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Measuring the highway capital in Finland 1900–2009

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Abstract

In this study, the values of the wealth and productive services capital stocks in Finland between 1900 and 2009 are estimated. Several modifications to the prevailing conventions of measurement are suggested.

First, the sudden death (one hoss shay) deterioration of the asset is the justifiable deterioration pattern in this context. Renovation investments that preserve the efficiency of the asset must explicitly be attached to the fundamental equation determining the asset price but they must not any more be included as separate investments in the estimate. With these modifications the wealth capital stock of highways obtains the value of 43 billion euros in 2009, the "official" figure being only 15 billion euros.

Secondly, the competitive market hypothesis in the case of infrastructure investments is questioned. Using a typical cost-benefit rule and parameter values applied in project appraisals to estimate the value of the expected benefits of a typical highway project, the wealth capital stock of highways obtains the value of 170 billion euros in 2009.

Thirdly, new road investments have a positive external effect on previous investments in improving the performance of the whole network. Using a spatial accessibility index and its changes to estimate the intensity of the external effects, the wealth capital stock of highways reaches the value of 200 billion euros in 2009.

Key words: highway capital, measuring capital, accessibility gains

JEL classes: C82, D24, H54

Tiivistelmä

Tutkimuksessa lasketaan varallisuus- ja tuottavan pääoman (pääomapalvelusten indeksin) arvot Suomen tieverkostolle vuodesta 1900 vuoteen 2009. Vallitsevia mittauskäytäntöjä kehitetään seuraavilla tavoilla:

1. "Äkkikuolema" -kuluminen on perusteltu kulumistapaoletus infrastruktuurihyödykkeen tapauksessa. Korjausinvestoinnit, joiden tarkoituksena on tiestön suorituskyvyn säilyttäminen, tulee sisällyttää varallisuusesineen hinnan ja odotettujen vuotuisten tuottojen välistä riippuvuutta kuvaavaan yhtälöön (investointiteorian perusyhtälö) mutta erillisinä investointeina niitä ei pidä enää sisällyttää pääomalaskelmiin. Näillä periaatteilla Suomen tiestön varallisuusarvoksi vuonna 2009 saadaan 43 miljardia euroa. Vastaava "virallinen luku" tällä hetkellä on vain noin 15 miljardia euroa (kirjanpidon tasearvo sekä Tilastokeskuksen laskelma).

2. Kilpailullisten markkinoiden hypoteesi ei ole pätevä infrastruktuuri-investointien kohdalla. Investointipäätöksiä ohjaa kustannus-hyötyanalyyttinen tarkastelu. Kaikkein kannattamattomimmankin investoinnin hyöty-kustannussuhde on yleensä reilusti ykköstä suurempi. Käyttämällä tyypillistä kustannus-hyötyanalyysin päätössääntöä ja sen parametrejä tieprojektien odotettujen hyötyjen arvon määrittämiseksi tiestön varallisuusarvoksi vuonna 2009 saadaan noin 170 miljardia euroa.

3. Tieinvestoinnit parantavat saavutettavuutta laajemmin koko tieverkostossa; samalla niillä on positiivisia ulkoisvaikutuksia aikaisemmin tehdyille tieinvestoinneille. Hyödyntämällä saavutettavuusindeksiä ja sen muutoksia verkoston eri pisteissä ulkoisvaikutuksen suuruuden arvioimiseen tiestön varallisuusarvoksi vuonna 2009 saadaan noin 200 miljardia euroa.

Tiestön varallisusarvon kasvu on taittunut lähestyttäessä 2000-lukua; tuottava pääoma on sen sijaan jatkanut kasvuaan.

Asiasanat: tiepääoma, pääoman mittaaminen, saavutettavuus, verkostovaikutukset

JEL -luokat: C82, D24, H54

Contents

1 Introduction

The concept of capital is a cornerstone in modern mainstream (neoclassical) economics. It has a central position in almost every fields of economics; economic growth, theory of production, industrial organization, public finance, studies of business cycles, theories of general equilibrium, environmental economics, etc. Capital together with other inputs in the production function is used to explain and predict, a.o., the actual or potential output, investments in durable equipments and nonresidential structures, multifactor productivity growth, sustainable growth and taxation of income from capital.

Capital theory has experienced profound controversies during the twentieth-century. The "Cambridge controversy" from the midst of 1950s to the midst of 1970s, one party, Cambridge England (Robinson, Sraffa, Pasinetti, a.o.) questioned the usefulness of the concept altogether and, in particular, its role in theories of growth and income distribution (see Harcourt, 1969). The other party, Cambridge USA (Solow, Samuelson, Hahn, a.o) defended the concept that now has reached its established position in economics. However, the fact that the mainstream view has survived by no means implies that the original anomalies had been solved (Cohen and Harcourt, 2003).

Problems associated with the concept of capital originate from the fact that one and the same concept should represent the production potential of multitude of nonhomogeneous inputs to production. Capital goods yield services over the course of several years, and they are, in general, owned by the utilizer.

Problems associated with the measurement of capital originate just from these same facts. Controversies in the theory of capital have their counterparts in the measurement of capital (Triplett, 1996). The theory of capital measurement has developed to its present state by the work of handful researchers. See, for example, Hulten (1990), Hulten and Wykoff (1981, 1981b, 1996), Jorgenson (1996), Triplett (1996), Diewert and Lawrence (2000), Diewert (1980, 2005), and OECD (2001).

In principle, there are three alternative ways to estimate the capital stocks: (i) direct surveys, (ii) the perpetual inventory method (PIM), and (iii) utilizing book values of companies, insurance records, etc.

Direct surveys are said to be very expensive and to involve intractable problems of classifying the capital goods (Usher, 1980). Insurance records are cheaper but often unreliable. Book values are, in fact, calculated by a method, which is a special case of PIM. In practice, PIM is the only relevant method.

PIM converts historical investment flows into a capital aggregate (e.g., Hulten, 1990; Triplett, 1996; Wykoff, 2005):

$$K_t = \omega_0 I_t + \omega_1 I_{t-1} + ... + \omega_T I_{t-T}, \tag{*}$$

i.e, aggregate capital stock in year t, K_t, is the weighted sum yearly investments (vintages), I_j; $j = t-T, \ldots, t$. Index $t-T$ refers to the year of the oldest surviving vintage.

The measurement problem is essentially tantamount to defining the weights ω_i; $i = 0, 1, \ldots$. These will depend on which capital stock we actually are measuring. There are two concepts of capital.

In the case of *wealth capital*, weights ω_i express the market value of i years old capital good relative to that of new capital good ($\omega_0 = 1$). The set $\{\omega_i\}$, relative productive capacities, is called the *age-price profile* of asset.

In the case of *productive capital*, weights ω_i express the value of *services* (capital rents) of i years old capital good relative to that of the new capital good ($\omega_0 = 1$). The set $\{\omega_i\}$, relative efficiencies, is called the *age-efficiency profile* of the asset.

According to the fundamental equation of investment theory the value of the asset equals the discounted sum of expected future capital rents generated by the asset. Using the fundamental equation, the age-price profile of the asset can be derived from its age-efficiency profile, and the *vice versa* (see Diewert, 2005). Thus, both profiles are interdependent, and there is an organic connection between the wealth and productive capital. Both concepts of capital are two sides of the same coin.

Once historical investment data is available, measuring capital stocks is, thus, essentially dependent on the data on the age-efficiency profiles or, alternatively, on the age-price profiles of investments.

The age-price profiles could be estimated from the market data of used capital goods. Unfortunately, markets of used capital goods are extremely narrow, if they exist at all, since the machines, equipments and structures are usually owned by the company itself. Hulten and Wykoff (1981) is one of the very few studies that have had the opportunity to exploit the market data.

More or less informed guesses and assumptions are used for the age-efficiency or age-price profiles to substitute for the lack of definite observations or estimation results. A few shape pattern for these profiles have become established; linear depreciation is a common depreciation method in bookkeeping, and geometric deterioration is a conventional method used by economists and statistical officials. Due to the imputed character of the age-efficiency or age-price profiles the associated rents are called with representational names: "implicit rent", "quasi rent", "user cost", etc.

In the real world normally machines, equipments and structures consisted of by the capital stocks are nonhomogeneous. The associated aggregation problem amounts to dividing the value aggregate to its price and volume components. Apart from special cases (e.g., homogenous capital goods) formulaes developed by the index theory are recommended (see Diewert, 1980, 2005).

There are numerous practical problems associated with the measurement of capital and researchers seem to have addressed these problems differently, if at all.

First, what is the relevant interest rate to be used in discounting. Is it the *ex ante* or the *ex post* interest rate and what is its level?[1]

Secondly, the investment data has to be deflated to a common price level. What is the price index that is to be used? In the case of structures and, in particular, in the case of infrastructure structures the price deflation may be a major problem (see Hulten, 1990; and Pieper, 1990). No price index may be available and one has to resort to a cost index instead. It normally doesn't take into account productivity changes in the construction sector, and, consequently, the deflated investment series may be heavily biased.[2]

Thirdly, how should the maintenance and repair investments be treated? Should they be considered as a primary labor input or as an investment?

[1] In principle, the interest rate issue is profound. It is related to the so-called Wicksell effect which in turn was lurking in the background of the Cambridge controversy (see Robinson, 1953-4).

[2] Bookkeeping conventions have been criticized in that they normally utilize historical investment data without corrections for inflation (e.g., Hulten, 1990).

If the latter, how should the age-efficiency profile be formulated (Berndt, 1990)?

Now, assume that the productive services and wealth capital stocks have been estimated. A question remains. What exactly have been estimated? What exactly are capital services? Hulten (1990) felicitously asks: "Is a chair in 'service' only when it is occupied? Or, does the availability of the chair for potential occupancy count for something too? If so, are potential services equivalent to actual services?" In any case, the actual flow of services, whatever they are, cannot remain constant over business cycles.

What has been said above, concerns in the first place private productive capital. This study deals with infrastructure capital, and in particular its largest component, the highway capital. We are interested in, whether the same principles developed for the measurement of private productive capital also pertain to public infrastructure capital, but we are also interested in the effects of various assumptions on the results.

Knowing of the amount of the public infrastructure capital is important for many reasons. The wealth stock of public capital tells about the prosperity of the country. Its level indicates the country's ability to endure shocks. Its changes convey information about the needs of replacement or renovation investments. The services provided by infrastructure investments may be an important source of tax receipts (e.g., Feehan, 1998; Feehan and Matsumoto, 2000 and 2002). Changes in infrastructure wealth indicates, then, changes in the tax base.

Obviously, infrastructure is important for the economic growth and for the economic performance of the private sector as well. The size and significance of these effects have been debated in a macroeconomic model framework since the end of the 1980s. The volume of studies on the subject is extensive. For example, a recent literature survey (Romp and de Haan, 2007) refers to over 120 studies. In these studies, infrastructure capital together with private capital and other inputs is placed in a production or cost function, the coefficients of the function are estimated, and, finally, the estimation results are interpreted. The infrastructure capital variable is undoubtedly of a critical importance for the results. Studies seem invariably to employ the wealth capital concept although surely the productive services capital concept should be used in this context (e.g., OECD, 2001). Due to the questionable concept of capital the results in this tradition, so far, are perhaps biased.

The measurement of infrastructure capital seems to follow invariably the procedures established for private productive capital: PIM is applied for deflated historical investment cost series, and geometric deterioration or linear depreciation of the asset is assumed. Repair and renovation investments are treated analogously with new investments. Both new and renovation investments are added to the capital stock, and to both are applied the same deterioration or depreciation profiles.

This study takes as its starting point that, in principle, the concepts of capital developed for private productive assets are relevant also for infrastructure assets. However, there are specific characteristics associated with infrastructures that necessarily modify the routines in the measurement of capital.

In this study, we focus on the following characteristics of infrastructures:

Firstly, infrastructure investments are normally long-lived, and they are associated with regular repair and maintenance investments. The purpose of renovations is to maintain the performance of the asset stable during its lifetime. The profiles of depreciation, e.g. linear depreciation or geometric deterioration, usually assumed for private productive investments, are now unjustifiable; the more appropriate profile is the sudden death (one hoss shay) deterioration. Moreover, productive investments and renovation investments must not be treated equivalently; that is, the latter should not be added directly to the capital stock. In the fundamental equation they must be included. The equation now expresses the price of the asset as a function of the expected rental prices of the asset and the expected renovation costs.

Secondly, public and private investments are determined in totally different economic environments. Private investments are determined in a market environment. If the discounted value of the expected returns exceeds the purchasing price of the capital good, investments will take place until the sum of the discounted returns equals the purchasing price.

Infrastructure investments pass through a public decision making process preceded by a cost-benefit analysis. For infrastructure investments, in general, the benefit-cost -ratio exceeds unity, and the discounted present value of the expected returns generated by the investment, exceeds the purchasing price of the investment. This is true even for the least profitable infrastructure investment, at least in Finland. Consequently, infrastructure investments must carry into effect more valuable wealth stocks of capital than private productive investments.

Thirdly, the services of many type of infrastructure (e.g., electricity, traffic, telecommunication) are supplied through a network. Investments improving the performance of the network are associated with positive external effects. Each successive investment improves the performance of the network besides for its own part but at the same time the performance of the whole existing network, i.e. that of all the preceding investments, improves. Thus, successive investments impose positive external effects on the preceding investments.

The importance of the above-mentioned factors in the measurement of capital — consideration of renovation costs, non-existence of competitive markets and positive external effects — can be assessed by comparing concrete numbers.

Section 2 incorporates the renovation costs to the measurement of capital. The capital stock values, using the modified formula and the sudden death deterioration assumption, are estimated and compared with those obtained with the conventional routine and assumptions.

Section 3 considers the measurement of capital as "a continuum to a cost-benefit -analysis". The fundamental equation of investment theory which relates the value of the asset to the expected capital rents is formally equivalent to "the fundamental equation of the cost-benefit analysis", the net-present-value -rule of public investments. The typical cost-benefit rule with the parameter values normally chosen in project appraisals is first utilized in assessing the benefits of a typical highway project. After that, these benefits are used in estimating the capital stock values.

Section 4 connects the positive external effects on the existing highway network associated with the new investments to the measurement of capital. New investments are assumed to enhance the accessibility of the network, apparently by different amounts at different points of the network. The development of accessibility in the Finnish road network in 1900–2009 is measured by using a conventional accessibility index. Changes in accessibility are used to describe the positive external effects associated with yearly investments.

This study differs also from others in its source of investment data (c.f., Fraumeni, 1999 and 2009). Regionally specified historical investment data does not exist for such a long period as 110 years — not even for a much shorter period. The problem is sidestepped by utilizing repurchasing prices of roads and bridges to the observed physical changes in the road network.

This method kills two birds at one stone: the data problem and the price deflating problem. A detailed description of the data and its manipulation is presented in the Appendix.

2 Measuring infrastructure capital in an established model

So far, the measurement of infrastructure capital has followed the conventions established in the measurement of private productive capital. Capital stock estimates are constructed using PIM. The depreciation methods used conventionally are the linear depreciation, specially in bookkeeping, and geometric deterioration, specially in economists' calculations. Renovations investments seem to have been treated invariably analogously with new investments.

It is argued in this section that expected renovation investments should be included in the fundamental equation relating the the asset value to capital rents. Renovation investments justify the sudden death (one hoss shay) depreciation profile. But at the same time, renovation investments should no more be appended to the capital stock.

Subsection 2.1 considers the measurement of private productive capital. Infrastructure capital is dealt in subsection 2.2. The calculations for the highway capital in Finland under various depreciation assumptions are presented in subsection 2.3. Subsection 2.4 lays ground for the topics of sections 3 and 4.

2.1 Private productive capital

The relationship between stocks and flows of capital

Capital is at the same time a source of productive services (flow) and a stock of wealth (asset). The value of the asset equals the discounted services flows that the asset is expected to generate in future years. (A year is the accounting period assumed here.) Let the price of n years old capital good be P_n and let the return on asset (rental price) at the beginning of year j be u_j. The fundamental equation relating the stocks and flows of capital (the fundamental equation of investment theory) is

$$P_n = u_n + \frac{u_{n+1}}{1+r} + \frac{u_{n+2}}{(1+r)^2} + \dots \quad , \tag{1}$$

where r is the interest rate which is assumed to be constant. (The equation ends with three dots since the service life of investments is unspecified.)

There are two things that influence the price capital good as time passes. In successive years, when the lifetime of investment is given, there are fewer and fewer terms on the right hand side of equation (1). Secondly, the capital input wears as it ages generating a lesser amount of services ($u_{n+1} \leq u_n$).

Vintage rental prices are assumed to be related to the efficiencies of the vintages which in turn are assumed to be related to the physical wear and tear of the vintages. These dependencies become more visible by dividing the right hand side of equation (1) by the rental price of the new vintage, u_0:

$$P_n = u_0 \left[\phi_n + \frac{\phi_{n+1}}{1+r} + \frac{\phi_{n+2}}{(1+r)^2} + \dots \quad \right], \tag{2}$$

where $\phi_j = u_j/u_0$ is the efficiency of j years old vintage relative to that of the new vintage. The series $\{\phi_0, \phi_1, \phi_2, ...\}$, where $\phi_0 = 1$ and $\phi_{j+1} \leq \phi_j$, is called *the age-efficiency profile* of the asset.

Equations (1) and (2) are independent from the point of time under consideration. However, in an inflationary environment, where prices change disproportionately, rents are influenced not just by the aging but also by the time itself. The price of capital good is influenced by changes in demand or invention of more efficient means of production (embodied technical change) or both. The rental prices for different vintages at the beginning of a given year differs from the future expected rental prices for the corresponding vintages (of the same age).

Let u_j^t refer to the rent of j years old capital good at the beginning of year t. Then, we have the following system of rents:

Table 1

Age ↓	Years →				
	t	$t+1$	$t+2$	$t+3$	$\dots$
0	u_0^t	u_0^{t+1}	u_0^{t+2}	u_0^{t+3}	$\dots$
1	u_1^t	u_1^{t+1}	u_1^{t+2}	u_1^{t+3}	$\dots$
2	u_2^t	u_2^{t+1}	u_2^{t+2}	u_2^{t+3}	$\dots$
3	u_3^t	u_3^{t+1}	u_3^{t+2}	u_3^{t+3}	$\dots$
4	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

For example, the future expected rental prices of the investment made at the beginning of year t, u_0^t, u_1^{t+1}, etc., is to be read from the main diagonal of the matrix.

The fundamental equation can now be rewritten as follows:

$$P_n^t = u_n^t + \frac{u_{n+1}^{t+1}}{1+r} + \frac{u_{n+2}^{t+2}}{(1+r)^2} + \dots \quad , \tag{3}$$

This equation expresses the price of the capital input with respect to the future expected rental prices of the vintage that is n years old at the beginning of year t, $n+1$ years old at the beginning of year $t+1$, etc.

Dividing the right hand side of equation (3) by the rental price of the new vintage, u_0^{t-n}, we obtain:

$$P_n^t = u_0^{t-n} \left[\phi_n^t + \frac{\phi_{n+1}^{t+1}}{1+r} + \frac{\phi_{n+2}^{t+2}}{(1+r)^2} + \dots \quad \right], \tag{4}$$

where $\phi_{n+j}^{t+j} = u_{n+j}^{t+j}/u_0^{t-n}$ $(j = 0, 1, 2, ...)$ is the efficiency of $n+j$ years old vintage relative to that of the new vintage, and the series $\Phi^{t-n} \equiv \{\phi_0^{t-n}, \phi_1^{t-n+1}, \dots, \phi_n^t, \phi_{n+1}^{t+1}, \dots\}$ defines the age-efficiency profile of the asset that was new at the beginning of period $t-n$.

The age-efficiency profiles Φ^s are now all, in principle, different, i.e. each vintage has a profile of its own. This is a problem that can be circumvented if the rental prices in Table 1 has a specific structure: the column vectors of the matrix of rental prices ($\mathbf{u}^j = [u_0^j, u_1^j, \dots]^T; j = t, t+1, \dots$) are identical besides by a multiplication by a scalar. This condition is satisfied if the demand of the services of different vintages all increase at the same inflation rate i: $\mathbf{u}^{t+s} = (1+i)^s \mathbf{u}^t$. Then, the asset price can be expressed with respect to the vintage rental prices prevailing at the beginning of year t (Diewert, 2005)[3]:

$$P_n^t = u_n^t + u_{n+1}^t \left(\frac{1+i}{1+r} \right) + u_{n+2}^t \left(\frac{1+i}{1+r} \right)^2 + \dots \quad . \tag{5}$$

Prices P_n^t are not affected by general inflation as it affects the asset inflation rate i and nominal interest r in a proportional manner.

In principle, i could change in time. Then, the rental price escalation factor that is expected to apply, e.g., from year $t+1$ to $t+2$ should be written as $(1+i_1^t)(1+i_2^t)$, where $i_1^t \neq i_2^t$ and $i_1^t \neq i_1^{t+1}$, etc. We assume that constant i is appropriate for the present purposes.

[3]This is an amendment to the existing tradition (e.g., Hall, 1968; Jorgenson, 1989; or Hulten, 1990) launched by Diewert (2005) and discussed by Wykoff (2005).

The asset inflation rate i can be positive or negative. It is positive, e.g., if the demand of the services of the asset increases more rapidly than the general inflation rate. It may be negative if there is expected obsolescence of capital inputs (embodied technical change).

Dividing the right hand side of equation (5) by rental price of the new vintage, u_0^t, we obtain

$$\begin{aligned} P_n^t &= u_0^t \left[\phi_n^t + \phi_{n+1}^t \left(\frac{1+i}{1+r} \right) + \phi_{n+2}^t \left(\frac{1+i}{1+r} \right)^2 + \dots \right] \\ &= u_0^t \left[\phi_n + \phi_{n+1} \left(\frac{1+i}{1+r} \right) + \phi_{n+2} \left(\frac{1+i}{1+r} \right)^2 + \dots \right], \end{aligned} \tag{6}$$

where the efficiency of j years old vintage relative to that of the new vintage, $\phi_j^t \equiv \phi_j$ for all j, since apart from constant coefficients the column vectors $\mathbf{u}^s$ (Table 1) must be identical by assumption. The series $\{\phi_0, \phi_1, \phi_2, ...\}$, depicting the age-efficiency profile of the asset, stays invariable in time.

Formula (6) also specifies the relationship between the age-efficiency profile of the asset and the sequence of prices $\{P_0^t, P_1^t, P_2^t, ...\}$, *the age-price profile* of the asset. See Diewert (2005) for analytical expressions for different age-efficiency profiles.

Aggregation over vintages

Let I_t be the year $t-1$ investment (available at the beginning of period t) in a homogeneous class of capital goods. The value of the capital stock, *the wealth capital stock, at the start of year t* is

$$W_t = P_0^t I_t + P_1^t I_{t-1} + P_2^t I_{t-2} + \dots \quad . \tag{7}$$

Correspondingly, the value of capital services for all vintages, *the productive services capital stock, during* year t is

$$S_t = u_0^t I_t + u_1^t I_{t-1} + u_2^t I_{t-2} + \dots . \tag{8}$$

Equations (7) and (8) represent linear aggregation rules applied traditionally in the measurement of capital (e.g., Jorgenson, 1989; or Hulten, 1990). Diewert (2005), however, suggests a more general form of aggregation; The use of index theory to decompose the aggregate value ratios to price change and quantity change components.

Also for the other conventional aggregation issue, aggregating over non-homogeneous capital goods, the index theory should be applied.

Note that formulae (7) and (8) represent specifications of the PIM (the perpetual inventory methods) introduced earlier.

Measurement in practice

The fundamental problem in the measurement of capital is due to that rental prices of the vintages cannot be observed. In general, the capital goods are owned by the utilizer, and as no market for used capital goods exists, rents cannot be obtained from the market data either.

A way out of the dilemma is to accept that rents must be imputed instead of observed and are, therefore, always more or less approximate. In order to be able to calculate the rents some assumptions are needed.

Assumptions

- A1 Profit maximizing behavior of firms and competitive product markets.
- A2 There is one-to-one relationship between the rental payments earned by the investment and its efficiency which, in turn, is determined by the rate of physical wearing.
- A3 The investment deteriorates according to a predetermined pattern, i.e. the age-efficiency or the age-price profile in predetermined.
- A4 The expected useful lifetime of investment is given.
- A5 Deterioration and depreciation of the various vintages do not depend on use; only on the age of the input.
- A6 Each vintage of the capital good is a separate vintage specific input into production.
- A7 In an inflationary environment the rental prices of the vintages of the homogenous group of assets at a given point of time are changing at the same rate.

The competitiveness of markets (A1) ensures that the value of a new investment is always exactly covered by the discounted sum of the expected future returns. Assumptions A2–A3 are the core assumptions in the measurement of capital. A3 is, in general made, for simplicity. Also A5 is made for simplicity; incorporating issues of capacity utilization heavily complicates matters.

Depreciation profiles

There are many candidates for age-efficiency profiles ϕ or age-price profiles P. In principle, it makes no difference which one of the profiles — the age-price or the age-efficiency profile — is chosen; the other can be obtained with respect to the other, and *vice versa*.

Following age-efficiency or age-price profiles are used in different connections:

- Linear deterioration: the *efficiency* of the asset decreases at the same amount each period.
- Linear depreciation: the *value* of the asset decreases at the same amount each period.
- Geometric deterioration: the productive efficiency of the asset declines at the same rate each period. Geometric deterioration is special in the respect that also the value of the asset declines at the same rate each year, the rates of decline in efficiency and value being equivalent.
- Hyperbolic deterioration: the rate of decline of the productive efficiency of the asset is moderate in earlier years, but increasing to the end of the lifetime of asset.
- Sudden death (one-hoss-shay) deterioration: the investment deteriorates like a light bulb; the efficiency is constant during the whole lifetime of investment, collapsing at the end of the life.

Which one of the profiles should be chosen, is in the end an empirical issue. Which one of the profiles is chosen in practice, is determined by convention, convenience, etc.[4]

[4]There are only a few empirical studies on the deterioration of capital goods. Oulton and Srinivasan (2003, p. 21–22) state felicitously: "Depreciation rates can in principle be found by econometric analysis of a panel of new and second-hand asset prices, following

Geometric depreciation is probably the most widely used assumption in economic applications. Linear depreciation is a common assumption in bookkeeping. One hoss shay -assumption has appealed to economists for its intuitiveness. Figure 1 illustrates the different age-efficiency profiles and the associated age-price profiles. (The lifetime of investment, T, in the sudden death deterioration and linear depreciation patterns is assumed to be 50 years and the interest rate $r = 4$ %.)

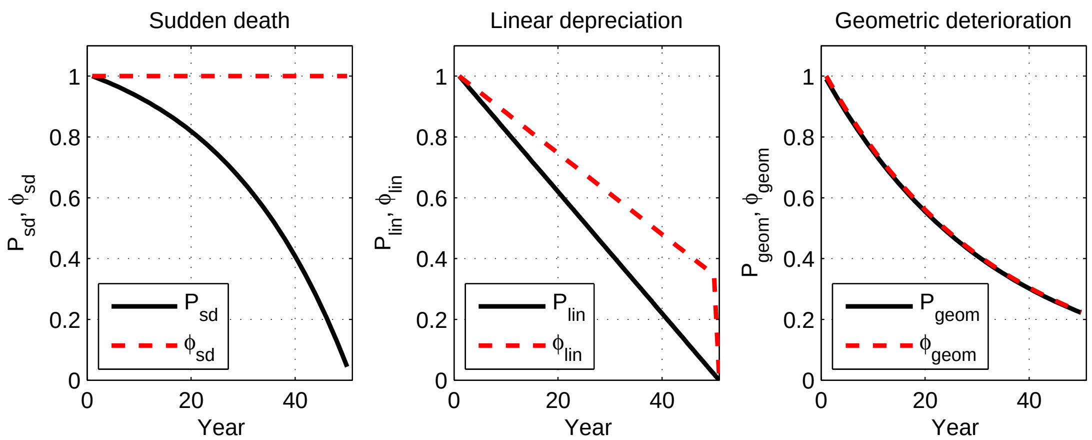

Figure 1. Age-price profiles for different age-efficiency profiles

In the sudden death pattern efficiency stays constant the whole lifetime of the asset; the asset price decreases increasingly.

In the linear depreciation pattern the asset price, by assumption, decreases linearly to zero during the lifetime of the asset. The associated age-efficiency profile is also linear in this case.[5] There is a striking drop in efficiency at the end of the lifetime of the asset.

In the geometric deterioration pattern the age-efficiency and age-price profiles are equivalent. In this case the lifetime of the asset is, in principle, infinite.

the method of Hulten and Wykoff (1981 and 1981b) for example... To apply this approach to all types of assets would constitute a very ambitious programme of empirical research, which has not been carried out in its full entirety anywhere in the world..."

[5]Formula (1) implies that $u_n = P_n - P_{n+1}/(1+r)$. Let L be the fixed service life of the asset. Then, $P_n = 1 - n/L$, and $\phi_n = u_n/u_0 = 1 - n/(1/r + L)$, for $n = 0, ..., L-1$. ϕ_n is linear if r is constant.

2.2 Infrastructure capital

Assume that there is no asset specific inflation, i.e. no changes in the demand of services of the asset, no technical change, etc.[6]

The life span of infrastructure construct is normally very long. For example, a road or bridge may easily sustain its continuous load for over hundred years. However, roads and bridges need regular repairs. Road beds and structures of bridges should be renovated on average in every 40th year, and there are normally two renovations during the lifetime. Road pavements are renewed at intervals of 2–10 years. With each new investment is normally associated a plan of maintenance and renovations devised by engineers.

The costs of repair are dispersed over several years, and the total maintenance and renovation costs during the lifetime may well exceed the initial investment costs. Obviously, the repair costs should explicitly be taken into consideration in the measurement of capital. But how should this be done?

Genuine repair investments don't augment the productive capacity of the infrastructure asset; their only function is to preserve or restore its performance or productive capacity.[7] But renovation investments must influence the original investment decision. If two investments are in all other respects comparable but for the other the discounted sum renovation costs is lower, then this investment should be chosen. Obviously, renovation investments must be included in the fundamental equation of investment. But there is no reason to count them as new investments that raise the productive capacity of the asset if their purpose is not to increase the productive capacity of the asset.[8]

Assume that the renovations are completed according to a plan of engineers at predetermined intervals. Let c_j be the renovation cost for original unit investment realized at the beginning of period j.[9] The price of the asset now

[6] This assumption will be relaxed in later sections.

[7] This is not the case if the quality of the infrastructure is improved simultaneously with renovation investments as it often happens in practice.

[8] Berndt (1990) pays attention to the role of maintenance expenditure: "Should they be expensed as primary labor input or amortized as investment? If the latter, how should their age-efficiency pattern be formulated, over what lifetime? This could be particularly important in the construction of public sector capital stocks, such as those for highways and airports."

[9] It is assumed that the size of the original investment doesn't influence the renovation

equals the discounted present value of expected returns less the present value of the renovation costs[10]:

$$P_n = u_0 \sum_{j=n}^{L-1} \frac{\phi_j}{(1+r)^{j-n}} - \sum_{j \in Z_n} \frac{c_j}{(1+r)^{j-n}}. \qquad n = 0, \ldots, L-1. \tag{9}$$

The investment is assumed to have a given fixed expected lifetime L. The set Z_n includes all the dates of the expected forthcoming renovations for n years old asset.

What is the proper age-efficiency assumption if the performance of the asset is restored by renovations? It could be expected that the development of the efficiency follows a jig saw pattern: decreasing at intervals between investments, jumping to the original level after each renovation.

A lion's share of total repair costs of road and bridges consists, in general, of renovation of the structures or the road beds. The deterioration has predominantly, then, a fatigue wear character, the actual performance not being influenced by this kind of a deterioration. The wear and tear of the road surfaces probably has observable effects on the performance of the road; driving speeds go down, driving comfort declines, etc. On the other hand, the road surfaces are normally renewed in quite frequent cycles. It is just the task of the road authority to maintain the roads in a good condition. This is the case in Finland as well.

Now, if infrastructure is associated with regular renovations, the purpose of which is to maintain the performance of the infrastructure intact or restore the original performance, the appropriate age-efficiency profile should be sudden death decay (one hoss shay) instead of any other of the conventional depreciation patterns.[11]

Presently Finland's statistical officials and road authorities apply (in bookkeeping) relatively short asset lives (40–50 years) and the geometric or linear depreciation method. In addition, renovation investments are treated independently of the initial investments which they are associated with. Both the new investments and the associated renovation investments separately and independently are accumulated to the capital stock using PIM, applying the

costs (per unit of investment).

[10]Cf., Diewert (2003; sec. 12; and 2009, sec. 7).

[11]Diewert (2009, fn. 10) suggests that the one hoss shay assumption may be indeed justifiable for infrastructures.

chosen depreciation method and the fixed asset life.[12]

The prevailing conventions imply the age-price profiles that look quite different from that implied by formula (9) with the sudden death assumption. Figure 2 illustrates this for a unit (one euro) investment. Figure 3 illustrates the related age-efficiency profiles.

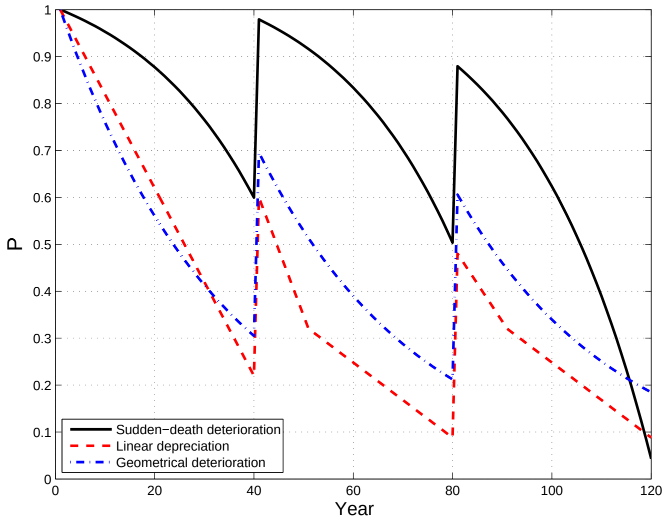

Figure 2. Age-price profiles of an infrastructure investment ($\delta = 3$ %, $c_j = 0.4$)

[12]Similar conventions seem to prevail in other countries, too.

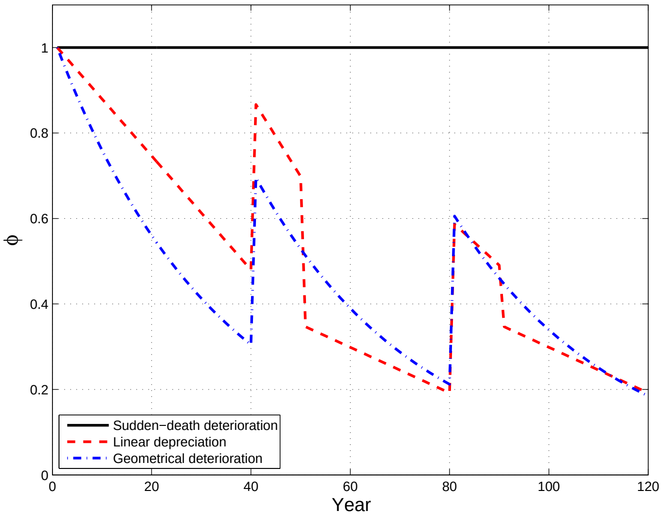

Figure 3. Age-efficiency profiles of an infrastructure investment ($\delta = 3$ %, $c_j = 0.4$)

The service life of investment in the accounting practices of Finland is normally assumed to be 50 years. On the other hand, renovation investments are carried out at intervals of (about) 40 years if the recommendations of engineers are to come true. These figures are used in the illustrative calculation below.

Without renovation investments the asset price associated with the traditional accounting practices would decrease to zero (linear depreciation) or near to it (geometric deterioration) during the assumed lifetime of investment (50 years) (see Figure 1). However, before expiration of the service life of the original investment, at the end of period 40, the asset price is increased by an amount of the renovation investment, c_j. The asset price starts decreasing again until, after another 40 years, it is increased again by an amount of the next renovation investment (Figure 2).

The age-price profile implied by formula (9) with the sudden-death deterioration pattern is a mirror image to the profiles associated with the traditional accounting practices. The asset price is decreased (at an increasing rate) by an amount of the renovation investment during intervals between adjacent investments. Renovations restore the asset price near to its original level.

However, successive peak prices are decreasing since with the passing of time the asset has lesser years of life left.

The differences in the age-efficiency profiles are also conspicuous. The efficiency in the sudden death pattern, by assumption, stays constant during the lifetime of the asset. The efficiency in the geometrical deterioration pattern decreases at a decreasing rate from the moment of one investment to that of the other. It jumps always upwards after a new renovation investment, but is never restored to the original level or even near to it. The age-efficiency profile of the linear depreciation pattern is even more curious. There are smoothly decreasing phases and upward jumps as in the geometrical deterioration pattern, but in addition, there is always an abrupt drop in the efficiency of the asset when the life of the investment (new investment or renovation investment) terminates (at the end of periods 50 and 90 in Figure 3; c.f., also Figure 2).

Obviously, it is very hard to justify empirically either of the conventional age-efficiency assumptions. If the purpose of renovations is to restore the performance of the asset, why cannot this be perceived in the age-efficiency profile of the asset?

Figures 2 and 3 show clear differences in the age-price and age-efficiency profiles, respectively, between the, in this context proper, sudden death assumption and the current practices. Evidently, the differences should be visible in the aggregate capital stock levels, too. This will be investigated in the next subsection.

2.3 Measuring the highway capital of Finland

In this subsection aggregate values of wealth and productive services capital stocks of the Finnish road network are composed using different age-efficiency assumptions are composed.

The method of measurement is based on the inventory of the physical changes in the network and applying repurchasing prices to these changes. This method has many advantages. Firstly, it solves the data problem. Secondly, the calculation is automatically in real terms. Inconvenient price index problems are avoided.[13] Thirdly, the method enables (necessitates) modern computer based data processing which render the results transparent and replicable with other assumptions.

Procedure of measurement

The calculations are made for three age-efficiency profiles:

(i) Sudden death deterioration

(ii) Linear depreciation

(iii) Geometric deterioration

Cases (ii) and (iii) use Formula (2), case (i) uses Formula (9). Renovation investments are treated as new investments in cases (ii) and (iii).

The road network consists of road sections, and separate constructions and equipments associated with them. The biggest group of constructions, the bridges are explicitly included in this study. There are in total N road sections and bridges (henceforth "components") in the network.

The method of measurement consists simply of determining for each component the year of construction, the investment cost, assuming the age-efficiency (or age-price) profile, determining the age-price (or age-efficiency) profile, and finally the aggregation to the wealth and productive services capital stock values using PIM.

The sudden death deterioration

The procedure of measurement can conveniently be described by using vectors and matrices:

Initial investment costs of the components:

[13]The constant price level greatly simplifies the matters (Oulton and Srinivasan, 2003).

$\mathbf{I} = [I^1, \ldots, I^N]$, where

$$I^i = \begin{cases} h^i d^i, & \text{for road sections} \\ g(x^i), & \text{for bridges.} \end{cases}$$

d^i is the length of the road section i, h^i is the price of construction per kilometer in the class where the road section i belongs to (Table I.6 in Appendix). x^i is the span of the bridge i, and function $g(\cdot)$ is estimated empirically (Figure I.4 in Appendix).

Renovation costs of the components:

$\mathbf{c} = [\mathbf{c}^1, \ldots, \mathbf{c}^N]$. The elements of $\mathbf{c}$ are (1×229)-vectors:

$$\mathbf{c}^i = [\ldots, 0, c_1^i, 0, \ldots, 0, c_2^i, 0, \ldots].$$

$\mathbf{c}^i$ contains two non-zero elements: the costs of the first and second renovation, c_1^i and c_2^i. Their places in $\mathbf{c}^i$ are determined by the periods when the renovations are realized or are expected to realize.

The estimates of c_1^i and c_2^i are based on repurchasing prices (Table I.7 in Appendix) for the three types renovations: reconstruction of the road bed, improvement of the geometry and the light repair (see below).

The length of $\mathbf{c}^i$ is determined by the length of the time period under consideration (years 1900–2009) and the fact that the remaining expected lifetime of investments made at the beginning of 2009 is 119 years.

The age-efficiency profiles of the components:

$\mathbf{\Phi} = [\mathbf{\Phi}^1, \ldots, \mathbf{\Phi}^N]$. The elements of $\mathbf{\Phi}$ are (1×229)-vectors:

$$\mathbf{\Phi}^i = [\ldots, 0, 1, 1, 1, \ldots].$$

For all those periods when the asset is or is expected to be alive the corresponding elements of $\mathbf{\Phi}^i$ obtain the value 1.

The rental prices of the new investments:

$\mathbf{U}_0 = [u_0^1, \ldots, u_0^N]$, where u_0^i is solved from equation (9) with respect to $\mathbf{c}^i$, r, $\mathbf{\Phi}^i$, and by setting $P_0^i = 1$.

The age-price profiles of the components:

$\mathbf{P} = [\mathbf{P}^1, \ldots, \mathbf{P}^N]$. The elements of $\mathbf{P}$ are (1×229)-vectors:

$$\mathbf{P}^i = [\ldots, 0, 1, P_1^i, P_2^i, \ldots].$$

> The non-zero elements of $\mathbf{P}^i$ — one element for each period when the asset is alive — are solved from equation (9) with respect to u_0^i, $\mathbf{c}^i$, $\mathbf{\Phi}^i$ and r.

The wealth capital stocks of the components of the road network can now be computed and arranged to a $(N \times 229)$-matrix:

$$\mathbb{W} = \begin{pmatrix} I_1^1 \mathbf{P}^1 \\ \vdots \\ I_1^N \mathbf{P}^N \end{pmatrix}.$$

The rows of $\mathbb{W}$ contain the wealth capital stocks of the components allocated on the realized and expected years of life of the components. The first 110 column sums of $\mathbb{W}$ give the aggregate values of wealth capital stock associated with highways over the time period under consideration.

Correspondingly, a $(N \times 229)$-matrix of productive services capital stocks of the components of the network can be composed as follows:

$$\mathbb{S} = \begin{pmatrix} u_0^1 I^1 \mathbf{\Phi}^1 \\ \vdots \\ u_0^N I^N \mathbf{\Phi}^N \end{pmatrix}.$$

The rows of $\mathbb{S}$ contain the values of the productive services capital stocks of the components of the road network allocated on the realized and expected years of life of the components. The first 110 column sums of $\mathbb{S}$ give the aggregate values of productive services capital stock associated with the highways over the time period under consideration.

Linear depreciation and geometric deterioration

Renovation investments $c_1^i I^i$ and $c_2^i I^i$ for $i = 1, \ldots, N$ are included in the set of the components as "new investments". The age-efficiency profiles are determined as follows:

$$\mathbf{\Phi}^i = \begin{cases} \text{From equation (2) with respect to } \mathbf{P}^i\text{; see fn 5,} & \text{Linear depreciation} \\ [\ldots, 0, 1, 1-\delta, (1-\delta)^2, \ldots], & \text{Geometric deterioration.} \end{cases}$$

The rental prices u_0^i are obtained from equation (2) by setting $P_0^i = 1$, and solving with respect to r and $\mathbf{\Phi}^i$.

The age-price profiles are determined as follows:

$$\mathbf{P}^i = \begin{cases} [\ldots, 0, 1, 1 - 1/L, 1 - 2/L, \ldots], & \text{Linear depreciation,} \\ \text{From eq. (2) with respect to } \mathbf{\Phi}^i \text{ (see Fig. 1), Geometric deterioration.} \end{cases}$$

Data

Data on the road network is from the road and bridge registers kept up by the Finnish Transport Agency. In principle, all roads in the possession of the Transport Agency, besides those on Åland Islands, are included in the study. Also roads remained on the surrendered area to the Soviet Union in 1944 are left out of this study.

The network is described by nodes and connecting edges (road sections) (see Figure I.2 in the Appendix). The number of road sections in the data is 33182. The average length of a section is 2.375 km. The number of bridges in the data is 14487. Hence, the total number of components of the network in the sudden death deterioration pattern is $N = 33182 + 14487 = 47369$. In the two other deterioration patterns N is three times larger since for each road section and bridge there are also two separate renovation investments associated with.

The acquisition costs of land (right of way), and the recurrent repair costs of road pavements are left out of the calculations.[14] The costs of cycle ways, ramps, lightning, safety fences, and other similar constructions are assumed to be included in the costs of road sections and bridges.

A reservation for the accessible data may be in order. In principle, qualitative changes in the network should be identified and incorporated in the measures. Modern roads are wider, pavements last longer and are more comfortable to drive than some decades ago. Modern roads are equipped with safety devices, lights, etc. The data on the road network is based on the present situation, and qualitative changes are insufficiently recorded in the data. For these reasons the earlier capital stock values may be somewhat upwards biased.

[14] In a preliminary investigation the repair costs of pavements had an insignificant effect on the results.

Roads are classified into four functional classes. Inside three classes roads are further classified according to the number tracks. The repurchasing prices and costs of renovation are chosen correspondingly (Tables I.6 and I.7 in the Appendix).

The total length of the road network at the beginning of 2009 was 78798.9 km. Information on when a road section has been build and possibly renovated is central to the study.

The Finnish road register has a strange practice of data logging that complicates matters. With each road section is associated information only on the latest technical operation that is either the building of the new road or the renovation of the existing road. In other words, if a road section has ever been renovated, information on when it has been build is lost. Other information, reasoning and assumptions must substitute for the missing information.

Figure 4A presents the new roads that have not yet been renovated. Figure 4B presents the road kilometers that have been renovated. Renovations have started intensively in the turn of the 1960s. The absent information on earlier renovations suggests that roads were renovated at intervals of 40–50 years. There is still a relatively small amount of road kilometers build before the turn of the 1960s (Figure 4A) that has not yet been renovated. Either the (economic) lifetime of renovation for these roads is larger than 40–50 years or their maintenance has been neglected.

Bridges (Figure 4C) provide an additional source of information. The date of accomplishment is usually available for bridges, and, especially, for bridges over a body of water it should coincide with that of the adjoining road. Allocating the bridges to road sections and picking up the oldest bridge on each section (if there is any) gives an estimate of the age of that road section.

A potential source of information is also provided by data about the transfers of the proprietary rights to roads. One-thirds of the roads has formerly been in a private or communal possession. The date of the change in proprietorship is known in general (Figure 4D).

These two additional data sources are useful particularly when information about the date of building or renovation is missing (red portions of the histograms in Figures 4C and 4D). For 40 % of road the sections no information about either the date of building or renovation is available.

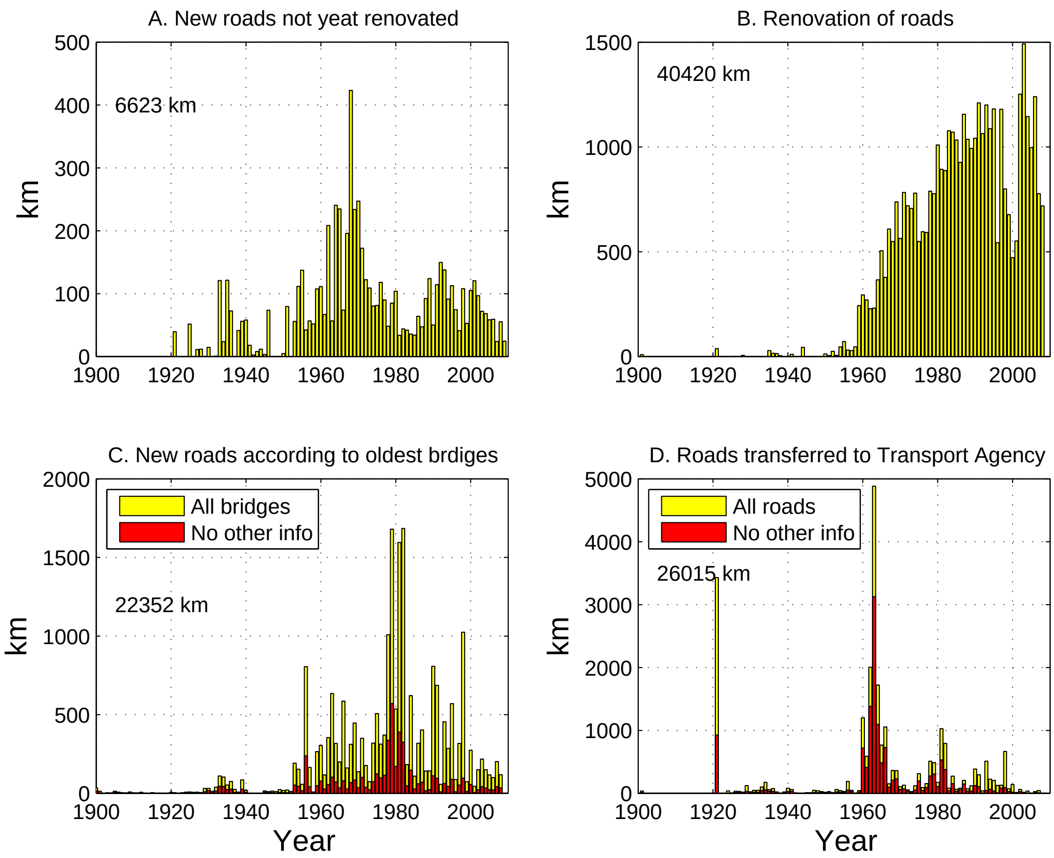

Figure 4. (A) Accomplishment of new roads not yet renovated, (B) renovation of roads, (C) accomplishment of roads according to the date of construction of the oldest bridges, and (D) transfers of proprietary rights to roads

Life cycle of investments and parameter values

For each road section a uniform life cycle is assumed — with some exceptions explained below. The road is renovated T years after its accomplishment, then again a second time T years after the first renovation, and, finally, the life of the road expires T years after the second renovation. The service life of the road section, L, is then

$$L = T + T + T. \tag{10}$$

The variable T, the "service life of renovation", is determined according to engineers' recommendations.

The life cycle of the road being known, one date on it is sufficient to guestimate other dates, too. For road sections underlying Figures 4A and 4C the date of accomplishment is given; the dates of renovations are obtained with the life cycle. For road sections underlying Figure 4B the date of the first renovation is given; the date of accomplishment and the date of second renovation are obtained with the life cycle.

For 4/5ths of the road sections either the date of accomplishment or that of the first renovation is known. For 1/5th of the road sections (red bars in Figure 4D) neither date is known; in these cases it is justifiable to assume that the latter date is missing simply because the road section has never been renovated. In what follows it is assumed that these road sections are accomplished T_A years before transfer into the possession of the Transport Agency.

The uniform life cycle hypothesis implicitly presumes that renovations are accomplished in due time. However, this is not always the case with the existing roads. There are many roads for which the time lapse between the present and the date of accomplishment of the last technical operation (building a new road or its renovation), T_2, exceeds the service life of renovation, T. (For roads transferred into the possession of the Transport Agency $T_2 = T_A + T_3$, where T_3 is the interval between the present and the date of change in the possession.) Then, whenever $T_2 \geq T$ it is assumed:

$$L = \begin{cases} T_1 + T + T & \text{Building a new road is the latest operation} \\ T + T_1 + T & \text{Renovation of the road is the latest operation,} \end{cases} \tag{11}$$

where T_1 is expected time lapse between the date of the forthcoming renovation and the preceding technical operation. It is assumed that "overdue" renovations are realized in a very near future:

$$T_1 = T_2 + 5,$$

i.e., in a single year, in five years' time from the present.

For bridges the dates of completion and possible renovation(s) are usually known. These are used directly.

Parameter values

The life cycle assumption and the data on the date of the last technical operation is used to estimate the dates of all the realized or expected future technical operations. These dates are then used in the measurement of capital stock values associated with different depreciation patterns. However, the service lives associated with the profiles of linear depreciation or geometrical deterioration need not be compatible with the life cycle assumption made above. The service life of investment associated with the different deterioration patterns are

$$L = \begin{cases} \text{From (10) or (11)}, & \text{Sudden death deterioration} \\ T_l, & \text{Linear depreciation} \\ T_g, & \text{Geometric deterioration} \end{cases} \tag{12}$$

(12) contains parameters T, T_A, T_l and T_g. The following values are assumed in the calculations below:

$T = 40.$

This figure is compatible with the recommendations of road engineers, fitting also well in with the observations (Figures 4A and 4B). (For the bridges of the data the time lapse between the accomplishment of the bridge and its first renovation is on average slightly over 37 years.)

$T_A = 20.$

This is a conservative and rigid guestimate. In many cases the road is clearly constructed over 20 years before its transfer into the possession of the government, and there is also probably a lot of divergence in T_A. This rigid assumption will probably have visible impacts on the results as the transfers of proprietorships are strongly concentrated in the beginning of the 1960s and a single year, 1921.

$T_l = 50.$

This figure is presently used in bookkeeping.

$T_g = \infty.$

This is the correct theoretical value.

The assumed values for T and T_A will be relaxed in a sensitivity analysis below.

For the other parameter values it is assumed:

The discount rate

$r = 4$ %.

The rate of decay (geometric deterioration)

$\delta = 3$ %.

Unit costs: see the Appendix.

A more detailed description of the data, the method and the assumptions is included in the Appendix.

Results

The yearly new investments into the road network and the development of the total road kilometers of the network can now be shown. Figure 5A presents the accomplishment of new roads. Figure 5B presents the development of the total length of the network.

There is a peak of new roads around the turn of the 1940s and a steady decline in the accomplishment new roads since the midst of 1940s. These characteristics are partly due to the assumptions associated with the roads having changed their ownership. In reality, the peak may be much lower and the decline in accomplishments may have started earlier.

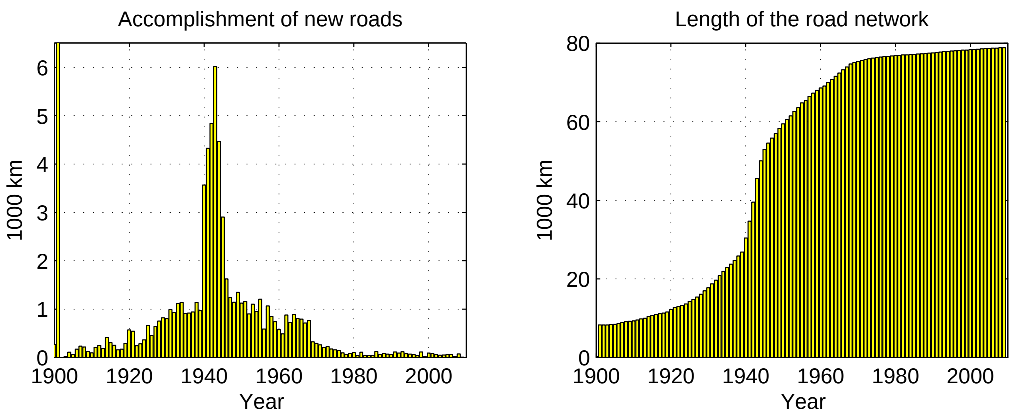

Figure 5. (A) Accomplishment of new roads, and (B) the total length of the road network in 1900–2009

The total investments in euros on the road network in a given year is obtained as a weighted sum of the new road kilometers (Figure 5A) unit prices per kilometer as weights. Figure 6A presents the distribution of new investments over time.

The shape of the distribution is similar to that of the accomplishment of new roads (in Figure 5A) besides that the peak of the 1940s is now relatively smaller. The roads having changed their owner are mainly those of cheaper lower category. Noteworthily, the share of bridges of total investments is relatively small. Investments on bridges have steadily increased from the 1950s till 2000s.

Figure 6B presents the realized and expected renovation investments till the year 2030. The expected investment peak in the 2010s is due to the overdue renovations — and the assumption that they are realized in a very near future, in a single year. (For clarity this huge peak is allocated over five years in Figure 6B.) The total value of the overdue renovations is slightly over 10 billion euros. The average time lapse between the present and the last technical operation is 62 years in overdue cases.

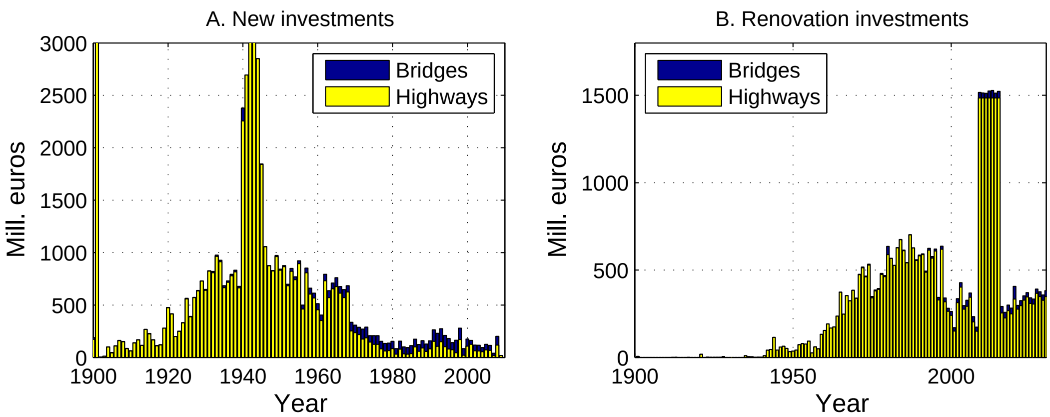

Figure 6. (A) New investments 1900–2009, and (B) renovation investments 1900–2030

Capital stocks

The aggregate capital stock values that are the product of the investment series and investment-specific age-price or age-efficiency profiles — depending on the concept of capital — can now be presented.

Figure 7 shows the aggregate values of the wealth capital stocks associated with the three depreciation profiles in 1900–2009, and, in addition, the realized book values in 1998–2008.

The straight line depreciation profile with the chosen parameter values exactly corresponds to the bookkeeping conventions made use by the Transport Agency since 1998 when the bookkeeping practice was started. Where the model of this study and the present bookkeeping conventions differ is in the data (possibly) and in the price indexing. Some items mentioned above are left out of this study. On the other hand, the opening balance sheet value at 1998 was partly based on discretionary judgements. The prices of this study are in a fixed price level whereas the book values are based on historical costs. Anyhow, the figures of the two models are amazingly close to each other. This should be a testimony that the model of this study performs well.

The aggregate value of wealth capital stocks associated with the geometric deterioration and linear depreciation pattern are close to each other. This was anticipated already on the basis of the associated age-price profiles (Figure 2).

Also was it anticipated that results associated with the sudden death deterioration pattern will differ substantially from those with the two conventional depreciation patterns; the aggregate value of the wealth capital stock associated with the sudden death pattern, 43 billion euros, in 2009 is 2.5–3 times larger than those associated with the conventional depreciation patterns. The book value of the Finnish road network was about 15 billion euros in 2009.

The aggregate values of the wealth capital associated with the conventional depreciation methods started to decrease already from the beginning of the 1970s. In the sudden death deterioration pattern the value of the aggregate wealth capital stock started to decrease not until in the midst of the 1990s.

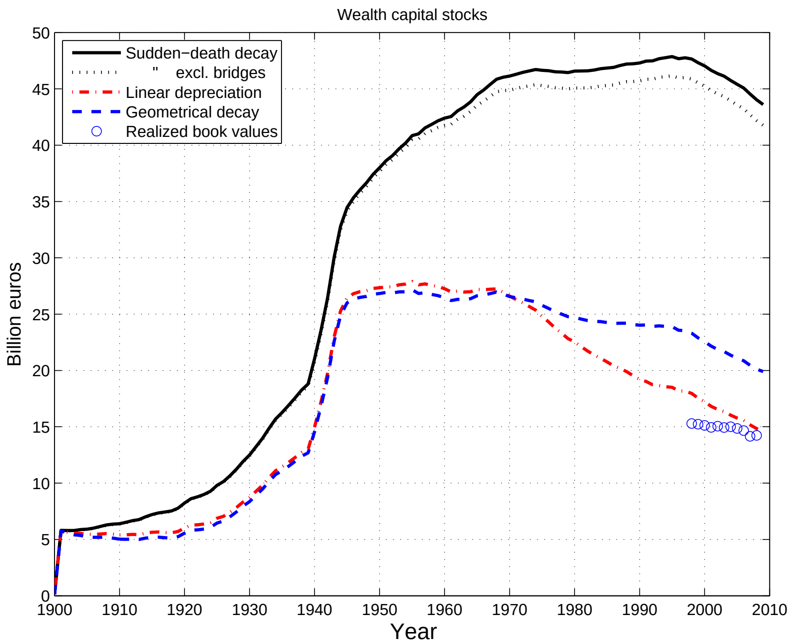

Figure 7. The aggregate value of the wealth capital stock of highways in 1900–2009 and the realized book values in 1998–2008

Figure 8 presents the aggregate values of the productive services capital stocks associated with the three depreciation patterns in 1900–2009.

The value associated with the sudden-death pattern at the end of the period under consideration is about twice as large as those associated with the conventional depreciation patterns. The productive services capital stocks associated with the conventional depreciation patterns started to decrease from the midst of 1950 (linear depreciation) or from the beginning of the 1970s (geometrical deterioration). It is increasing over the whole period 1900-2009 in the sudden death pattern — albeit at a decreasing speed from the midst of the 1940s.

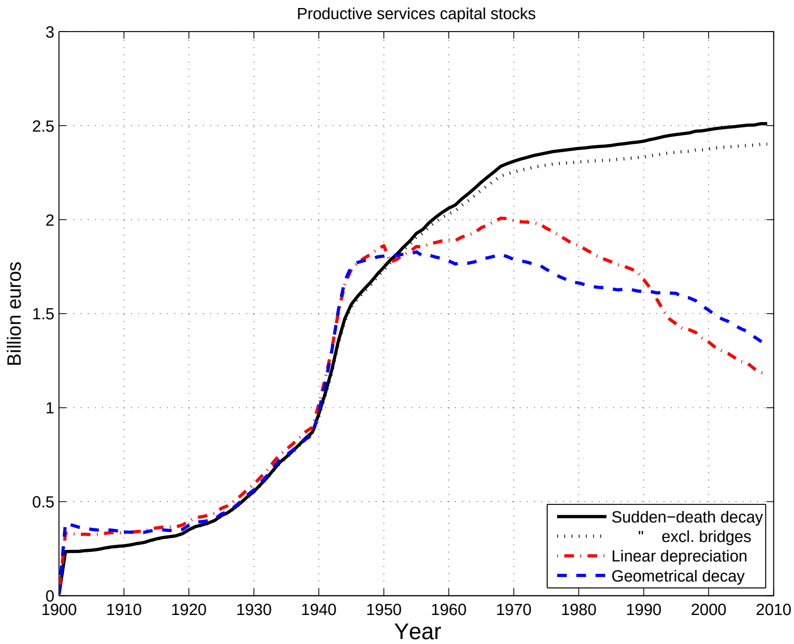

Figure 8. The aggregate value of the productive services capital stock of highways in 1900–2009

It is clear now that there is a clear difference between shapes of the value of capital stock curves within the capital concept (wealth vs. productive capital) and between the capital concepts. So, the concept of capital and the way it is measured (underlying assumptions) must have a substantial relevance for empirical studies utilizing an infrastructure capital variable, or any other capital variable.

2.4 Sensitivity analysis

The results depend on our assumptions and on the parameter values. In particular, the uniform value chosen for the service life of renovations, T, may have an appreciable effect on the time paths of the capital stock values. A change in T changes the estimated dates of accomplishment of investments, and the lengths of the age-price and age-efficiency profiles in the sudden death deterioration pattern. A change in T_A has similar effects for a large portion of investments.

To investigate the sensitivity of the values of T and T_A on the results, the calculations are also carried out for values: $T = 60$ and $T_A = 40$. Those results are presented in Figures 9–11.

Figure 9A shows the distribution of new investments based on the new values for T and T_A. Expectedly, the distribution has shifted leftwards. The distribution around the main peak has curtailed somewhat. The distribution of realized and expected renovations (Figure 9B) is almost the same as before apart from the peak of the 2010s is now lower. In any case, the total value of the overdue renovations is still 8 billion euros.

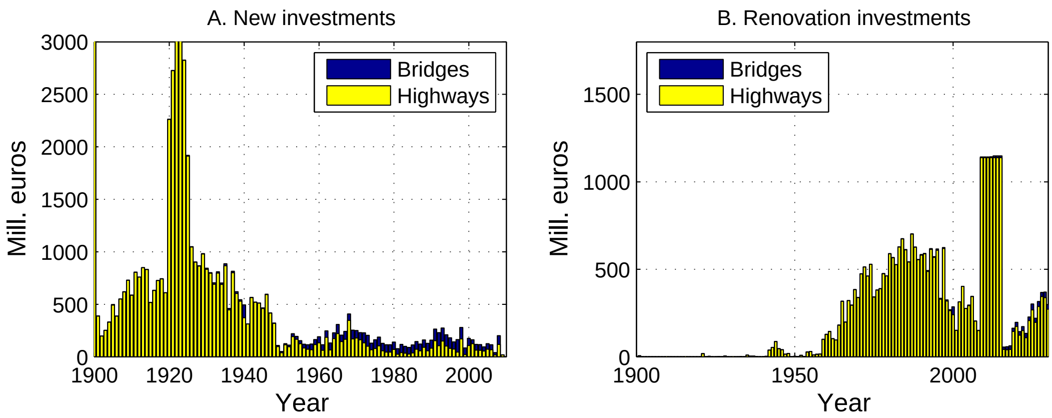

Figure 9: (A) New investments, and (B) renovation investments: the service life of renovations $T = 60$ years

Figure 10 presents the aggregate wealth capital stock values. There are now two peaks in the curves. The first one, around the beginning of the 1950s, is due to the investment peak of the 1920s. The value decrease thereafter is a normal phenomenon associated with the behavior of age-price profiles and aging. The second peak around the end of the 1990s is due to the intensive renovations of the 1970s and 1980s.

The aggregate productive services capital stock value curves (Figure 11) behave as before, though the growth has began earlier.

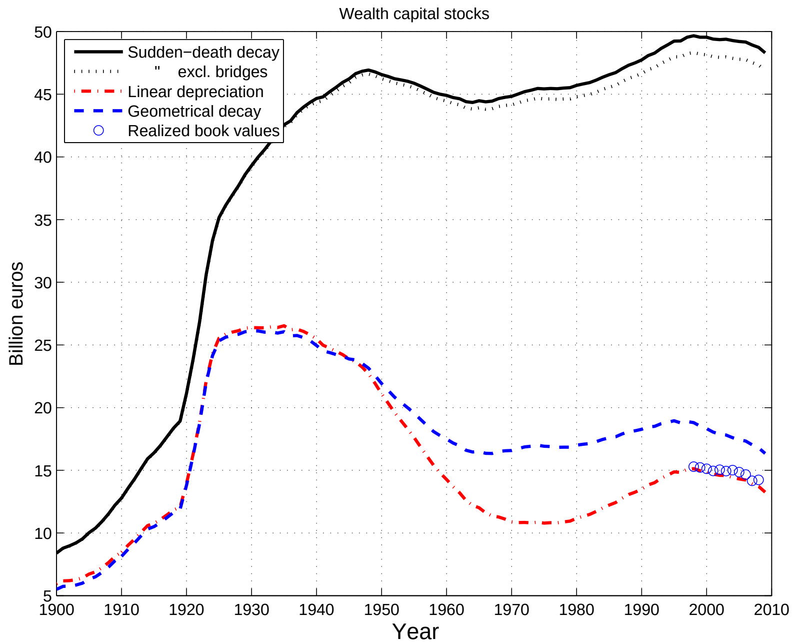

Figure 10. The aggregate value of the wealth capital stock of highways: the service life of renovations $T = 60$ years

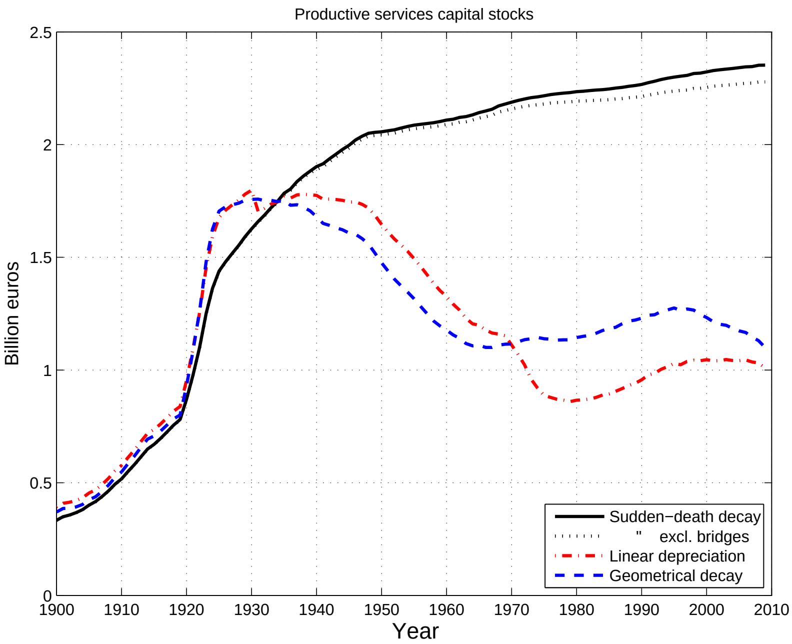

Figure 11. The aggregate value of the productive services capital stock of highways: the service life of renovations $T = 60$ years

2.5 About the relevance of the established model

The model presented in this section is "established" in the sense that it rests on the same set of assumptions (a.o. A1–A7 on p. 13) as those used for the measurement of private productive capital stocks. Some amendments to prevailing practices was suggested; the use of the sudden-death deterioration profile instead of the more conventional profiles, and the inclusion of renovation costs in the formula defining the age-efficiency and age-price profiles, not counting them any more as "new investments".

The following sections of this study will argue for more profound amendments. By and large, it is a small wonder that, so far, infrastructure investments and private productive investments have been treated equivalently in the measurement of capital; so different are the environments where supplies for these goods are determined.

Let us consider more closely two of the assumptions which are fundamental in the measurement of private productive capital.

A1 Profit maximizing behavior of firms and competitive product markets.

This assumption was needed to fix the level of the returns on investments. Competitive product markets ensures that the present value of returns on investment equals the cost of investment at the date of completion of the project.

No markets exist for the services provided by infrastructure goods. Investment decisions are made in a public decision making process preceded by a cost-benefit analysis of the project. According to the established cost-benefit rule (the so-called Net Present Value (NPV) -rule) each investment should be carried out for which the net present value is greater than or equal to zero. Consequently, for many most investments the present value of benefits exceeds the present value of costs. It will be argued in section 3 that in practice for *all* the highway infrastructure investments the present value of returns exceeds the present value of costs. This should have implications for the capital stock values.

A6 Each vintage of the capital good is a separate vintage specific input into production.

Roughly, this assumption says that the whole is the sum (or a "well behaved function") of its parts. However, in the case of highway infrastructure the whole may be more than a simple sum of its parts.

A single road or road section is a part of the whole, the road network. A new connection benefits the residents and industry in its vicinity. In the course of time wider areas are gaining from new connections as drivers are finding the fastest routes and factories adjust to a better access to markets for raw materials and end-products. With each new connection positive network effects are associated whose intensity depends on the structure of the existing network.

Noteworthily, a new road may enhance the productivity of existing roads. That is, each new investment causes a *positive externality* on existing investments. This effect is taken into consideration in the measurement of capital in section 4.

3 Measuring infrastructure capital as a continuum to cost-benefit analysis

3.1 A stylized fact of cost-benefit calculations and its implications

Infrastructure investments are not determined by market forces. Infrastructure investments are decided on a public decision making process. Each decision, at least in Finland, is preceded by a cost-benefit (henceforth 'cb') analysis of the project.

According to the fundamental equation of cb-analysis, the so-called npv-rule, each project whose net present value, NPV, is positive or equal to zero should be implemented:

$$\mathrm{NPV} \equiv \sum_{j=0}^{M} \frac{V_j}{(1+r_c)^j} - I - \sum_{j \in Z_m} \frac{C_j}{(1+r_c)^j} \geq 0. \tag{13}$$

I is the investment cost[15], V_j is the expected value of the benefits of the j years old asset realized at the beginning of period, C_j, is the expected renovation (or whatever) cost realized at the beginning of period j, Z_m contains the planned dates of renovations, $M+1$ is the expected service life of investment, and r_c is the discount rate.[16]

Cb-analysis has been an integral part of highway project appraisals since the 1970s in Finland. Meantime, the practices and evaluation methods have been harmonized. Consequently, also the npv-rule has undergone modifications. Presently, the following modified version of equation (13) is generally used (Road Office, 2000):[17]

$$\lambda I = V_0 \sum_{j=0}^{N} \left(\frac{1+\rho}{1+r_c} \right)^j + \frac{qI}{(1+r_c)^N}. \tag{14}$$

[15] For simplicity, the project is assumed to be realized at a single point of time, $t = 0$.

[16] For the state of art and challenges of cb-analysis see Vickerman (2007) and European Commission (2008). See Mackie ja Preston (1998) for a critique of established routines.

[17] Formula (14) simplifies somewhat the original formula by excluding other costs except for those of the new investment; these usually have no great importance for the outcome. In addition, for simplicity, the new investment is assumed to be realized at a single point of time.

λ is the benefit-cost ratio (henceforth, the 'bc-ratio'), measuring the profitability of the project, V_0 is the value of benefits of the new asset (realized at the beginning of period), ρ is the expected growth rate of the benefits, and qI is the salvage value of the investment ($0 \leq q < 1$).

Formula (14) modifies Formula (13) in the following respects:

- Introduction of the variable λ, the bc-ratio, substitutes for the inequality sign of (13).
- Two variables, V_0 and ρ, in Formula (14) replaces the whole profile of benefits, $\{V_j\}$, $j = 0, N$. (The growth rate ρ need not be constant although this is normally assumed.)
- Renovation costs are omitted in (14). This may be due to the fact that the commonly assumed service life, $N + 1 = 30$ years, is too short for that. The short service life has been rationalized by resorting to uncertainty.

  Introduction of the last term in (14), indicating the salvage value of investment, has also been justified by uncertainty.

The sudden death deterioration profile is assumed implicitly in Formula (14).

In practice, Formula (14) is applied as follows. First, an estimate of the investment cost I, the first year benefits V_0 and their growth rate ρ is made by experts. Setting of the parameters M, r_c and q follows conventions, official decisions or both. Finally, the bc-ratio, λ, is solved from (14) with respect to the other variables.

The bc-ratio λ plays a central role in decision-making. To be qualified for implementation, the project's λ should exceed a given predetermined critical value (the "critical λ"), normally greater than one.

Estimation of the benefits of the project is a central task of the cb-analysis. Travel time savings valued in monetary units constitute usually the main component of the benefits and the changes in the value of time is the main explanation for the growth of the value of benefits. The growth in economic activities and real wages explain the growth of the value of time savings. Views about the magnitude of this growth differ. According to some views elasticity of the value of time savings to changes of GDP is unity, according to other views it is slightly less (see Mackie *et. al.*, 2001; Hensher and Goodwin, 2004; and the literature cited therein).

The profitability of projects vary. In a given year there are very profitable projects while some projects only just reach their critical λ value. The average value λ in a given year can be calculated as a weighted sum of the λ values of realized projects.

It would be useful to know how this average λ changes over time. This could help to determine how the other variables of Formula (14) change, too.

No systematic collection of data on the λ values of realized projects exists. Either there is no evidence or casual observations that the average λ would be changing over time.

However, there is an economic rationale for the hypothesis that the average λ is invariable in time. If it were increasing (decreasing), this would be a sign for rational policymakers to increase (decrease) implementation of new projects until the "long run" average of λ has been restored. A constant increase or decrease in the λ values of realized would also put political pressures on the decision makers.

So, we have "a stylized fact":

Stylized fact The benefit-cost ratio λ is (on average) invariable in time.

This stylized fact is taken to be true, and it has certain implications for other variables. To investigate them, a dynamic version of formula (14) is introduced.

Let I^t denote the investment cost, and V_n^t the value of benefits of the n periods old infrastructure asset at the beginning of period t. Then, the cost-benefit rule for the average investment accomplished in period t states:

$$\lambda I^t = \sum_{j=0}^{N} D^j V_j^{t+j} + D^N q I^t, \tag{14'}$$

where D^j, $j = 0, N$, is the discount factor.

In project evaluations the values of the variables r_c, q and N are normally set consistently. It is, therefore, justifiable to assume that they are constant in time.

The investment cost, I^t, is the product of two components, the unit price of the new asset (unit construction cost), p_0^t, and the volume of investment in physical units (e.g., road kilometers), J^t: $I^t = p_0^t J^t$. By assumption there is no general inflation; the development of p_0^t is purely asset specific.

Equation (14′) can now be expressed as follows:

$$\lambda = \frac{1}{p_0^t}\left(v_0^t + D^1 v_1^{t+1} + D^2 v_2^{t+2} + \ldots + D^N v_N^{t+N}\right) + D^N q, \qquad (15)$$

where $v_j^{t+j} = V_j^{t+j}/J^t$, i.e., the value of benefits of the j years old asset per physical unit at the beginning of period $t+j$.

The value of benefits of n years old asset at the beginning of period t, v_n^t, is the product of the value of travel time in period t, b^t, and the travel time savings of the new asset in the beginning of period $t-j$ when the project was implemented, per physical unit of the asset, h^{t-n}: $v_n^t = b^t h^{t-n}$. The value of travel time, b^t, is, thus, tied to the current period t and the travel time savings to the moment of the project's start-up.

Assuming exponential growth and constant growth rates, b^t and h^t can be expressed as $b^t = b_0 e^{\rho t}$, and $h^t = h_0 e^{\gamma t}$. b_0 and h_0, respectively, are the value of travel time and the amount of travel time savings in period 0. Also the price p_0^t is assumed to grow exponentially: $p_0^t = p_0 e^{\alpha t}$, where p_0 is price in period 0, and α is the growth rate. More generally, p_n^t refers to the price of an n period old asset: $p_n^t = p_0 e^{\alpha(t-n)}$.

In project evaluations, the expected growth rate of benefits, ρ, is normally set equal to or slightly less than the long run average growth rate of GDP. No apparent changes in the latter have occurred in Finland, at least, during that relatively short time when project evaluations have been done. It is, therefore, justifiable to assume that ρ is constant. The constancy and sign of γ are not apparent; these will be shown below.

The value of benefits of an n years old vintage at the beginning of period t can now be expressed as

$$v_n^t = b_0 h_0 e^{(\rho+\gamma)t-\gamma n}. \qquad (16)$$

Utilizing expression (16), equation (15) can be expressed as follows:[18]

$$\lambda = v_0 e^{(\rho-\alpha+\gamma)t}\left(1 + D^1 e^{\rho} + D^2 e^{2\rho} + \ldots D^N e^N\right) + D^N q$$
$$\approx v_0[1+(\rho-\alpha+\gamma)]^t \sum_{j=0}^{N}\left(\frac{1+\rho}{1+r_c}\right)^j + \frac{q}{(1+r_c)^N}, \qquad (17)$$

where $v_0 = b_0 h_0 / p_0$.

It is clear that if the average λ is to stay constant in time, then $\rho - \alpha = -\gamma$. Formula (17) is, then, also equivalent with (14).

$\rho - \alpha > 0$ is a reasonable assumption. It is commonly argued that the value of travel time is increasing at the same or somewhat lower rate than GDP (e.g., Mackie *et. al.*, 2001). The rate of increase (if indeed it increases) in the construction cost purified from the general inflation is hardly greater than the growth rate in the value of time. Thus, as $\rho - \alpha > 0$, then $\gamma < 0$, which means that travel time savings must be decreasing in time.

We, thus, have the following corollary of the stylized fact:

Corollary For constant growth rates for the value of time, ρ and the unit construction cost, α:

$$\rho - \alpha = -\gamma.$$

If $\rho - \alpha > 0$, the order of implementation of projects is such that the most travel time saving projects are carried out first, each successive project saving less travel time than the preceding one (i.e., $\gamma < 0$).

Each project shares the same real value of benefits in its first period of operation, i.e. $v_0^t / p_0^t = b_0 h_0 / p_0 \equiv v_0$ for all t.

So, each project shares the same value of benefits at the start of the project. $\gamma < 0$ implies that every period t, older vintages always gain larger travel time savings than a new vintage, the difference being the larger, the older is the vintage.

Figure 12 illustrates the above. Assume that there are two projects of one euro except that one is carried out 30 years after another. The real value of

[18] Expression of the form e^{xt} is a continuous time version of the discrete time expression $(1+x)^t$. The former is used here in order to simplify the analysis.

the yearly benefits of the first project at the start of the second has already reached the value $v_0(1+\rho)^{30}$ that is a much bigger figure than v_0, the value of benefits of the newer project.

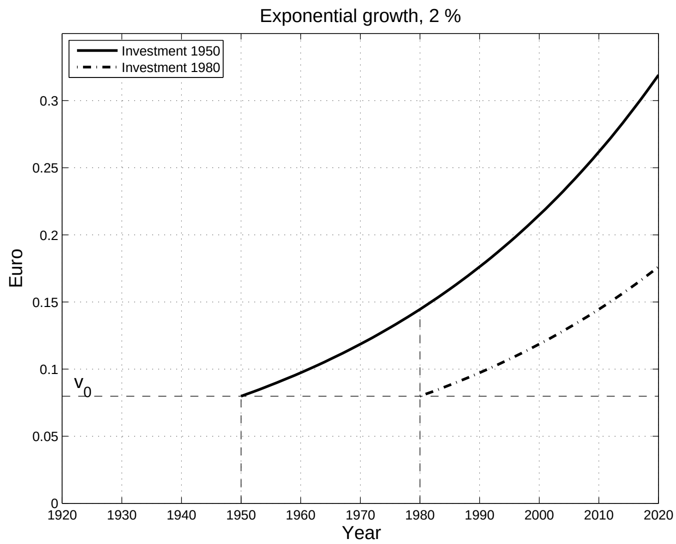

Figure 12. Growing benefits of two independent projects accomplished at different dates ($\lambda = 1.5$, $\rho = i = 2$ %)

Generally, the real value of the yearly benefit of the n years old vintage at the beginning of period t is

$$\frac{v_n^t}{p_n^t} = v_0[1 + (\alpha - \gamma)]^n = v_0(1+\rho)^n \tag{18}$$

that is larger than that of the new asset, $v_0^t/p_0^t = v_0$. Using Formula (18), Table 1 on page 9 obtains now the following specification:

Table 2: v_n^t/p_n^t

Age ↓ n	Years → t	$t+1$	$t+2$	$\dots$
0	v_0	v_0	v_0	$\dots$
1	$v_0(1+\rho)$	$v_0(1+\rho)$	$v_0(1+\rho)$	$\dots$
2	$v_0(1+\rho)^2$	$v_0(1+\rho)^2$	$v_0(1+\rho)^2$	$\dots$
3	$v_0(1+\rho)^3$	$v_0(1+\rho)^3$	$v_0(1+\rho)^3$	$\dots$
4	$\vdots$	$\vdots$	$\vdots$	$\ddots$

The columns of Table 2 are identical. Thus, assumption A7 on page 13 is valid.

3.2 Utilizing the npv-rule in the measurement of infrastructure capital

The investment criterion for infrastructure projects is in practice of the following type:

$$\lambda \leq v_0 \sum_{j=0}^{N} \left(\frac{1+\rho}{1+r_c} \right)^j + \frac{q}{(1+r_c)^N}. \tag{17'}$$

This criterion is applied in transport infrastructure project appraisal in Finland. In practice the theoretically justifiable npv-rule (13) is violated: (i) the value of the bc-ratio, λ (the "critical λ"), is normally greater than one. (ii) The service life of the asset, N, is normally much shorter than the true expected service life of the asset. Consequently, expected renovation investments associated with the project do not fit in the short service life. (iii) It could be possible to rectify the apparent misjudgments by selecting the value of q suitably. However, in practice the value chosen for it is based on entirely other justifications.

Nevertheless, criterion (17′) is useful; it can be used to solve the value of the benefits v_0 associated with new projects. Although the other variables (λ, ρ, r_c, q, and N) may be misspecified, the value of benefits, v_0, is based on experts' thorough evaluations. Thereby, criterion (17′) can be used to solve the essential information problem associated with the measurement of capital.

The value of v_0 depends on r_c, N, q, ρ and λ. Values of r_c, N and q in project appraisals are based on conventions and directions of the authorities. The expected growth rate of benefits, ρ, follows the long run average growth rate of GDP. Thus, the typical values of these variables in project evaluations can be determined afterwards. Then, the value of v_0 based on these variables should also be typical.

However, the problem is that the realized project specific values for λ are not known and, consequently, the average λ cannot be estimated. The value of critical λ is better known. The best that can be done is to base the estimates on this critical λ value. The capital stocks based on this represent, then, a kind of lower limit for the true values.[19]

When the value (i.e., the lower bound of the values) of the benefits of new infrastructure assets, v_0, has been obtained, this can be used in estimating the infrastructure capital stocks.

The fundamental equation relating stocks and flows of capital is now written as follows:

$$P_n = v_0(1+i)^n \left[1 + \frac{1+i}{1+r} + \ldots + \left(\frac{1+i}{1+r}\right)^{L-n}\right] - \sum_{j \in Z_n} \frac{c_j}{(1+r)^j}. \tag{19}$$

The price of an n years old asset, P_n is a function of the value of the new asset, v_0, the expected growth rate of the value of benefits, i, the discount rate, r, the service life, L, and the realized/expected costs of renovation (per the value of investment), $\{c_j\}$.

[19]There is, thus, a fundamental difference between infrastructure and private productive investments. In the latter case, a single equation, the fundamental equation of investment theory [e.g., (2) or (6)] in a perfectly competitive environment represents all the investments. Infrastructure investments are carried out in no competitive environment. No single equation can represent all the investments; the npv-rule [e.g., (13)], the counterpart for infrastructure investments of the fundamental equation of investment theory, is realized as an inequality. There will always be more profitable and less profitable infrastructure assets of the same age. In the present study the best that can be done is to base the estimations on the profitability of the least profitable investments.

3.3 Measuring the highway capital

The procedure of measurement consists of two phases:

(i) The value of benefits of a new asset (per km), v_0, is solved from (17) with respect to variables λ, ρ, r_c, q, and N (with $\rho - \alpha + \gamma = 0$).

(ii) For each investment (road section) the age-price profile is obtained from (19) with respect to v_0, i, r, and the realized and expected renovation costs $\{c_j\}$. The age-price profiles of road sections may differ due to differences in profiles $\{c_j\}$. (As shown by equation (19), the sudden death deterioration pattern is assumed.)

Customarily, the price profiles of investments, $\{P_j\}$, are used as weights in composing the aggregate wealth capital stocks, and the profiles of returns $\{v_j\}$ are used in composing the aggregate productive services capital stocks for highways (c.f., section 2.3).

The reliability of the estimate for v_0 does not depend on how realistic are the chosen values for variables λ, ρ, N, r_c and q. What matters is representativeness of these values. That is, they should be values used customarily or on average in project appraisals.

The values of the variables i, r and L, respectively, need not be equal to those of the corresponding variables in Formula (17′), ρ, r_c and N.

Parameters utilized

The following parameter values are chosen:

1. phase

$L = 30$ years
$q = 30$ %
$\rho = 2$ %
$\lambda = 1.5$
$r_h = 6$ %.

These values of L, q and r_h are commonly used in recent project appraisals (e.g., Road Adminstration, 1999; and Road Office, 2000).

$\lambda = 1.5$ represents the critical bc-ratio in project appraisals during the last decades. It is certainly below the long-run average λ. Calculation are also made with $\lambda = 1$. This case serves chiefly as a baseline.

The chosen growth rate of benefits $\rho = 2$ % is less than the long-run average growth rate of GDP in Finland, slightly over 3 % (Hjerppe, 1989).

2. phase

Growth rate of benefits $i = \rho = 2\%$.

This value represents a conservative guesstimate. Calculations are also made for $i = 0$ %, which serves as a baseline.

Other parameter values are as in the standard (sudden death) case in Section 2.

Cases

We, thus, have four cases:

Case	λ	i (%)
I	1	0
II	1	2
III	1.5	0
IV	1.5	2

Case IV is the most realistic one (with the proviso that the results represent a lower bound for the true estimates).

Comparing results for cases I–IV may help to interpret the behavior of the model with respect to the parameter values (sensitivity analysis).

Comparing case I with the standard (sudden death) case of section 2 shows how much, in today's project evaluations, results are distorted by selection of the values for N, q and r_c.

Results

Figures 13A and 13B, respectively, present the growth of the value of benefits, v_j $(j = 0, 119)$, and the age-price profiles of a unit investment in cases I–IV. Here we assume service life of 40 years for renovation investments.

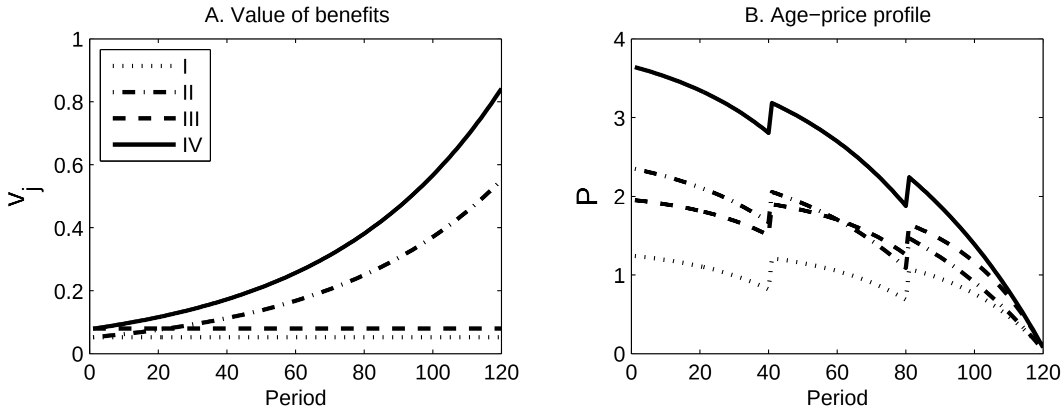

Figure 13: (A) Growth of the value of benefits, and (B) age-price profile of an investment (40 years service life of renovations, $c_j = 0.4$)

The value of benefits of the new asset in cases I–IV and in the standard case of section 2 are as follows:

	Case I, II	III, IV	Standard (Section 2)
v_0, u_0	0.0522	0.0798	0.0427

All cases I–IV show higher value of benefits than the standard case of Section 2.

In cases I and III the benefits are constant in time ($i = 0$ %) and in cases II and IV by assumption they grow exponentially. The rate of growth $i = 2$ % raises the value of benefits to $1.02^{120} = 10.8$ -fold during the service life of investment (120 years).

Age-price profiles (Figure 13B) are upwards scaled curves of the standard age-price curve of section 2 (see Figure 2 on page 17) except that the heights of the upwards jumps at the dates of renovation are unaltered. The prices of the new asset, P_0, in cases I–IV, respectively, are 1.2, 2.4, 2 and 3.8 times larger than in the standard case. As the latter is based on the same set of assumptions that those made in the measurement of private productive capital, these results indicate that the highway investments must have been more profitable than the private productive investments.

The aggregate wealth capital and productive services capital stocks in period 1900–2009 are measured as before [case (i) in section 2.3]; the age-price profiles are used as weights in calculating the aggregate wealth capital stock and the profiles of benefits are weights in calculating the aggregate productive services capital stocks.[20] Results are presented in Figures 14 and 15.

The shapes of the aggregate wealth capital stock curves associated with cases I–IV (Figure 14) are similar to that in the standard case (Figure 7) and in all cases the stocks are at a higher level than in the standard case. The increase in λ from 1 to 1.5 (case III) or the increase in the growth rate i from 0 to 2 % (case II) have effects of the same magnitude on the wealth capital stocks. Both changes together (case IV) have a drastic effect on the aggregate values of wealth capital stock. At its best, the aggregate value of wealth capital stock has been 190 milliard euros in the turn of the 1970s. In 2009 it was still over 170 billion euros.

Also the the aggregate values of productive services capital stock in 1900–2009 (Figure 15) are higher than that of the standard case (Figure 8). The positive growth rate of benefits (cases II and IV) is directly and drastically reflected in the aggregate values of the productive services capital stock.

[20]Both profiles may differ by investments due to the differences in the profiles of renovation costs $\{c_j\}$.

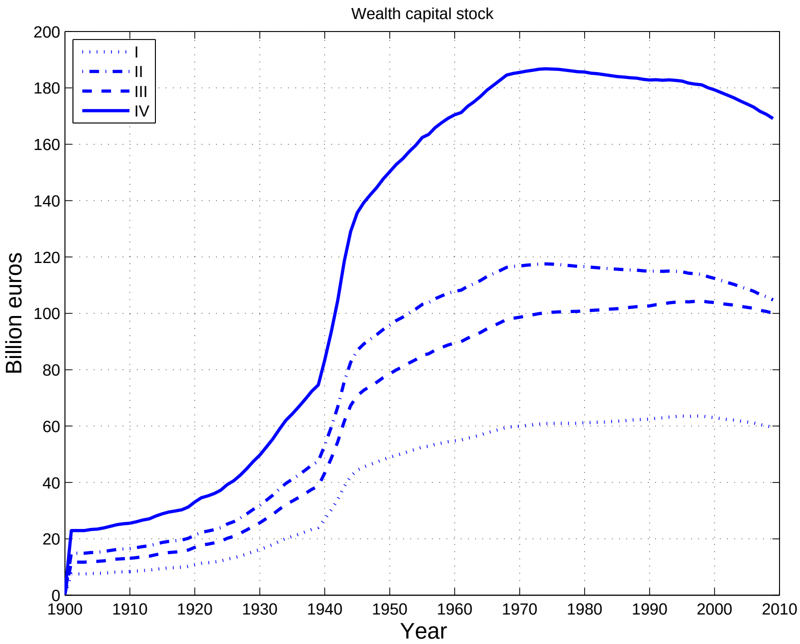

Figure 14. The aggregate value of the wealth capital stock of highways in 1900–2009 as a continuum to cb-calculations

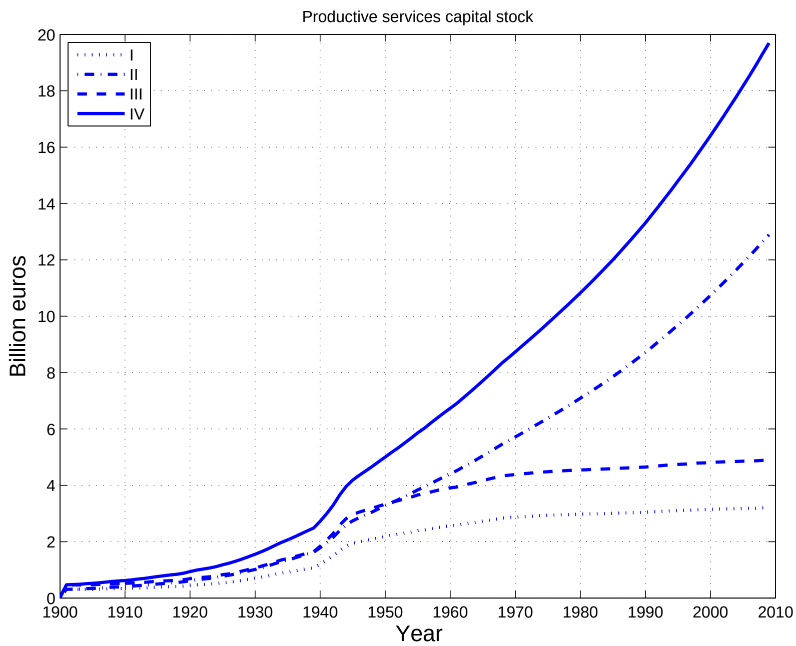

Figure 15. The aggregate value of the productive services capital stock of highways in 1900–2009 as a continuum to cb-calculations

3.4 Remarks

In this section the net-present-value rule with its typical parameter values was used to derive the profile of the value of benefits associated with the highway investments. Thereafter these benefits were used in the measurement of the capital stocks.

The reliability of the results depends on the representativeness of the chosen parameter values. We have chosen them with conservatism preferring to underestimate than overestimate the results.

The credibility of the results depends on the premise that investment decisions are consistently based on cost-benefit considerations and that the method and practice of cost-benefit analysis comprehensively takes into account the benefits associated with separate road investments as well as the whole road network. These premises are not necessarily justified.

First, it it well known that the recommendations implied by cost-benefit considerations are not always followed by decision makers. Considerations of regional equity, regional policy issues, financial constraints, economic cycles, etc. may outweigh the recommendations of a cost-benefit analyst (see also Rietweld and Boonstra, 1995).

Secondly, the view taken above is atomistic. It was argued that the travel time savings of individual projects follow a long-run run average trend and the aggregate values of the capital stocks are obtained as a weighted sum of the values associated with individual projects. However, the whole may be more than its parts. In attempting to figure out the benefits of the road network, one should try to treat the network in its totality. Introduction of the accessibility indicators in the next section may be a step to this direction.

Finally, project appraisals are commonly criticized in that they do not estimate comprehensively all the benefits of a project. This criticism does not concern merely the above-mentioned network effects (for these, see, e.g., Laird *et. al.*, 2005; and Straatemeyer, 2008); the overall macroeconomic effects of transportation infrastructure investment are generally given no attention in project appraisals (see, e.g., Weisbrod and Treyz, 1998). There is a viable tradition in the sphere of macroeconomic research that analyzes the effects of public infrastructure investments on the economic growth and the private sector performance (see Romp and de Haan, 2007, for a survey).

So far, the research results generally show positive macroeconomic effects for public infrastructure investments.[21]

Despite these reservations about the cost-benefit method and the ways of its application the results based on them can still be regarded as useful. The magnitude of the results is certainly closer to the true values than is any of the conventional estimates so far.

Finally, this section has shed light on the consequences of the fundamental difference between the environments in which public and private investments are determined. In a market environment the returns of all the investments of the same age equalize, whereas in the case of public investments, there are always (socially) profitable and less profitable investments. The returns of different investments of the same age do not usually equalize, except by chance.

[21]No doubt, all the benefits (productive services) should be included in the measurement of infrastructure capital stocks, also macroeconomic benefits. In trying to do this, we are faced with a serious methodological problem. Untangling the macroeconomic effects necessitates a definition and estimation of a production (or cost) function that describes the production potentials of the economy. Productive services infrastructure capital stock should be an independent variable among the other variables in this function. The problem lies in that in the measurement of infrastructure capital we need macroeconomic effects but finding out those requires, in turn, an infrastructure capital variable. The problem is related to those of the famous Cambridge controversy around the 1960s (see Harcourt, 1969). A possible way out of the dilemma might be utilizing a general equilibrium framework (c.f., Bliss, 1975).

4 Inclusion of accessibility gains in the measurement highway capital

Road investments improve the accessibility in the network. Accessibility gains fall not only on some restricted area but, in principle, on the whole network. Each new investment creates, then, a positive externality on the preceding investments on the network. In this section these accessibility gains will be taken into consideration in this section in the measurement of capital stocks.

The concept of accessibility and its measurement is discussed in section 4.1. Section 4.2 shows the improvements of the potential population accessibility in Finland. Section 4.3 connects the accessibility improvements in the measurement of capital.

4.1 Accessibility gains of road investments

Single roads and road sections constitute a road network. The network evolves piecemeal as new connections are connected to it. Functioning of the network depends, on one hand, on the physical qualities of single road sections (the number of lanes, geometry, width, condition of the surface, protective devices etc.), and, on the other hand, on how it is organized to a functioning whole. Graph theory and optimizing models can tell a lot of the intrinsic influence of topological and geometric properties of the network on its performance (e.g., Gastner and Newman, 2006; Jiang and Claramunt, 2004; Porta *et al.*, 2006; Ahn *et al.*, 2007; Donetti *et al.*, 2006). Structural properties are also essential for reliability and vulnerability of the network (e.g. Latora and Marchiori, 2005; Chen *et al.*, 2007; Jenelius *et al.*, 2006; and Murray *et al.*, 2008).

Accessibility is a fundamental concept in transportation analysis and planning.[22] A few authors find a correspondence between accessibility measures and benefit measures of microeconomic theory (e.g., Ben-Akiva and Lerman, 1979; and Small, 1992).

[22] For a discussion of complementary views and the general nature of this concept, see Miller (1999) and Harris (2001).

Accessibility is a measure of ease of access. There are many alternative general characterizations, e.g., "ease of spatial interaction", or more precisely, attractiveness of a node in a network taking into account the mass of other nodes and the costs to reach those nodes via the network (Rietveld and Bruinsma, 1998). A large number of alternative accessibility measures have been presented in literature. Early measures were introduced in the context of graph theory 50–60 years ago (Pooler, 1995).[23]

As accessibility can be defined in various ways, it may also be measured accordingly. The most widely used type is the so-called "market potential measure" (Keeble *et al.*, 1982).[24] The traditional market potential concept is also justified in the framework of modern urban economics (see Fujita *et al.*, 1999).

A typical mathematical representation of the market potential accessibility measure is

$$A_i = \sum_j \frac{P_j}{T_{ij}^a}, \tag{20}$$

where A_i is the accessibility in location i, P_j is a measure of the size or mass of location j, and T_{ij} is the travel cost between locations i and j. Travel times are often used as proxies for travel costs in empirical studies.

The exponent a relates to "the friction of distance". The greater is a, the greater is the difference between near and remote locations. In principle, the value of a should depend on the type of activity in question. Most commonly used value in empirical studies is one.

According to (20), the accessibility of a location is the weighted sum of the sizes (e.g. populations or GDPs) of all locations, the inverse of travel costs or travel times as weights.

Accessibility is closely related to economic development. Measures, such as (20), are widely used in describing changes of accessibility in a nation (e.g., Axhausen *et al.*, 2004), or in analyzing impacts of large-scale transport infrastructure building programmes (e.g., Gutiérrez *et al.*, 1996; Gutiérrez and Urbano, 1996; Gutiérrez, 2001; and Holl, 2007). Accessibility measures have been used to describe the (uneven) regional economic development, e.g.,

[23] See Rietveld and Bruinsma (1998), or Geurs and van Wee (2004) for a survey of accessibility measures.

[24] See also Holl (2007) for a categorization of the accessibility measures.

by Vickerman (1996), and Vickerman *et al.* (1999).

Accessibility can be equated with a production factor, and by including accessibility indicators directly into a production function, regional productivity and economic development can be explained (e.g., Forslund and Johansson, 1995; Weisbrod and Treyz, 1998; and Wegener, 2008). Gutiérrez *et al.* (2009) uses accessibility indicators to assess and monetize spatial spillovers of transport infrastructure investments. Holl (2004) argues that access to road transport infrastructure plays an important role in manufacturing plant location decisions.

4.2 Accessibility improvements in the Finnish highway network

In what follows we, first, evaluate the accessibility development in the Finnish highway network since 1900.

The accessibility measure used is the one presented in Formula (20). In the absence of detailed data on regional economic activities, populations in locations are used as proxies for the sizes of locations, P_j. Thus 'the population potential accessibility' variant of the measure is applied. Travel times are used as proxies for travel costs and the value of a is set to 1.[25]

There are some well-known practical problems in the measurement: reconstructing of the historical networks, choice or demarcation of the nodes for calculations, treatment of the internal accessibility, and assessing the travel times. Different sources seem to settle these problems differently (c.f., Rietweld and Bruinsma, 1998; Vickerman *et al.*, 1999; Axhausen *et al.*, 2004; Holl, 2007; or Gutiérrez *et al.*, 2009). These problems are considered below.

Reconstruction of the historical networks

For each road section the date of construction is given or estimated by the procedure described earlier on page 25 in section 2.3. The problem is that for

[25]Other functional forms of the population potential accessibility index were also attempted in this study but the end results did not differ substantially.

many roads, even for adjacent road sections, the estimated dates of construction differ such that these roads would be disconnected for several periods at one of more points. This an unpleasant feature for an accessibility analysis. Therefore, instead of the realized/estimated dates of construction, we use their convex hull (see Figure 17 for illustration) in the accessibility analysis. (More on this on page 80 in the Appendix.)

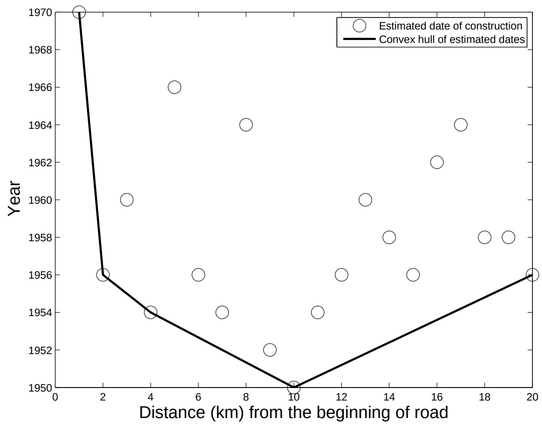

Figure 17. Convex hull of the estimated dates of construction of the road sections

Choice of the nodes and treatment of the internal accessibility

The total area of Finland is divided into squares of 10×10 km (3319 pieces) (Figure 18). A few restricted fringe areas in the northern part of Finland and Åland Islands are ignored. The centroid of a square serves as the origin of the fastest path problem underlying the accessibility index [subscripts i in Formula (20)]. The center of a municipality (i.e. the node of the road network closest to the center of a municipality) serves as the destination of the fastest path problem underlying the accessibility index [subscript j in Formula (20)]. Populations are assumed to be concentrated in the center of municipalities. The fastest route from an origin to a destinations is composed of three phases:

1. As the crow flies from the centroid of the square i to the closest node

(say, w) of the road network with the speed 25 km/h.

2. From node w to the closest node (say, z) of the center of the closest municipality using the fastest route.

3. From node z to the final destination, the center of municipality j using the fastest route.

For each accessibility index i there are 332 destinations j (the number of municipalities in 2009).

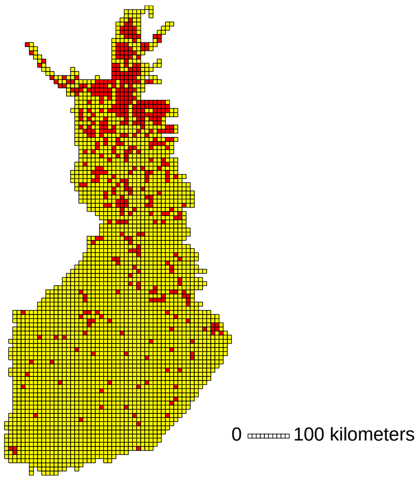

Figure 18. Grid network of Finland (red squares contain no junctions)

Travel times and vehicle speeds

Travel times, T_{ij}, in Formula (20) are obtained as a solution to a fastest path problem. The solution depends on available route alternatives, and on the traveling speeds on the road sections.

Traveling speeds depend on the attainable vehicle speeds, drivers' driving habits and speed limits on the road sections. All of them have changed in time.

Figure 19 presents the average traveling speeds of all the vehicles in Finland in the period 1900–2009.[26] The drop in the curve in 1974 is explained by the introduction of differentiated speed limits. The average speeds after 1974 concern roads with the speed limit 100 km/h. As can be seen, the average speeds are clearly below the maximum admissible limit.

Unfortunately, information on average speeds on roads with a speed limit other than 100 km/h is unavailable. This information is obtained from the model developed later on.

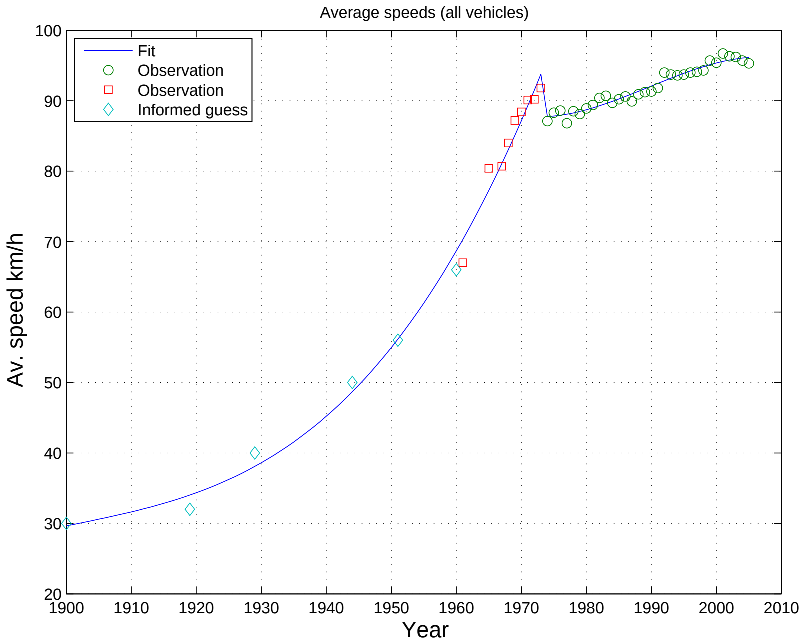

Figure 19. Average vehicle speeds on Finnish highways in 1900–2009

Model on average vehicle speeds

The average vehicle speed is explained by two factors; the speed limit and the drivers' driving habits (or preferences). Drivers differ regarding their preferred overall travel speed. Driving habits are also influenced by the quality and type of the vehicles.

[26]Data after 1960 is from Kangas (2006). Earlier data is based on disjointed figures presented in a historiography (TVH and Suomen Tieyhdistys, 1977).

The distribution of driving habits at the given date is assumed to follow the Weibull -distribution:

$$W(x) \equiv f(x|\mu, \theta) = \mu(x-\theta)^{\mu-1}e^{-(x-\theta)^{\mu}}, \tag{21}$$

where μ is the shape parameter, θ is the location parameter, and x is the speed (km/h).

Using this distribution of driving habits, the average speed, v_a, on a given road section in a given year is obtained by

$$v_a = \begin{cases} \int_0^{\infty} W(x)x dx, & \text{No speed limit} \\ \int_0^{R} W(x)x dx + \left[\int_R^{\infty} W(x)dx\right]R, & \text{Speed limit} \end{cases} \tag{22}$$

where R is the speed limit (km/h). Till (after) 1974 the average speed is determined according to the upper (lower) equation. The latter equation takes into consideration that part of the drivers may freely choose the speed according to their preferences (the first term on the right hand side) and another part is forced to drive according to the given speed limit R (the second term).

Driving habits (with the properties of vehicles) are changing with time. Consequently, the distribution of preferences must be shifting horizontally to the right (Figure 20).

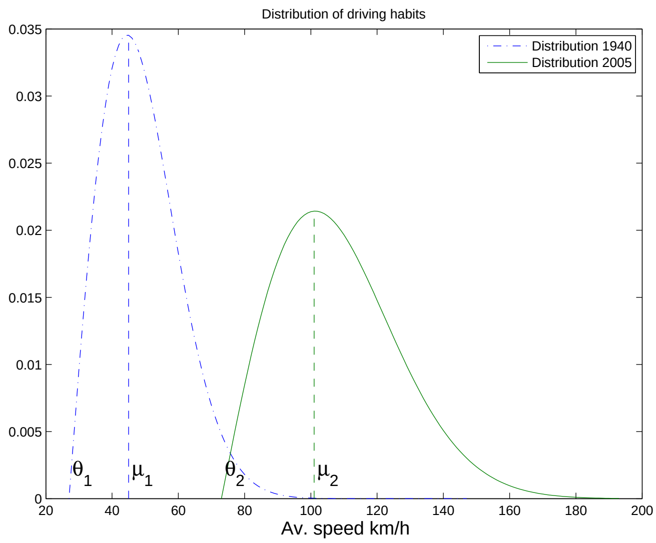

Figure 20. Weibull -distributions of driving habits in 1940 and 2005

Changes in preferences are captured by changes in parameters μ and θ. In principle, their values at each points in time could be obtained as a solution to a data-fitting problem. Nevertheless, in this study we content ourself with the experimentally found values for μ and θ (Figure 21). The fit (solid line in Figure 19) generated by these experimental values conforms to observations well enough.

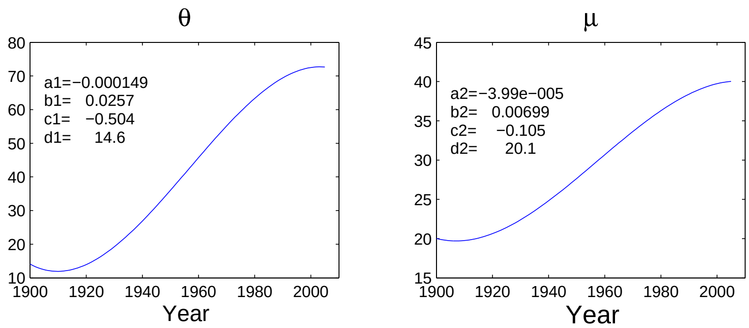

Figure 21. The parameter values μ and θ of the driving habit distributions:
$\theta = a_1t^3 + b_1t^2 + c_1t + d_1$,
$\mu = a_2t^3 + b_2t^2 + c_2t + d_2$; $t =$ Year$-$1899.

Results

The fastest path problems are solved with the Dijkstra-algorithm (Dijkstra, 1959) using the MATLAB -software.

In order to save computer time calculations were carried out at intervals of five years from 1900 to 2009. The resulting precision is sufficient enough for the present purposes.

Figure 22 displays the maps of accessibility in Finland for 1920, 1950, 1980 and 2008. Each map shows the regional accessibility levels compared the national average at the point of time in question.

A spectacular feature is the wide divergence in accessibility levels, and each successive point of time displays a greater divergence. The accessibility levels from the national average range from 0.23 to 2.8 in 1920 and from 0.25 to 4.7 in 2008. As expected, the highest accessibility levels are in the capital city, Helsinki, and in its surrounding area. The lowest levels are in the northern part of Finland. Tables 3 and 4 reveal the same tendencies.

Figure 23 displays the relative changes in accessibility levels in the periods 1921–1950, 1951–1980 and 1981–2008. Each period witnesses an improvement in accessibility but in each successive period the improvement is less than in the preceding period. The average improvement is 204 % (on average 3.8 % per year) during the period 1921–50, 63 % (1.6 % per year) in the period 1951–80 and 15 % (0.5 % per year) during the period 1981–2008 (Table 5).

In the period 1921–50 accessibility has improved relatively evenly around the whole country; in the subsequent periods it is chiefly the surrounding of the capital city as well as the district of Oulu in the last period to lesser extent that have gained from the improved accessibility. This trend is visible also in the development of the inequality indices (Table 4).

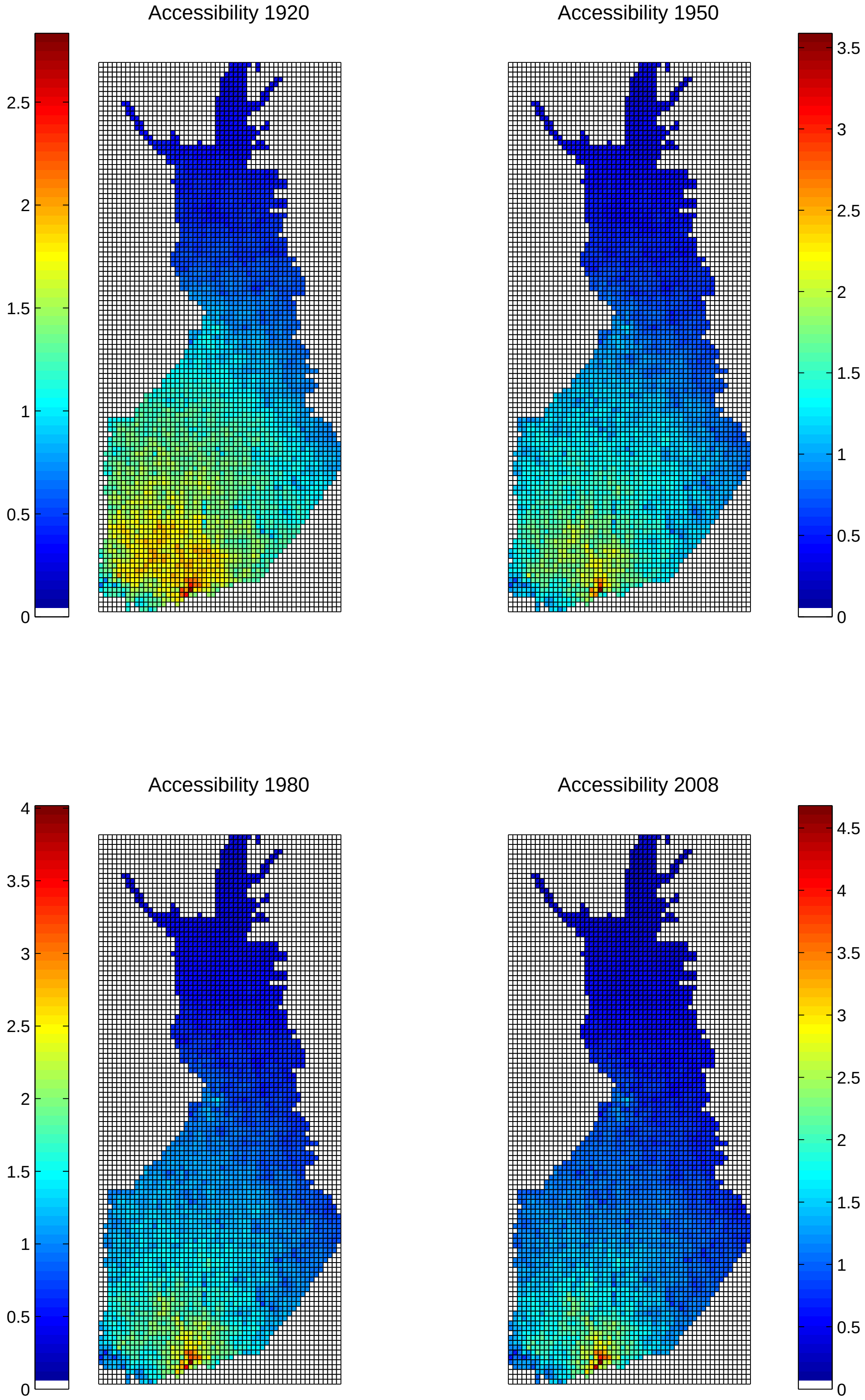

Figure 22. Population potential accessibility 1920, 1950, 1980 and 2008 (National mean = 1)

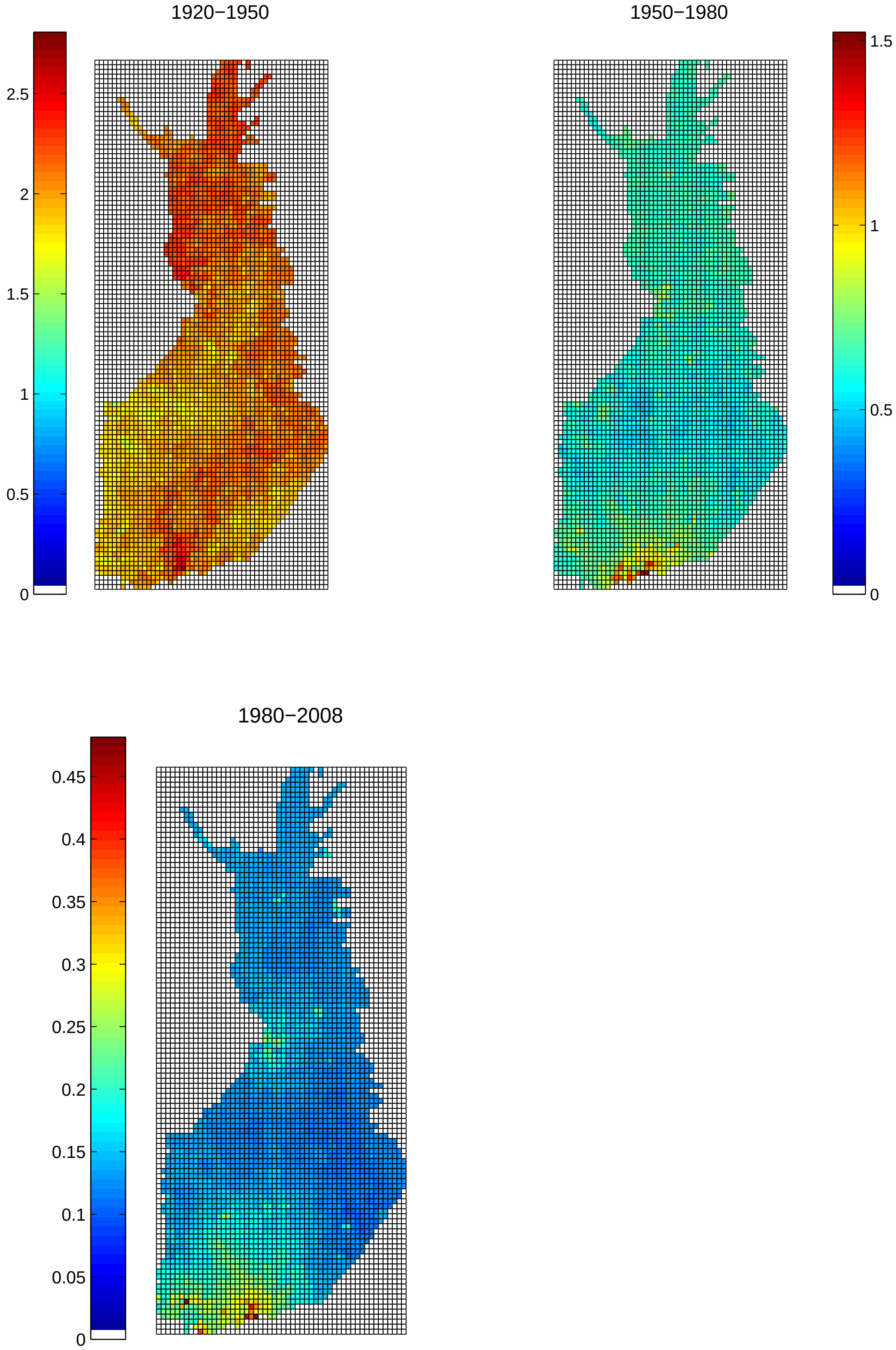

Figure 23. Relative changes in population potential accessibility 1920–1950, 1950–1980 and 1980–2008

Table 3. Summary statistics of the accessibility index (10^3)

	1920	1950	1980	2008
Mean	256.4	771.1	1260.9	1462.5
Std dev.	118.0	350.7	609.5	759.1
Min	59.2	190.9	313.2	357.1
Max	726.8	2767.5	5066.4	6843.7

Table 4. Inequality indices

	1920	1950	1980	2008
Coeff. of variation	0.1059	0.1034	0.1168	0.1346
Gini	0.2640	0.2588	0.2695	0.2830
Theil	0.1120	0.1071	0.1157	0.1283

Table 5. Summary statistics of relative changes in accessibility index

	The whole period			On average per year		
	1920–50	1950–80	1980–08	1920–50	1950–80	1980–08
Mean	2.04	0.63	0.15	0.038	0.016	0.005
Std dev.	0.149	0.086	0.038	0.0017	0.0017	0.0011
Min	1.509	0.460	0.096	0.031	0.013	0.003
Max	2.808	1.523	0.482	0.046	0.031	0.013

Accessibility improvements are mainly due to two factors; (a) the development of the network, i.e. the yearly increments of new connections and the way how they are organized, and (b) on the vehicle speeds on the roads, i.e., the drivers' driving habits and the speed limits.

Figure 24 shows the role of a vehicle speed in the total development. The "total accessibility", i.e., the sum of accessibility indices in the country, has increased over seven-fold during the period 1900–2009. At the same time the estimated average vehicle speeds have increased slightly over three-fold.

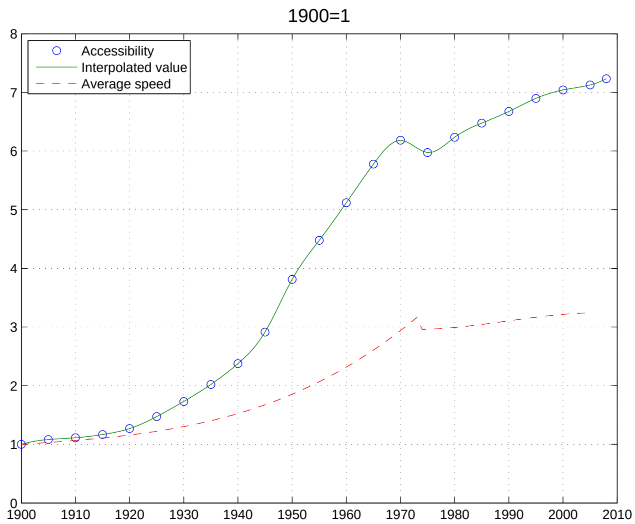

Figure 24. Development of the network accessibility and the average speed on the roads

4.3 Including accessibility gains in the highway capital measures

A road project by definition shortens travel times. Besides for those extending to neighboring areas, travel times are also shortened for trips aimed to more remote destinations. Consequently, local road project improves the accessibility in a multiplicity of points on the road network. In line with this idea is the distinction between local and spatial spillover effects of transport infrastructure investment (Gutiérrez *et al.*, 2009). In principle, the positive effects on all the travel times — either concerning shorter or longer trips — should be included in the cost-benefit -calculation of the project.

If a single road investment improves accessibility on a multitude of locations of the network, the opposite is valid as well; the multitude of road investments on different locations improve the accessibility on a given location of the network. A network is defined by a countless number of successive locations on a large number of road sections. For each location accessibility in terms of the rest of the locations can be measured. All the investments on the network that improve the accessibility on a given location after its creation is a benefit that falls freely to the credit of that location and that road section.

There is a considerable amount of literature analyzing the economic effects of public infrastructure investments (see Romp and Haan, 2007, for a survey). In these studies the (wealth) capital stock is mainly used as a variable describing the productive services of the road network.

Axhausen (2004) presents a well-founded critique against the use of the conventional capital stock measures for this purpose (in Shirley and Winston, 2004). These capital stock variables implicitly assume a constant ratio between the value of the capital stock and the services provided by the road network. This assumption is not empirically justifiable. Better solutions for empirical research than to utilize a conventional capital stock variable would be to substitute an accessibility variable, which directly measures the network services, for the capital stock variable (e.g., Forslund and Johansson, 1995), or complementing the latter with a variable describing "network or spillover effects" (e.g., Cohen and Morrison Paul, 2004).

But if the capital stock variable itself is ill-defined, perhaps the best strategy for empirical research is to correct the variable itself!

In terms of economics the accessibility improvement on a location caused by outside road investments is an external effect or externality. This effect can directly be included in the measurement of capital. Assuming that the efficiency of a road section is preserved by regular renovation investment (sudden death deterioration), the price of an n years old (road) asset on location i is given by the following formula:

$$P_n^i = u_0^i \sum_{j=n}^{L-1} \frac{A_j^i / A_0^i}{(1+r)^{j-n}} - \sum_{j \in Z_n^i} \frac{c_j}{(1+r)^{j-n}}, \qquad n = 0, ..., L-1 \tag{23}$$

A^i_j is the accessibility in period j, and A^i_0 is the accessibility at the date of accomplishment of the investment project on location i. Formula (23) modifies (9) by including the term A^i_j/A^i_0, the accessibility in period j relative to the accessibility in period 0 when the project was accomplished.

The ratio A^i_j/A^i_0 can also be expressed as

$$A^i_j/A^i_0 = \Pi^{j-1}_{k=1}(1+\tau^i_k), \tag{24}$$

where τ^i_k is the rate of change in the accessibility k periods after the date of investment on location i.

The procedure of measurement

The procedure of measurement is the same as that applied for the sudden death deterioration case of section 2 (page 20). First, for each investment (road section) i the returns of the new asset, u^i_0 is solved for the given dates of renovation Z^i_n, renovation costs $\{c^i_j\}$, and the discount rate r. Then, the age-price profile $\{P^i_j\}$ is solved with respect to u^i_0, the ratios of accessibility $\{A^i_j/A^i_0\}$, the dates of renovations, renovation costs and the discount rate. Finally, the profile of returns (benefits) $\{u^i_0 A^i_j/A^i_0\}$ is determined.

The age-price profiles and the profile or returns, respectively, are used as weights in calculating the aggregate values of wealth and productive services capital stocks [Formulas (7) and (8)].

Data and assumptions associated with it are as in section 2.

The yearly improvements in accessibility in existing road sections after 2009 is assumed to be the same as in the period 2005–2009, on average.

Results

The aggregate values of the wealth capital stock with and without accessibility gains, respectively, are presented in Figure 25. The value of the wealth capital stock with (without) accessibility gains is 200 (43) billion euros in 2009. The aggregate value of the wealth capital stock with accessibility gains is 4.6 times larger than that without accessibility gains in 2009.

There is a downturn in the values of the wealth stock without accessibility gains in the 2000s; no such downturn is visible in the values with accessibility gains. Accessibility gains thus outweigh the decrease of the asset price due to the expected renovation investments in the nearby future.

The aggregate values of the productive services capital stock with and without accessibility gains, respectively, are presented in Figure 26. The value of the productive services capital stock with (without) accessibility gains is 8.2 (2.5) billion euros in 2009. The aggregate value of the productive services capital stock with accessibility gains is 3.3 times larger than that without accessibility gains in 2009.

There is a clear drop in the value of the productive services capital stock with accessibility gains in 1974, due to the introduction of the differentiated speed limits.

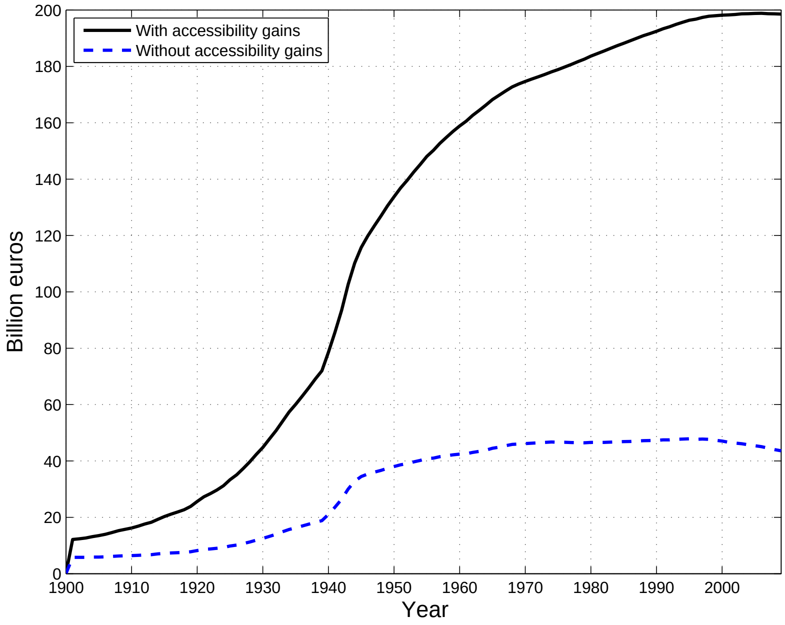

Figure 25. The aggregate values of the wealth capital stock of highways in 1900–2009 with and without the accessibility gains

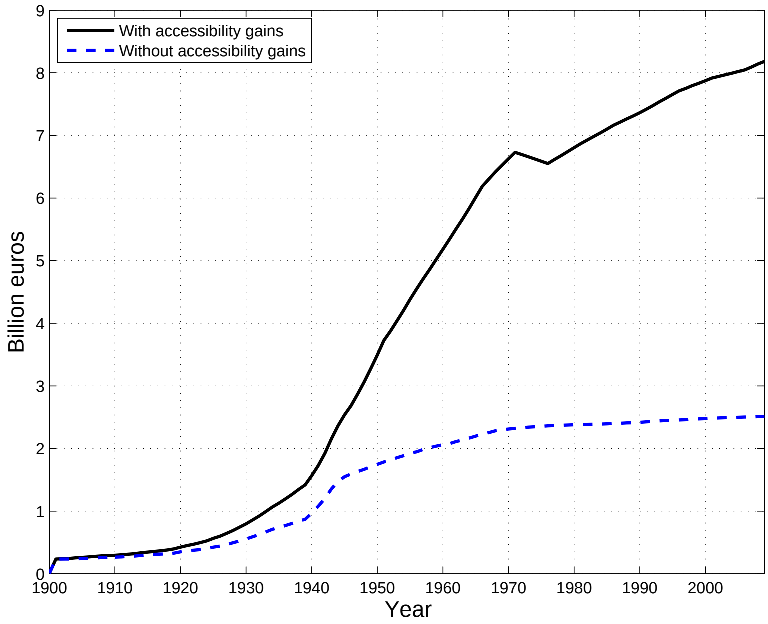

Figure 26. The aggregate values of the productive services capital stock of highways in 1900–2009 with and without the accessibility gains

5 Summary and concluding remarks

In this study we measure the values of the Finnish highway capital stock in the period 1900–2009 under different assumptions.

The book value of the Finnish highways was about 15 milliard euros in 2009. The value of the wealth capital stock of highways estimated by Statistics Finland was of the same order. Both estimates with the associated time series are badly flawed.

Conventional estimates of infrastructure capital are based on methods and assumptions established for measuring the private productive capital. In the highway infrastructure case these are unjustified.

The service life of the infrastructure asset is very long. With regular maintenance and renovation investments the efficiency of the asset is kept stable. Therefore, the sudden death (one hoss shay) age-efficiency profile of the asset is justifiable in this context. Renovation investments must explicitly be included in the formula expressing the relationship between the asset price and returns of investment (the fundamental equation of investment theory). Renovation investments must not be included any more as separate investments in the estimate. With these modifications to the current practices the wealth stock of highways in Finland obtains the much higher value 43 billion euros in 2009.

Private productive investments are assumed to be made in a competitive environment. Then, the value of the asset equals the present value of the expected returns of the asset. There are no competitive markets for infrastructure investments. Infrastructure projects pass through a public decision making process preceded by a cost-benefit analysis. Infrastructure projects are unique with varying benefit-cost ratios. But even for the most unproductive infrastructure investment the benefit-cost ratio exceeds unity. These facts have marked implications for the capital values.

Using the typical cost-benefit rule and parameter values applied in calculations to asses the value of the benefits of a typical highway project, the wealth capital stock of highways in Finland obtains the value 170 billion euros in 2009.

Single roads and road sections form a network. The network evolves piecemeal along with an introduction of new connections. Each new connection increases the value of the network for its own part but simultaneously the performance and value of the rest of the network increases. In other words, each new investment has a positive external effect on the previous investments.

An accessibility index and its changes is used as a proxy variable to describe the positive external effects. Including these effects in the measurement of capital, the wealth capital stock of highways in Finland obtains the value 200 billion euros in 2009.

Besides the wealth capital stocks, the values of the productive services capital stocks of the highways (under different assumptions) are estimated in this study. The value of the productive services capital stock has increased at a higher rate than that of the wealth capital stock in the period under consideration and it still increases in periods in which the latter decreases (the models of section 2 and 3).

These empirical findings strongly suggest that the concept of capital used in productivity studies — the wealth capital vs. the productive services capital — must have relevance for the results.

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Appendix: Data and its manipulation

Roads

The data on roads and bridges, respectively, comes from the road and bridge registers maintained by the Road Administration of Finland (situation 1.1.2009).

Information on the 9498 roads are first collected to a *structure array* (using MATLAB's terminology). Each road specifies one *element* of this variable (see below), and each attribute specifies a *field* (or row) in the element. The fields are vectors whose length (apart from one exception) are determined by the number of nodes included in the road.

For example, information on highway 4 is organized as follows:

Table I.1

Variable	Type of data	Explanation
no:	1×1 double	Road number
nodes:	1×845 double	Node codes (Bridge=0)
bridges:	1×845 double	Bridge codes (Node=0)
road sections:	1×845 double	Codes of road sections which nodes/bridges belong to
municipality:	1×845 double	Codes of municipalities which nodes/bridges belong to
edges:	1×844 cell	Lengths between nodes
so-coord:	1×845 cell	Coordinates of nodes
si-coord:	1×845 cell	Coordinates of bridges
t-tmp:	1×844 cell	Type and date of the latest technical operation
a-tmp:	1×844 cell	Type and date of the latest administrative operation
Speed:	1×844 cell	Speed limit
Road class:	1×844 cell	Administrative road class (1,...,4)
Width:	1×844 cell	Road width
Road type:	1×844 cell	Road type: motor way, trunk road, ordinary road
track2:	1×844 cell	Existence of second track
Surface:	1×844 cell	Pavement type

Thus, highway 4 is comprised of 845 nodes and 844 edges. (A bridge always constitutes a node.) "Piece" of information associated with each node (edge) is an element in a (1×845)-vector [(1×844)-vector]. "Pieces" of information may be scalars (data types "double" above) or itself vectors (data types "cell" above), e.g., coordinate pairs.

A 'technical operation" (variable t-tmp) can be one of the following: building of a new road, reconstruction of the road-bed, improvement of the geometry or a light repair. An "administrative operation" (variable a-tmp) stands for the transfer of the road section to the possession of the Road Administration.

In order to establish the history of the network, information is reorganized as follows:

Table I.2

Variable	Type of data	Explanation
nodes:	1×839 double	Node code
bridges:	1×839 double	Bridge code
d_I:	1×839 double	Date of new investment
d_r:	1×839 double	Date of reconstruction of road-bed
d_g:	1×839 double	Date of improvement of geometry
d_l:	1×839 double	Date of light repair
d_A:	1×839 double	Date of administrative operation
d_B:	1×839 double	Date of building of the bridge
cvali:	1×839 double	Length of the edges cumulatively
Speed:	1×839 double	Speed limit

The number of edges on highway 4 have decreased from 844 to 839 since the original data involves edges that have a length of zero meters.

Dates of construction

With each road section (edge) information is associated on the date and type of one and only one, the most recent technical operation. Consequently, if a road section has been repaired afterwards, its construction date is lost. In these cases the date is estimated using the date of repair, the engineers' recommendations for a lifetime of renovations, the dates of building of the (potential) bridges on the road sections, and the dates of (potential) transfers of road sections to the possession of the Road Administration.

For a road that is constituted by m edges, the history is defined by two (1×m)-vectors or "profiles": the vector of dates of building the road sections, say D_I, and the vector of (realized or planned) dates of renovations, say D_R. The elements of these vectors, respectively, refer to the dates of new investments and renovation investments of the road sections.

The construction date of section j ($j = 1, m$) on a given road is estimated as follows:

$$D_I(j) = d_I(j),$$

if this information is available. Otherwise:

$$D_I(j) = \min\{d_R(j) - v_R, d_A(j) - v_A, d_B(j)\}.$$

Symbols d_I, d_A and d_B refer to variables in Table I.2. $d_R(j)$ is the date of the latest technical operation other than building of the new road: $d_r(j)$, $d_g(j)$ or $d_l(j)$ (see Table I.2) depending for which one this information is available.

Constant v_R and v_A, respectively, are the lifetime of renovations and the assumed time lapse between building of the road section and its transfer to the possession of the Road Administration. The following values are assumed for these constants: $v_R = 40$ (years) and $v_A = 20$ (years). The first one accords with the engineers' suggestions for a lifetime of renovations and the data at hand. The chosen value for v_A is a conservative guestimate; in most cases the true value of v_A must rather be larger than that assumed here. In reality, true values of v_A may deviate a lot from case to case. However, utilization of dates d_A and the assumption of a constant value for v_A can still be considered useful since it is predominantly just in those cases when information on dates d_A exists but all other information is missing (see Figure 4 on page 25).

Figure I.1 illustrates a typical history for a relatively long highway, highway 2. It is 223.3 km long and has 184 road sections. Noteworthy, the profile estimated dates of building (thin line) varies considerably. Even for neighboring road sections, estimated construction dates may deviate unrealistically. Deviations are partly due to the fact that true values of the lifetimes of investments and renovations differ from case to case, i.e., they are not constant-valued as assumed here. Large deviations are also caused by the fact that in cases where relatively new road sections replace old ones, knowledge on the latter are lost.

For a historical analysis of accessibility, large (and implausible) deviations in profile D_I are unsuitable. Therefore, in the analysis of accessibility, the convex hull of profile D_I (bold line in Figure I.1) is applied. Due to rounding of the numbers, the "convex hull" of Figure I.1 is not strictly convex. The convex form of the profile of construction dates implies that the road will never be disconnected during its existence.

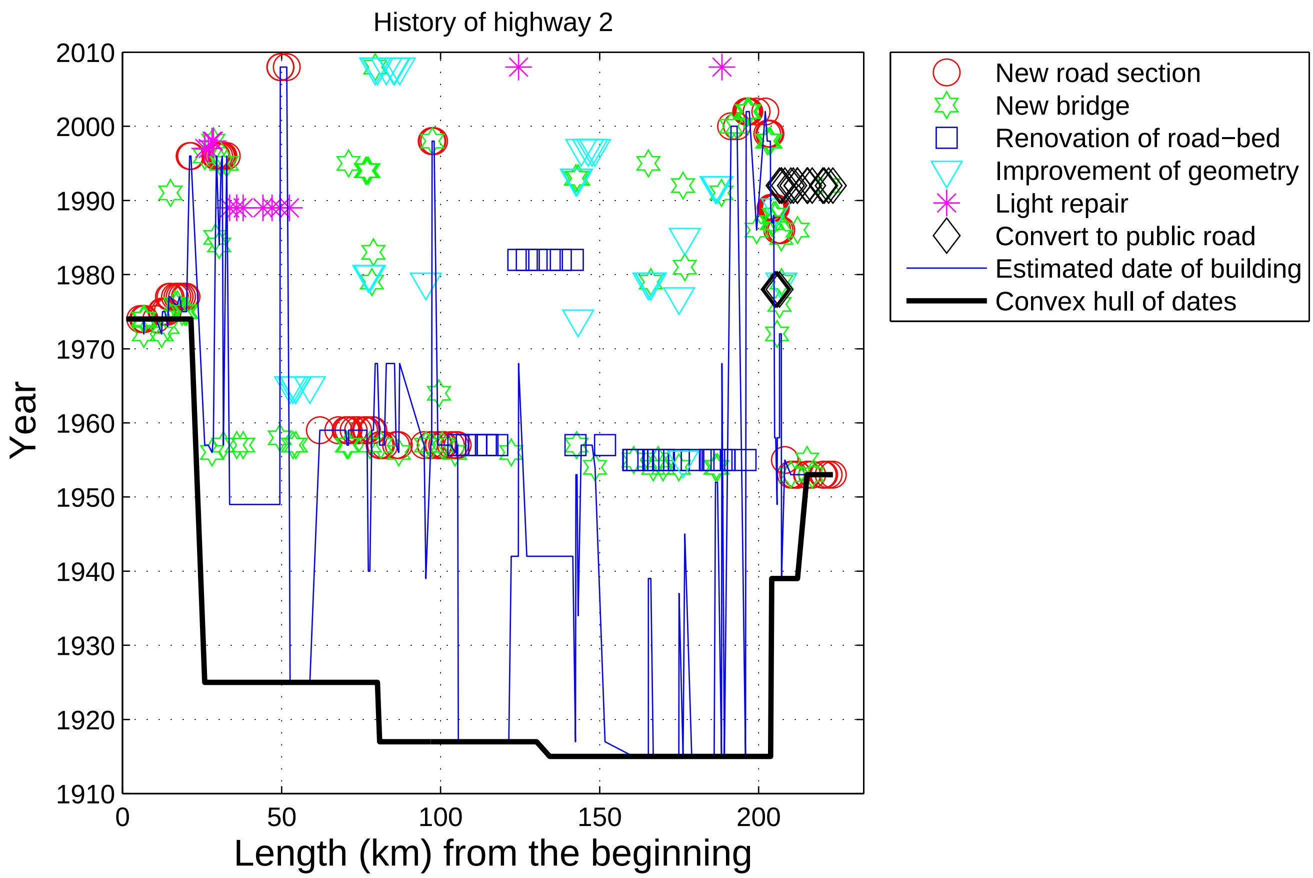

Figure I.1. History of highway 2

The measurement of accessibility entails an innumerable amount of fastest path problems. For this purpose the original description of the road network is unnecessary detailed. It includes nodes that are not on a junction or at the beginning or end of the road. For the fastest path problems a "reduced network" is applied, in which unnecessary nodes are eliminated. A reduced network contains 12967 nodes, where the original number of nodes is 33182.

Figure I.2 presents the map of the reduced highway network.

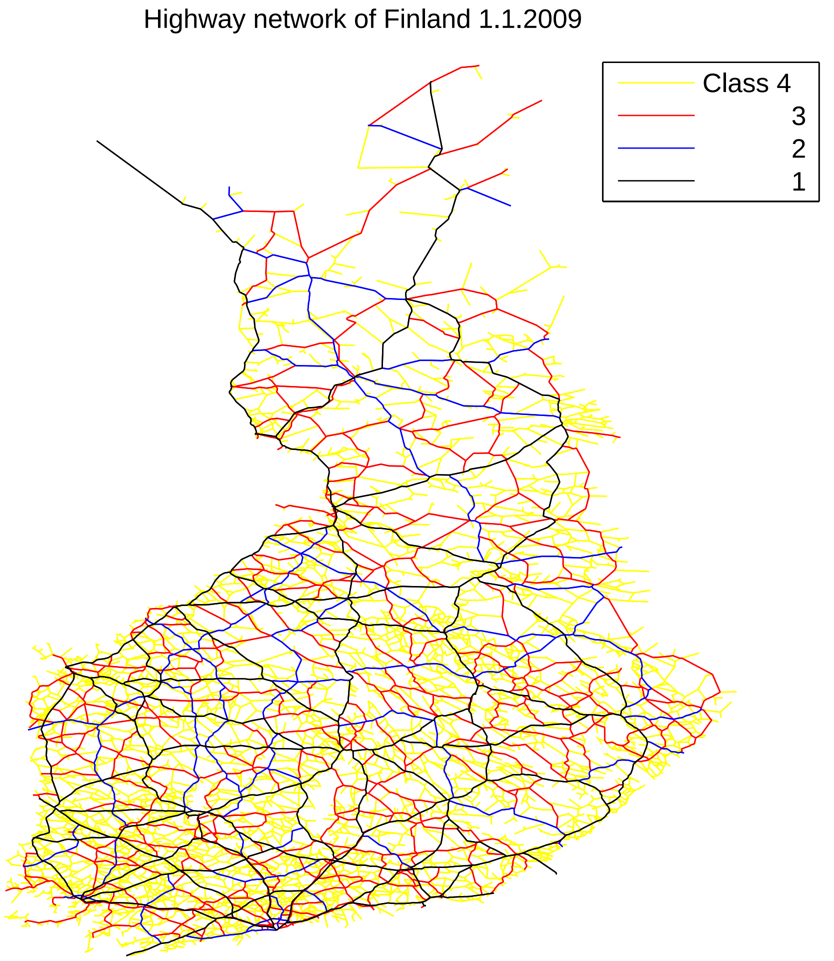

Figure I.2. The road network of Finland 1.1.2009 in the possession of the Road Administration

Bridges

The data on bridges comes from the Bridge Register maintained by the Road Adminstration. The data is comprised of 14487 bridges.

For example, data on a specific bridge on road 9 contains the following information:

Table I.3

Variable	Data	Explanation
Name:	Pikkaraisenpuron silta	Name of the bridge
no:	9	Number of the bridge
Municipality:	Kirkkonummi	Municipality
Rno:	110	Number of the road
Rsec:	9	Road section
coord:	[6685900 3360800]	Coordinates
Span:	2.4000	Bridge span
Idate:	[1933 NaN]	Dates of building
Icost:	NaN	Investment cost
Cdate:	2007	Date of renovation
Tmp:	NaN	Type of renovation
Ccost:	NaN	Cost of renovation
Adt:	[2103 80]	Average daily traffics

Vector Idate includes two dates; the construction date of the present bridge and that of its (potential) predecessor. Vector Adt includes the average total and heavy daily traffics. The value "NaN" means that this piece of information does not exist.

Information on bridges are utilized in establishing the history of the road network and in estimating the average investment and renovation costs of bridges.

Investment costs

For most of the bridges information on the investment costs is missing. There is, however, enough data to build a model for investment costs that can be used to substitute for the missing data. The model explains investment costs by the bridge span.

Data consists of those bridges build after 1974 for which information on the investment costs is available. Investment costs are deflated to the 2008 price level and 15 % are added to cover the costs of planning.

Figure 1.4 presents the average investment costs as a function of a bridge span. This model is used to substitute for the missing information.

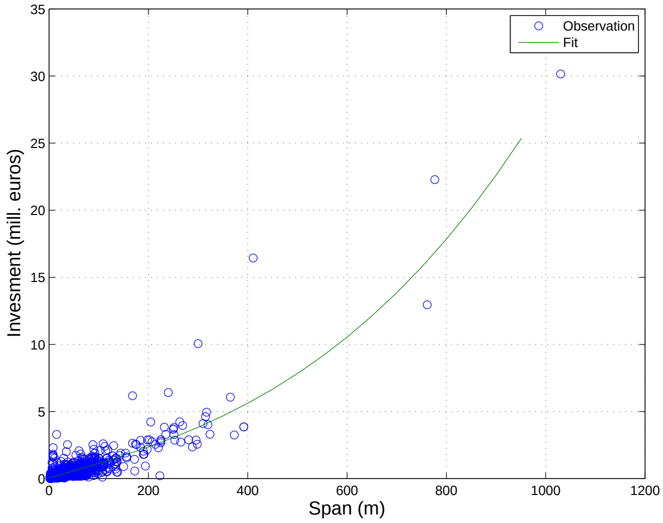

Figure I.4. Average investment costs of bridges as a function of bridge span

Renovation costs

The average time lapse between the construction date and the date of the first renovation on the data is 35.3 years (6023 observations). The average cost of renovation is 37.0 % of the investment costs given by the investment cost model (1844 observations). These figures are used in estimating the capital stocks.

Municipalities and population

The historical population data is from Sarvimäki and Kangasharju (2010). Using data on Finnish municipalities and their changes (Statistics Finland, 2009) populations in 1900–2009 are reallocated to geographic areas of present municipalities (1.1.2009).

The data on municipalities is organized as follows. This example is about the Simpele municipality that joined the Rautjärvi municipality in 1973.

Table 1.4

Variable	Value	Explanation
No:	752	Code of municipality
Name:	Simpele	Name
NewName:	Rautjärvi	New name
NewNo:	689	New code
Lyear:	1973	Date of consolidation of municipalities

The road register also contains municipality-specific data that is utilized in the accessibility analysis. For this purpose the data has to be manipulated. For example the field associated with Helsinki in the structure array is as shown below:

Table 1.5

Variable	Value/Data type	Explanation
No:	91	Code of municipality
Name:	Helsinki	Name
Neigh:	[49 92]	Codes of neighboring municipalities
Nodes:	[1x135 double]	Nodes in the area of municipality
xco:	[1x135 double]	x-coordinates of nodes
yco:	[1x135 double]	y-coordinates of nodes
xa:	3386965	Average of x-coordinates
ya:	6680492	Average of y-coordinates
Nnod:	11967	Nearest node to municipality center

Unit prices

Tables I.6 and I.7, respectively, show the repurchasing prices of new investments and renovation investments.

Table I.6. Unit prices of building of a new road (million euros/km) (Road Administration, 2006)

Motorway	2.0
Trunk road	1.9
Road with overtaking lanes	1.7
2-lane highway	1.1
4-lane main road	1.5
Road with overtaking lanes (main road)	1.3
2-lane main road	1.0
2-lane regional road	0.8
2-lane connecting road	0.6

Table I.7. Renovations costs: % of the investment cost of new road (Road Administration, 2006; and its preceding version)

Reconstruction of road bed	40 %
Improvement of geometry	100 %
Light repair	20 %