# A Qualitative Analysis of Periodic Maintenance of Roads Understanding the Mechanisms in Pavement Management


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*Abstract*
Many transportation agencies are experimenting with innovative contractual arrangements for the procurement of construction, maintenance and operation of roads. They are changing from traditional contracts that prescribe the kind of work that need to be done in a specific section of the network, to more flexible contracts, increasing the contractors freedom to its maximum level, where the contractor itself decide which section, when and what kind of work he will perform, with the only condition of keeping a certain level of performance for a whole road network. Advanced computer models have been developed that estimate what would be the resulting road condition for given investment decisions and maintenance actions. Nevertheless it remains uncertain if contractors are given the freedom: What trade-offs would they make? Will road quality decrease? Will road agencies be able to monitor or control contractors? Before all these choices and freedom are transferred to the private sector, it is urgent to develop a clear view of the most important trade-offs that are now already made by the public authority. In order to contribute to the building of this understanding this paper explores the issue of road condition and some of the most relevant and conflicting aspects of it.



*Keywords*: management of road maintenance, procurement strategy, road policy, integral contracts, winter maintenance.

## I. Introduction

The public obligation of providing a transportation network can be divided in four different kinds of tasks, a) capital projects which means the construction of green fields projects or new roads, b) routine maintenance of the existing road network, which includes daily activities- that ensure the continuous availability of the road, and are mainly superficial- like roadway and shoulder maintenance (include pothole patching, crack filling), drainage, roadside vegetation maintenance, and winter maintenance and c) periodic maintenance of the same network, which refers to the management of pavements and the planning of activities required to return the state of the road to its original condition by repairing road damage and thereby substantially altering the asset condition. The following activities can be included in extraordinary maintenance: pavement strengthening, resurfacing, in-situ recycling, road mixing, and rehabilitation of existing pavements; d) operation of roads, which mainly includes incidental traffic and safety services.

For the delivery of these different kinds of activities, transportation agencies around the world have discovered that traditional project delivery methods and contracts do not meet current demands. Some of the problems being faced by Road Administrations around the world are; insufficient funds to meet satisfactory levels of all roads (Miller 2000; Cox, Molenaar et al. 2002; Pakkala 2002), little innovation (Manley and McFallan 2003), little value-added services for the client and a general lack of integration between the phases of the road life cycle.

In response, they are experimenting with innovative contractual arrangements that are mainly characterized by four aspects or trends (Altamirano and Haraldsson 2005; Altamirano and Herder 2006). First, with respect to project delivery, more and more projects are contracted for the whole life cycle of the road. Second, contractors are given increasingly more freedom or design space (Herk, Herder et al. 2004), as the indicators used for monitoring their work become less operational and more performance based (Cervera and Minchin 2003). The third trend, concerns project financing in which private investors are playing and increasingly higher role and governments follow a dual track strategy (Miller 2000); managing a portfolio of directly and indirectly financed projects; dependent on the project characteristics. Fourth, contracts are granted for longer term.

A large portion of capital projects and routine maintenance activities are already being contracted out in these new way in many countries in Europe; for example, 60% of the capital projects in Finland use Design-Build (DB) instead of the traditional Design-Bid-Build (DBB) approach, while all routine and winter maintenance activities are contracted integrally in the form of Service Area Agreements. Meanwhile periodic maintenance seems to remain rather traditional tendering work orders instead of integral long term contracts and selecting contractors on the basis of price and telling them what and how to do the different tasks needed.

This was found out from field research conducted in Finland, the Netherlands and Spain as part of a Cross-National Comparison of Procurement Strategies in Road Infrastructure (Altamirano, Herder et al. 2007). It is therefore in this sub sector of road management where important reforms and changes are expected in the near future. Finland tendered just last year 2 pilot projects for the maintenance of a large networks of concrete roads for 10 years (http://www.klekoon.com 2007) while Spain just one month ago, May 2007, listed the offers for the 19 year integral contracts of maintenance and operation of the main radial highways of Madrid (Casas 2006).

All these changes are taking place in the middle of much uncertainty and many knowledge gaps; partly driven by financial deficits of governments (as actors declared for the case of Spain), insufficient human resources in road agencies (as it seems the case in Finland) or simply trend following.

If we consider; first, the nature of the periodic maintenance tasks - activities that ensure the basis on which the routine maintenance act upon, the long term life of the road-; second, the non linear dynamics of the underlying road condition - with reinforcing degradation processes, time delays and besides not possible to check by visual inspections or otherwise very expensive to inspect – ; third, the relative higher impact these tasks have on the future condition of the road network - if compared with routine maintenance activities that are mainly superficial or with capital projects that per year would never represent more than 5% of the total extension of the network – ; the research of the possible consequences of these new contracts and procurement policies – that grant more freedom to contractors for a much longer period of time that traditional contracts- seems urgent. With the same urgency is needed more understanding of the most important trade-offs that are nowadays made on a daily basis by public servants in charge of these road networks and that are to be handed over to private agents.

In order to understand these trade-offs and the characteristics of this subsystem of road maintenance and shed some light on the risks that granting more freedom could pose, a qualitative (system) analysis has been conducted. Such an open box kind of analysis allow us to investigate future scenarios and discuss in a more structured way the possible implications of these new contracts for the condition of the road network, the economic performance of the system and the protection of public values.

The analysis carried out will be presented in this article as follows. First a short overview of the situation of periodic maintenance – actual organization, actors involved and possible scenarios in the future- will be presented and the system to be studied will be defined. Then will go further to explore, by using causal diagrams and loop analysis, the most important issues or trade-offs in the management of pavements (periodic maintenance). Finally it will expand to show how this system is part of a bigger environment where new changes are also being implemented and therefore continuously influencing the behavior of it – and to draw conclusions.

## Relevance of the work

Extensive work has been realized on the development of quantitative models (HDM models) by organizations as the WB (2000) to help road agencies make good decisions and planning of their maintenance actions. More specific mathematical models have been developed for the prediction of pavement deterioration rates (George, Rajagopal et al. 1989; Duffell and Pan 1996) and pavement life cycle management . However these models need careful "adaptation" to each country conditions – see the work of (Bennett and Chakrabarti 1994; Sharma 1994)- and seem to be more focused on developing countries where service levels and standards are somewhat lower and user's expectations and demands do not make visible some of the important trade-offs that road administrators of countries with more developed networks, like Finland or the Netherlands, face. They are actually meant as hand-on models for road engineers working in road agencies and treat therefore more operative and planning related decisions than strategic ones.

The analysis realized and presented in this article aims instead to reflect upon more strategic kind of decisions. The choice for white box analysis of the kind proposed by System Dynamics seems appropriate to discover the most relevant trades-offs faced by decision makers responsible for the maintenance of roads and to make them more accessible for policy makers in the area. As Mass describes: "A system dynamics model is intended to yield operational insights about feedback relations that can produce or contribute to problems, can counteract policy interventions, or can reinforce benefits of policy action aimed at high leverage points"(Mass 1991, p.68)

System Dynamics and other modeling techniques have certainly been already used to study road management and road policies. In an extensive literature search, three main groups of work, depending on the focus or research objective, have been noticed.

The first group treats with rather operational problems with a somehow lower level of aggregation. Here we can find works like the one of (Wang, Yang et al. 2005) on the prediction of traffic volume. The second group of works does show a higher aggregation level and tackles more strategically important issues of road procurement, but concentrates on project performance or performance of construction companies; and therefore has less relationship with maintenance and operation of roads, the main focus of our analysis. Here we find the works of Reichelt and Lyneis (1999); Lyneis, Kooper et al (2001); Chritamara, Ogunlana et al. (2002); Ogunlana, Li et al. (2003) and Lee, Peña-Mora et al. (2005).

The third group does research on road maintenance at the same aggregation level that the analysis we propose. Here we found important contributions in the works of Garza, Drew et al. (1998) ; Vassallo and Izquierdo (2002); Friedman (2006). First, Friedman (2006) investigates the impact of highway maintenance policies on accident development. He argues that a counter-productive policy may be creating serious consequences on road safety. He uses a system dynamics model to evaluate the effect of road condition on accident development, and the results ask for a reevaluation of the concept of maximizing road repairs. The analysis shows that an increase in repairs causes an increase, not a decrease, in the rate of accidents occurrence; "This is counter to both the reasoning and actions being taken by pavement managers to reduce the rate of accidents" (Friedman 2006,p. 378) . The results suggest that alternative highway design should be considered in order to decrease the rate of accidents and to avoid increasing spending aimed at improving conditions.

Second, we find the work of Garza, Drew et al. (1998). The difference with the previous one is that it does not research on the issue of safety and it rather concentrates on the classification of factors and the description of the model; and less on presenting the understanding gained by building and using the model. This is probably the result of the original aim of the study. The model was developed as a comprehensive Decision Support System for Virginia Department of Transport (VDOT) and it is consequently more similar in capabilities to the HDM models than to the model developed by Friedman.

Finally, another key work is the one of Vassallo and Izquierdo (2002), which even though it does not use System Dynamics, it does develop a complete and integrated model of road management and it is therefore interesting to review. Vassallo and Izquierdo (2002) also touch upon financing and maintenance of roads, but from a different perspective than Friedman. Their work is also different from the one of Friedman, since they do not evaluate the impact of financing on safety. It is different than previous works in that they do not estimate best investment strategies for fixed budget policies, but they instead research the benefits in terms of productivity increase;

of different financing and contracting formulas. These formulas range from public budgets to levying a variable charge (proportional to the capacity for deterioration of each vehicle class) on road users to finance road maintenance. Here special attention is given to performance-based maintenance contracts and indirect financing, two of the 4 trends previously mentioned. They developed a model comprised of 5 sectors (pavement deterioration, transport cost, maintenance expenses, traffic volume and management and financing sub model); of which 3 condition-related ones are mainly based on the mathematical equations of HDMIII and HDMIV models. They validated results with an application on a secondary road in Spain. They concluded that there is no great deal of difference between total benefits of the different mechanisms, but only if optimum resources are allocated and it is precisely in this problem of insufficient funding where indirect financing could help removing the budgetary barriers.

However, between the practitioners in the road sector, the use of System Dynamics for the decision making process does not seem to be widely spread and the daily business of maintaining the road network seems rather characterized by specialized studies realized by different experts, who emphasize or advocate for different problems depending on the perspective they take when studying it or the role they play in the road agency.

A large amount of technical research has been undertaken by mechanical engineers on road deterioration, road design and related issues, but most of this work aims at explaining or developing model for one single causal relationship. Within the so called "vehicle dynamics" –from mechanical engineering- many authors research on the impact of automotive technology on road deterioration. This is rather important since changes in this technology could dictate the obsolescence of many relationships (as the Vehicle Operation Cost or VOC) that form the basis of the HDM models. Some of the causal relationships explored in this discipline are: the relationship between vehicle design and road deterioration rate (Ahmed, Gawthorpe et al. 1985; Ren and Jin 2004; Ren, Zhang et al. 2005) , between road condition and drivers' experience (Schiehlen 1984; Misun 1990) of the road and between road design and vehicle speed control and therefore safety (Salau, Adeyefa et al. 2004). Other specialists have researched widely on the impact of winter weather conditions on maintenance costs and fewer on the impact of these conditions on safety (Strong and Shvetzov 2006) .

In this way – road engineers emphasize the problems of cracks and ruts, and propose measures as reconstruction and enforcing the strength of unbound structures. Meanwhile traffic experts see the "road network" and its condition as given (assuming total availability and serviceability or at its maximum considering it a constrain) and focus on problems such as travel time, best routes and would probably propose expansion of the network and on time travel information.

The user's too have their view and for them is important the service they receive as a whole, independently of who is the responsible for it –winter maintenance or periodic maintenance- they judge the road system, not the physical network apart from the services. But important to remember is that they also have an influence on the way the system behaves and performs.

Therefore the construction of a system view, and when possible a simulation model could be of great help to understand the behavior of the system as a whole, to discover and understand the tradeoffs between decisions of one area of expertise and another, and their consequences; to discover solutions with more synergetic power (leverage points) and longer term effects; and even to communicate with society about their own responsibilities and the hard choices that need to be made.

## II. The Sector of Periodic Maintenance of Roads

Until now the design freedom given to contractors is quite small. Periodic maintenance is outsourced but payments and quality controls are done immediately after the project is realized with no functional specifications but rather supervising them in the process and the final thickness of the pavement, roughness, and other physical characteristics. Projects are until now also tendered as work orders, for small sections and one time works. Therefore the contractual relationship last has a very short time, last only the same time than the duration of the work.

Nevertheless plans for the future are either to combine periodic maintenance with routine or winter maintenance activities (like snowplowing and deicing) and eventually with operation tasks; or to reorganize the actual work order kind of contracts into bigger work packages like all the bridges of a municipality or road sections of longer extension. Both possibilities envision longer term contracts and would require a different distribution of responsibilities and risks between the actors already active in this sector, like contractors, consultants – in design and geotechnical areas- and of course the Road Agency.

### Maintenance Management Cycle

The Maintenance Management Cycle consists of main tasks such as Policy, Management, Programming, Planning and so forth, which translate progressively very general guidelines into a concrete list of "works" to be realized by each district or region and further into a set of contracts to be tendered.

Until now the regional offices have done the Programming, Planning and Procurement themselves, with some support from consultants. Nevertheless there are plans to organize contracts and activities in such a way that; either contractors take care of the whole process starting even from planning and hire consultants as subcontractors; or the other way around, consultants may do all the activities from programming on and hire themselves construction contractors. In total there are 4 possible arrangements.

### Future Scenarios in Periodic Maintenance

Possible future scenarios for the maintenance of roads are the following:

1) Traditional situation: where Road Administration tenders out a specific section of the road and with a specific action and mix of bitumen's prescribed.
2) Contractors are hired to repair a specific section of road, not told exactly what to do, but expected to give a guarantee of 5 years.
3) Contractor takes care of a whole area, programming and planning, is paid a fixed service fee per year (lump sum) and in coordination with Design Consultants perform the proper works to ensure a certain Service Level of Annual Objective ( I.E. 80% of Roads are in Sufficient condition).
4) Design consultants take care of a whole area, they are paid a fixed service fee and they are the ones who hire construction subcontractors and look after the quality of their job, in order to ensure a certain Service Level.

## Actors

"The process of identifying and creating the knowledge which is relevant to the problem environment starts with identification of main (real-life) actors within that environment (Wenzler 1996) . The most important actors in the sector of periodic maintenance are:

- Road Administration (Headquarters). Goal: keeping the national road network in a condition that ensure certain public values (mobility, accessibility, and so forth)
- Road Administration regional offices. Goal: keeping the local road network in the condition required by higher government levels. "Their drive is to not only to keep roads in a usable condition but to also keep the rate of accidents, and their associated costs to a minimum " (Friedman 2006, p. 374).
- Contractors. Goal: To earn Money by maintaining roads.
- Design consultant. Goal: To earn Money by delivering information to consultants or the Road Administration.
- Users and residents. Goal: to reach place A or B, comfortable, fast and safe trip.
- Society in general: keep the number of accidents at its minimum.

## The problem

Advanced computer models have been developed in both countries that can calculate what would be the resulting road condition for given investment decisions (prioritizing high or low volume networks) and actions (from very light actions such as filling potholes to very heavy actions such as reconstruction of structural or unbound layers). Nevertheless it remains uncertain what kind of decisions would be better to leave to consultants, to contractors or to the Road Administration, given their special know-how and interests; and therefore which arrangement or scenario would be the best. What decisions would they actually take, given the different weights they may assign to technical, economical or political criteria?

Further, if contractors are given the freedom: What trade-offs would they make? Will Quality of Road decrease or actually increase? Will efficiency in the sector decrease or increase? Will Regional Road Administrations be able to monitor or control contractors? How would the private road maintenance sector develop?

All in all, before all these choices and freedom are transferred to the private sector, it is urgent to develop a clear view or understanding of the most important trade-offs that are now already made by the public authority. In order to contribute to the building of this understanding the following sections will explore the issue of road condition and some of the most relevant and conflicting aspects of it.

## Defining the System

For the study of the periodic maintenance system the following boundaries have been set:

- The physical road network and its condition will be explored, assuming a fixed quality or level of service of winter maintenance
- The causal map represents the interrelations for either of the networks –low volume and high volume-. The importance or magnitude of these relationships will be differentiated by assigning different parameters when the specificities of the model are being worked out in a further stage.

- Seasonal differences –like the problem of sliding during the winter or hydroplaning during the summer- will be also worked out properly during specification of the model.

Once fixed the boundaries for the system analysis, it is important to define the main outcomes to be considered and that will serve as reference point to weight the different trade-offs and make proper decisions between different policy alternatives. The outcomes of interest considered, taking the public road authority as the problem owner, are:

- Environmental pollution
- User's cost: understood as travel time plus vehicle cost (e.g. change of tires)
- Actual level of service: offered to users – as defined in the 5 classes or condition categories being used by many national governments[1]- and being the result of; actual overall (physical) road condition and quality of routine maintenance.
- Societal costs: understood as the number of accidents and specially of fatal accidents taking place on the road network
- Total costs of periodic maintenance

The main factors that influence the performance of this system and that are not under the control of the Road Authority:

- Demand for heavy and light traffic (we considered them dependent on the different sectors)
- Climate and/or weather and herein more specific: temperature, moisture, rain, and circumstances on the road.

Further, not under the control of the pavement managers:

- Quality of routine maintenance
- Regulations for summer and winter tire (and other seasonal regulations)
- Users' driving behavior, like driving speed
- Regulation on heavy vehicles

Now considering the instruments, measures that can be taken to influence the performance of the system, we could mention –from lighter to heavier:

- Reparation of potholes and similar problems
- Heating up of old pavement
- Paving or resurfacing
- Reconstruction

Besides these instruments there are all kind of parameters or standards that make part of the policies of the Road Administration that also influence the performance of the system, for example:

- Coverage of the maintenance action[2]

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[1] Belgium, the Netherlands and the UK use a system of 5 categories – very good, good, reasonable, mediocre and bad- to classify the condition of their roads. A condition of 1 means perfect or very good with no signs or damage or just signs of initiation and a condition of 5 is bad with a degree of damage that represents a threat to safety and functionality.

- Threshold values
- Weight limits

All the elements reviewed lead to a system depicted as follows (see Figure 1).

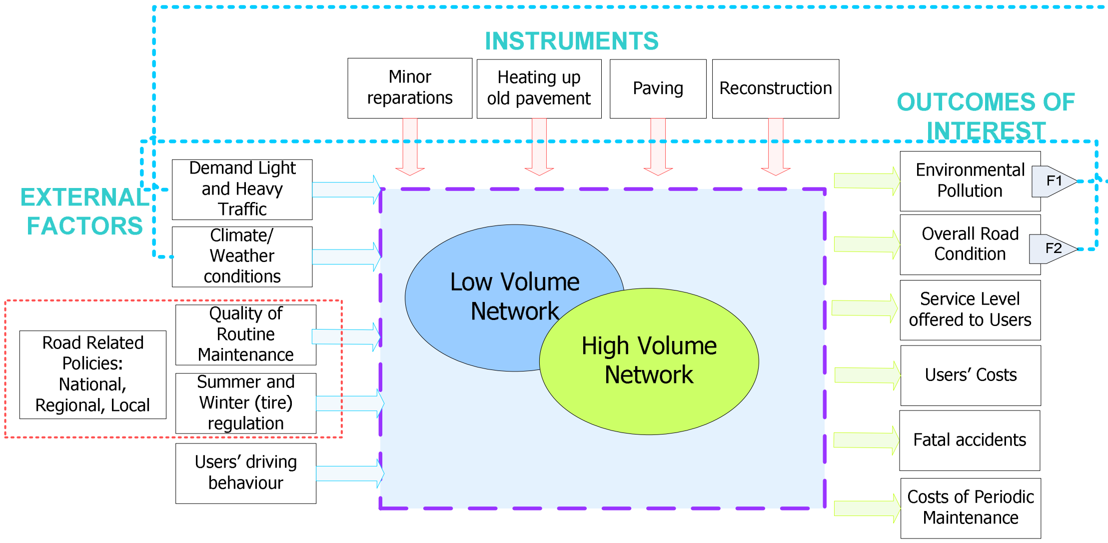



**Figure 1 System Diagram of the Pavement Management System**

## Defining Road Condition or Level of Service

Since the main indicator for periodic maintenance is and will continue to be the condition of the road network, it is essential to give first an outline of all the aspects that define this condition or the so called serviceability of the pavement. These aspects will come back in all the causal diagrams that will follow.

| Profile | Variable | Proxy | Meaning | Direction |
|---|---|---|---|---|
| Transversal | Ruts | | The lateral profile of the road is important for the safety of driving and the comfort of the driver. Distinctive lane grooves can make additional steering powers necessary and can lead to aquaplaning. The relevant quantities for the lateral profile of the roadway are the depths of the lane grooves, the depth of the profiles and the theoretical water gauges under the right and left wheel of a lane. | The less the better |
| Longitudin al | Longitudin al evenness | IRI | The IRI (International Roughness Index) measures the cumulative deviation from a smooth surface in inches per mile (or meters per kilometer). The difference with texture is that this includes the dynamics of the vehicle and the wavelength is different. | The less the better |

[2] Coverage of the maintenance action is to some extent a measure of the efficiency of it. It quantifies how many meters were in poor condition of the total road section repaired with that action.

| | | | | |
|---|---|---|---|---|
| | Road texture | | Texture means the geometric fine shape of the road surface, expressed in the parameters wavelength and amplitude. Texture contains form, size and distribution of the aggregates. Texture ranges from a wide wavelength spectrum from micrometer to decimeter. One distinguishes between micro texture, macro texture and mega texture. Wavelengths above 0.5 m are assigned to evenness. The parameter labeled here as texture belongs to macro texture. | |
| | Categories | Micro Texture | (up to 0.5 mm wavelength) | |
| | | Macro texture | (0.5 mm - 50 mm wavelength) In moist conditions the macro texture of a road surface is essential for the drain behavior and the level of the tire grip. | The more the better |
| | | Mega texture | (50-500 mm wavelength)<br>This variable is associated with the roughness (or evenness) of a road and therefore causes: sound, tire wear and rolling resistance (fuel use) | The lowest the better |
| Structural Defects | Cracks | | The phenomenon of cracks is a difficult one. Cracks can be classified as: transversal, longitudinal, edge, alligator or multiple cracking. A proxy that can be used to measure them in general is percentage of surface cracked. | The less the better |
| | Sum of defects | | Important for low volume roads, and if structural strength is not known could be important to have this measure. | The less the better |

**Table 1. Condition variables for a road section**

The most important condition variables – defined in Table 1- are:

a. Referring to the condition of the Unbound Structure: Structural Strength or bearing capacity
b. Referring to the condition of the Bound Layers or Surface: There are two profiles that measure the condition of the surface layer, transversal and longitudinal. The transversal profile include ruts, and sum of defects. The longitudinal includes longitudinal evenness (IRI) and road texture. The longitudinal profile of the roadway is important for the driving comfort as well as the driving safety.
c. Besides in a somewhat different category is the phenomenon of cracks that also define the condition of the road but cannot be considered part of the transversal or longitudinal profile alone. Ruts together with sum of defects are considered structural defects because their appearance points out to the probable low quality of the unbound structure.

Further it is important to explain that road condition could be decomposed in three aspects:

- Actual or real condition in certain point in time – which is a stock
- The deterioration taking place yearly – which is a yearly rate and therefore a flow
- The upgrading taking place- which is like deterioration a flow

For the specification of road condition – when building the model- two alternatives are possible within the system dynamics methodology. First, as presented in Figure 2 where road condition is considered a continuous scale with a numeric value. Then upgrade is considered an inflow that increases the road condition and deterioration and outflow that decreases

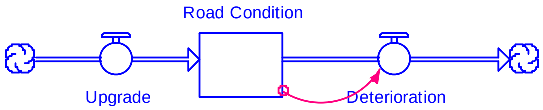



**Figure 2 SFD for Road Condition when considered a continuous scale**

Second, when road condition is to be conceived not as a continuous scale but rather as a group of different stocks that relate to different condition categories (A, B, C, and so forth); then the best option is to consider deterioration as a flow that brings roads in top quality to become roads in a lower quality and contrarily, upgrades would bring roads in a lower class to a higher one. This could be probably the best option given the actual classification used for road condition and the units used in many of the measurements, which normally are road sections of a determined length.

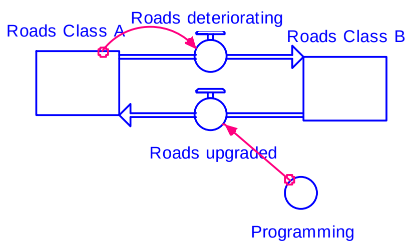



**Figure 3 SFD for Road Condition when considered as a set of intervals**

The final choice will depend on the abstraction level used and the purpose of the quantitative model. It will depend whether the goal is to simulate one single section of the road and the behavior of it throughout the years or to simulate the behavior of the whole national network. At the national policy level, the discussion about road condition and the setting of goals is mainly based on the statistics that classify roads in different condition categories -mostly five- from very good to very poor where the road is considered to have no more functional life. Nevertheless most of the quantitative data available is in terms of deterioration levels or damage rating for each of the aspects previously mentioned –cracks, rut depth, texture, and so forth- in a separate way and remains difficult to define which level of damage for each of these aspects make a road section classify in top or mediocre condition.

## III. Exploring the causal relationships and discovering trade-offs

In the following sections the different parts of the system will be reviewed and a causal analysis will be realized for each of them.

### Winter tire condition vs. rut depth

In this causal diagram are shown the two opposite effects of winter tire condition (grip or skid) on safety, represented by number of accidents:

- First, a direct positive effect -more important during winter- by increasing the total friction between tires and road, which makes easier for drivers to keep control of their cars and therefore reduces the chances of accidents.

- Second, a negative effect -more important during summer- due to the acceleration they cause in the deterioration rate of the road, through the phenomenon of Wear and Tear. The heavier the tire skids the more the rutting deterioration rate and the actual rut depth. The deeper the ruts on the road, more water can be accumulated (in case of rainy road circumstances) increasing the chances of hydroplaning accidents.

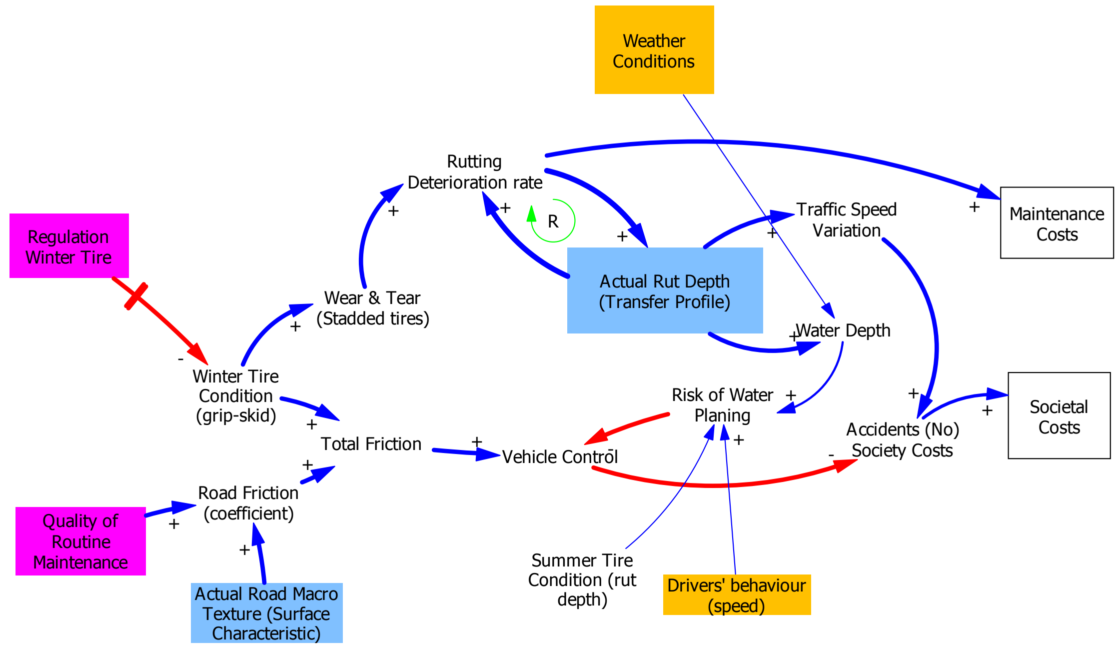
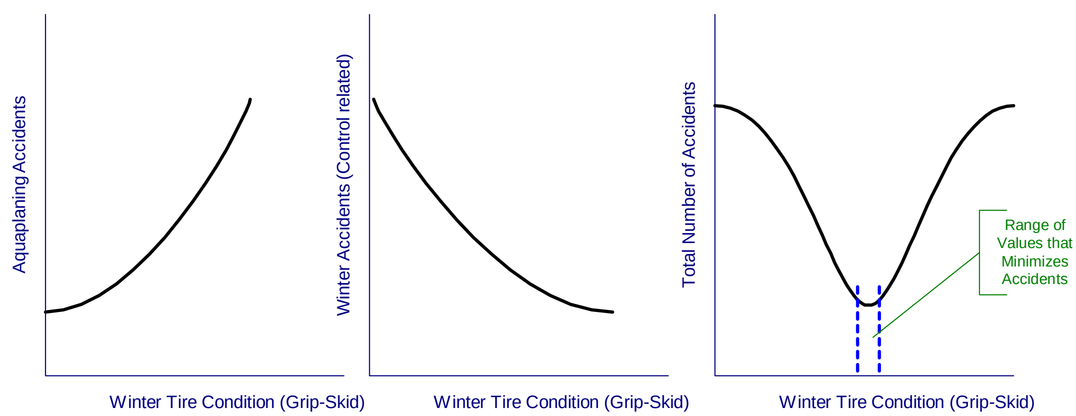



**Figure 4 Causal Diagram of winter tire condition vs. rut depth**

It is therefore important to weight both effects and find the range that is best for reducing both kind of accidents, or that allows the most cost effective maintenance of the road. As shown on the following curves, the variable Winter Tire Condition does not have a single direction but rather shows a (asymptotic) parabola like behavior (as shown in curve c), which results from the combination of both effects previously explained and shown in curves a and b.




(a) Hydroplaning accidents (b) winter accidents ( c) total number of accidents

**Figure 5. Effect of winter tire condition on the number of accidents**

The boundaries of the system can be broadened to explore the impact of other policies in the friction related accidents. By doing so we discover that total friction can be increased also through a higher service level of winter (routine) maintenance or improving the macro texture of the road section. Therefore it is important to research the maximum levels possible of these different variables and their behavior in terms of costs (it is achieving the last 5% much more expensive than the first 95%?). Once information about these different aspects is known, better informed decision making could be achieved, a process that will include, for example, the following possibility:

- Could it maybe be invested extra in winter maintenance actions what is now invested in the reparation of ruts and achieve in this way a much better performance in terms of safety and costs?

Important to notice in this first causal diagram is the reinforcing loop that takes place in the rutting process (the more the Actual Rut Depth, the bigger the Rutting Deterioration Rate and the higher this, the more the Actual Ruth Dept will be) and which could provoke a fast and exponential process of deterioration. Such reinforcing processes do not seem to take place in the area of routine maintenance. This could mean that one could expect an investment in the reduction in the rate of Rut Deterioration to be more effective or have a higher impact in the overall performance of the system (in terms of safety) than other measures with the same cost. In other words, it could be more effective to try to increase friction through other ways that do not activate or worsen the Rutting Deterioration Rate as the winter tire grip does.

It seems also then that improving winter maintenance is an easier point of influence, since this does not show side effects, as winter tire skids do. Here the questions would be, can we really improve the quality or winter maintenance much further?

Other aspects to be noticed are the factors dependent on road users – that could also be a way to solve the whole issue of safety and risk of hydroplaning. Here only two are considered:

- Driver's behavior, mainly speed
- Summer tire condition

## The Influence of Routine Maintenance

Continuing along these lines, Figure 6 explains in more detail all the factors that play a role in Road Friction and Vehicle Control, and ultimately result in Societal Costs (mainly accidents). These factors are:

- Quality of routine maintenance (through the use of sand and salt , snowblowers and de-icing equipment) and Macro Texture of the Road
- Condition of Winter Tire
- External Factors such as drivers' behavior and weather

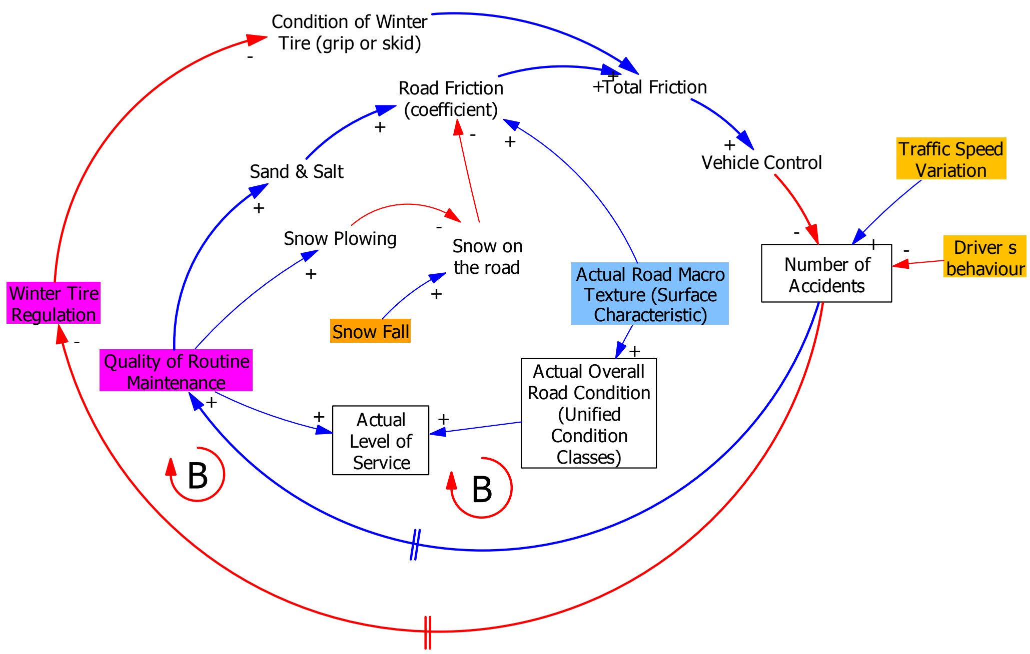



**Figure 6 Causal Diagram of Routine Maintenance Sector and its influence on the system performance**

In the diagram we can see two important balancing loops. The first goes from number of accidents to Winter Tire Regulation and total friction. The number of accidents during this winter – if exceeding a certain value - will probably have an effect on next year winter tire regulation, specially if the statistics show an important increase, the government will probably allow next winter tires with more grip. Though other solutions may be better, this is an immediate measure that makes everybody –especially drivers- feel more in control of the problem.

The same happens in the second balancing loop with the quality of routine maintenance required from contractors. However, it is important to mention that this policy may have a limit, since it may be too expensive or impossible to reach higher standards of winter maintenance after a certain threshold.

These two balancing loops and delays will probably cause oscillating behavior of the system performance in term of number of accidents. If one considers the effect of winter tire regulation on hydroplaning, here instead of a balancing loop a reinforcing loop would be turned; one that will gradually along the years mean a continuous deterioration of the road network.

## Structural strength and the influence of heavy traffic

From all the causal relationships shown in Figure 7 the most important to mention are the two big feedback loops, one reinforcing and one balancing. In the balancing loop we see first that demand for heavy traffic is created due to the growing activity in public transportation and industrial, commercial and agricultural sector. This demand results in more heavy traffic flowing through the road network, which increases the structural strength deterioration rate and therefore worsen the actual structural strength of the network. The lower the structural strength of the road, the more cracks will appear making the overall road condition and experience of the road by users less appealing, reason why heavy traffic would choose to opt for an alternative network. This alternative network probably comprises secondary roads which besides being less good prepared to carry heavy weights represent longer journeys. This lower capacity to carry heavy weights is what gives origin to the reinforcing loop of further road deterioration.

All in all if the condition of the road is so bad that heavy traffic reallocate to other networks, their travel distance and travel time will increase (which directly increase their costs and reduces their competitiveness in the market of transportation) making the transport sector in that country or area less attractive. This lower attractiveness could eventually or in the long term translate in a decrease in demand for Heavy Traffic. This will happen with bigger probabilities if the time the network remains in bad condition is long enough and if there are alternative ways of transport mode or routes in neighboring countries. In this way the loop is closed and the initial high demand of heavy traffic, affected itself back in a negative way, or in other ways, it balanced itself. However, the problem here is the presence of a reinforcing loop in the deterioration process, which means that even assuming that heavy traffic will diminish, once the condition of the road is poor, it will keep getting worse and worse in a faster pace. In the meantime the competitiveness and attractiveness of the national transportation network will diminish.

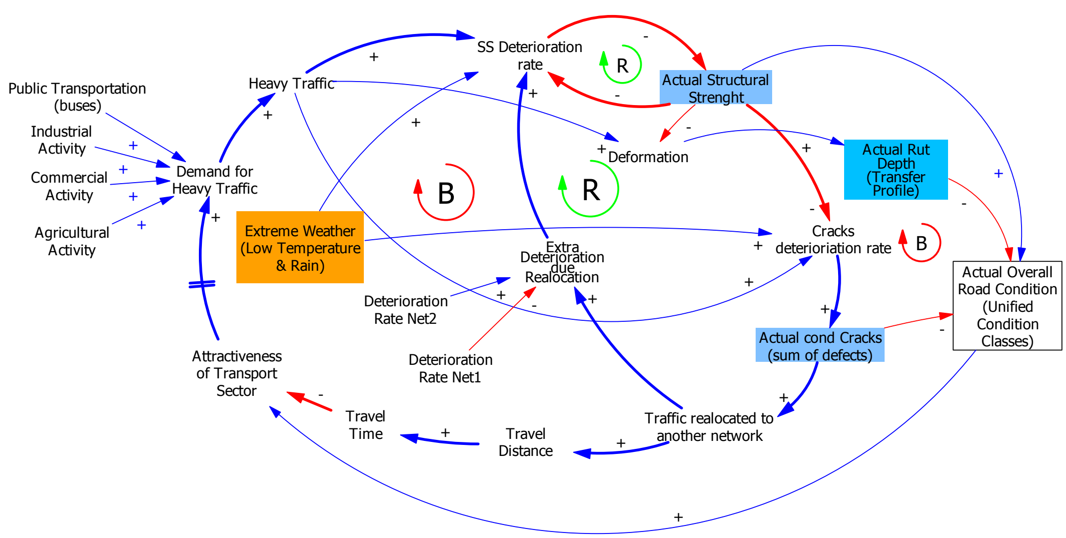



**Figure 7 Causal Diagram Structural Strength and consequences of heavy traffic**

The main reinforcing loop starts with a higher deterioration rate of structural strength, which worsen the overall road structural strength, accelerating the process of creation of cracks and worsening the road condition (sum of defects), which as explained before, result in heavy traffic choosing for an alternative networks. If this second network being opt for has a lower structural strength than the initial network, the more heavy traffic is making of it, the more extra deterioration will take place, accelerating the process of deterioration of structural strength of the overall road network. In this way the deterioration process reinforces itself, creating a sort of vicious cycle; unless corrective actions are taken on time.

## Interdependencies between condition variables and users' perception

In the administration of roads there has been an increase in the use of performance indicators not only for the internal management of the assets but also for determining payments of contractors. Therefore it is expected that these indicators will become integral elements of the new periodic maintenance contracts between road agency and contractor. There are ongoing discussions about the idea to give –within this list of indicators- higher importance to users' opinion about their experience of the road and the service delivered by the responsible contractors. To contribute to these discussions, it becomes necessary to analyze how all these condition variables – previously listed and explained- used for the planning of periodic maintenance activities; are interconnected between them and with the driver perception of the road.

Figure 8 shows these variables, the factors that influences them and how them, in combination with external factors (i.e. traffic, temperature, demand) result in good or bad performance in terms of users' satisfaction and users' cost, environmental effects and actual level of service.

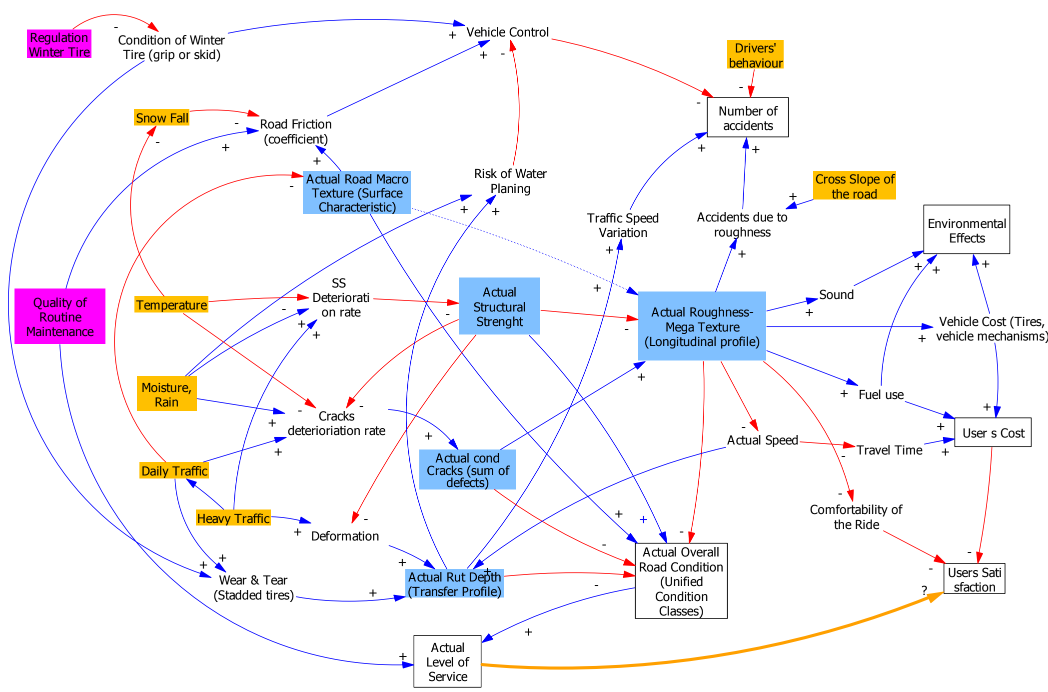



**Figure 8 Causal Diagram of the interdependencies between Condition Variables, Users' Satisfaction and other Outcomes**

In order to understand better the different causal relationships shown, we will first define what is meant by the actual overall road condition, then we will explain the effect of the different external factors in the road condition, and finally we will explain the different outcomes or key performance indicators of the system.

As shown on Figure 8, overall road condition depends on:

- Structural Strength: the more the better the condition of the road
- Macro Texture: the more the better, but notice that this has a limit. As explained before if this surpasses the value of 0.5m of wavelengths, then it is not

considered as macro texture anymore, but rather an issue of evenness or roughness. For this reason these two has been separated in the diagram.

- Cracks: the more cracks, the worse the situation of the road.
- Rut Depth: the bigger the rut depth, the worse the situation of the road.
- Roughness: the more the worse the condition of the road.

Here it should be highlighted that these condition variables are interdependent and with one exception (that relationship between macro texture and roughness) reinforce each other. So if the structural strength of roads is higher, the fewer problems of roughness, ruts and cracks will roads undergo. In the same way if a road has more cracks, the worse will be the problem of roughness in that road. The case of texture is different, because if this increases more and more –which in the one hand is considered good-, the condition of the road in terms of roughness will get worse.

Now the variables defining road condition have been reviewed, we can look at the effect of external factors in the condition of the road:

- Temperature: in general one could say that the lower the temperature, the worse the consequences for road condition. Extreme low temperatures affect negatively structural strength and accelerate the creation of cracks. Besides, low temperatures together with road circumstances (in this case snow) affect the road friction coefficient negatively, increasing the chances of accidents. Since structural strength influences the other road condition variables in an important way, one could say that extreme low temperatures are the external factor with the worse effect in the Finnish network. One that makes the problems of road administration in Finland very different from the problems faced in the Netherlands or elsewhere.
- Moisture and rain: these have also a rather negative effect on the road condition. The more moisture is on the roads, combined with extreme low temperatures, the faster the process of deterioration of structural strength and creation of cracks. Rain also has a temporal effect on the safety aspect, as temperature has it through snow. In this case, if it rains and there are problems of ruts in the network, the chances of aquaplaning accidents increase.
- Traffic: as could be expected, traffic understood as use of the road, has a degrading effect on the condition of the road. Heavy traffic in particular weakens structural strength and accelerates deformation and the creation of ruts, while traffic in general affects negatively the road texture, and accelerates the creation of ruts and cracks.

Finally, we can explain the outcomes or performance indicators of the system:

- **Level of service**: the level of service offered to users is the result of the combination of purely physical road condition (more pavements related) and the quality of routine or winter maintenance.
- **Societal costs** –number of accidents: apart from the direct cost of individual users, there are societal costs, which in this case are considered to be mainly accidents. We can distinguish 2 main causes of accidents: loose of vehicle control (where aquaplaning is the cause during summer and too little road friction the cause in winter) and traffic speed variation (because if there are ruts, people start breaking).
- **Environmental effects**: the 3 main effects mapped here are sound, pollution due to usage of fuel, and pollution from the extra wear and tear of tires.

- **Users' cost:** in users' cost we distinguish the direct costs they have due to the degrading of their vehicle (i.e. replacement of tires, reparation of vehicle mechanisms) – which are reduced the better the condition of the road- , their costs due to additional fuel consumption and the indirect costs of travel time.
- **Users' satisfaction**: the satisfaction of users is not only determined by their costs but also by the comfort of the ride they experience. Their satisfaction not always directly relate to the overall road condition. Research is still going on about which aspects of road condition matter the most for the experience road user's have of the road.

This last aspect, users' satisfaction, deserver further discussion, since is till certain extent a contra intuitive result. The fact that road condition does not directly correlate with users experience rings a bell if decisions are to be made whether to make users opinion decisive of contractors' payment, in the new maintenance contracts. In the previous graphic it can already be seen how some aspects or road condition variables that ensure a safer ride, affect negatively the comfortability of the ride and consequently the perception of the road user. The following section shows other possible problematic aspects that may arise, if drivers' experience of the road is assigned relatively more weight than other performance indicators.

### Efficiency versus Users' Satisfaction: the battle of two public values

Figure 9 shows the trade-off between two public values, the efficient use of public funds and the focus on users' satisfaction. While society in general demand an efficient use of funds, which means that the threshold value of coverage needs to be higher (percentage of coverage is the measure of efficiency of the pavement action, it measures how many meters are in poor condition of the total section repaired) this would affect users' satisfaction negatively in two ways:

- To increase the percentage of coverage it is necessary to make the total length of the section to be repaired shorter, which will affect negatively the homogeneity of the road network and therefore will make the ride less comfortable for users.
- An alternative to shortening the length of the section to be repaired is to wait that more problems are shown on the section, which makes that users' experience the problem (i.e. cracks or ruts) more times than usual and also affects negatively their satisfaction.

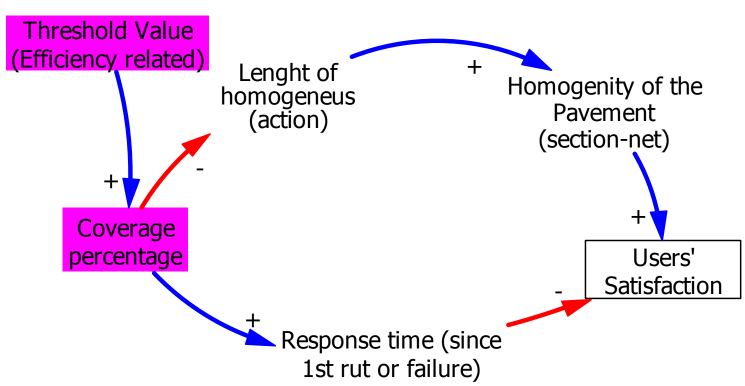



**Figure 9 Trade-off between efficiency and user's satisfaction**

This diagram shows how top quality it is frequently too expensive to be achieved. It also pictures an important conflict of values or trade-off that road agencies may be transferring to private companies, in the new contracts. This conflict becomes crucial if new contracts are to make these private companies responsible of entire road networks and judge them on the basis of mainly users' satisfaction. Before this transfer of responsibilities is carried out, it seems necessary to establish within the agency; first, which thresholds are reachable and could ever be required from contractors; and second, which historic levels of the threshold values have shown to be optimal in efficiency and users' satisfaction terms.

The conflicts, concerning users' perception, reviewed in the last two sections point out the need of a thorough research and discussion on which should be the maximum weight assigned to users' satisfaction –comparatively with other performance indicators- to avoid inefficient use of public resources - like gold plating – or unfair payment or retribution to contractors' effort and good work.

Users opinion could be also a double side sword, as explained by Äijö, Altamirano et al (2006) from all indicators of road condition, this is the most subjective and easy to be influenced, through marketing campaigns and the like. So if too much weight is given to this factor, the road agency could end up either with public resources being used inefficient or in the worse of the cases, with "satisfied users" but "underground" a road network in very poor condition.

Figure 10 as the previous one, goes on picturing factors that though are not so directly related to the physical condition of the road, do influence the decisions made about periodic maintenance.

## IV. The wider environment of the periodic maintenance system: the influence of procurement strategies

As mentioned before, Figure 10 shows the impact of two additional policies in the performance of the system. These two policies are, first the tendering and procurement strategy and second, the safety related policy.

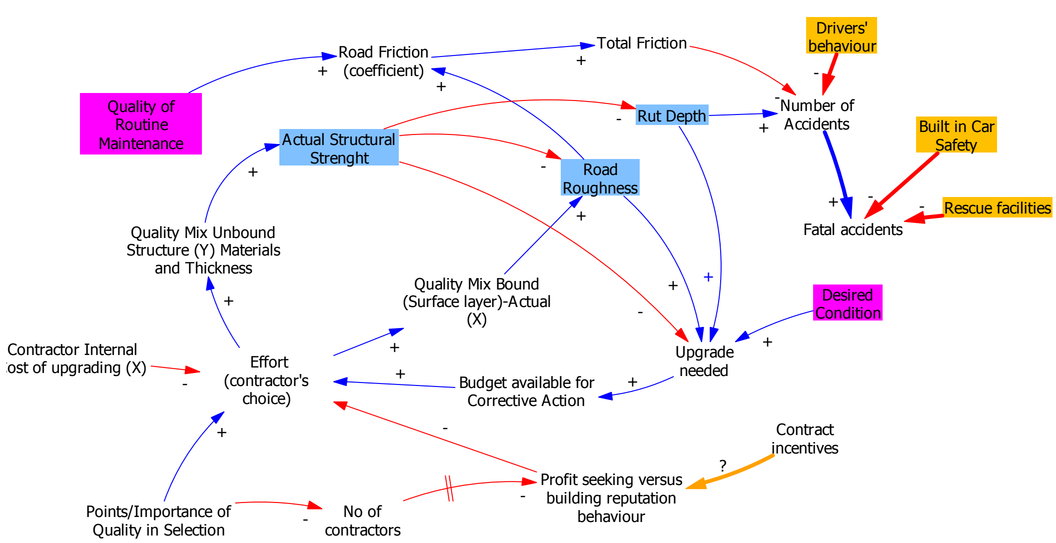



**Figure 10 Mapping other external variables**

As can be seen in the causal diagram, the actual road condition (i.e. structural strength) in combination with the desired road condition (which is a value set probably by external actors such as the Ministry of Transport) define the upgrade needed or the magnitude of the corrective action that needs to be implemented. Then, one could assume that the bigger the need, the more budget will become available for the action. However, this does not directly translate in an improvement of the structural strength or at least, not directly into one proportional to the budget invested. Here the influence of the procurement policy comes into play. Though one could expect that if more budget is offered for a particular work (in periodic maintenance) the more the effort the contractor will put on the project and the higher the quality of the bitumen mix and work he realizes; there are other aspects that influence the level of effort he will invest in that project. These other aspects are:

- **Contractor internal cost of upgrading**: the more expensive is for the contractor any additional point of quality and/or effort, the more he will tend to save effort and provide a lower quality solution.
- **Profit seeking versus building reputation behavior**: if the contractor selected is more driven by the desire of increasing its profit than of building a reputation, the most probable is that he will invest the less effort possible in the work. The attitude of the contractor is affected by the incentives included in the contract as well as in the long term by their position in the market or market power.
- **Points assigned to quality in contractors selection process**: if more importance is given to quality, one could expect that there are more chances that the contractor selected has the capability to realize a better quality job. Besides he is to some extent legally more forced to provide the service described in the tender, which includes quality aspects, and which are normally not covered in price only selections.

Nowadays competition for periodic maintenance works is mainly price driven, since this is the overarching criteria for the selection of the winner contractor. Paradoxically the asphalt business – due to its technical characteristics- is also characterized by quasimonopolistic competition levels that keep prices relatively high. These two factors leave to contractors few incentives to work hard for better reputation.

The new integral maintenance contracts may improve the situation in this area, since the idea is to consider more quality aspects in the selection of contractors. The inclusion of additional tasks than only asphalt related works, - like routine maintenance and operation task- will also mean that different companies take part in the competition and the status quo of the asphalt business is disturbed.

Now, referring to the safety related policy, we discover that though the number of accidents in general is very dependent on the road condition; the number of fatal accidents it is not necessarily that dependent; since one could prevent that normal accidents become fatal by increasing the built-in safety in cars or by improving the availability and quality of rescue services.

In this way we could see how the merely physical problem of road condition correlates with aspects in a wider scale and therefore solutions for the problem can be also achieved by cooperating with the instances in charge of these other policies and by opening in general a wider discussion process in society.

The new maintenance contracts seem to go along these lines. Since they will probably include not only routine and periodic maintenance tasks, but also operation tasks like incidental traffic and safety services, they are expected to promote more coordination between the responsible of road maintenance and other agents like the police and first-aid teams; all aiming at reducing the number of fatal accidents.

## V. Conclusions and recommendations

The analysis realized shows that important trade-offs concerning the maintenance of existing road networks are:

- First, related to winter tire regulation - how heavy is the grip/skid allowed to drivers in their tires- it was discovered the two opposite effects this regulation has on safety or number of accidents. On the one hand prevents one type of accidents during the winter, but on the other, it accelerates the process of creation of ruts, causing more hydroplaning accidents in the summer. From here the need to weight both effects and research into the optimal range of values that could reduce both kind of accidents and ensure a more cost effective maintenance of the road network.
- Further, when analyzing other factors that could reduce the number of accidents during winter, it was found that alternatives are to improve the quality of winter (routine) maintenance or macro texture of the road, so as to raise the friction coefficient and increase vehicle control. Important questions that arose here are which could be the maximum levels of these different variables and what their behavior in terms of cost is. Could it maybe be invested extra in winter maintenance actions what is now invested in the reparation of ruts and achieve in this way a much better performance in terms of safety and costs?
- Second, related to users' satisfaction, two important conflicts were found. The first conflict is between road condition and users' satisfaction, since a better condition does not directly relate to more satisfaction. The second is between two public values, the efficient use of public funds and the focus on users' satisfaction.

All the trade-offs need further thinking and society wide discussion if the idea is to transfer them to private agents. The issue of users' satisfaction deserves special attention since there seems to be a trend to make indicators related with it more decisive for the payment received by contractors.

In the one hand, the new maintenance contracts being discussed and put into practice recently in some countries, do pose some risks, mainly derived from transferring these decisions and trade-offs to private agents with different interest than the public road agency.

On the other hand, once the wider context of these contracts was reviewed, seems that these new contracts being proposed; characterized by not only longer term contracts and bigger networks but also by more quality based selection of contractors and the inclusion of operation tasks; could improve indeed the performance of the road network by:

- Causing a different attitude in the traditional asphalt contractors
- Ensuring more competition in the asphalt market or enlarging the pool of contractors that could compete for such new contracts. The asphalt market is

characterized nowadays in many countries for quasimonopolistic levels of competition that keep prices rather high.
- Including incidental traffic and safety services that promote more coordination between the responsible of road maintenance and other agents like the police and first-aid teams; all aiming at reducing the number of fatal accidents.

However, before transferring more decision power and responsibilities to private contractors the policy makers in road agencies need to
- Related to the trade-off between winter tire regulation and the quality of winter maintenance, the main advice is that thresholds and ranges should be specified in contract to avoid conflicts and more importantly continuous impoverishment of the road network condition.
- Concerning users' satisfaction: establish reachable values and maximum levels ever expected from contractors and the limits on the weight to be given to this indicator in comparison with other performance indicators more directly correlated with road condition and contractors effort.
- Further numeric analysis of factors reviewed in this work that will define or help them in the designing of a fair payment mechanism of contractors or a distribution of contract incentives that would ensure the sustainability of the sector and the network.

Finally, if users are to become more important in judging the performance of contractors, and of the road infra, they need also to be more informed about what their preferences mean and how they may translate in conflicting values or choices for the operators of the network.

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