# Modeling Functional Quality of Rigid Pavement Systems During its Life Cycle, A Systemic Approach

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## Abstract

Decision making about evaluating, planning, design, construction and maintenance of pavements are made through pavement management systems. Resources are assigned according to the priority results of each segment within the network; this requires a deep knowledge about the present and future state of the pavement system. The correct evaluation of the information related to pavement condition is crucial for determining the present and future needs.

Determination and forecast of the *functional quality* of rigid pavement systems in terms of design, construction, environmental and rehabilitation variables is presented. It will be generated a model and several sceneries will be run in a simulation process based on a real case. Through simulation process, it will be possible to estimate a *Combined Quality Index* for a specific year of service and/or to approximate future behavior as a function of its life cycle.

It is pretended to state and to evaluate from a systemic point of view the factors and inter-relationships affecting rigid pavement, since those factors are fundamental elements used by network managers to test different strategies and to assign maintenance or rehabilitation economic resources.

Key words:

- Pavement Performance
- Pavement Serviceability
- Concrete Pavement Evaluation
- Pavement Predictive Models

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David Garcés was a master's degree candidate at the ITESM School of Engineering during the present study. His professional and research objectives focus on systems thinking application in planning and developing large-scale infrastructure projects, thus policy implications of including dynamic complexity to these fields. The Functional Quality Model of Rigid Pavement Systems described in this paper is available in Ithink format upon request. Contact: ITESM Campus Monterrey, Depto. Ing. Civil. Av. Eugenio Garza Sada 2501, Col. Tecnológico, Monterrey, N.L. 64849, México. Phone: (52) 8328 4213 ext. 101; e-mail: dgarces@infosel.net.mx.

## Introduction

The rigid pavement types covered by this study are known as highways and these are conformed according to their use by two main characteristics: high load intensity and high traffic velocity and according to their design, these structures are built out of plain concrete within steel reinforced joints.

Maintenance resources are assigned according to the priority results derived from a cost-benefit comparison of each segment of the network. A correct decision concerning the priority results requires a deep knowledge about the current state (functional quality or service index) of the pavement system [Hass, 1993; Sedesol, 1993]. The acquisition, interpretation and correct evaluation of the information related to the conditions of the different pavement systems are the basis of any highway management system [TRB, 1984] and they are crucial to determining the present and future needs. This study attempts to state and to evaluate from a systemic point of view the factors and their inter-relationships affecting rigid pavement, since those factors are fundamental elements, which enable the network manager to test different strategies and assign economic resources to maintenance or rehabilitation.

## Objective

The purpose of this study is to determine and forecast the *functional quality*, of rigid pavement systems in terms of their design, construction, environmental and rehabilitation variables. It will be generated a model and several sceneries will be run in a simulation process. Later, through the simulation process it will be possible to estimate a *Combined Quality Index* of the rigid pavement system during a specific year of service and/or to approximate its future behavior as a function of its life cycle.

To reach the planned objective, it is proposed to system dynamics [Forrester, 1975; Forrester, 1991], as an integral tool to successfully model the current and future state of a rigid pavement system, since it is possible to incorporate statistical or Bayesian regression algorithms, data obtained from mechanistic methods and subjective information curves with information which is more complex to interpret [Azarang and García, 1996; Cellier, 1991; Hajek, et al, 1996; Shannon, 1975].

Decision-making to assign maintenance and rehabilitation resources is done by determining a state of priorities [Sedesol, 1996; Simap, 1993]. The present status and as a consequence behavior forecasting at a network level are the fundamental elements of the state of priorities mentioned. The *functional quality* model proposed in this study will mainly offer:

- an opportune and economic support alternative to complement actual analytic methods of physical and structural inspection, in order to evaluate more accurately the pavement system performance; and
- the possibility of immediate knowledge about the complexity of the pavement system due to the possibility of reviewing and evaluating numerous behavior sceneries.

## Impact on pavement management

Pavements do not perform in an isolated form, since they are planned, they acquire its “own personality” according to the purpose, the type of service required, the geophysical conditions where they will be built, their materials and construction procedures. Once pavements are in service, other factors will affect their performance: the number and type of loads (traffic), climatic conditions and maintenance programs during their life cycle.

The practice of modeling pavement behavior is not new; every day new and more accurate models appear and are used as a powerful tool in pavement management to establish the present state and forecasting the pavement performance. It is normally included in different design methodologies, the accumulated load effect and behavior conditions (soil and raw materials) [AASHTO, 1986; Butt, et al, 1987; Hass, 1993]. However, once the pavement is in service, it becomes necessary to progrma periodic inspection of their superficial and structural state to feed models and to determine the combined performance. This determination is done through a Serviceability Index [Al-Omari and Darter, 1992].

The analytic methodology for superficial and structural inspection is justified, since pavement system damage usually occurs before is predicted; this means that accumulated loads and environmental conditions cause a higher destructive force into the system than was predicted in its design [Darter, et al, 1985; Hall, et al, 1988; HRB, 1962].

At network level, which is the full integration of highway systems, priority programs during the maintenance phase are based on the physical evaluation conditions of each in service pavement system included in that level. Present and expected future conditions (Serviceability Index) of each system pavement included in it, have a direct impact on maintenance or rehabilitation strategies [Simap, 1993].

Timely and effective evaluation of the entire network level is important for developing precise and proper strategies; unfortunately to do this through physical evaluation methodology certainly is expensive and mainly very time consuming. Thus dynamic modeling is proposed as an appropriate tool fort performing the required evaluation under different sceneries in order to implement proper strategies.

## The Rigid Pavement System: How does it work?

People observe and generate assumptions about surrounding systems. Such assumptions do constitute mental models that are subsequently used as a base in the decision-making process [Hannon, 1994; Senge, 1990]. It is possible to model broadly the pavement system, if more factors that contribute to completing the assumptions are added, such as urban development, maintenance tasks and rehabilitation strategies.

Rigid pavement systems are defined as open systems, where their state is constantly changing according to the in-out flows affected by feedback loops that “stabilize” the variables. The following figure represents the pavement system and its environment.

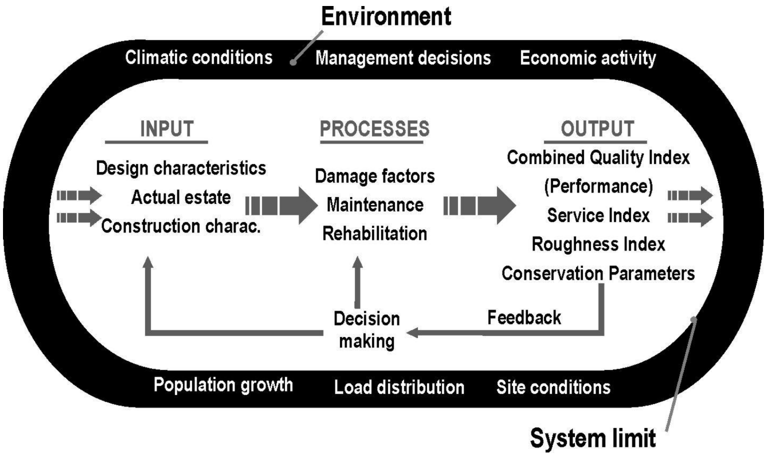


FIGURE 1. The Rigid Pavement System and its environment.

As can be observed, the system is circumscribed to an external environment, and although this environment is outside of its limits, the open system is very dependent on it [Turban, 1998].

## Generic Variables of the System

Rigid pavements are constructions designed and built by man to satisfy vehicle transit necessities in a smooth, comfortable and safe way. Once it is in operation, it becomes on other element in a system called: rigid pavement system. The controllable and uncontrollable variables composing the mentioned system are shown below.

*A. Controllable Generic Variables:*

- Design characteristics.
- Construction characteristics.
- Actual estate of the system.
- Maintenance Decisions.
- Rehabilitation Decisions.

*B. Uncontrollable Generic Variables:*

- Climatic conditions.
- Foundation conditions.
- Socio-economic factors.
- Direction and utilization factors.
- Accumulated loads effect.
- Accumulated overloads effect.
- Actual and projected loads rate demand.

*C. Answer Variables:*

- Combined Quality Index.
- Damage level.
- Strategies.

## Functional Quality Modeling Variables

Once system limits as well as generic variables were determined, specific variables were defined. Below, is shown the model's main variable chart.

| EXOGENOUS VARIABLES | NUM*. | MECHANISM | TYPE |
|---|---|---|---|
| • Temperature Variation | CL1 | CVT** | Uncontrollable |
| • Rain Volume | CL2 | CVT | Uncontrollable |
| • Modulus of Reaction of Sub Base | C3 | CVT | Controllable |
| • Real Accumulated Single Axles [a] | EE1-17 | CVT | Controllable |
| • Economic Impulse | S1 | Flow | Uncontrollable |
| • Population | S2 | Estate | Uncontrollable |

TABLE 1. Exogenous Variables.

* Classification Number.

**CVT = Constant or Variable as a function of Time.

a. Includes unpredicted loads and overloads.

| ENDOGENOUS VARIABLES | NUM. | MECHANISM | TYPE |
|---|---|---|---|
| • Remaining Time of Service | DG1 | CVT | Controllable |
| • Mean Embankments | DG4 | CVT | Controllable |
| • Design Accumulated Single Axles [a] | D1-D11 | CVT | Controllable |
| • Modulus of Rupture | C1 | CVT | Controllable |
| • Modulus of Elasticity | C2 | CVT | Controllable |
| • Roughness Index | C4 | CVT | Controllable |
| • Load Transfer Coefficient | C6 | CVT | Controllable |
| • Drainage Coefficient | C7 | CVT | Controllable |
| • Maintenance Decisions | S3 | Flow | Controllable |
| • Rehabilitation Decisions | S4 | Flow | Controllable |
| • Accumulated Single Axles (EM#) | EM1-14 | Estate | Uncontrollable |
| • Direction Factor | EM15 | CVT | Uncontrollable |
| • Utilization Factor | EM16 | CVT | Uncontrollable |
| • Net Annual Growth Rate | EM17 | CVT | Uncontrollable |
| • Combined Quality Index | IC1 | Estate | Answer |
| • Combined Quality Index Modified | IC2 | Estate | Answer |
| • Damage Level | IC4 | Estate | Answer |
| • Strategies (Conservation activities) | -- | Support | Answer |

TABLE 2. Endogenous Variables.

a. Includes only predicted loads.

## Reference Model

From models consulted [ACPA, 1987; Hass, 1993; Jiang, et al, 1996; Lee and Darter, 1994; Liu, et al, 1996; Wu, 1992], the AASHO Road Test, now the AASHTO (American Association of State Highway Officials) was selected. The 1986 AASHTO model completely fits with the Functional Quality Model mechanistic part, however the 1986 AASHTO model will be used only as a reference to establish the behavior of variables inside the model presented here.

The AASHO Road Test consisted of a deep study about pavements and bridges performance under determined and controlled loads in movement. It was conducted from 1958 to 1960 near Ottawa, Illinois [HRB, 1962a]. The actual AASHTO method consists of a design model product of several regression analysis modified over time. In 1986, it was dramatically improved as follows in the next expression [AASHTO, 1986]:

$$\log W_{18} = Z_R S_o + 7.35\cdot\log(D+1) - 0.06 + \frac{\log\dfrac{\Delta PSI}{3}}{1+\dfrac{1.624\times10^{7}}{(D+1)^{8.46}}}$$

$$+(4.22-0.32p_t)\cdot\log\left[\frac{S'_c\cdot C_d(D^{0.75}-1.132)}{215.63\cdot J\left(D^{0.75}-\dfrac{18.42}{(E_c/k)^{0.25}}\right)}\right] \tag{1}$$

Where:

$W_{18}$ = accumulated 18 kip axle load applications over service period;
$Z_R$ = selected level of reliability (standard normal deviate);
$S_0$ = overall standard deviation for rigid pavement materials and procedures;
$\Delta PSI$ = loss of Serviceability ($p_i$ - $p_t$);
D = Portland cement concrete slab thickness;
$S'_c$ = concrete modulus of rupture;
$C_d$ = drainage coefficient;
$E_c$ = concrete modulus of elasticity;
K = modulus of subgrade reaction;
J = load transfer coefficient;
$p_i$ = initial Serviceability Index; and
$p_t$ = terminal Serviceability index.

The design model expressed in equation 1 is based on empiric field data, and its inferential space is then highly correlated to site and pavement test conditions [Darter, 1980; Darter, et al, 1996; Liu, et al, 1988]. Therefore, it is necessary to adjust the model to reach a more holistic phenomena interpretation. Such adjustments include different loads mixtures and pavement construction characteristics as well as climatic and foundation conditions. Even though those adjustments include theoretical analysis and subjective considerations they are necessary to develop an accurate appreciation of the dynamic variables until now unattended.

## Performance Measurement: Combined Quality Index

It is important to keep a uniform pavement evaluation through an index generally accepted today; therefore the Combined Quality Index is correlated to the AASHTO 1986 model design performance scale. Both, the Present Serviceability Index and the Combined Quality Index are numerical designations between 0.0 and 5.0. This scale indicates the service capability of any road or highway [Al-Omari and Darter, 1992; HRB, 1962]. According to pavement management specifications, an evaluation of 2.0 or 2.5 indicates that the pavement has reached its limit condition service and it has failed when it has fallen to an index level of 1.50.

The Combined Quality Index as a serviceability measurement is shown in Figure 2, and it is based on following assumptions:

- Pavements (rigid pavement in this case) are made for user convenience.
- User opinions about performance are the most important point for evaluation. This is valid even when these opinions are subjective.
- there may be certain differences of opinion concerning the functional quality of the pavement, then a mean opinion reasonably represents pavement serviceability.

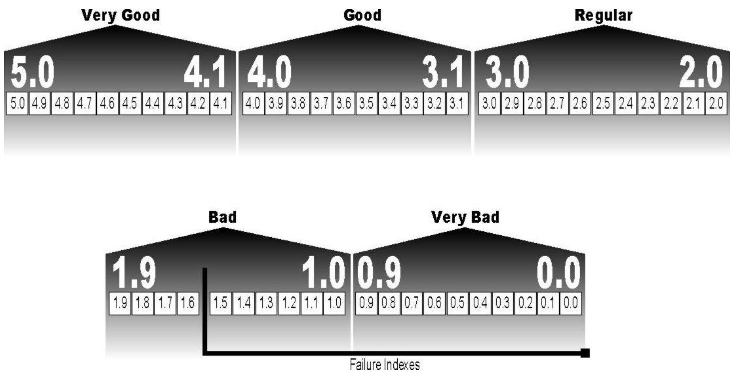
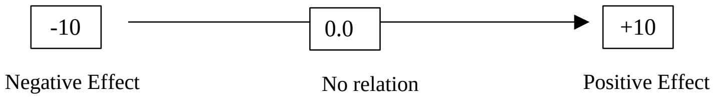


FIGURE 2. Combined Quality Index performance scale.

## Model Variables Behavior

The object of this analysis is to reinforce the model by determining causal relationships between different model variables [Martin, 1997; Sterman, 1988]. A causality scale was developed to represent the degree to which a certain variable is affected by another or others. The proposed scale is represented below.



The causality criteria followed to obtain different causality results is based on three core concepts according Singer and Ackoff [Ackoff, 1978]:

- known mathematic expressions;
- product-producer moderate relation and;
- heuristic perceptions.

The complete number of endogenous and exogenous variables previously identified is represented in a detailed way in Tables 3 and 4. These are the variables used to generate the Functional Quality Model of Rigid Pavement Systems.

| # | NAME | VARIABLE | DENOM. | MIN | MAX | UNIT | D1 | D11 | C1 | C2 | C3 | C4 | C6 | C7 | EM15 | EM16 | EM17 | EM# |  | IC1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | DG1 | Remaining Time on Service | Ao | 1.000 | 30.000 | YEARS | 0 | 0 | -5 | -5 | -4 | 0 | 6 | -5 | 0 | 0 | 5 | 0 |  | -8 |
| 2 | DG4 | Mean Embankments | APT | 0.000 | 35.000 | in | 0 | -4 | 0 | 0 | -3 | -2 | 0 | 0 | 0 | 0 | 0 | 0 |  | -4 |
| 3 | D1 | Concrete Slab Thickness | D | 4.500 | 20.000 | in |  | 8 | 0 | 0 | 0 | 0 | -5 | 0 | 0 | 0 | 0 | 0 |  | 8 |
| 4 | D2 | Level of Reliability | R | 50.000 | 99.990 | % | 0 | -8 | -3 | 3 | -3 | 0 | 3 | -3 | 3 | 3 | 4 | 0 |  | -9 |
| 5 | D3 | Overall Standard Deviation | So | 0.200 | 0.600 | -o- | 0 | -4 | -2 | 2 | -2 | 0 | 2 | -2 | 2 | 2 | 3 | 0 |  | -4 |
| 6 | D4 | Concrete Modulus of Rupture | S'c | 500.000 | 800.000 | lb/in2 (psi) | 0 | 8 | 0 | 0 | 0 | 0 | -2 | 2 | 0 | 0 | 0 | 0 |  | 7 |
| 7 | D5 | Concrete Modulus of Elasticity | Ec | 2,000,000.000 | 5,000,000.000 | lb/in2 (psi) | 0 | -5 | 0 | 0 | 0 | 0 | 2 | -2 | 0 | 0 | 0 | 0 |  | -5 |
| 8 | D6 | Load Transfer Coefficient | J | 2.000 | 5.000 | -o- | 0 | -8 | 0 | 0 | 0 | 0 | 5 | 3 | 0 | 0 | 0 | 0 |  | -8 |
| 9 | D7 | Modulus of Subgrade Reaction | k | 25.000 | 450.000 | lb/in2/in (pci) | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 5 |
| 10 | D8 | Drainage Coefficient | Cd | 0.700 | 1.250 | -o- | 0 | 9 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 |  | 7 |
| 11 | D9 | Initial Serviceability Index | PSI | 3.000 | 5.000 | -o- | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 5 |
| 12 | D10 | Terminal Serviceability Index | PST | 1.000 | 3.000 | -o- | 0 | -6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | -3 |
| 13 | D11 | Design Equivalent Single Axles Load | E 18's | 1,000.000 | 10 BILLION | E 18's | 8 |  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 8 |
| 14 | C1 | Concrete Modulus of Rupture | S'c' | 500.000 | 800.000 | lb/in2 (psi) | 0 | 7 |  | 5 | 0 | 0 | -5 | 3 | 0 | 0 | 0 | 0 |  | 6 |
| 15 | C2 | Concrete Modulus of Elasticity | Ec' | 2,000,000.000 | 5,000,000.000 | lb/in2 (psi) | 0 | 5 | 0 |  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | -5 |
| 16 | C3 | Modulus of Subgrade Reaction | k' | 25.000 | 450.000 | lb/in2/in (pci) | 0 | 4 | 0 | 0 |  | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 4 |
| 17 | C4 | Roughness Index | IPI | 2.000 | 80.000 | in/10mi | 0 | 5 | 0 | 0 | 0 |  | 0 | 0 | 0 | 0 | 0 | 0 |  | -7 |
| 18 | C6 | Load Transfer Coefficient | J' | 2.000 | 5.000 | -o- | 0 | -6 | 0 | 0 | 0 | 0 |  | 0 | 0 | 0 | 0 | 0 |  | -6 |
| 19 | C7 | Drainage Coefficient | Cd' | 0.700 | 1.250 | -o- | 0 | 8 | 0 | 0 | 0 | 0 | 0 |  | 0 | 0 | 0 | 0 |  | 8 |
| 20 | CL1 | Temperature Variation | TEMP | -10.000 | 50.000 | CELSIUS | 0 | 0 | -3 | 0 | -2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | -4 |
| 21 | CL2 | Rain Volume | PRPV | 0.000 | 150.000 | mm | 0 | 0 | 0 | 0 | -6 | 0 | 0 | -6 | 0 | 0 | 0 | 0 |  | -8 |
| 22 | EM15 | Direction Factor | FD | 0.000 | 100.000 | % | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 0 | 0 | 5 |  | -4 |
| 23 | EM16 | Utilization Factor | FU | 0.000 | 100.000 | % | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 0 | 5 |  | -5 |
| 24 | EM17 | Net Annual Growth Rate | TC | 0.000 | 12.000 | % | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  | 10 |  | -8 |
| 25 | EM# | Accumulated Single Axles Load | E 18's | 1000 | 10 BILLION | E 18's | 0 | 0 | -9 | 0 | -8 | 0 | 0 | 0 | 0 | 0 | 0 |  |  | -10 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 26 | IC1 | Combined Quality Index | CQI | 1.000 | 5.000 | -o- | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

0 No causal relation

1 . . . . 10
Low Increment High Increment

-1 . . . . -10
Low Decrement High Decrement

TABLE 3. General Causality Matrix.

| # | NAME | VARIABLE | DENOM. | MIN | MAX | UNIT | S2 | S3 | S4 | EM15 | EM16 | EM17 | EM# |  | IC1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | S1 | Economic Impulse | INV | 0.000 | 1.000 | -o- | 8 | 8 | 7 | 0 | 0 | 7 | 6 |  | 0 |
| 28 | S2 | Population | SP | 0.000 | 20.000 | -o- | 0 | 0 | 0 | 7 | 7 | 7 | 7 |  | -5 |
| 29 | S3 | Maintenance Decisions | DM | 0.000 | 1.000 | -o- | 0 |  | -3 | 0 | 0 | 0 | 0 |  | 8 |
| 30 | S4 | Rehabilitation Decisions | DR | 0.000 | 1.000 | -o- | 0 | 0 |  | 0 | 0 | 0 | 0 |  | 10 |
| 22 | EM15 | Direction Factor | FD | 0.000 | 100.000 | % | 0 | 0 | 0 |  | 0 | 0 | 5 |  | -4 |
| 23 | EM16 | Utilization Factor | FU | 0.000 | 100.000 | % | 0 | 0 | 0 | 0 |  | 0 | 5 |  | -5 |
| 24 | EM17 | Net Annual Growth Rate | TC | 0.000 | 12.000 | % | 0 | 0 | 0 | 0 | 0 |  | 10 |  | -8 |
| 25 | EM# | Accumulated Single Axles Load | E 18's | 1000 | 10 BILLION | E 18's | 0 | 0 | 0 | 0 | 0 | 0 |  |  | -10 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 26 | IC1 | Combined Quality Index | CQI | 1.000 | 5.000 | -o- | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

0 No causal relation

1 . . . . 10
Low Increment High Increment

-1 . . . . -10
Low Decrement High Decrement

TABLE 4. General Causality Matrix. Socio-economic effect.

# Functional Quality Model Construction

## *Main Structure (Influence Diagram)*

Vensim© [Vensim, 1996] modeling software was useful for generating the influence diagram or causal structure; including all identified variables shown in the generic causality matrix.

The main structure was divided into five areas, grouping the variables according to their core function. One reinforcing loop, labeled $R_1$, and five balancing loops, labeled $B_\#$, are identified in the diagram shown in Figure 3.

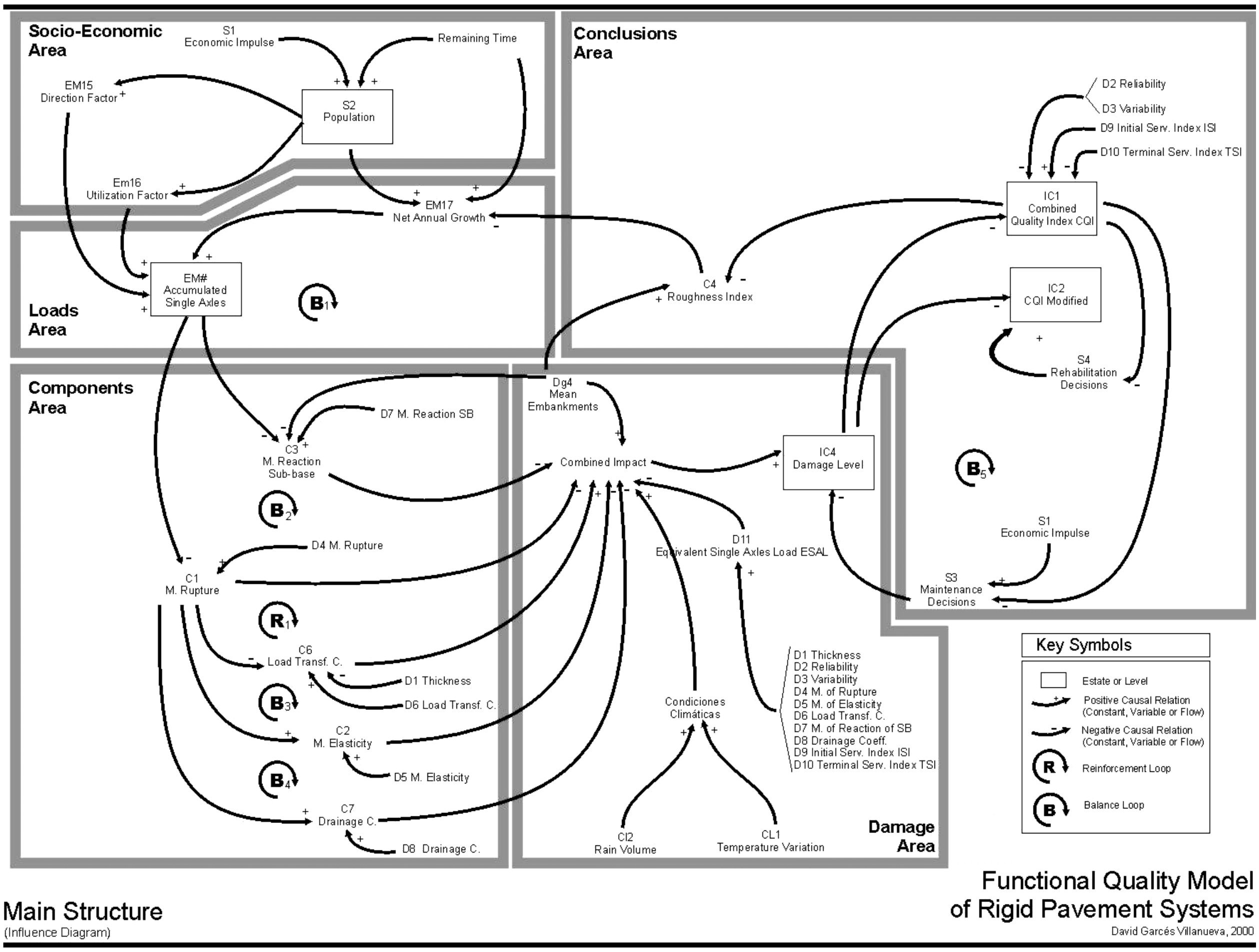


FIGURE 3. Main Structure or influence diagram of the Functional Quality Model.

## *Recreating the Real Situation*

Once rigid pavement is in service, load accumulation begins the deterioration process of the surface as well as of the pavement structure. This load application generates a constant fatigue condition in all hydraulic concrete components ($B_2$ and $B_3$). On the other hand, the applied load progressively affects the subgrade layer until the damage becomes notorious ($B_1$).

The constant fatigue of the elements mentioned produces a greater load transfer necessity ($R_1$). It has a negative influence on the drainage capability of the pavement ($B_4$). Additionally, over time new human settlements are formed along the way, and this represents unpredicted loads on the design.

Climatic conditions and the mean rain volume of the zone constitute another important pavement damage factor. The incident cyclical temperature changes and seasonal precipitation generate accelerated fatigue processes on the surface, structure and infrastructure of rigid pavement. This occurs along with load application damage, which generates a dynamic deterioration process that cannot be determined in an isolated matter due to its complexity.

The Combined Quality Index (CQI) is initially 5.0 or 4.5, but the damage level will increase over time, and the CQI continuously will decrease. Once pavement damage is sensible it will negatively affect the load rate because the pavement will become less attractive to certain users (B1 to B4).

Meanwhile, network highway managers may plan maintenance activities ($B_5$) to improve CQI by means of extending pavement life. This will simultaneously enable an indirect increase in loads application and human settlements along the way ($B_1$ to $B_4$).

Finally, when the CQI has reached a certain unacceptable value since pavement is no longer smooth, comfortable and safe, it is time to carry out a rehabilitation strategy to allow for an improvement in its functional quality. With this, the deterioration cycle starts again.

### *Peripheral Structures*

It was necessary to design two additional structures to make the model more functional for the model user.

*1. Design and Control Structure.*

It includes the D1 to D11 input variables needed it to determine the initial rigid pavement design. The values of these variables are established once the load analysis, site conditions, hydraulic concrete type, geometric design, feasibility study, etc. have been carried out.

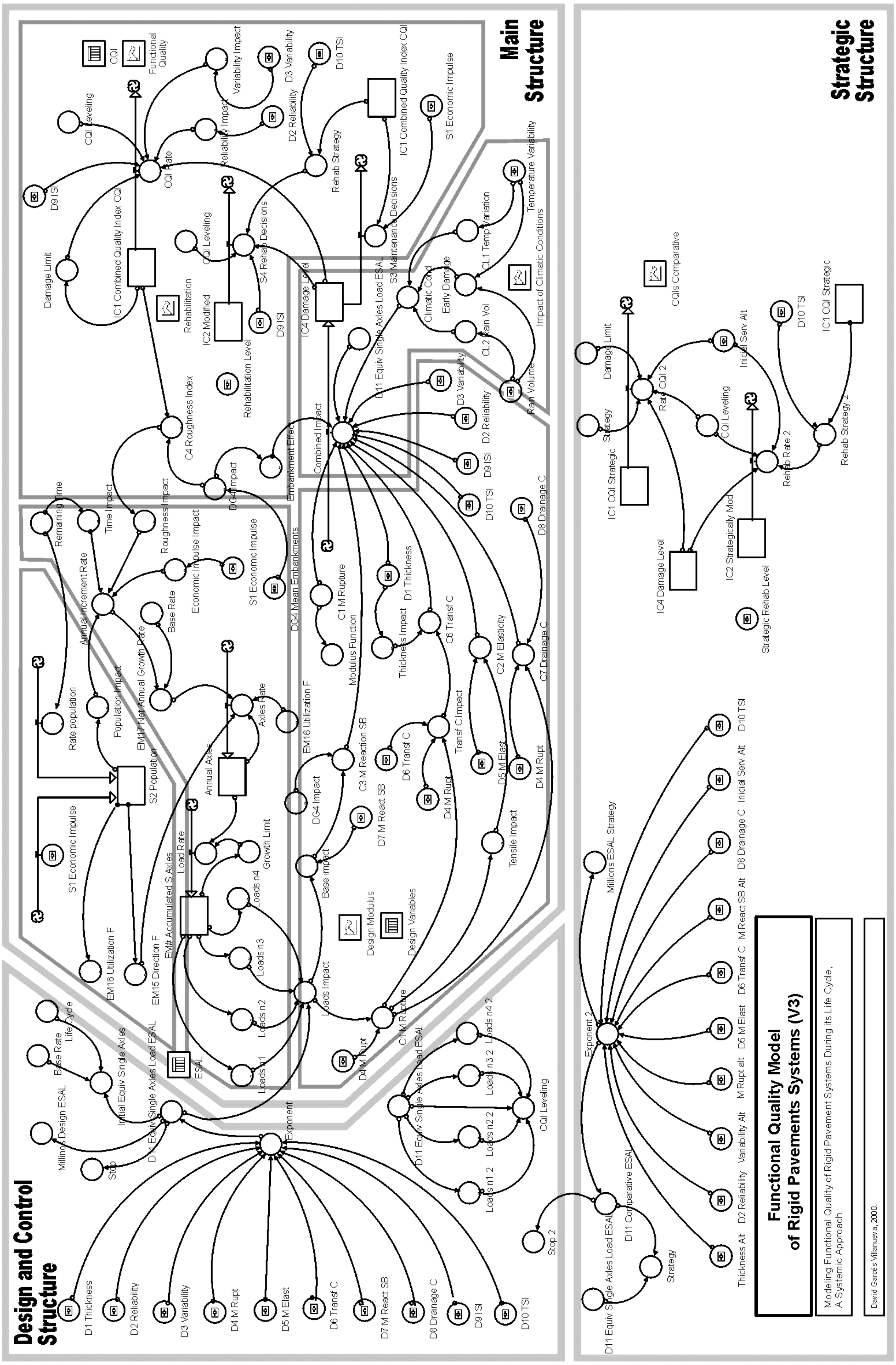
*2. Strategic Structure.*

The variables disposition in this area does not affect system behavior; its function is to help the user of the model by modeling several alternative (strategic) designs.

## The Functional Quality Model

Systems thinking [Senge, 1990; Phillips, 1996] allows for the assembly of the different variables and the construction of a dynamic and complete image of the real situation; it was possible to present a wider “truth” about reality with a more comprehensive system performance measurement.

The causal structure was modeled with Ithink Analyst 4.0© modeling software [HPS, 1996]. Figure 4 shows the General Structure. The main structure with the five mentioned areas and two peripheral structures may be viewed.


Main Structure
Design and Control Structure
Strategic Structure
Functional Quality Model of Rigid Pavements Systems (V3)
Modeling Functional Quality of Rigid Pavement Systems During its Life Cycle. A Systemic Approach.
David Garcés Villanueva, 2000.
CQI
Functional Quality
CQI Leveling
CQI Rate
Variability Impact
D3 Variability
Reliability Impact
D2 Reliability
D10 TSI
D9 TSI
Damage Limit
IC1 Combined Quality Index CQI
Rehab Strategy
IC1 Combined Quality Index CQI
S1 Economic Impulse
Temperature Variability
S4 Rehab Decisions
S3 Maintenance Decisions
Rehabilitation
IC2 Modified
D9 ISI
IC4 Damage Level
Climatic Cond
Early Damage
CL1 Temp Variation
Impact of Climatic Conditions
CL2 Rain Vol
Rain Volume
D11 Equiv Single Axles Load ESAL
Rehabilitation Level
C4 Roughness Index
Combined Impact
Embankment Effect
DG4 Impact
D3 Variability
D2 Reliability
D9 ISI
D10 TSI
D8 Drainage C
Remaining Time
Time Impact
Roughness Impact
Economic Impulse Impact
S1 Economic Impulse
DG4 Mean Embankments
Annual Increment Rate
Base Rate
EM17 Net Annual Growth Rate
C1 M Rupture
Modulus Function
D1 Thickness
Thickness Impact
C6 Transf C
C2 M Elasticity
C7 Drainage C
Rate population
Population Impact
Axles Rate
EM16 Utilization F
S2 Population
Annual Axles
C3 M Reaction SB
D6 Transf C
Transf C Impact
D5 M Elast
D4 M Rupt
S1 Economic Impulse
Load Rate
Growth Limit
DG4 Impact
D7 M React SB
Tensile Impact
EM# Accumulated S Axles
Loads n4
Base impact
Design Modulus
Design Variables
EM16 Utilization F
EM15 Direction F
Loads n3
Loads Impact
Loads n2
C1 M Rupture
Life Cycle
Base Rate
Initial Equiv Single Axles
ESAL
Loads n1
D4 M Rupt
D11 Equiv Single Axles Load ESAL
Loads n4 2
Loads n3 2
Loads n2 2
Loads n1 2
CQI Leveling
Millions Design ESAL
Stop
Exponent
D1 Thickness
D2 Reliability
D3 Variability
D4 M Rupt
D5 M Elast
D6 Transf C
D7 M React SB
D8 Drainage C
D9 ISI
D10 TSI
Stop 2
Damage Limit
Strategy
Rate CQI 2
Inicial Serv Alt
CQI Leveling
Rehab Rate 2
Rehab Strategy 2
IC1 CQI Strategic
D10 TSI
CQIs Comparative
IC4 Damage Level
IC2 Strategically Mod
Strategic Rehab Level
Millions ESAL Strategy
Exponent 2
D11 Comparative ESAL
D11 Equiv Single Axles Load ESAL
Strategy
Thickness Alt
D2 Reliability
Variability Alt
M Rupt alt
D5 M Elast
D6 Transf C
M React SB Alt
D8 Drainage C
Inicial Serv Alt
D10 TSI

### *Control Panel of the Model*

Three controls sections form the control panel (see Figure 5):

*Design Variables:* This section allows for the introduction of input design variables for rigid pavement. The control characteristics coincide with the AASHTO design model, therefore it is necessary to consult the guide tables to set initial values.

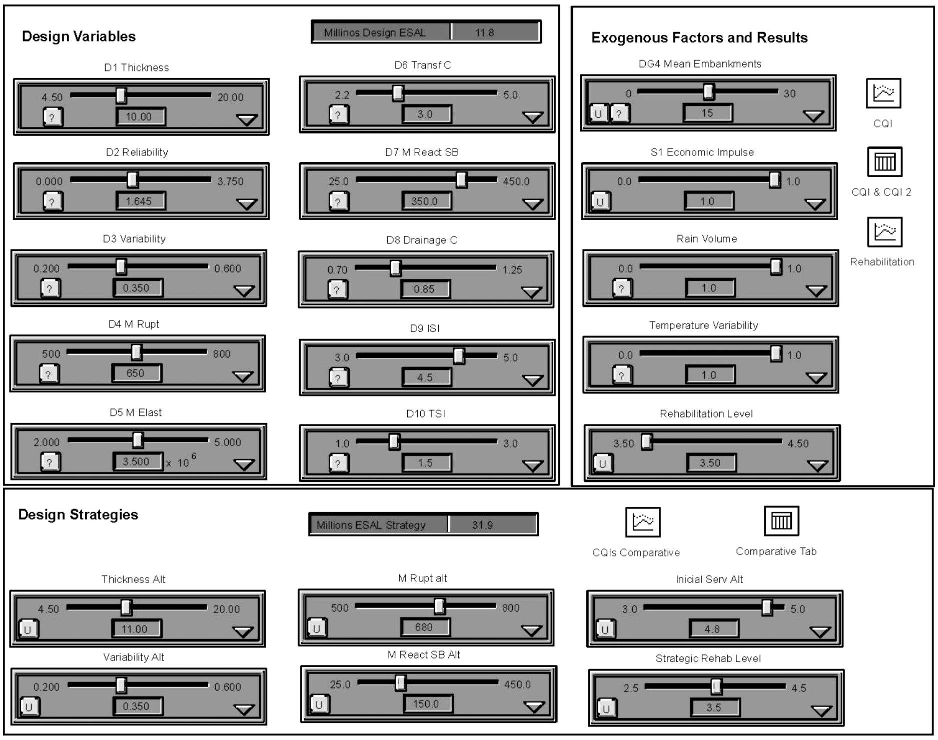
*Exogenous Factors and Output Information:* This section is useful for setting the environmental variables that will affect pavement performance. Here output tables and graphs can be found.

*Design Strategies:* This is a useful section for comparing several design choices, since it allows the user to "play" with design, environmental and maintenance parameters. This section also contains output tables and graphs to facilitate analysis.

## Running the model: Different Sceneries for a Real Case

A real case is proposed to validate the model output information. The case information was obtained from Mexican SCT (Communications and Transportation Department) [Padilla, 1996; SCT, 1983; SCT, 1986]. The rigid pavement analyzed consisted of JRCP (Joint Reinforced Concrete Pavement) pavement with high construction specifications (see Figures 6 and 7) built in Mexico during the last decade.

Next a first simulation is presented showing the original design and three different choices obtained with the proposed model. The original design variables are considered in all running in order to compare the performance curve initially proposed to it produced with the other simulations.



Millinos Design ESAL 11.8

D1 Thickness 4.50 20.00 10.00
D2 Reliability 0.000 3.750 1.645
D3 Variability 0.200 0.600 0.350
D4 M Rupt 500 800 650
D5 M Elast 2.000 5.000 3.500 $x\ 10^6$
D6 Transf C 2.2 5.0 3.0
D7 M React SB 25.0 450.0 350.0
D8 Drainage C 0.70 1.25 0.85
D9 ISI 3.0 5.0 4.5
D10 TSI 1.0 3.0 1.5

DG4 Mean Embankments 0 30 15
S1 Economic Impulse 0.0 1.0 1.0
Rain Volume 0.0 1.0 1.0
Temperature Variability 0.0 1.0 1.0
Rehabilitation Level 3.50 4.50 3.50

Millions ESAL Strategy 31.9

Thickness Alt 4.50 20.00 11.00
Variability Alt 0.200 0.600 0.350
M Rupt alt 500 800 680
M React SB Alt 25.0 450.0 150.0
Inicial Serv Alt 3.0 5.0 4.8
Strategic Rehab Level 2.5 4.5 3.5

FIGURE 5. Control Panel. Functional Quality Model of Rigid Pavement Systems.

## *Original Design Proposal*

The variable table according to the AASHTO design model is described below. The expected service life of rigid pavement under these conditions was established at 20 years. The design is compared to predicted equivalent single axles load obtained from a traffic study in the area. On the right side of the table can be found the different values that design variables can take.

| DESIGN VARIABLES | | | | VALUES | |
|---|---|---|---|---|---|
| AASHTO DESIGN METHOD | | | | MINIMUM | MAXIMUM |
| Predicted Equivalent Single Axles Loads | (E18) | 18KIP | **11,780,000** | 1,000 | 10 BILLION |
| Level of Reliability | (Zr) | % | 95.000 | 50.000 | 99.990 |
| Overall Standard Deviation | (So) | - | 0.350 | 0.200 | 0.600 |
| Concrete Modulus of Rupture | (S'c) | PSI | 640.000 | 500.000 | 800.000 |
| Concrete Modulus of Elasticity | (Ec) | PSI | 4,181,628.000 | 2,000,000 | 5,000,000 |
| Concrete Slab Thickness | (D) | IN | **10.00** | 4.000 | 20.000 |
| Initial Serviceability Index | (ISI) | - | 4.500 | 3.000 | 5.000 |
| Terminal Serviceability Index | (ISF) | - | 2.500 | 1.000 | 3.000 |
| Load Transfer Coefficient | (J) | - | 2.700 | 2.000 | 5.000 |
| Drainage Coefficient | (Cd) | - | 1.000 | 0.700 | 1.250 |
| Modulus of Subgrade Reaction | (k) | PCI | 132.000 | 25.000 | 450.000 |
| **DESIGN EQUIVALENT SINGLE AXLES LOADS (18 KIP)** | | | **11,802,034** | 1,000 | 10 BILLION |

TABLE 5. Rigid Pavement design information.

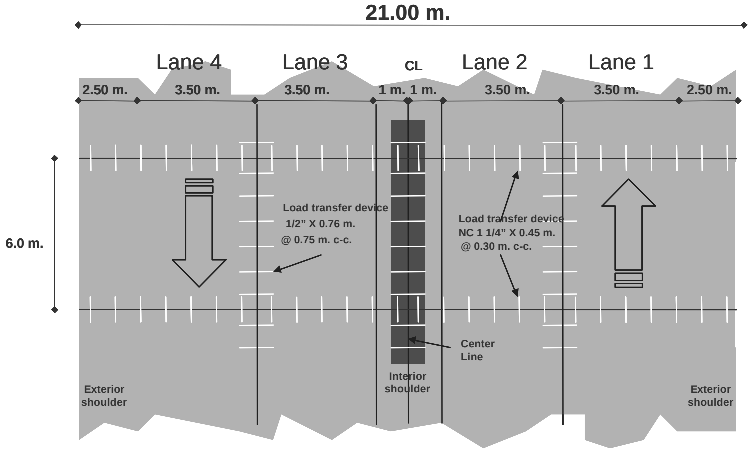


FIGURE 6. Plant view. Joint distribution and load transfer devices shown.

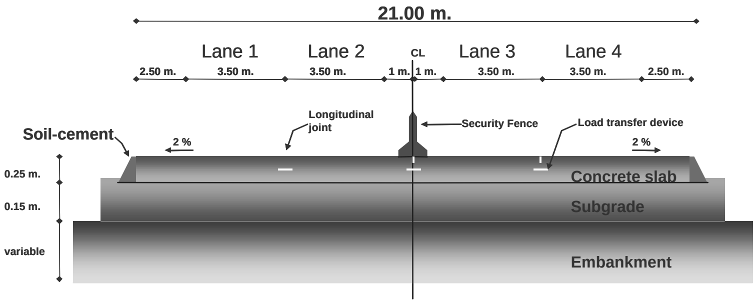
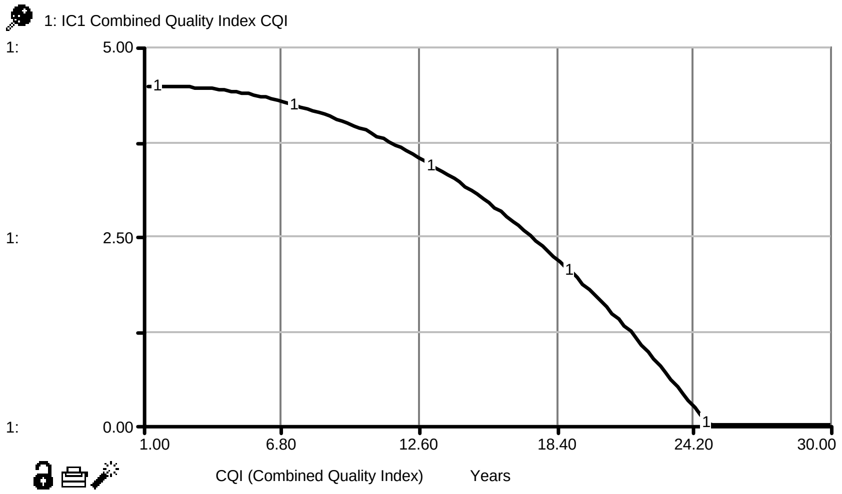


FIGURE 7. Section view. Embankment, subgrade and concrete layer shown.

## *Original Design Simulation*

The design information reviewed before was fed into the "Design Variables" model section. This simulation does not include any exogenous or strategic variables, since it is necessary to identify if the simulation result is similar to that predicted by the original proposal. The following performance curve was obtained.



**ORIGINAL DESIGN SIMULATION**

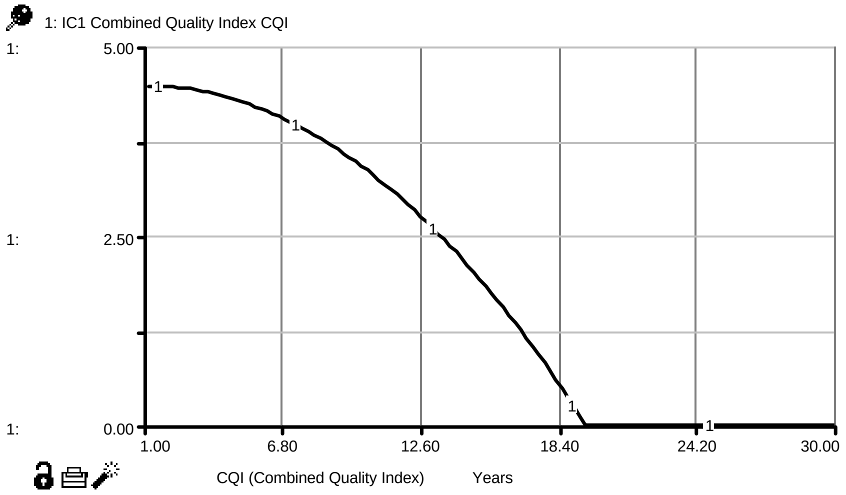
| YR | CQI | YR | CQI |
|---|---|---|---|
| 0 | **4.50** | 15 | **2.82** |
| 1 | **4.50** | 16 | **2.57** |
| 2 | **4.48** | 17 | **2.30** |
| 3 | **4.45** | 18 | **2.02** |
| 4 | **4.40** | 19 | **1.71** |
| 5 | **4.34** | 20 | **1.39** |
| 6 | **4.27** | 21 | **1.05** |
| 7 | **4.17** | 22 | **0.69** |
| 8 | **4.06** | 23 | **0.31** |
| 9 | **3.94** | 24 | **0** |
| 10 | **3.80** | 25 | **0** |
| 11 | **3.64** | 26 | **0** |
| 12 | **3.46** | 27 | **0** |
| 13 | **3.26** | 28 | **0** |
| 14 | **3.05** | 29 | **0** |

FIGURE 8. Original design simulation. Functional quality expected during rigid pavement life cycle.

This simulation shows a minimum expected QCI (2.50) of between years 16 and 17, which is very close to the value predicted by the original proposal. The fact that the present simulation does not include any exogenous variable makes it a very optimistic design proposal; therefore, it is reasonable to expect that the pavement studied will run out its service life before expected.

### *Alternative 1 Simulation: Exogenous Effects included*

Mean rain volume is considered between low and high volume (input value: 0.5), temperature variability is identified between normal and severe according to model parameters (input value:0.5) and mean embankments are of a middle secure height (input value: 15 m.) Economic impulse and strategic design are not included in this simulation process. It is presented below the performance curve obtained.



**ALTERNATIVE 1 SIMULATION**

| YR | CQI | YR | CQI |
|---|---|---|---|
| 0 | **4.5** | 15 | **1.55** |
| 1 | **4.49** | 16 | **1.14** |
| 2 | **4.45** | 17 | **0.70** |
| 3 | **4.38** | 18 | **0.23** |
| 4 | **4.28** | 19 | **0** |
| 5 | **4.16** | 20 | **0** |
| 6 | **4.02** | 21 | **0** |
| 7 | **3.85** | 22 | **0** |
| 8 | **3.65** | 23 | **0** |
| 9 | **3.43** | 24 | **0** |
| 10 | **3.19** | 25 | **0** |
| 11 | **2.91** | 26 | **0** |
| 12 | **2.62** | 27 | **0** |
| 13 | **2.29** | 28 | **0** |
| 14 | **1.94** | 29 | **0** |

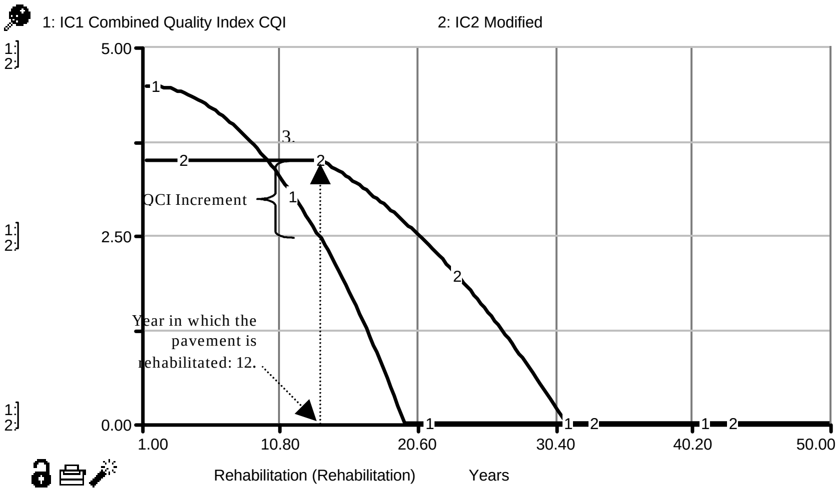
FIGURE 9. Alternative 1. Exogenous effects over functional quality of rigid pavement during its life cycle.

This simulation shows a minimum expected QCI (2.50) of between years 12 and 13. Compared with the original proposal, the total life cycle is reduced about 35% (7 years); this is because environmental variables increase the deterioration level, since rain weakens the subgrade, and the subgrade is altered by additional earth volume (embankments) while changes in temperature produce a fatigue process in the concrete. Additionally, the embankments are considered as probable failures zones.

### *Alternative 2 Simulation: Rehabilitation Decision*

Alternative 1 simulation is more reasonable than the original. This was used to introduce rehabilitation activity. The CQI terminal is set at 2.50, and when rigid pavement reaches that level a rehabilitation activity will increase the CQI to 3.50. It is possible to determine the life cycle impact with these kind of decisions, since the model user can prove several rehabilitation values (CQI modified).

In Figure 10, the functional quality curve indicated as “1” indicates alternative 1 simulated previously. The functional quality curve indicated as “2” represents the rigid pavement life cycle improvement. Figure 11 presents a simplified version of the functional quality simulated in this alternative.



**ALTERNATIVE 2 SIMULATION**

| YR | CQI | YR | CQI |
|---|---|---|---|
| 0 | **4.50** | 15 | **3.20** |
| 1 | **4.49** | 16 | **3.06** |
| 2 | **4.45** | 17 | **2.91** |
| 3 | **4.38** | 18 | **2.76** |
| 4 | **4.28** | 19 | **2.59** |
| 5 | **4.16** | 20 | **2.41** |
| 6 | **4.02** | 21 | **2.22** |
| 7 | **3.85** | 22 | **2.02** |
| 8 | **3.65** | 23 | **1.81** |
| 9 | **3.43** | 24 | **1.59** |
| 10 | **3.19** | 25 | **1.36** |
| 11 | **2.91** | 26 | **1.11** |
| 12 | **3.50** | 27 | **0.86** |
| 13 | **3.44** | 28 | **0.59** |
| 14 | **3.33** | 29 | **0.31** |

FIGURE 10. Alternative 2. Rigid pavement life cycle is improved through a rehabilitation activity, when it has reached its CQI terminal (year 12).

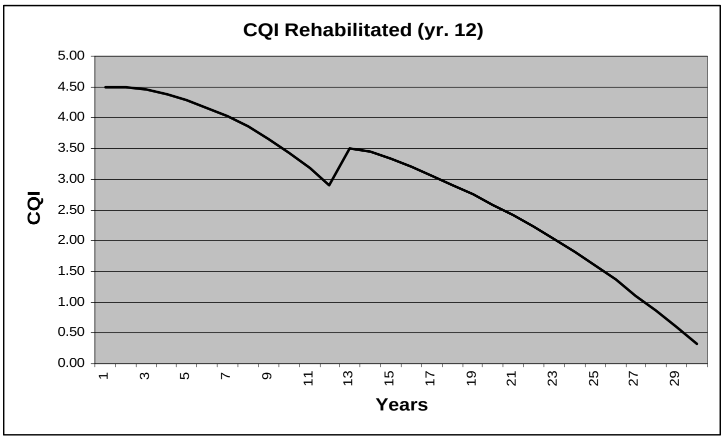


FIGURE 11. Alternative 2. Complete functional quality curve.

The CQI change can be observed through year 12 to 13.

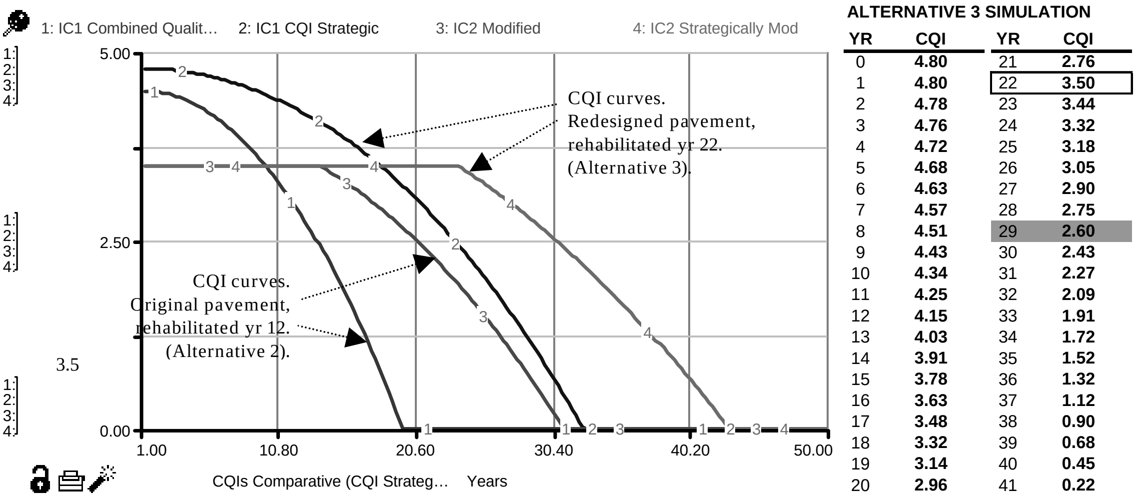
## *Alternative 3 Simulation: Strategic Design*

An alternate design is presented in this simulation. The strategic design allows visualizing different rigid pavement proposals to help the decision-maker to obtain the best choice confronting cost and service life. It is known that an increase in pavement load capacity ensures a longer life; it is possible to determine with this section how long the pavement will be functional.

Below, the proposal for alternative 2 and the present one can be appreciated. Other variable values correspond to those in alternative 2.

| Alternative 2 | | Alternative 3 | |
|---|---|---|---|
| **Variable** | **Value** | **Variable** | **Value** |
| D11 Equivalent Single Axles Load | 11.8 M. | Strategic Equiv. Single Axles Load | 31.9 M. |
| D1 Slab Thickness | 10" | Alternative Slab Thickness | 11" |
| D4 Modulus of Rupture | 640 psi | Alternative M. of Rupture | 680 psi |
| D7 M. of Subgrade Reaction | 132 pci | Alternative M. of Subgrade Reaction | 150 pci |
| D9 Initial Serviceability | 4.5 | Alternative Initial Serviceability | 4.8 |
| Rehabilitation Level | 3.5 | Rehabilitation Level | 3.5 |

In Figure 12, functional quality curves “1” and “3” represent the pavement performance simulated in alternative 2. The curves “2” and “4” indicate the pavement life improvement because the strategic design. Figure 13 shows a simplified representation of the functional quality curves.



CQI curves. Redesigned pavement, rehabilitated yr 22. (Alternative 3).

CQI curves. Original pavement, rehabilitated yr 12. (Alternative 2).

ALTERNATIVE 3 SIMULATION

| YR | CQI | YR | CQI |
|---|---|---|---|
| 0 | 4.80 | 21 | 2.76 |
| 1 | 4.80 | 22 | 3.50 |
| 2 | 4.78 | 23 | 3.44 |
| 3 | 4.76 | 24 | 3.32 |
| 4 | 4.72 | 25 | 3.18 |
| 5 | 4.68 | 26 | 3.05 |
| 6 | 4.63 | 27 | 2.90 |
| 7 | 4.57 | 28 | 2.75 |
| 8 | 4.51 | 29 | 2.60 |
| 9 | 4.43 | 30 | 2.43 |
| 10 | 4.34 | 31 | 2.27 |
| 11 | 4.25 | 32 | 2.09 |
| 12 | 4.15 | 33 | 1.91 |
| 13 | 4.03 | 34 | 1.72 |
| 14 | 3.91 | 35 | 1.52 |
| 15 | 3.78 | 36 | 1.32 |
| 16 | 3.63 | 37 | 1.12 |
| 17 | 3.48 | 38 | 0.90 |
| 18 | 3.32 | 39 | 0.68 |
| 19 | 3.14 | 40 | 0.45 |
| 20 | 2.96 | 41 | 0.22 |

Figure 12. Alternative 3. Strategic design compared to a rehabilitated pavement.

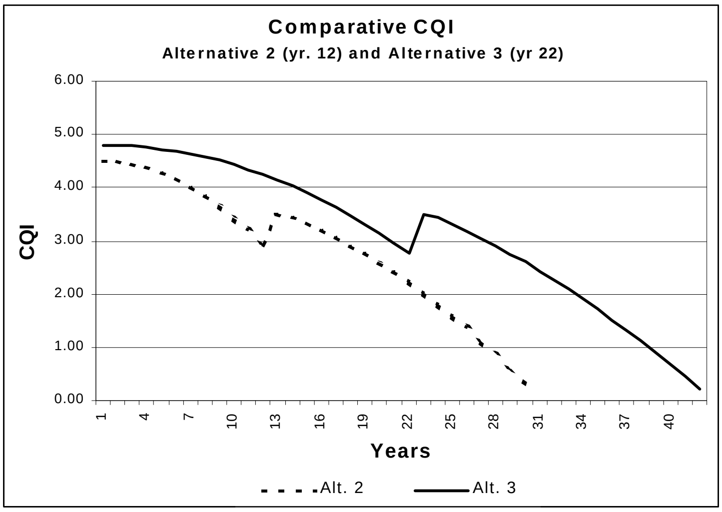


Figure 13. Alternative 3. Original pavement (Alternative 2) and redesigned pavement (Alternative 3).

The CQI change can be observed through year 21 to 22 on alternative 3.

The CQI increase shown in this alternative, improves pavement functional quality by almost 10 years as compared to that simulated in alternative 2. The rehabilitation strategy improves pavement functional quality by 7 years for any proven alternative. This case illustrates that the pavement in alternative 3 will perform better with any rehabilitation activity than the other analyzed in alternative 2 even with rehabilitation.

At network level planning phase, designer may compare both alternatives: original design with rehabilitation and strategic design without rehabilitation, then select the best choice according to assigned resources and available time. The cost-time comparison as a function of CQI may let several strategies arise and allow identification of the optimal one with most future added value.

## Conclusions

1. The Functional Quality Model of Rigid Pavement Systems simulates joint reinforced concrete pavement (JRCP) performance during its life cycle; it is expressed through functional quality curves. The information obtained from these curves is useful to pavement management to determine the present and expected condition of a single highway or overall pavement network. Future rehabilitation strategies can be proven in order to get the better design-maintenance-rehabilitation combination according to the particular endogenous and exogenous factors of the pavement.
2. The Combined Quality Index (CQI) holistic function is comparable to damage curves historically observed for unrehabilitated or rehabilitated JRCP rigid pavements [AASHTO, 1986; Hass, 1993; Hudson, et al, 1991; Jackson, et al, 1996; Li, et al, 1996].
3. The model presented pretends to understand (learning and abstraction) the rigid pavement system dynamics complexity. It is integrated by a high heuristic content, thus it has possible cognitive limitations for certain system variables. However, since there are no extreme variations in initial assumptions it can be considered to be a first estimate, a first systemic process to demonstrate the rigid pavement system operation.

4. The following estimations can be obtained from model sensibility analysis:
    - The service life of rigid pavement may decrease up to 21% due to mean embankments near to 30 m.
    - Climatic conditions: temperature variation and rain volume, are factors that influence rigid pavement performance [Darter, et al, 1996; Huang, 1993; Liu, et al, 1988]. The model estimates that these factors may reduce service life up to 31%.
    - The economic impulse in terms of periodic maintenance improves igid pavement service life up to 19%.
    - When CQI is renewed from 2.50 to 4.50 through rehabilitation activities, rigid pavement service life is prolonged to almost 14 years.

## Recommended Research

The following recommendations are proposed based on the actual study:

1. For a broader understanding of the environmental impact and other site conditions on rigid pavement systems, real and model deterioration curves can be compared. The model architecture allows the incorporation of needed variable adjustments for each particular case and design improvements for better performance of new pavement according identified environmental behavior.
2. The Functional Quality model should be extended to include all types of rigid pavement, by complementing the present efforts made to model different types of rigid pavements with the systemic point of view. The results obtained from the extended model may be valuable to the Long-term Pavement Performance (LTPP) of the Strategic Highway Research Program (SHRP).
3. Civil Engineering is an almost unexplored field to system dynamics. Since pavement may be treated as systems, there are many other situations that can be modeled from a holistic approach. Transportation is an example where dynamic complexity has been successfully applied, but other cases such as large-scale construction projects, maritime systems, space construction projects, regional and urban development projects are susceptible to being accessed from a systemic point of view.

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