocation processes linked to road maintenance. Thus, the National Development Plan (PND) and the National Infrastructure Program (PNI), which are prepared at the beginning of each six-year federal administration, define general goals and provisions related to maintenance and development of the federal road network [4] [5].

Following the guidelines set out in the PND and the PNI, the General Directorate of Road Maintenance (DGCC) of the Secretariat of Communications and Transport (SCT) prepares a six-year plan and an annual work program for the maintenance of the federal toll-free network (40,752 km of paved roads). Performance targets linked to the above instruments are defined in terms of road length in “good”, “satisfactory” and “non-satisfactory” condition. In turn, these categories correspond to ranges of the International Roughness Index (IRI) selected by DGCC. The IRI is also applied for specifying intervention thresholds that would eventually lead to achieve the defined performance targets. Both the six-year plan and the annual work program are prepared using HDM-4 as an investment analysis tool.

On the other hand, the General Directorate of Road Development (DGDC) of the same secretariat, which is responsible for monitoring toll expressways (8,900 km), employs a specific IRI threshold to classify the performance of road sections as either “good” or “poor”. Annual evaluation of this index allows DGDC to require action from operators should anytime a section’s IRI exceeds the defined threshold.

It is worth mentioning that, until now, approaches of DGCC and DGDC to measuring road performance only refer to pavement serviceability.

In recent years, some stakeholders have started questioning if the current IRI standards are strict enough to rate properly the performance of the federal network or to ensure that existing planning processes are producing the best value for available funding. However, before adopting new standards, responsible agencies should evaluate their consequences in terms of additional resources needed and performance of the network as a whole. Although current standards have been selected taking into account to some degree both historical resource allocations and international practice, the actual approach used has been essentially empirical. In fact, presently there is no formal method to conduct the required impact analysis.

Considering the above, a HDM-4 based procedure for assessing the consequences of various IRI standards has been developed. This procedure makes use of the general principles provided by asset management to develop a performance management framework, including aspects such as alignment to national and corporate goals and priorities, affordability of targets and sustainability of investment strategies.

As mentioned previously, HDM-4 is being used by DGCC to support preparation of its six-year plan and its annual work program. Other federal agencies, as well as state governments and private operators, have made efforts to implement HDM-4 as part of their analysis tools. Consequently, this tool has been chosen to develop the proposed method.

2. GENERAL DESCRIPTION OF PROPOSED PROCEDURE

The evaluation procedure is made up of the following steps: data preparation and processing, setup of a HDM-4 strategy analysis, generation of the unconstrained works program, analysis of constrained budget scenarios and scenario feasibility assessment. The following paragraphs provide some relevant details about the above steps.

2.1. Data preparation

This involves the preparation of the following data items:

- Road network. It is a data representation of the network of interest, obtained from the aggregation of individual road segments into families with similar values of key attributes comprising information such as road design, pavement type, pavement condition, traffic volume and composition, and environmental parameters.

- Vehicle fleet. Collection of representative vehicles assumed to travel over the road network. For each vehicle, a series of physical characteristics and unit operating costs should be specified. HDM-4 uses this information to calculate vehicle operating costs and other costs for the road user, together with profitability indicators for the investment alternatives considered.

- IRI standard. A series of IRI ranges intended to rate the performance of road sections using a good-fair-poor scale. The standard also contain IRI thresholds that trigger the execution of periodic maintenance or reconstruction works.

- Maintenance standard. Listing of road works with the following associated data: design parameters, intervention criteria, unit costs and works effects. Intervention criteria are linked to the IRI thresholds defined within IRI standards. The proposed method consider only two maintenance standards: routine and periodic maintenance.

- Configuration data. Supplementary data required to perform the HDM-4 run. This include information about hourly traffic distribution, road capacity, accident rates and climate zones. Much of the above data inputs are irrelevant for the analysis type underlying the proposed method so default HDM-4 values are used in most cases.

2.2. HDM-4 Analysis Setup

HDM-4 allows to carry out three analysis types: project, program, and strategy analysis. From these, strategy analysis has been found to be the most suitable for implementing the proposed procedure since it is specifically intended to evaluate investment options at the network level over the medium to long term, using aggregate data.

For the strategy analysis to be executed, the following additional information should be provided:

- Objective function for budget optimization. Available options are: maximize net present value, maximize IRI improvement and minimize cost for target IRI. Given that this study focus on achieving best performance for the available resources, the second option has been selected.

- Parameters for the economic analysis: starting year, analysis period and discount rate. In all cases, these variables have been set respectively to current year, ten years and 10%.

- Analysis sections, which correspond to road lengths resulting from aggregating individual sections, as described in paragraph 2.1.

- Investment alternatives. A HDM-4 investment alternative consist of a set of maintenance standards, each of which is assigned a specific starting year. As mentioned above, only two maintenance standards are considered: routine and periodic maintenance. From these, two alternatives can be initially defined: a “base alternative” for routine maintenance and a “project alternative” for periodic maintenance. However, by deferring by increments of one year the starting year for the periodic maintenance standard, a total of eleven alternatives can be defined, as shown in paragraph 4.1. In this manner, a works item not selected in a given year due to budget limitations, may still be triggered in another year during the constrained budget scenario analysis if the necessary resources become available.

2.3. Generating an unconstrained work program

Running the HDM-4 strategy analysis results in a listing of road works (and associated budget requirements) scheduled for execution so that the IRI thresholds specified in the periodic maintenance standard are never surpassed. This listing is called the “unconstrained works program” because it does not consider any limitation of resources.

The unconstrained work program might tend to concentrate works (and, consequently, budget requirements) on the first years of the analysis period since a significant number of road sections may not initially meet IRI thresholds.

Underlying the generation of the unconstrained work program are HDM-4 deterioration models, which predict the evolution of IRI over time and allow to trigger maintenance works when applicable.

2.4. Analyzing scenarios of restricted budget

HDM-4 defines constrained budget scenarios by means of budget periods, which are collections of time periods (in start-year end-year format) and amounts of resources available for each period.

Perhaps the best way to represent the current practice of road maintenance budgeting in Mexico is by using time periods of one year with a fixed amount of resources, setting the total length of budget scenarios to six years in order to match the period of federal administrations. At the end, a ten-year period for the strategy analysis has been chosen so that, on one hand, it can accommodate the six budget periods of one year and, on the other hand, it allows to examine how the decisions made in one administration might have potentially adverse effects for their successors.

Since budget is always limited for constrained budget scenarios, the main output of this analysis is the resulting performance of the road network.

2.5. Assessing scenario feasibility

The feasibility of each constrained scenario can be determined from the amount of resources involved and the associated behavior of the network. Once a scenario has been identified as feasible, performance targets can be defined based on the IRI ranges used to generate that particular scenario.

The analysis can be iterated using different IRI standards and/or intervention thresholds when no acceptable solution is found in the first instance or when a given solution needs to be optimized.

In the following sections, an application example based on data from the Mexican federal road network is presented. The example considers three alternative IRI standards. Details on the data used and its processing are given in section 3 . Section 4 contains a description of the unconstrained works programs generated for each of the IRI standards considered. Further on, in section 5, budget restrictions are introduced through three scenarios corresponding to different levels of resource availability. These scenarios are applied to each of the IRI standards, producing nine different constrained works programs.

3. APPLICATION EXAMPLE: INPUT DATA

3.1. Road network

The road network for the analysis was generated from a subset of the federal network of toll expressways. This choice was based on the greater availability of data for this part of the network. The selected subset corresponds to four-lane expressways, which comprise the biggest portion of existing toll-roads. Information used refers to year 2010, and covers 4,680 km of two-lane separate carriageways.

The original data were aggregated using the following attributes: IRI, AADT, central deflection measured with FWD (D_0) and mean monthly precipitation (MMP). For each attribute, three levels named as “low”, “medium” and “high” were defined and assigned a representative value, as shown in Table 1. The combination of attributes and attribute levels produced a total of 81 section types for data aggregation, from which only 47 resulted with a road length greater than zero.

Table 1 – Attributes for data aggregation.

Attribute	Attribute level (representative value)		
	Low	*Medium*	*High*
IRI (m/km)	≤ 2.00 (1.5)	2.00 – 3.50 (2.75)	> 3.50 (4.25)
AADT	≤ 5000 (3500)	5000 – 15000 (7500)	> 15000 (17500)
D_0 (mm)	≤ 0.250 (0.125)	0.250 – 0.500 (0.375)	> 0.500 (0.750)
MMP (mm)	≤ 50 (30)	50 – 165 (110)	> 165 (250)

Road attributes not included in Table 1 were assigned default values, depending on the traffic level.

3.2. Vehicle fleet

The SCT carries out annual vehicle counts for a set of seven of the most representative vehicle types circulating over the federal road network. Since there is no other source of traffic data, the vehicle fleet was defined based on the SCT vehicle set. Moreover, the Mexican Institute of Transport (IMT) has compiled most of the vehicle fleet data required by HDM-4 for the same vehicle set [6]. Table 2 list the types and descriptions of the vehicles that make up the vehicle fleet to be used in the analysis.

Table 2 – Vehicle fleet used in the analysis.

Vehicle type	Description
A	Light vehicle
B3	Three-axle bus
C2	Two-axle truck
C3	Three-axle truck
T3-S2	Articulated truck with single trailer and five axles
T3-S3	Articulated truck with single trailer and six axles
T3-S2-R4	Articulated truck with double trailer and nine axles

3.3. IRI standards

As mentioned in paragraph 2.1, an IRI standard consist of a series of IRI ranges that describe various performance ratings using a good-fair-poor scale. Each range also define IRI thresholds that trigger the execution of periodic maintenance works. For this application example, three IRI standards were considered, each of which represent certain performance boundaries and is linked to a specific standard for periodic maintenance. Table 3 contains the details of the defined IRI standards.

Table 3 – Details of IRI standards.

	Performance level (IRI, m/km)			Intervention thresholds (IRI. m/km)	
Name	*Good*	*Fair*	*Poor*	*Periodic maintenance*	*Reconstruction*
Standard 1	≤ 1.5	1.5 – 2.5	> 2.5	2.5	3.5
Standard 2	≤ 2.0	2.0 – 3.0	> 3.0	3.0	4.5
Standard 3	≤ 2.5	2.5 – 3.5	> 3.5	3.5	5.5

As shown in Table 3, periodic maintenance thresholds were defined so that they coincide with the upper limit of the "fair" performance level. This can obviously be modified to better reflect the corporate objectives or to optimize a given solution.

3.4. Maintenance standards

The collection of maintenance standards was defined in a way that, at any given year, HDM-4 can select either a routine maintenance standard or a periodic maintenance standard. However, separate instances of the periodic maintenance standard were defined for each of the IRI standards, which resulted in a catalog with a total of four maintenance standards. This allowed to define technical specifications and costs adequate for the various IRI standards.

Periodic maintenance standards include the following works items:

- Routine maintenance.
- Mill & replace.
- Reconstruction.

As an additional variant, separate specifications of mill & replace and reconstruction works were prepared to take into account the three different traffic levels used for generating the aggregate road network. The general layout of the collection of maintenance standards is represented in Table 4.

Table 4 – General layout of the maintenance standards collection.

Standard name	Work items	AM depth (mm)	Unit cost (USD/m^2)	Intervention	Effects (IRI, m/km)
Routine	Patching	NA	9	Annually	NA
	Crack sealing	NA	4	Annually	NA
Standard 1	Patching	NA	9	Annually	NA
	Crack sealing	NA	4	Annually	NA
	Mill and replace (3)	70 to 150	21 to 32	IRI ≥ 2.5	1.0
	Reconstruction (3)	70 to 150	32 to 50	IRI ≥ 3.5	1.0
Standard 2	Patching	NA	9	Annually	NA
	Crack sealing	NA	4	Annually	NA
	Mill and replace (3)	70 to 150	19 to 28	IRI ≥ 3.0	1.5
	Reconstruction (3)	70 to 150	29 to 44	IRI ≥ 4.5	1.5
Standard 3	Patching	NA	9	Annually	NA
	Crack sealing	NA	4	Annually	NA
	Mill and replace (3)	70 to 150	15 to 26	IRI ≥ 3.5	2.0
	Reconstruction (3)	70 to 150	23 to 40	IRI ≥ 5.5	2.0

According to this table, the depth of the asphaltic mix and the unit cost (mill & replace and reconstruction works items), depend on both the traffic level and the particular maintenance standard considered. Table 4 also shows that works effects are different for the three standards of periodic maintenance.

4. APPLICATION EXAMPLE: UNCONSTRAINED WORK PROGRAM

4.1. Definition of alternatives and execution of the HDM-4 analysis

IRI standards defined in paragraph 0 were evaluated through separate HDM-4 strategy analyses. Using the routine maintenance standard and the periodic maintenance standard associated with each IRI standard, a set of 11 intervention alternatives were created for each analysis.

A "base alternative" was first defined based on the routine maintenance standard, with a starting year equal to the beginning of the analysis period, i.e. 2015. Then, a group of ten "project alternatives" were added, each of which was assigned the periodic maintenance standard with different starting years, ranging from 2015 to the end of the analysis period.

For project alternatives starting after 2015, the routine maintenance was also included with 2015 as the starting year. The purpose of this additional assignment was to cover the time frame between the beginning of the analysis period and the starting year defined for periodic maintenance. As pointed out in paragraph 2.2, this way of defining alternatives is intended for providing additional options for works items to be selected during the constrained budget scenario analysis. Table 5 summarizes the alternative definition described above.

In turn, the alternative set was assigned to each of the aggregate segments that make up the road network prepared for the study. Once this step was completed for all of the IRI standards, the corresponding HDM-4 strategy analyses were executed. These produced the unconstrained works programs, whose budget requirements and effects on network performance are discussed in the following paragraphs.

Table 5 – Definition of alternatives.

<table>
<tr><th rowspan="2">Alternative</th><th colspan="2">Maintenance standards assignments</th></tr>
<tr><th>Standard</th><th>Starting year</th></tr>
<tr><td>Base alternative</td><td>Routine</td><td>2015</td></tr>
<tr><td>Project alternative - 2015</td><td>Periodic</td><td>2015</td></tr>
<tr><td rowspan="2">Project alternative - 2016</td><td>Routine</td><td>2015</td></tr>
<tr><td>Periodic</td><td>2016</td></tr>
<tr><td rowspan="2">Project alternative - 2017</td><td>Routine</td><td>2015</td></tr>
<tr><td>Periodic</td><td>2017</td></tr>
<tr><td>(…)</td><td>(…)</td><td>(…)</td></tr>
<tr><td rowspan="2">Project alternative - 2024</td><td>Routine</td><td>2015</td></tr>
<tr><td>Periodic</td><td>2024</td></tr>
</table>

4.2. Budget requirements by IRI standard

HDM-4 assembles the unrestricted works program from the road works items defined within the maintenance standards. In this example, works items could be extracted from either the routine or the periodic maintenance standards. The choice was dependent upon the contribution of each works item to improving the IRI while minimizing the agency costs [7].

Works descriptions contained in the unconstrained work program include the corresponding unit costs and works quantities, form which the budget required to deliver the program can be calculated. The estimated annual resources necessary to implement the unconstrained works program associated with each IRI standard are presented in Table 6, and depicted graphically in Figure 1. Figure 2 shows the total budget requirements, together with the resources needed in the first year.

Table 6 – Annual budget requirements (million USD).

Year	Standard 1	Standard 2	Standard 3
2015	881.990	230.948	76.694
2016	2.497	220.777	116.416
2017	43.207	242.001	31.960
2018	0.000	103.809	111.481
2019	19.264	0.000	66.896
2020	0.293	44.183	169.217
2021	57.195	16.043	0.000
2022	95.075	22.462	0.000
2023	6.551	7.656	23.328
2024	0.000	49.105	2.127
Total	1106.071	936.986	598.119

As indicated in Table 3, “Standard 1” represents the IRI standard with the highest performance level associated. Although this has an effect on the total cost, the most noticeable impact has to do with the resources needed to implement “Standard 1” in the first year. This was somehow expected as a drastic increase in the required performance for a given network always entails the execution of a large volume of road works. In fact, the investments required to achieve road improvements in the short term might only be affordable under a framework for the participation of the private sector. In any case, a radical action such as the one represented by “Standard 1” normally results in a better road performance over the medium to long term.

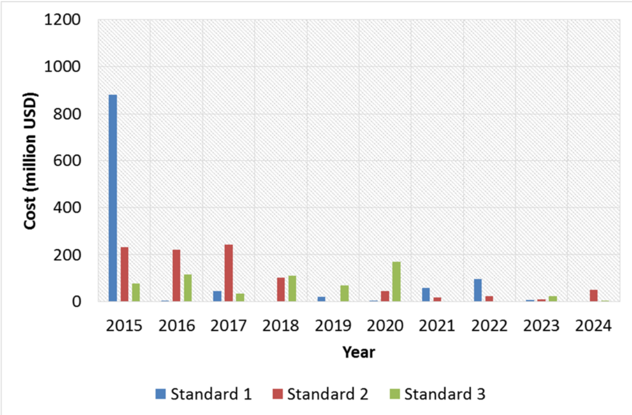

Figure 1 - Annual budget requirements.

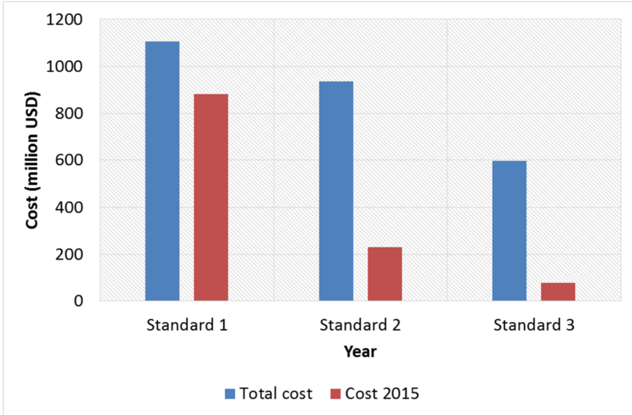

Figure 2 - Total budget needs and budget requirements for 2015.

With respect to “Standard 2”, although the total implementation cost is comparable with that of “Standard 1”, investments required at the beginning of the analysis period are distributed among the first three years. Yet, the total amount required for this short period is still very high.

As for “Standard 3”, the concentration of initial investment needs is considerably lower, which might be indicating that this standard has a closer match with the current performance of the network.

4.3. Overall network performance

With regards to the effects of the IRI standards on network performance, Figure 3 illustrates the evolution of the mean IRI of the network (weighted by length) for each IRI standard. The deterioration trend associated with the base alternative is also provided as a reference.

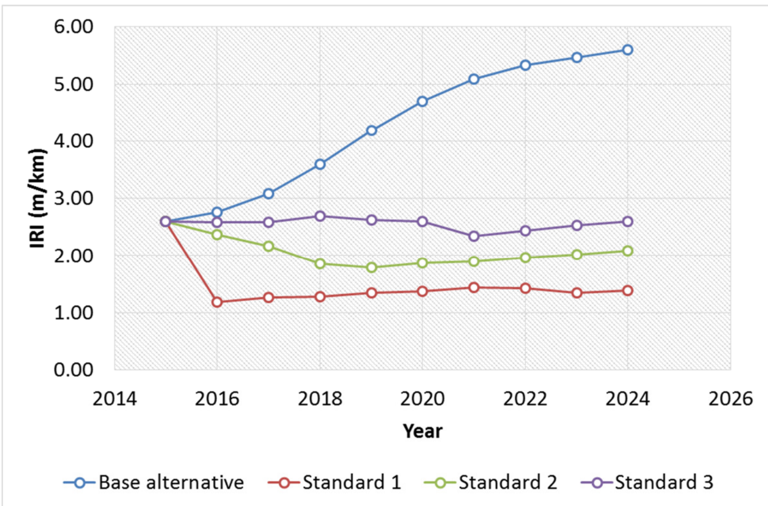

Figure 3 - IRI evolution patterns for the different IRI standards and the base alternative.

As expected, Figure 3 translates the expense previsions of the different standards into consistent behaviors of the mean network IRI. These behaviors can be described as follows:

- “Standard 1”: Sharp decline of IRI in the first year followed by a steady state.
- “Standard 2”. Gradual improvement in the initial three years, which is reversed in year 2019 to start a tendency of minor but continuous worsening. The fact that no global improvement can be noticed after 2019 suggest that a significant road length is not reaching the intervention thresholds defined within the standard.
- “Standard 3”. Network IRI remains practically constant and equal to the initial value until 2020, when a noticeable improvement occurs. According to Figure 1, the highest investment amount for “Standard 3” is programmed for this year.

Moreover, it should be noted that IRI mean values keep relatively close to the good / fair boundary set for each standard.

5. APPLICATION EXAMPLE: SCENARIOS OF RESTRICTED BUDGET

5.1. Setting up scenarios

The results from the last section show that the implementation of unconstrained works programs derived from higher performance requirements is not feasible. Therefore, budget restrictions should be introduced in the analysis and their impact on road performance should be evaluated carefully.

In countries like Mexico, road maintenance budgets are negotiated and allocated on an annual basis, and their yearly variations tend to remain within well-known boundaries. On the other hand, the time horizon for road maintenance planning is normally limited to the period of government administrations.

Taking the above into account, the HDM-4 budget periods required for the analysis of constrained budget scenarios were defined as follows:

- A medium-term budgeting period of six years was selected so that it coincide in length with the period of the Mexican administrations.
- Annual budget constraints would be specified within the medium-term budgeting period.
- A reference value to determine the annual budget constraints was calculated as the sum of the most prominent budget allocations observed in the unconstrained work programs.
- Three level of annual constraints were defined as the 100%, 67% and 33% of the reference value divided by six. The corresponding scenarios was labeled as “high”, “medium” and “low” annual budget scenarios.
- Starting in year six, the budget was left unconstrained to determine the investments necessary after the six-year period to comply with each of the defined IRI standards.

Again, the analysis was performed separately for each IRI standard. Results in terms of budget requirements and expected network performance are discussed in paragraphs 5.2 and 5.3.

5.2. Budget requirements by IRI standard and budget scenario

Results of budget allocations by scenario for each IRI standard are presented graphically in Figures 4 through 6.

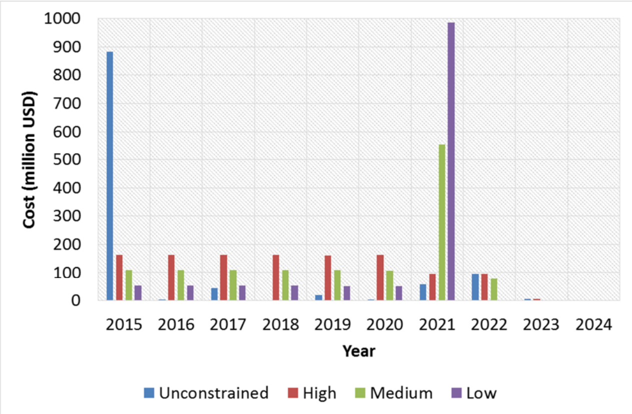

Figure 4 - Constrained budget scenarios for Standard 1.

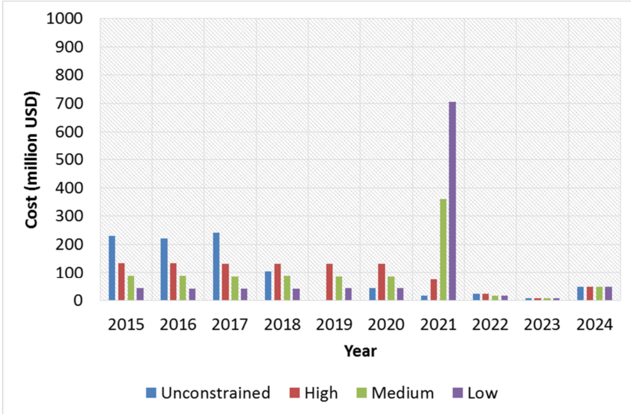

Figure 5 - Constrained budget scenarios for Standard 2.

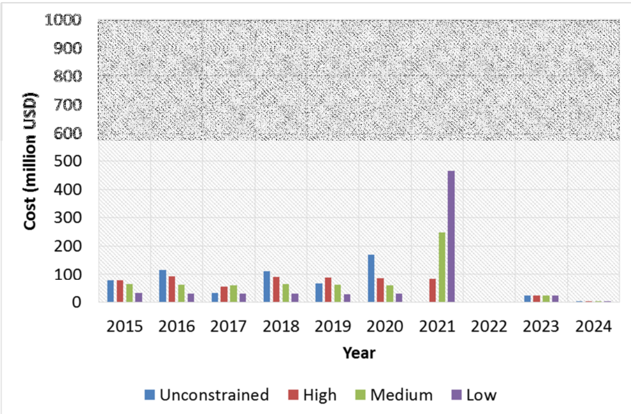

Figure 6 - Constrained budget scenarios for Standard 3.

First, this set of graphs show that, regardless of the IRI standard, the distribution of the most significant part of the unconstrained budget among six annual budgets has no adverse consequences on the resources required after year six. This distribution corresponds to the data series labeled as “high”. However, and again irrespective of the IRI standard, when these annual budgets are restricted, the budget requirements for year seven increase dramatically, which in practical terms creates a potential budgeting problem for the next administration.

The smooth transition from the concentration observed in the unconstrained works programs to the even distributions of the “high” budget scenario suggest that this scenario should always be investigated.

5.3. Expected network performance

In order to determine the effects of the constrained budget scenarios on network performance, a set of graphs depicting the percentage road length in good, fair and poor condition, as defined by each IRI standard, were created. Figures 7 through 10 contain the graphs obtained for “Standard 1”. When comparing the graphs corresponding to the unconstrained and the “high” budget scenarios, it becomes apparent that the waiting time required to have the network performing at the “good” level will be much longer if the budget is allocated annually. However, it should be noted that a sharp improvement like the one represented in Figure 7 is normally not affordable nor technically feasible.

On the other hand, Figures 9 and 10 show that a significant reduction of the annual budget may lead to severe sustainability problems of the road management approach. As can be seen in these figures, as time increases, the part of the network in poor condition tends to grow. Nonetheless, it is interesting that the optimization criteria used by HDM-4 appear to favor maintenance of sections in good to fair condition at the expense of sections in fair to poor condition requiring reconstruction. Indeed, these criteria adhere to asset management good practice.

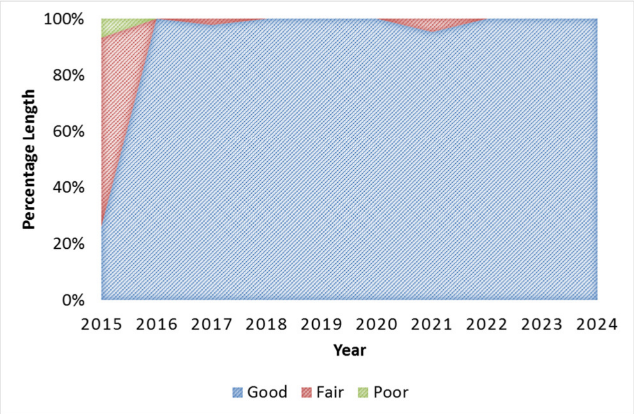

Figure 7 - Network rating for Standard 1, unconstrained scenario.

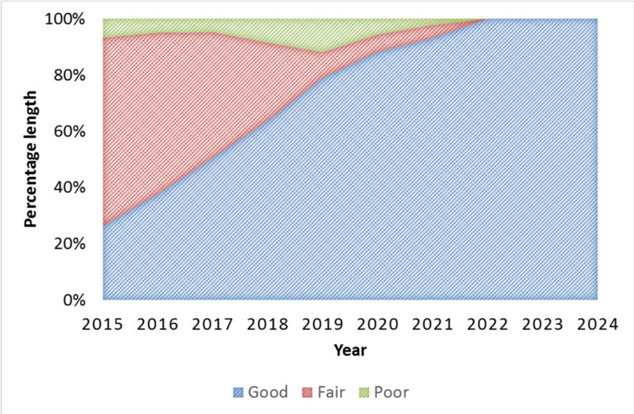

Figure 8 - Network rating for Standard 1, high annual budget scenario.

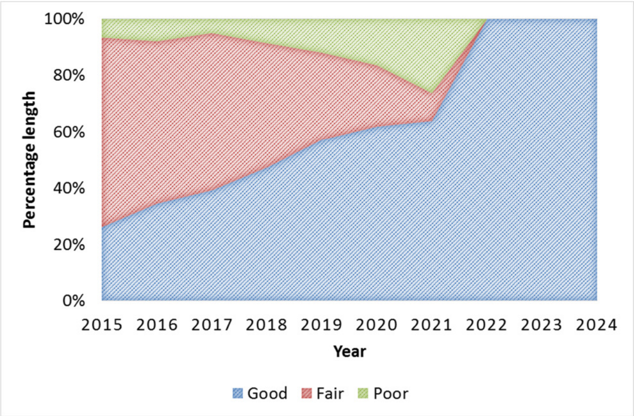

Figure 9 - Network rating for Standard 1, medium annual budget scenario.

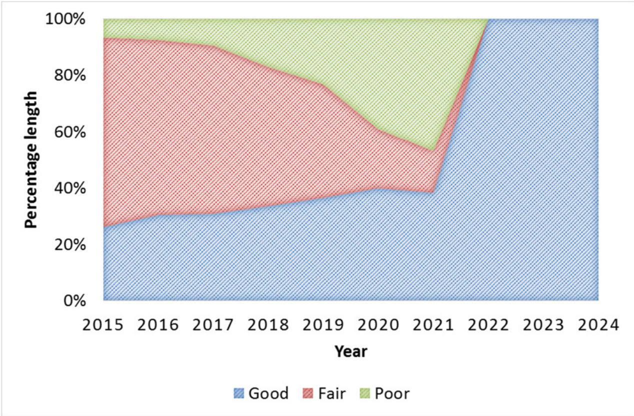

Figure 10 - Network rating for Standard 1, low annual budget scenario.

By year seven, scenarios represented in Figures 9 and 10 have created significant backlogs, which could only be overcome by making substantial investments.

In any case, results such as those presented above can be useful for the definition of new performance targets. For instance, if the scenario portrayed in Figure 8 was deemed feasible, it could be used as a basis to formulate performance targets like “increase annually in 10% the percentage length of roads in good condition”, or “by 2020, have 80% of network length in good condition”.

6. CONCLUSIONS

The following conclusions can be drawn from the topics addressed in this document.

- Performance management is an essential component of any asset management framework since it provides all the necessary elements to determine the extent to which the objectives of a road agency are being met.

- The elements of performance management already present in some Mexican road agencies should be used as a starting point to develop a formal performance management framework.

- Applications of the HDM-4 strategy analysis include policy studies such as changes in maintenance standards. The revision of existing performance measures and targets can be regarded as one of these policy studies.

- The implementation of unconstrained works programs derived from higher performance requirements is normally not feasible due to the high funding levels required for the first year of the analysis period.

- Failing to provide enough resources to support the adoption of a new performance management framework may result in serious risks for the sustainability of the road asset management approach in the medium term.

- The application example developed shows that the proposed procedure can be useful for reviewing the impact of changes in performance measures and targets.

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