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Measuring the Cost-Effectiveness of an R&D Tax Credit for the UK

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Abstract

This paper investigates the economic impact of the government's proposed new UK R&D tax credit. We measure the benefit of the credit by the effect on value added in the short and long runs. This is simulated from existing econometric estimates of the tax-price elasticity of research and development (R&D) and the effect of R&D on productivity. For the latter, we allow R&D to have an effect on technology transfer (catching up with the technological frontier) as well as innovation (pushing the frontier forward). We then compare the increase in value added to the likely exchequer costs of the programme under a number of scenarios. In the long run, the increase in GDP far outweighs the costs of the tax credit. The short-run effect is far smaller, with value added only exceeding cost if R&D grows at or below the rate of inflation.

JEL classification: H2, O4.

I. INTRODUCTION

R&D tax credits are again on the policy agenda. In his March 2001 Budget, the Chancellor announced his intention to extend the R&D tax credit for small and medium-sized enterprises to larger firms in the following Budget and issued a consultative document on how it should be implemented (HM Treasury and Inland Revenue, 2001). In this paper, we consider what impact such a policy is likely to have on UK productivity and growth.

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One of the main justifications for government subsidies to research and development (R&D) is the belief that social rates of return are in excess of private rates of return. Firms' decisions to undertake R&D are based on their private return to R&D, which is generally thought to be lower than the return to society as a whole. This means that we have underinvestment in R&D. In order to achieve the optimal level of R&D investment, government policy should aim to bring private incentives in line with the social rate of return.

The main reason why the social rate of return is believed to be higher than the private return is that the knowledge generated from R&D 'spills over' from the inventor to other firms.[1] Once invented, an idea can be imitated by others (it is non-rivalrous and only partially excludable), although intellectual property protection and delays in the dissemination of new ideas enable the innovator to appropriate a share of the rents from a new idea. Knowledge is also 'tacit' in nature: it takes time and effort to explain new ideas to others and to codify inventions in manuals and textbooks.[2] This means that imitation is not costless and R&D activity may be important for understanding the discoveries of others. Mansfield, Schwartz and Wagner (1981) present evidence of substantial costs of imitation (on average, 65 per cent of innovation costs), while the average length of time for imitation is found to be 70 per cent of that taken for innovation. Recent theoretical research has emphasised the idea that R&D not only leads to innovation but also enhances one's ability to imitate.[3] This second role is often termed the 'second face of R&D'. Empirical evidence lends support to these ideas.[4]

In this paper, we consider the implications of the two faces of R&D for the analysis of public policies that seek to stimulate private sector R&D activity. The policy we consider is an R&D tax credit of the form set out in the Treasury's 2001 Consultative Document. The paper is structured as follows. Section II outlines the idea that R&D plays a dual role in both innovation and imitation in a simple analytical framework. Section III looks at the impact and cost-effectiveness of introducing an R&D tax credit in the UK. We do this in several stages: (1) estimating the fall in the user cost of R&D for a typical firm; (2) using the change in the user cost to estimate the change in R&D; (3) estimating the impact of the change in R&D on total factor productivity; and (4) examining the exchequer cost of the policy. The Appendix provides a more technical description of the model and approach. A final section summarises and offers some concluding remarks. Unsurprisingly, we find that, in the short run, the

[1]Note that the 'social rate of return' to R&D in this literature refers to the private rate of return plus any externalities.

[2]For informal discussions of the tacit nature of knowledge, see David (1992) and Rosenberg (1982).

[3]See, *inter alia*, Aghion and Howitt (1998), Cohen and Levinthal (1989), Grossman and Helpman (1991) and Neary and Leahy (1999).

[4]See, for example, Geroski, Machin and Van Reenen (1993), Jaffe (1986) and Griffith, Redding and Van Reenen (2000).

exchequer costs will probably outweigh the increase in GDP. More interestingly, we find that the long-run effect on GDP easily outweighs the likely costs under a range of scenarios.

II. AN ANALYTICAL FRAMEWORK: THE TWO FACES OF R&D

A large empirical literature has sought to estimate the rate of return to R&D. In general, the empirical literature finds the social rates of return to R&D substantially above private rates of return. These findings are summarised by Griliches (1992): 'In spite of (many) difficulties, there has been a significant number of reasonably well-done studies, all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates'.

The private rate of return can be estimated by looking at the impact of a firm's own R&D on the firm's output. Estimates of the private rate of return to R&D are obtained using US firm-level data in Griliches (1992). The estimated elasticity of output with respect to R&D is around 0.07. This says that, for a 10 per cent increase in R&D expenditure, there will be a bit less than a 1 per cent increase in output (0.7 per cent) holding other factors constant. The elasticity of output with respect to R&D is related to the rate of return to R&D by

Elasticity of output with respect to R&D
= (Rate of return to R&D) × (R&D stock/output).

The R&D stock/output ratio in the USA was estimated to be around 26 per cent. This implies a rate of return of around 27 per cent (= 0.07/0.26) for R&D. Hall (1996) summarises empirical work in this area and reports that estimates of private rates of return to R&D cluster around 10 to 15 per cent, though can be as high as 30 per cent in some studies.

What about estimates of the social rate of return to R&D? Care must be taken in interpreting these. Ideas can spill over between firms in the same industry, across industries and across countries. Production function estimates using firm-level data, where R&D in other firms is included in the regression, attempt to capture the social rate of return to firms' R&D (often within the industry).[5] Regressions of industry-level productivity against industry-level R&D seek to capture the social rate of return to the industry but not spillovers to other industries (unless other industry R&D has been incorporated in some way). Similarly, production function estimates conducted at the national level capture within-country spillovers but not those between countries. In addition, an

[5]The critical problem here is in constructing the 'knowledge weighting matrix' which links the R&D conducted by one firm to the productivity of the recipient firms. Using information contained in patent technology classes has proved relatively successful here (see Jaffe (1986) for an early example or Branstetter (2001) for a more recent case).

important part of innovative output is the introduction of new goods, and there are considerable difficulties that arise in measuring the value and benefit of these new goods.[6]

Cameron (1996a) and Jones and Williams (1998) summarise existing empirical estimates of the social rate of return to R&D from the empirical literature on R&D and productivity. Many studies have been undertaken using US data and are typically for manufacturing industries. Estimates of the social rate of return to own-industry R&D include 21–76 per cent in Griliches and Lichtenberg (1984b), 24–73 per cent in Schankerman (1981) and 29–43 per cent in Scherer (1982 and 1984). Once we take into account that R&D conducted in one industry may have an impact on productivity in other industries (for example, downstream industries), the estimated social rate of return to R&D rises further and can be as high as 100 per cent. Jones and Williams (1998) show how estimates of R&D's social rate of return from industry-level data can be incorporated into a macroeconomic model of endogenous innovation and growth. They find that estimates actually provide a lower bound to R&D's true social rate of return once one takes into account the dynamic general equilibrium effects emphasised in the endogenous growth literature.

Another way in which the existing industry-level literature may underestimate both the private and the social rate of return to R&D is in assuming that imitation is costless. Knowledge is 'tacit' in nature: it takes time and effort to explain new ideas to others and to codify inventions in manuals and textbooks. This means that imitation can itself be costly. Recent work has emphasised the fact that R&D not only leads to innovation but also enhances one's ability to imitate.[7] Many of the benefits to this second role of R&D activity may be internalised by firms, and the externalities from R&D-based imitation might in themselves be less than those from innovation. However, in a world where imitation is no longer costless, the knowledge spillovers emphasised in the innovation literature are now dependent on other firms undertaking R&D activity.

Griffith, Redding and Van Reenen (2000) present an empirical framework in which innovation and technology transfer provide two potential sources of productivity growth for countries behind the technological frontier. The rate of return to R&D is composed of an effect on productivity through innovation and an effect through increased potential for imitation. A country's distance from the technological frontier is used as a direct measure of the potential for technology

[6]There are a large number of other caveats to the approach of aggregating to capture externalities. These are discussed in some detail in various chapters of Griliches (1998).

[7]See, for example, Cohen and Levinthal (1989), Geroski, Machin and Van Reenen (1993), Jaffe (1986) and Griffith, Redding and Van Reenen (2000).

transfer, where the frontier is defined for each industry as the country with the highest level of total factor productivity (TFP).[8]

More formally, we assume that value added, *Y*, is produced with a standard neo-classical production technology,

$$(1) \qquad Y_{it} = A_{it} F(K_{it}, L_{it}),$$

where *i* indexes countries, *t* denotes time, *A* is an index of technical efficiency or TFP, *L* corresponds to labour input and *K* denotes physical capital. The endogenous growth and empirical productivity literatures emphasise R&D-based innovation. Here, A_{it} is a function of R&D activity. In the conventional specification, we have[9]

$$(2) \qquad \Delta \ln A_{it} = \rho \left(\frac{R}{Y} \right)_{it-1} + \gamma X_{it-1} + u_{it},$$

where *R* denotes R&D expenditure, $\rho = \mathrm{d}Y/\mathrm{d}G$ is the social rate of return to R&D where *G* denotes the stock of R&D investment, X_{it-1} is a vector of control variables and u_{it} is an error term capturing stochastic determinants of TFP growth.[10] The arguments above suggest that the conventional specification needs to be augmented in order to allow for a second face of R&D in promoting technology transfer. Equation 2 becomes

$$(3) \qquad \Delta \ln A_{it} = \rho_1 \left(\frac{R}{Y} \right)_{it-1} + \underbrace{\beta \Delta \ln A_{Ft} - \delta_1 \ln \left(\frac{A_i}{A_F} \right)_{t-1}}_{\text{technology transfer}} - \underbrace{\delta_2 \left(\frac{R}{Y} \right)_{it-1} \ln \left(\frac{A_i}{A_F} \right)_{t-1}}_{\text{absorptive capacity}}$$
$$+ \gamma X_{it-1} + u_{it}.$$

Technology transfer is made up of two components. The presence of the first component ($\beta \Delta \ln A_{Ft}$) allows the contemporaneous rate of TFP growth in the frontier (*F*) to have a direct effect on TFP growth in non-frontier countries. The second of these components ($\delta_1 \ln(A_i/A_F)_{t-1}$) allows for autonomous technology transfer independent of R&D activity. For non-frontier countries, relative TFP

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[8]See Cameron (1996b) for an analysis along these lines of Japan and the USA and see Cameron, Proudman and Redding (1998) for an analysis of the UK and the USA.

[9]See, in particular, Griliches (1980) and Griliches and Lichtenberg (1984a). The microeconomic rationale for this relationship is provided by the endogenous growth literature. See, for example, Aghion and Howitt (1992 and 1998).

[10]There is a debate in the endogenous growth literature about whether the *level* of R&D activity can have permanent effects on the *rate of growth* of output (the 'scale effects' debate as in Jones (1995a and 1995b)). The conventional specification above exhibits such a scale effect, although it is straightforward to eliminate it by introducing diminishing returns to R&D.

($\ln(A_i/A_F)_{t-1}$) is negative; the more negative relative TFP, the further a country lies behind the frontier and the greater the potential for technology transfer. Therefore, with technology transfer, the estimated coefficient on relative TFP (δ_1) should be negative.

Absorptive capacity is captured by an interaction term that captures the second face of R&D. The more negative relative TFP, the further a country lies behind the frontier and the greater the potential for R&D-based technology transfer. Therefore, if there is a second face of R&D, the estimated coefficient on the interaction term (δ_2) should be negative.

In steady-state equilibrium, TFP in country *i* will grow at the same constant rate, equal to TFP growth in the frontier ($\Delta\ln A_i = \Delta\ln A_F$ for all *i*). The frontier will be whichever of the countries has the highest rate of TFP growth from innovation alone. All other countries will lie an equilibrium distance behind the constantly advancing frontier such that TFP growth from innovation and technology transfer in a non-frontier country exactly equals TFP growth from innovation alone in the frontier.

The sum of the estimated coefficients on the R&D intensity in equation 3 is R&D's full social rate of return for an industry ($\rho \equiv \rho_1 - \delta_2\ln(A_i/A_F)_{t-1}$) and depends on both innovation and technology transfer. Our estimate of the social rate of return to R&D from innovation (ρ_1) is about 40 per cent, which is broadly comparable to existing estimates of R&D's social rate of return using industry-level data. The existing estimates are largely for the USA, which is typically the frontier in our data-set. The rate of return to R&D in the USA should therefore largely consist of a rate of return to innovation.

The full social rate of return to R&D depends upon how far a country lies behind the technological frontier. Griffith, Redding and Van Reenen (2000) present empirical estimates. The relative level of TFP in the UK relative to the USA in total manufacturing over the period 1974–90 was around 62.6 per cent. The implied social rate of return to R&D in the UK (from both innovation and technology transfer) is around 90 per cent. The social rate of return to R&D in the USA is indeed due almost entirely to innovation (a total rate of return of 43.9 per cent compared to a rate of return from innovation of 43.3 per cent).

One important conclusion from the analysis in that paper is that many existing studies, in so far as they are based on data from the USA (a country that is typically the frontier), will tend to underestimate the social rate of return to R&D. In non-frontier countries, there is the potential for R&D to generate TFP growth from both innovation and technology transfer. This conclusion receives independent support from Eaton, Gutierrez and Kortum (1998), who calibrate a computable general equilibrium model of endogenous innovation and growth to economy-wide data from 21 OECD countries. With the exception of Portugal, research productivity is found to be higher in all other OECD countries than in the USA.

This raises the question of why many non-frontier countries do not undertake more R&D. One answer may be that there are larger differences between private and social rates of return in these countries. If some of the technology transfer induced by R&D activity takes the form of an externality, it will not be internalised by private sector agents. The explanation provided by Eaton et al. (1998) is that research incentives are lower due to smaller market size. Market failures, such as underdevelopment of financial markets, and government policies may also act as barriers to R&D investment.

A second conclusion is that a distinction needs to be drawn between the social rate of return to R&D at the *national* and *supranational* levels. In the theoretical model presented above, an increase in R&D in the frontier raises the steady-state rate of TFP growth in *all other countries*. In steady state, TFP in all countries grows at the same rate, equal to TFP growth in the frontier. Thus, although *national* social rates of return to R&D are higher in non-frontier countries, there is an important *supranational* externality to R&D undertaken in the frontier.

III. POLICY ANALYSIS

One of the policy implications of finding social rates of return in excess of private is that it would be welfare-improving to stimulate more R&D in the private sector. How should a policy-maker seek to do this? Tax incentives seem a natural policy tool for a market-oriented government wanting to increase R&D expenditures. Firms decide where and how to spend their R&D investment rather than have it determined through a bureaucratic central authority. The policy instrument is targeted closely at the source of the market failure. Many countries have turned to fiscal incentives for R&D, often involving substantial sums of taxpayers' money.

What impact would we expect the introduction of an R&D tax credit in the UK to have?

We consider the impact that an incremental R&D tax credit would have on UK TFP growth and value added in the context of the model laid out above. Our estimates relate to UK manufacturing only, but, as this represents around 80 per cent of UK R&D, this should give a fairly complete picture. In order to answer the question of how cost-effective a tax credit would be, we need to specify the following:

- how the tax credit will change the price (user cost) of R&D;
- how R&D expenditure will respond to a change in the price of R&D;
- how TFP will respond to a change in R&D expenditure;
- how manufacturing value added will respond to a change in TFP;
- how much the tax credit will cost the Inland Revenue.

We draw on estimates from our econometric work to provide answers to the first four of these questions. The fifth, on revenue costs, we estimate from aggregate data. In order to answer the question of whether an R&D tax credit is cost-effective, we need to estimate how much it will cost the Inland Revenue. Note that this is not the same as evaluating whether the policy is welfare-improving. We do not consider potential deadweight welfare costs from any distortionary taxation used to finance the R&D tax credit. We also do not consider the opportunity cost of the funds allocated to the R&D tax credit, which could be spent in other areas of government expenditure. However, a necessary (though not sufficient) condition for the tax credit to be welfare-improving is that the social surplus it generates is greater than the direct monetary cost. Moreover, a comparison of the increase in value added as a result of the policy with its monetary cost constitutes an important part of a wider welfare evaluation.

We estimate what the immediate impact will be and what the effects will be in the long run. This is an important distinction as there are significant adjustment lags between a change in the user cost and R&D expenditure and the change in R&D and the subsequent increase in GDP. The details of how we do our calculations are sketched out here. A technical appendix provides the detail. While our analysis accounts for many features of R&D tax credit design and the ways in which firms are likely to respond to the introduction of a tax credit, there are a number of assumptions that we make in the interests of tractability. In particular, we assume that the accumulation of physical and human capital is unaffected by the tax credit; we do not consider the welfare costs that may arise from additional distortionary taxation used to finance the tax credit; we also do not consider the returns to alternative possible uses of the funds allocated to the tax credit.

1. The Impact of an R&D Tax Credit on the Price of R&D

The impact that an R&D tax credit has on the price of R&D depends on the precise details of its design. We consider a credit that is designed as proposed in the 2001 Consultative Document (HM Treasury and Inland Revenue, 2001). The main features of this are that it is an incremental credit on a two-year rolling-average base, the base is indexed by inflation and the credit is implemented as a deduction to corporate tax at a 50 per cent rate.[11]

We use estimates of the user cost of R&D and the own-price elasticity of R&D from Bloom, Griffith and Van Reenen (2001) and Bloom, Griffith and Klemm (2001). We assume that only R&D performed in the UK is eligible for

[11]The Consultative Document also proposes many other details; one important one is using a credit bank whereby firms carry forward a ‘shadow’ negative credit. The impact of this is not considered here as it does not affect the user cost in our model firm. However, it would greatly affect the dispersion of marginal rates faced by different firms. See Bloom, Griffith and Klemm (2001).

the tax credit. The impact of the credit on the price of R&D is measured by comparing the user cost of R&D in the absence of the credit with the user cost including the credit (see the Appendix). The value of the tax credit to a firm receiving it depends upon the time path of the firm's R&D expenditure. We calculate the user cost for a 'model firm' where R&D is always expected to increase by at least the rate of inflation and where the firm is never in a tax-exhausted position.[12] We assume that the real interest rate (and also the firm's discount rate) is 10 per cent and that inflation is 5 per cent.

The user cost combines a measure of the net present value of the tax credit with information about other features of the tax system to tell us about how the tax credit changes the price of investing an additional pound in R&D. The proposed tax credit yields a change in the user cost of 1.9 per cent (i.e. the user cost of R&D capital has declined from about 0.386 to 0.379). The figure of 1.9 per cent is considerably lower than the statutory tax rate which is 50 per cent. This is for a number of reasons. The three main features affecting the user cost are the following:

- The R&D tax credit is implemented as a deduction. This means that the equivalent rate as a tax credit is 15 per cent (the statutory rate of corporate income tax is 30 per cent, so the value of a 50 per cent deduction is 30%×50% = 15 per cent).
- The tax credit is paid on incremental R&D, with the increment defined with respect to a two-year rolling-average base. This means that the firm receives a credit on the additional R&D it does over the average of the past two years. When a firm does more R&D in one year, this earns it a credit in that year, but it also reduces the value of the credit to the firm in the next year by increasing its base.
- The credit is paid on the increase in *real* R&D; that is, the base is indexed by inflation. The 2001 Consultative Document proposes using the retail price index (RPI).

Although a fall of under 2 per cent seems small, it is relatively large by the UK's historical standards. The tax component of the R&D user cost in the UK has varied by only 0.1 of a percentage point between any two years from 1979 to 1997.

[12]These are reasonable assumptions for many large firms. Bloom, Griffith and Klemm (2001) use data on a sample of 138 UK quoted firms to obtain estimates of the impact the various credits will have on the price of firms' R&D and thus look at heterogeneity in user costs across firms.

TABLE 1

Impact of the R&D Tax Credit on the Price and Amount of R&D

Change in user cost of R&D	–1.9% (from 0.386 to 0.379)
Increase in R&D intensity, %Δ(*R*/*Y*):	
Impact	0.23%
Long-run	1.6%
Initial level of R&D intensity (without tax credit)	5.7%
Implied R&D intensity with tax credit:	
Impact	5.713%
Long-run	5.791%

Notes: $\%\Delta(R/Y) = \ln(R/Y)_t - \ln(R/Y)_0$, where t is the period under consideration and 0 denotes the base period. See the Appendix for details.

2. The Response of R&D Expenditure to a Change in the Price of R&D

We use estimates of how R&D expenditure will respond to changes in the tax price of R&D from Bloom, Griffith and Van Reenen (2001).[13] The results in that paper suggest that the own-price impact elasticity is around 0.12 and the long-run elasticity is around 0.86 (see the Appendix for details). This means that a 10 per cent change in the price of R&D will lead to an immediate increase of 1.2 per cent in R&D intensity and an 8.6 per cent increase in the long run. In order to estimate the amount of new R&D that is done in response to a change in the tax price, we assume that the cost of capital calculated above gives a good approximation of the average cost of capital faced by firms.

Table 1 shows the change in the user cost and our estimates of the resulting change in R&D intensity. The immediate or impact effect is to increase the R&D intensity by 0.23 per cent, and the long-run effect is 1.6 per cent. To give some idea of the size of this change, over the period 1973–97 the annualised growth rate in the R&D intensity was 1.0 per cent (there is considerable annual variation, from –7 per cent to 16 per cent). The impact of reducing the user cost of R&D by 1.9 per cent would thus increase the growth rate by around a quarter of its usual annual growth rate. This is quite a large effect.

3. The Response of TFP and Value Added to a Change in R&D Intensity

First, we analyse the effects of the tax credit when R&D only affects innovation. This is the special case of the model above where R&D has no effect on the propensity to imitate (in the context of equation 3, this means $\delta_2 = 0$). This corresponds to the conventional specification with 'one face' of R&D and provides a useful benchmark for our results. In this case, total manufacturing

[13]See Hall and Van Reenen (1999) for a survey of the empirical evidence on the effectiveness of R&D tax credits.

TFP growth is given by equation 2, and the increase in R&D intensity following the tax credit raises TFP growth in both the short and long runs. The estimated R&D innovation coefficient in Griffith, Redding and Van Reenen (2000) is 0.433. The percentage increase in TFP growth following the tax credit is therefore 0.433 times the original level of the R&D intensity times the percentage increase in R&D intensity due to the tax credit (see the Appendix). That is, an effect of 0.433×0.057 (= 0.025) times the percentage increase in R&D intensity, where the short- and long-run values for the latter are evaluated in Table 1.

Second, in line with recent empirical evidence, we allow for R&D to affect both innovation and imitation. This is the general case where there are 'two faces' of R&D so $\delta_2 \neq 0$. In this case, total manufacturing TFP growth is given by equation 3. The implications of the tax credit for TFP growth for the short run are now different from those for the long run or steady state. In the short run, the increase in the R&D intensity following the tax credit raises TFP growth through both the rate of innovation and the rate of imitation. In the long run, assuming that the tax credit does not result in a change in technological leadership, the increase in the R&D intensity can have no effect on UK TFP growth. In steady state, UK TFP growth from both innovation and imitation must equal the (unchanged) rate of TFP growth in the frontier from innovation alone. Since the increase in the R&D intensity following the tax credit raises both innovation and imitation for a given size of the technological gap, something must adjust in order for this steady-state equilibrium condition to hold. The variable that adjusts is the size of the technological gap: higher levels of UK TFP relative to the frontier imply a smaller potential for imitation. The adjustment process is as follows. The short-run increase in TFP growth following the introduction of the tax credit results in a progressively higher level of relative TFP, which reduces the potential for imitation until TFP growth in the UK from innovation and imitation again equals TFP growth in the frontier from innovation alone. The steady-state effect of the R&D tax credit is to lead to a higher steady-state level of relative TFP. Note that steady-state TFP growth will always be higher in a model where R&D promotes imitation as well as innovation: TFP growth in the UK is no longer constrained by domestic rates of innovation, but can benefit from spillovers from a more rapid rate of innovation in the frontier.

With two faces of R&D, the short-run effect of the increase in the R&D intensity due to the tax credit depends on the initial level of relative TFP. The further a country initially lies behind the technological frontier, the greater the potential for R&D-based imitation. For our main estimates, we use a value for the initial level of relative TFP of 0.85 for the UK; this says that TFP levels in the UK are initially 85 per cent of what they are in the USA. We consider how the effect of the R&D tax credit changes with different sizes of this productivity gap. As shown in Table 2, these values imply that the short-run percentage

TABLE 2

Percentage Increase in TFP Growth[a]

	Impact	*Long-run*
Innovation effect	0.0056%	0.32%
Innovation and imitation effect (UK TFP initially 85% of frontier)	0.0077%	—
Innovation and imitation effect (UK TFP initially 75% of frontier)	0.0093%	—

[a]See equation A.14 in the Appendix.

change in TFP growth following the introduction of the tax credit is 3.4 per cent of the percentage increase in R&D (see the Appendix). When we consider only the direct impact of R&D (the first row), the immediate impact of the R&D tax credit is to increase the growth rate of TFP by 0.0056 per cent and the long-run effect is to increase it by about a third of 1 per cent. Once we take into account the second face of R&D, the immediate impact increases to 0.0077 per cent. Thus the short-run effect on rates of TFP growth when we consider the two faces of R&D (innovation and imitation) is about a third again as much as when R&D only affects innovation. In the final row, we show how the increase in the TFP growth rate varies with the relative TFP gap. If we assume an initial gap of 75 per cent, then the increase in the growth rate is higher, at 0.0093 per cent.

In the Appendix, we show how the model presented above may be solved for the effect of the R&D tax credit on steady-state levels of relative TFP when there are two faces of R&D. This steady-state effect is independent of the initial level of relative TFP. Our estimates also depend on the rate of TFP growth in the USA (which is the frontier country). We use a value of 1.5 per cent, which is the average rate of growth over the past two decades. We also consider how sensitive the estimates are to using alternative values. Table 3 presents the implied effect of the tax credit on steady-state equilibrium levels of relative TFP. Since this refers to an effect on levels of relative TFP, while Table 2 was concerned with rates of growth, it is hard to compare these numbers directly. We show below how the sets of figures may be made comparable by examining the implied increase in manufacturing value added.

To do so, we employ a standard growth accounting decomposition that suggests that the rate of growth of output equals TFP growth plus the weighted growth of factor inputs (see the Appendix). The effect of the R&D tax credit on

TABLE 3

Percentage Increase in Relative TFP[a]

	Long-run steady state
Innovation and imitation effect	0.43%

[a]See equation A.16 in the Appendix.

TABLE 4

Increase in Manufacturing Value Added

£ million

	Impact	*Long-run*
Innovation effect	8.7	491.9
Innovation and imitation effect (UK TFP initially 85% of frontier)	11.9	670.1

manufacturing value added in the year after it is introduced is simply the short-run increase in TFP growth from Table 2 times the initial level of manufacturing value added. This is shown in the column headed 'Impact' in Table 4 for the one-face-of-R&D and two-faces-of-R&D models (using the 1999 value for manufacturing value added of £155 billion as the initial value).

When R&D only affects innovation (the one-face model), the long-run effect of the tax credit is a permanently higher rate of TFP growth in each subsequent year. As shown in the Appendix, this may be converted into an effect on manufacturing value added in any given year by multiplying the annual increase in TFP growth by the initial level of manufacturing value added at the beginning of that year. The last column of Table 4 reports the implied effect on manufacturing value added in 1999.

When R&D affects both innovation and imitation (the two-faces model), the long-run effect is a permanently higher level of TFP relative to the frontier, where the frontier is constantly advancing at a rate greater than UK-based rates of innovation. Again as shown in the Appendix, this may be converted into an effect on manufacturing value added in any given year by multiplying the increase in steady-state levels of relative TFP growth by the initial level of manufacturing value added at the beginning of that year. The last column of Table 4 reports the implied effect on manufacturing value added in 1999. The effect is larger than in the one-face model because R&D raises manufacturing value added by enhancing both innovation and imitation.

4. The Cost-Effectiveness of an R&D Tax Credit

How much is such a policy likely to cost? In order to answer this question, we need to know what the real growth rate of R&D would be in the absence of the tax credit. Since we do not know this, we calculate the cost-effectiveness for a range of real growth rates between 0 per cent (R&D grows at the same rate as the RPI) and 5 per cent, as presented in Table 5. Over the period 1973–97, the annualised real growth rate in R&D was 0.8 per cent. It varied substantially year to year from –6.0 per cent to 17 per cent. In the last five years, it has ranged from –1 per cent (1994–95) to 3.9 per cent (1998–99). We thus consider the likely counterfactual rate of growth to be towards the lower growth rates shown in the first few rows of the table.

TABLE 5

Revenue Cost

£ million

Real growth rate of R&D (in the absence of the credit)	*Incremental R&D without credit* (1)	*Credit paid on incremental R&D without credit (from column 1)* (2)	*Credit paid on incremental R&D with credit (impact effect)* (3)	*Credit paid on incremental R&D with credit (long-run effect)* (4)
0%	0	0.0	3.0	21.4
1%	130	19.5	22.5	40.9
2%	257	38.6	41.6	60.0
3%	380	57.0	60.0	78.4
4%	500	75.0	78.0	96.4
5%	617	92.6	95.6	114.0

The Inland Revenue (IR) has to pay 15 per cent on every pound of incremental R&D. Incremental R&D is defined as the amount of R&D done today minus the average amount done in the past two years, indexed for inflation. This means that, even if firms had not responded at all to the credit, the IR would have had to pay out 15 per cent of the increase in real R&D. This means that the revenue cost depends mostly on the growth rate in R&D. Therefore we calculate estimates of the revenue cost for different assumed growth rates. Column 1 in Table 5 shows the amount of R&D that would be defined as incremental under the rules of the proposed tax credit (under the assumption that the credit had no impact on R&D spending). Column 2 shows the amount of credit the IR would have to pay out on this R&D. This is one form of deadweight loss from such a credit.

The IR would also have to pay out a credit on new R&D that resulted from the credit. Manufacturing business enterprise R&D (BERD) expenditure was £8,782 million in 1999. From the estimate of the impact effect of the R&D tax credit in Table 1, this means that the immediate effect of the R&D tax credit will be to raise R&D spending by £20.2 million, which will cost the IR £3 million a year. In column 3, we add this number to the figure in column 2, which yields an estimate of the immediate revenue cost of the tax credit, taking into account both the incremental growth in R&D that would have occurred without the tax credit and new R&D due to the policy intervention. Combining the long-run response of R&D to the tax credit from Table 1 with the 1999 figure for manufacturing BERD above implies a long-run increase in R&D of £140.5 million, which will cost the IR £21.4 million per year. In column 4, we add this number to the figure in column 2 to get an estimate of the long-run revenue cost of the credit. It should be noted that these revenue costs are very approximate. They do not take into account any of the complexities of taxation at the firm level.

TABLE 6

Cost-Effectiveness

Real growth rate of R&D (in the absence of the credit)	Innovation		Innovation and imitation	
	Impact	*Long-run*	*Impact*	*Long-run*
0%	2.90	23.01	3.97	31.35
1%	0.39	12.04	0.53	16.39
2%	0.21	8.22	0.29	11.19
3%	0.14	6.28	0.20	8.55
4%	0.11	5.10	0.15	6.95
5%	0.09	4.32	0.12	5.88

In Table 6, we calculate the cost-effectiveness of the proposed tax credit using the estimates of the increase in manufacturing value added from Table 4 and the estimates of revenue cost from Table 5. The cost-effectiveness is simply additional value added divided by revenue cost. In the first pair of columns, we use the increase in value added implied by the model of TFP where R&D only has a direct effect through increasing the rate of innovation. Here we see that only if R&D does not grow above the rate of inflation (in the absence of the credit) is the tax credit cost-effective in the short run. This is because, with higher growth rates, the deadweight of the tax credit is greater. A similar picture arises looking at the model in which R&D also contributes to TFP growth by enhancing imitation, although the cost-effectiveness ratios are higher. In the long run or steady state, the credit is cost-effective whichever model or growth rate we consider.

The upsurge in US productivity growth between 1995 and 2000 has stimulated a vigorous debate over whether there has been a structural shift in the growth of TFP associated with rapid computer-based technological change.[14] Since the USA is generally the technological frontier, according to our model this will affect the long-run TFP growth rate of the UK economy. What is more relevant to this paper, however, is that the impact of the UK R&D tax credit will vary depending on our assumptions regarding US TFP growth. In particular, a faster TFP growth in the frontier is associated with a higher equilibrium TFP gap between the UK and the USA. In this circumstance, an extra pound of R&D is more valuable because it helps the UK to catch up more quickly with the USA (the second face of R&D-based technology transfer becomes stronger).

Our baseline estimates assume that US TFP growth is 1.5 per cent. If US TFP growth were higher, at 2 per cent, then this would mean a long-run increase in value added of £710 million rather than the £670.1 million of Table 4. The two-faces steady-state cost-effectiveness for 2 per cent real growth (for example)

[14]See Van Reenen (this issue) for a discussion of the hard evidence over the 'new economy'.

would be 11.8 (rather than 11.2 as shown in Table 6). If US TFP growth were 2.5 per cent, the equivalent numbers would be £750 million and 12.5. So, although there are additional benefits associated with R&D policy if there has been an increase in frontier steady-state growth, these are not huge.

IV. CONCLUSION

In March 2001, the Chancellor of the Exchequer announced his intention to extend an R&D tax credit to large firms in his next Budget. In this paper, we have examined the likely impact of this policy and whether it will be cost-effective. There is obviously a large degree of uncertainty surrounding these calculations, but we think it is a valuable exercise. Much progress has been made in recent years in examining the impact of fiscal incentives on R&D and in analysing the effect of R&D on growth. We use estimates from recent econometric work to simulate the effect of the proposed R&D policy based on the design contained in the Treasury's Consultative Document (HM Treasury and Inland Revenue, 2001). Our model allows R&D to have a dual impact through its increase in the rate of innovation and through its 'second face' of improving technology transfer. We find that the short-run effect of the R&D policy on manufacturing value added is very limited when we assume that, in the absence of the R&D tax credit, the real rate of growth of R&D would be 1 per cent or more. In this case, the exchequer cost is greater than the extra output generated in the first year. This is due to the design of the credit (it is not very generous), the slow adjustment of R&D to changes in its price and the slow impact of R&D on long-run TFP. In the longer run, however, the policy seems far more attractive and is cost-effective under a wide range of assumptions.

There are a number of important limitations to the paper. First, we have assumed that R&D is neutral with respect to other factors of production. Although this is a common assumption in the literature, we are rather uneasy with it as there are likely to be complementarities between R&D and physical and human capital.[15] A more general analysis would take these into account. A corollary of non-neutrality is that the demand for R&D scientists is likely to rise as a result of the subsidy. To the extent that the labour supply of these highly skilled workers is fixed, much of the subsidy may be captured in the form of higher wages, at least in the short run.[16] In the longer run, labour supply will adapt, but even the small gains we identify in the shorter run may be illusory.

A second limitation of the study is our focus on manufacturing. This is necessary because most of the existing estimates are based on data from this sector. Although it is true that 80 per cent of R&D is conducted in manufacturing, under 20 per cent of people are actually employed in this sector.

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[15]See, *inter alia*, Machin and Van Reenen (1998).
[16]See Goolsbee (1998) for evidence of this effect in the USA.

Since we do not focus on interindustry spillovers (such as those from the manufacturing industries to the service industries), we may be underestimating the benefits of the R&D tax credit.

A third limitation is that we have not modelled the international dimension of R&D in any detail. Although we do allow for technology transfer across countries within industries, we have not taken into account the effect of UK policy on other countries. On the positive side, there are likely to be some spillovers from the UK to other nations (even in the terms of our model, the UK is frontier in some industries). On the negative side, some of the additional UK R&D may come from multinationals simply relocating their R&D activity.[17] This is clearly a concern of the European Union, and an R&D tax policy may eventually be blocked because of these concerns over 'State Aid' rules.

Finally, and from a policy point of view the most problematic, is the issue of timing. We have focused on the impact effect and the long-run effect. We have not modelled the transition to steady state. This is due to the highly complex nature of the dynamics and our uncertainty over the various adjustment processes. Yet, for a Chancellor with his eye on the electoral cycle, the issue of exactly *when* the policy will become cost-effective and start bridging the productivity gap is clearly important. We hope to address these concerns in future work.

APPENDIX
DETAILS OF THE CALCULATIONS

This appendix gives a technical explanation of our modelling strategy and calculations. Our aim is to provide sufficient detail to allow the reader to

TABLE A.1

Values Used for Key Parameters

Inflation, π	5%
Real interest rate, r	10%
Statutory tax rate on corporate income, τ	30%
Economic depreciation rate of R&D, δ	28%
Manufacturing value added	£155 billion
Manufacturing BERD	£8,782 million
R&D/Y in UK	0.057
R&D/Y in USA	0.079
US TFP growth	1.5%
UK TFP relative to the USA	85%
Net present value of existing depreciation allowances on R&D, A^d	28.7%

[17]See Bloom and Griffith (this issue) for evidence on this.

reproduce our calculations making alternative assumptions. Values used for key parameters are given in Table A.1.

1. How Will an R&D Tax Credit Change the Price of R&D?

The standard methodology for measuring the impact of a tax credit on the price of investment is the user cost. This tells us what the impact of the tax credit would be on the price of investing an additional pound in R&D. Let i index countries and t index years. The impact of an R&D tax credit on the price of R&D can be summarised by a user cost of R&D of the following form:

$$\text{(A.1)} \qquad p_{it} = \frac{1-\left(A_{it}^{c}+A_{it}^{d}\right)}{1-\tau_{it}}\left(r_{it}+\delta\right),$$

where A^c is the net present value of the tax credit, A^d is the net present value of tax depreciation allowances, τ is the statutory tax rate on corporate income, r is the real interest rate and δ is the economic depreciation rate. Bloom, Griffith and Van Reenen (2001) provide estimates of this for the G7 countries plus Australia and Spain for the period 1979–97.

The net present value of the credit, A^c, will depend on the precise design. The fact that the credit is on incremental expenditure means that, by tying the amount of credit given to the past levels of spending, the value of the credit is reduced. This is because, by spending an extra pound today, the firm earns a credit today, but it also reduces the amount of credit it will get in the future. In addition, the fact that the credit is implemented as a deduction means that it is worth the credit rate, c, times the statutory rate, τ. The proposal is also for the base to be indexed by inflation. The net present value of this tax credit is given by the formula

$$\text{(A.2)} \qquad A^{c} = c\tau\left[1-\frac{1}{k}\sum_{j=1}^{k}\frac{1+\pi}{\left(1+r\right)^{j}}\right],$$

where we have assumed that R&D grows by at least the rate of inflation in every year, c is the nominal credit rate, π is the inflation rate, r is the firm's discount rate (the real interest rate) and k is the number of years over which the moving-average base is calculated.[18] The credit proposed in the 2001 Consultative Document has a two-year moving-average base, R&D will be indexed by the RPI and it is proposed that the credit will be implemented as a deduction at the rate of 50 per cent. This means that $c\tau$ is equal to $0.5 \times 0.3 = 0.15$. We assume that inflation is 5 per cent and the real interest rate is 10 per cent. The net present value of the proposed tax credit is thus

[18] See Bloom, Griffith and Klemm (2001), Eisner, Albert and Sullivan (1984) and Hall (1993).

(A.3) $A^c = 0.15 \times (1 - 0.5 \times 0.955 - 0.5 \times 0.868) = 0.013$.

Using the other parameters set out in Table A.1, this gives a UK user cost without the tax credit of

(A.4) $$p_t = \frac{1 - (0 + 0.287)}{1 - 0.3}(0.1 + 0.28) = 0.386$$

and a UK user cost with the tax credit of

(A.5) $$p_t = \frac{1 - (0.013 + 0.287)}{1 - 0.3}(0.1 + 0.28) = 0.379,$$

which give a change of 1.9 per cent in the user cost of R&D as a result of the R&D tax credit.

2. How Will R&D Expenditure Respond to a Change in the Price of R&D?

An equation for the effect of the price (generally measured as a user cost defined in equation A.1) on the R&D intensity is given by

(A.6) $$\ln\left(\frac{R}{Y}\right)_{it} = \theta \ln\left(\frac{R}{Y}\right)_{it-1} - \phi \ln p_{it} + \eta_i + S_t + \omega_{it},$$

where R is R&D, Y is value added, η captures country-specific characteristics, S captures common macroeconomic shocks and ω captures idiosyncratic shocks. The parameter ϕ provides an estimate of the own-price elasticity of R&D, while θ captures dynamics in the R&D investment process. Bloom, Griffith and Van Reenen (2001) estimate such a model using data on a panel of countries and obtain estimates of $\theta = 0.86$ and ϕ =0.12 (Table I, column 4).

Consider the effect of a permanent R&D tax credit that reduces the user cost of capital by z per cent in a non-frontier country. The instantaneous effect on the R&D intensity is given by

(A.7) $$\Delta \ln\left(\frac{R}{Y}\right)_{it} = \phi z\% = 0.12z\%.$$

The long-run percentage change in the R&D intensity following the introduction of an R&D tax credit that reduces the user cost of capital by z per cent is

(A.8) $$\Delta \ln\left(\frac{R}{Y}\right)_{i} = \left(\frac{\phi}{1-\theta}\right) z\% = \frac{0.12}{0.14} z\% = 0.86z\%.$$

Equations A.4 and A.5 suggest that the proposed tax credit will change the user cost by 1.9 per cent. Plugging this into equations A.7 and A.8 yields predictions that the R&D intensity will increase by 0.23 per cent immediately and by 1.6 per cent in the long run.

3. How Will TFP Respond to a Change in R&D Expenditure?

We begin by analysing the effects of the R&D tax credit when R&D only influences TFP growth through the rate of innovation (i.e. there is no effect on the ability to imitate). In this case, total manufacturing TFP growth is given by the empirical version of equation 2,

$$\text{(A.9)} \quad \Delta \ln \tilde{A}_{it} = \rho \left(\frac{R}{Y} \right)_{it-1} + \psi_i + T_t + \varepsilon_{it} ,$$

where the tilde denotes that we only consider R&D's effect on innovation, ρ gives an estimate of the rate of return on R&D, ψ_i is a fixed effect that controls for unobserved heterogeneity across countries in the determinants of TFP growth, T_t is a vector of time dummies controlling for common macroeconomic shocks and ε_{it} is a serially uncorrelated error. Griffith, Redding and Van Reenen (2000) obtain an estimate of $\rho = 0.433$. We also use the fact that, in the UK, total manufacturing value added in 1999 was £155 billion and business enterprise R&D expenditure was £8.782 billion.[19] This yields an R&D intensity of 0.057. Plugging these into equation A.9 yields

$$\text{(A.10)} \quad \Delta \ln \tilde{A}_{it} = 0.433 \times 0.057 + \psi_i + T_t + \varepsilon_{it} = 0.025 + \psi_i + T_t + \varepsilon_{it} .$$

With a tax credit, we have

$$\text{(A.11)} \quad \begin{aligned} \Delta \ln \tilde{A}_{it}^{C} &= 0.433 \left(\frac{R}{Y} \right)_{it} \left(1 + \%\Delta(R/Y)\right) + \psi_i + T_t + \varepsilon_{it} \\ &= 0.025\left(1 + \%\Delta(R/Y)\right) + \psi_i + T_t + \varepsilon_{it} , \end{aligned}$$

where the superscript C indicates the adoption of the R&D tax credit, and $\%\Delta(R/Y)$ is the increase in R&D intensity measured from equation A.7 or equation A.8. The implied change in TFP growth following the tax credit is thus

$$\text{(A.12)} \quad \Delta \ln \tilde{A}_{it}^{C} - \Delta \ln \tilde{A}_{it} = 0.025\left(\%\Delta(R/Y)\right) .$$

[19]Manufacturing value added is from Table 15.4 of *Annual Abstract of Statistics, 1999*. Manufacturing BERD is from Table 5 in First Release *Business Enterprise Research and Development 1999*, National Statistics — www.statistics.gov.uk — and equals DLEP plus DLEX.

From our calculations above, we know that the impact effect of the tax credit is to increase R&D by 0.23 per cent, so this gives us an immediate increase in TFP growth of 0.0056 per cent. Note that, because the equation for TFP growth is linear (rather than log linear) in the R&D intensity, the effect of the R&D tax credit on TFP growth depends on the level of the R&D intensity.

We now extend the analysis to allow R&D to play a role also in promoting imitation. In the absence of a tax credit, TFP growth is given by equation 3. In the presence of a credit, we have

$$\text{(A.13)} \quad \Delta \ln A_{it}^{C} = \rho_1 \left(\frac{R}{Y} \right)_{it-1} \left(1 + \%\Delta(R/Y)\right) + \beta \Delta \ln A_{Ft} - \delta_1 \ln \left(\frac{A_i}{A_F} \right)_{t-1} - \delta_2 \left(\frac{R}{Y} \right)_{it-1} \left(1 + \%\Delta(R/Y)\right) \ln \left(\frac{A_i}{A_F} \right)_{t-1} + u_{it} .$$

The difference between these two is given by

$$\text{(A.14)} \quad \Delta \ln A_{it}^{C} - \Delta \ln A_{it} = \left[\rho_1 \left(\frac{R}{Y} \right)_{it-1} - \delta_2 \left(\frac{R}{Y} \right)_{it-1} \ln \left(\frac{A_i}{A_F} \right)_{t-1} \right] \%\Delta(R/Y) .$$

Griffith, Redding and Van Reenen (2000) estimate $\rho_1 = 0.433$, $\beta = 0.124$, $\delta_1 = 0.068$ and $\delta_2 = 1.00$. We use the same initial value for the R&D intensity as above. The increase in the R&D intensity due to the tax credit will affect TFP growth through both the rate of innovation and the rate of imitation. The second effect depends on a country's distance behind the technological frontier. We assume that TFP in the UK is 85 per cent of that in the USA.

Plugging these estimates into equation A.14, we get an implied change in TFP growth following the tax credit of

$$\text{(A.15)} \quad \Delta \ln A_{it}^{C} - \Delta \ln A_{it} = 0.034\left(\%\Delta(R/Y)\right) .$$

With an immediate increase in R&D of 0.23 per cent, this gives us an immediate increase in TFP growth of 0.0077 per cent. It is hard to interpret the magnitude of this number. In Section 4 of this Appendix, we will show how it may be converted into an effect of the R&D tax credit on manufacturing value added. The long-run effect of the R&D tax credit on TFP growth is greater, as R&D gradually responds over time to the change in its user cost.

So far, we have assumed that the UK's distance behind the technological frontier is fixed. However, the model above can also be used to solve for steady-state equilibrium levels of relative TFP.

Our model implies the following first-order difference equation for the evolution of relative TFP:

$$\text{(A.16)}\quad \Delta \ln\left(\frac{A_i}{A_F}\right)_t = \rho_1\left[\left(\frac{R}{Y}\right)_{it-1} - \left(\frac{R}{Y}\right)_{Ft-1}\right] + \beta\Delta\ln A_{Ft}$$
$$- \left[\delta_1 + \delta_2\left(\frac{R}{Y}\right)_{it-1}\right]\ln\left(\frac{A_i}{A_F}\right)_{t-1} + \left(u_{it} - u_{Ft}\right),$$

where $u_{it} = \psi_i + T_t + \varepsilon_{it}$. In steady state, TFP in all non-frontier countries is an equilibrium distance behind TFP in the frontier, such that all countries exhibit the same rate of TFP growth as the frontier. Steady-state equilibrium relative TFP is

$$\text{(A.17)}\quad \ln\left(\frac{A_i}{A_F}\right)_t^* = \frac{\psi_i + \rho_1\left(\frac{R}{Y}\right)_i^* + T_t - (1-\beta)\Delta\ln A_F^*}{\delta_1 + \delta_2\left(\frac{R}{Y}\right)_i^*},$$

where * denotes the steady-state level of all variables. In steady state, the increase in R&D will have no effect on the non-frontier's rate of TFP growth (unless it induces a change in the frontier country), but it will affect the steady-state level of relative TFP.

4. How Will Output Respond to a Change in TFP?

What is the immediate impact of an increase in TFP on levels of output? Here we use the fact that

$$\text{(A.18)}\quad \Delta\ln Y_{it} = \Delta\ln A_{it} + \left(\frac{\alpha_{it} + \alpha_{it-1}}{2}\right)\Delta\ln L_{it} - \left[1 - \left(\frac{\alpha_{it} + \alpha_{it-1}}{2}\right)\right]\Delta\ln K_{it},$$

where Y denotes value added in total manufacturing, α is the share of labour in value added, L is the number of workers employed and K is the real capital stock, and where the second and third terms on the right-hand side are assumed to be invariant to the R&D tax credit. The change in output attributable to the R&D tax credit is

$$\text{(A.19)}\quad Y_{it}^C - Y_{it} = Y_{it}\left(\Delta\ln A_{it}^C - \Delta\ln A_{it}\right).$$

Equation A.19 can be used for a cost–benefit analysis of the R&D tax credit based on its instantaneous effect.

To look at the steady-state impact, we use the fact that

$$\text{(A.20)}\quad \ln\left(\frac{Y_i}{Y_F}\right)^{*} = \ln\left(\frac{A_i}{A_F}\right)^{*} + \ln\left(\frac{F(K_i, L_i)}{F(K_F, L_F)}\right)^{*},$$

where the second term on the right-hand side is assumed to be invariant to the R&D tax credit. If we could observe actual steady-state output without the R&D tax credit, it would be straightforward to calculate the change in steady-state output attributable to the R&D tax credit,

$$\text{(A.21)}\quad \ln\left(\frac{Y_i}{Y_F}\right)^{*C} - \ln\left(\frac{Y_i}{Y_F}\right)^{*} = \ln\left(\frac{Y_i}{Y_F}\right)^{*}\left[\ln\left(\frac{A_i}{A_F}\right)_t^{*C} - \ln\left(\frac{A_i}{A_F}\right)_t^{*}\right],$$

where we again use the fact that equation A.20 must hold as an accounting identity. However, since steady-state output in the frontier is unaffected by the R&D tax credit, equation A.21 simplifies to

$$\text{(A.22)}\quad \ln Y_i^{*C} - \ln Y_i^{*} = \left[\ln Y_i^{*} - \ln Y_F^{*}\right]\left[\ln\left(\frac{A_i}{A_F}\right)_t^{*C} - \ln\left(\frac{A_i}{A_F}\right)_t^{*}\right].$$

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