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Infrastructure maintenance, regeneration and service quality economics: A rail example

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ABSTRACT

This paper proposes a formalized framework for the joint economic optimization of continuous maintenance and periodic regeneration of rail transport infrastructure taking into account output consisting not only in traffic levels but also in track service quality. In contrast with much optimization work pertaining to spatially contiguous maintenance works, its principal economic emphasis and objective focus are centered on the optimal allocation of current maintenance and periodic renewal expenses, on their yearly distribution among large network partitions, and on infrastructure pricing. The model equations are based on very simple assumptions of infrastructure degradation laws and on a manager's objective function optimized through optimal control procedures. Equations are tested on national French rail track segment databases using Box–Cox transformations and match rail regeneration and maintenance practices prevailing in France. More generally, the paper makes a broad contribution to capital theory, on the optimal maintenance and renewal of equipment, and defines a method applicable not only to other transport infrastructure but to a wide range of capital goods, including housing, cars and industrial machines.
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1. Infrastructure service, maintenance and regeneration

Optimization of transport infrastructure maintenance, notably for roads and railways, is a longstanding research concern. Most work belongs to the operations research literature where the types and sequencing of maintenance operations are addressed to technical maintenance staff, in order to guide decisions, but little attention is paid to their economic consequences. Other work, more concerned with economics and planning process, and notably with pricing, focuses on the econometrics of current maintenance expenditures but takes little account of interactions among types of maintenance, notably between current maintenance and regeneration (or renewal), and is only weakly related to extant technical knowledge on infrastructure degradation and its consequences for service quality.

We build, at the juncture of these two research directions, a model embodying some core knowledge of degradation mechanisms but simultaneously linking policies on current and regenerative maintenance categories to their service quality impacts. We deduce pricing implications that significantly differ from usually maintained marginal cost pricing rules.

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These methods, developed with a rail infrastructure focus, admit of numerous key features common to other transport infrastructure such as roads or airport runways and taxiways, as already pointed out in the first version of this paper (Gaudry and Quinet, 2011), in French, and also to many capital goods such as housing, cars and industrial machines.

Section 2 consists in a short literature review which brings out the novelty of the proposed approach with respect to current research streams. Section 3 presents the intertemporal optimization model structured by an objective function balancing continuous maintenance expenditures and discretely timed renewal expenditures against service quality benefits for users. As noted below, the objective function in question can be interpreted either as the owner's profit or as a collective surplus, depending on how service quality is valued. The optimization starts from an infrastructure degradation function which reflects the fact that service quality decreases with traffic and increases with current maintenance expenditure, in accordance with a simple law compatible with technical knowledge. But the results of optimization differ profoundly from classical processes because current maintenance expenditures turn out to be low just after and just before a renewal and because their time path is an inverted U. This path not only tracks the evolution over time of both optimal service quality and optimal current maintenance but also provides the required timing of renewals: simulations show that the results reproduce current rail practices. Also, one can extract optimal prices from such path profiles: they differ from the usually recommended marginal infrastructure cost pricing solutions.

In this Section 3, no uncertainty is assumed and the model is solved by Pontryagin's method, making the optimal solutions analytically tractable, In Section 4, however, the effects of maintenance on track quality are treated as random: this requires the use of numerical simulation methods. Lessons from the reasonable results so obtained are drawn.

Econometric tests are found in Section 5, all carried out with a database on the French rail network graciously made available by SNCF. They assume, as frequently done in microeconomic supply work, that the rail system operator maximizes profit in the case of a private operator and social surplus in the case of a public operator. The tests first verify that the time profile of current maintenance expenditures is indeed an inverted U and then address the estimation of the three other relationships brought out by the adopted approach, all significant. The first is a degradation function relating service quality to traffic, which worsens it, and to current maintenance, which improves it. Another explains optimal maintenance expenditures and the third pertains to the evolution of optimal service quality over time. These results are compared both to traditional econometric study results and to observed practices. The conclusion points to limitations and potential refinements.

2. Context of the approach adopted

The first literature stream just mentioned derives from engineering knowledge managerial rules pertaining to maintenance operations and their scheduling. It includes both academic studies and administrative documents produced by national and international agencies supplying advice and computer-based decision tools.

The operations research orientation of such work is clear from recent reviews (e.g. Gu et al., 2012; Kobayashi et al., 2012; Sathay and Madanat, 2011). A notable example of computer-based methods produced by agencies is the Highway Development and Management program (currently HDM-4) distributed by the World Bank to make recommendations on the analysis, planning, management and appraisal of road maintenance, improvements and investment decisions. Tsunokawa and Schofer (1994) use optimal control theory to deduce optimal pavement policy, but do not include in their analysis any reference to quality of service and deliberately adopt a goal of optimal technical policy. Friesz and Fernandez (1979) propose a model which takes into account quality of service, but in an environment of wide uncertainty, and with a view to maintenance policy optimization.

The second literature stream, centered on the estimation of cost functions, takes a more usual economic approach and renounces any detailed analysis of technical processes to estimate econometric linkages among total costs, outputs and input prices if available. Typically, a behavioral assumption of short run cost minimization by infrastructure owners is made with an eye for pricing implications, especially in European countries where the marginal cost pricing doctrine of the European Union Commission is applied.

A particularly complete synthesis of this stream is found in the numerous 2008–2009 country reports of the Cost Allocation of Transport INfrastructure cost (CATRIN) Consortium, summarized in Wheat et al. (2009), and in more recent related contributions (e.g. Andersson et al., 2012). CATRIN studies notably provide, among other contributions, comparable coordinated statistical analyses[1] linking annual maintenance expenditures to traffic and technical track characteristics for five[2] European country rail networks. The resulting cost functions rely on minimal technical knowledge and avoid dealing with the interaction between current and regenerative types of maintenance expenditures, a matter abundantly dealt with in literature of the first category where it is addressed primarily in a technical manner. Andersson et al. (2012) and Andersson and Björklund (2012) do bring up or study the rarely mentioned matter of regeneration expenditures but without relating it to that of current maintenance expenditures.

Accounting for the interaction between periodic regeneration and continuous maintenance dimensions of assets, and duly deriving implications for pricing, is rare. For Feldstein and Rothschild (1974), current maintenance has no effect on

[1] In particular, Box–Cox transformations are applied by all to CES, and by some to other specifications.
[2] Austria, France, Great Britain, Sweden, Switzerland.

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