WORKING PAPERS

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An application of optimal control techniques

by

IAN G. SHARPE and PAUL A. VOLKER*

No. 25 February 1978

IN ECONOMICS

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ABSTRACT

Linear quadratic optimal control techniques are applied to a simplified reduced form model of the Australian money market to examine the tradeoff between improved monetary control and interest rate variability. We focus on a series of questions. Is quarterly control of the money supply feasible in Australia? Is the tradeoff different for M1 than for M3? Does the setting of dual monetary targets worsen the tradeoff? Is the tradeoff different for open market operations than for changes in reserve requirements? Can the tradeoff be improved by the joint manipulation of reserve requirements and open market operations?

I INTRODUCTION

The primary objectives of this paper are to examine the feasibility of short-run control of the money supply and the nature of the tradeoff between improved short-run monetary control and market interest rate variability in Australia. Such a study is of particular interest as the Australian Government has recently provided in the annual budget papers a range for the expected rate of growth of the broadly defined money supply (M3) for the budget period. While the Government has had considerable success in achieving these annual growth targets, significant variations in the rate of monetary growth (seasonally adjusted) throughout the fiscal year remain.

In recent U.S. studies, Pindyck and Roberts (1974 and 1976), using optimal control techniques, have found that M1 can be closely controlled but at the cost of considerable variability in market yields. As there is no similar Australian study we initially focus on a similar set of issues, and a number of questions are pertinent in this regard. Is short-run (quarterly) control of the money supply feasible in Australia? What is the nature of the tradeoff between improved monetary control and market yield variability? Is the tradeoff different for M1 than for M3, the definition preferred by the Australian authorities? Can the setting of dual targets (M1 and M3) improve the tradeoff in Australia as was found by Roberts and Margolis (1976) for the U.S.?

Several modifications to the U.S. studies are made in order to incorporate institutional factors which influence the money supply process in Australia. Particularly important is the extensive use of direct controls, such as frequent changes in statutory reserve deposit (SRD) requirements of the Trading Banks, to directly influence bank liquidity. Recent studies by Sharpe (1977) and Sharpe and Volker (1978) have found that whereas open market operations have a significant effect on the Australian money supply in the current quarter, the major impact of SRD requirement changes occurs with a lag of two quarters. This finding suggests that it may be desirable to view monetary base changes and SRD changes as partial substitutes rather than as perfect substitutes as is the case in many U.S. studies [e.g. Burger (1975) and Laufenberg (1976)]. The need for such an approach was foreshadowed in a recent survey of the literature on monetary policy in Australia by Davis and Lewis (1977, p.36) in which they indicate that they "know of no study (particularly in an Australian context) which examines the appropriate mix of direct controls and open market operations in achieving a money supply or interest rate target while minimising fluctuations in the other variable". By comparing the tradeoffs associated with the use of either the monetary base or SRD requirements as the sole instrument with the dual instrument results we hope to partially remedy this gap in the existing literature.

II A SIMPLIFIED MODEL OF THE MONEY MARKET

The approach adopted in the paper involves the application of linear quadratic optimal control techniques to a simplified reduced form model of the money market. As in Pindyck and Roberts (1974) we apply both deterministic and stochastic closed loop control experiments. While the use of the reduced form model of the money market is not completely satisfactory, the unavailability of an adequately specified structural model of the Australian money market at the present time precludes the more appropriate approach.[1] Nonetheless, as Davis and Schadrack (1974, p.60) argue, reduced form studies based on structural models "might be useful for short-term projections of the key monetary aggregates as a check on, and perhaps a 'cheaper' substitute for, the difficult process of estimating and simulating a detailed structural model".

The reduced form model is derived from the following simplified structural model of the money market:

$$M^S = BASE + BC + ONA \quad (1)$$

$$ONA = f_1\ (\frac{Y}{P},\ RCBILL) + u_1 \quad (2)$$

$$\frac{M^D}{P} = f_2\ (\frac{Y}{P},\ RCBILL,\ \frac{P}{P_{-1}}) + u_2 \quad (3)$$

$$M^S = m(SRD,\ RCBILL)\ .\ BASE + u_3 \quad (4)$$

$$M^S = M^D \quad (5)$$

where BASE is the monetary base defined as the sum of all Trading and Savings Banks' Accounts at the Reserve Bank, Coin and Bullion of Trading and Savings Banks, Treasury Bills and Notes held by Savings Banks, and Currency of the Public;

BC is bank credit defined as loans, advances and bills discounted of the Trading and Savings Banks;

ONA is other net assets of the banking system defined as $ONA = M^S - BASE - BC$;

P is the GDP price deflator;

Y is GDP;

RCBILL is the yield on 90 day bank endorsed commercial bills;

M^D & M^S are respectively the demand and supply of nominal money balances;

m is the money supply multiplier;

SRD is Trading Bank SRD Accounts and Savings Bank required cash reserve defined as the required reserve ratio times savings deposits held with the Commonwealth Savings Bank and the Private Savings Banks; and

u_1, u_2, & u_3 are random error terms.

Equation (1) is the balance sheet identity of the banking system while equation (5) is the market clearing condition. Equations (3) and (4) are behavioural equations for the demand for real money balances and the supply of nominal money balances respectively. Finally equation (2) may be viewed as the demand for other net assets by the banking system, the supply of such assets by the non-banking sector(s), or a reduced form incorporating both supply and demand factors.

In order to examine short-run issues of monetary control we assume that real output and the price level are exogenously determined. That is, we assume that there is a significant lag between changes in monetary policy instruments and their effect on prices and output and a further lag in the feedback effect from prices and output to the monetary aggregates.

In the context of the structural model of equations (1) to (5) the money stock and bank credit are often viewed as potential intermediate targets of monetary policy while the interest rate, RCBILL, and reserve base, BASE, are possible monetary instruments.[2] The selection of either the interest rate or reserve base as the policy instrument implies that the other variable is determined endogenously within the model. For the purpose of this paper it is assumed that BASE and/or SRD is the policy instrument[3] so that the reduced form equations are given by:[4]

$$M = g_1(P, \frac{Y}{P}, \frac{P}{P_{-1}}, BASE, SRD) + v_1 \qquad (6)$$

$$RCBILL = g_2(P, \frac{Y}{P}, \frac{P}{P_{-1}}, BASE, SRD) + v_2 \qquad (7)$$

Whereas the price level elasticity of nominal money balances is unitary in the money demand function, this restriction does not apply to the reduced form.

O.L.S. estimates of the reduced form model appear in Table 1. As the estimates have been extensively discussed in Sharpe & Volker (1978) at this point we need only make several general observations. Firstly, the equations predict reasonably well both within and outside the sample period. Secondly, there is a significant lagged relationship between changes in the monetary base and/or statutory reserve deposits and changes in the money supply.[5] Thirdly the equations were tested for statistical stability using the cusum of squares and cusum tests of Brown, Durbin and Evans (1975) but little evidence of instability could be detected. Fourthly, each of the equations was tested for instrument instability as outlined in Holbrook (1972). With BASE as instrument, regression estimates (1) and (2) corresponding to M1 and M3 respectively manifest instrument stability when a quarterly control horizon is adopted. However control horizons of three and two quarters respectively for M1 and M3 are consistent with instrument stability when SRD is the policy instrument. Control of RCBILL requires a one quarter horizon for instrument stability when SRD changes are used as the instrument but one year is required when BASE is used as the instrument. These dynamic properties of the model are influential in determining the results of the optimal control experiments in the following sections.

TABLE 1: O.L.S. ESTIMATES OF REDUCED FORM EQUATIONS*

QUARTERLY RAW DATA 1966(3) - 1976(2)

Adjustment for first order autoregressive process

$$\text{DEP VARIABLE} = k + a\,\Delta\ln P_t + \sum_{i=0}^{n} b_i\,\Delta\ln\left(\frac{Y}{P}\right)_{t-i} + \sum_{i=0}^{1} c_i\,\Delta\ln\left(\frac{P_{t-i}}{P_{t-i-1}}\right)$$

$$+ \sum_{i=0}^{3} d_i\,\Delta\ln BASE_{t-i} + \sum_{i=0}^{3} e_i\,\Delta\ln SRD_{t-i} + e_t$$

$$\text{where } e_t = \rho e_{t-1} + u_t$$

REGRESSION ESTIMATES	(1)	(2)	(3)
DEP VARIABLE	Δln M1	Δln M3	Δln RCBILL
k	-.010	-.009	-.084
a	.354(1.63)	.551(3.03)	.970(6.81)
$\sum_{i=0}^{n} b_i$	.577	.773	5.70
$\sum_{i=0}^{1} c_i$	-.325	-.759	2.89
d_0	.360(4.46)	.305(5.67)	-1.008(1.52)
d_1	.117(1.34)	.088(1.41)	.585(.80)
d_2	.179(2.17)	.086(1.35)	-.316(.46)
d_3	.003(.03)	.100(1.46)	1.919(2.65)
e_0	-.108(1.39)	-.062(1.07)	1.43(2.67)
e_1	-.129(1.84)	-.215(3.99)	.085(.16)
e_2	-.253(4.02)	-.148(3.12)	.442(.94)
e_3	-.112(1.77)	-.126(2.72)	-.184(.37)
S.E.E.	.0114	.0078	.0768
$\bar{R}^2$	.906	.891	.692
ρ	.350(1.74)	.386(1.69)	.045(.14)
D.W.	1.79	2.08	1.95
SCHMIDT's D2 STATISTIC	4.31	3.99	3.63
WALLIS D4 STATISTIC	2.10	1.71	1.90
BOX-PIERCE STATISTIC	6.95	4.65	14.09

* 't' statistics in parentheses

III DETERMINISTIC OPTIMAL CONTROL EXPERIMENTS

The deterministic linear quadratic optimal control tracking problem, in general terms, is to select μ_i^*, x_i^* to minimise the quadratic loss function

$$L = \frac{1}{2}\sum_{i=0}^{n} \{(x_i-\hat{x}_i)' \, Q(x_i-\hat{x}_i) + (\mu_i-\hat{\mu}_i)' \, R(\mu_i-\hat{\mu}_i)\} \tag{8}$$

subject to the constraints of the economic system

$$x_{i+1}-x_i = Ax_i + B\mu_i + Cz_i \tag{9}$$

and to the initial condition

$$x_o = \varepsilon \tag{10}$$

where x_i, μ_i and z_i are the vectors of state, control and exogenous variables respectively, $\hat{x}_i$ and $\hat{\mu}_i$ are the desired (ideal or target) state and control vectors, and Q and R are matrices defining penalties for deviations from target levels of state and control variables.

The nature of the solution to this tracking problem is described in Pindyck & Roberts (1974). Unlike the recent American study by Roberts & Margolis (1976) we have, however, adjusted the model for serial correlation as found in Table 1. Various combinations of costs for deviations from target were assumed for the diagonal elements of the Q and R matrices and the corresponding optimal track for each of the state and control variables determined. In order to examine the monetary control/interest variability trade-off, the root-mean-squared deviation of each state variable from target over the control period is computed. For the purpose of the exercise a twelve quarter period, 1969(3) to 1972(2), was utilised. Actual values of exogenous variables were used in the experiments while the target values of the state and control variables were also set at historical values.

In Table 2 we report the results of three sets of experiments with the BASE as the sole control variable. We have assumed that deviations of BASE from target are relatively costless as reflected in a weight (cost factor) of .001. As a guide to the relative magnitude of the root-mean-squared-deviations reported in Table 2 it is useful to bear in mind that the S.E.E. of the regression estimates for M1, M3 and RCBILL were found to be .0114, .0078 and .0768 respectively.[6] The first set of results depicts the M1/RCBILL tradeoff under the assumption that deviations of M3 from target are costless. When equal weights (costs) of unity are assigned to M1 and RCBILL, M1 tracks relatively poorly, as indicated by the root-mean-squared-deviation from target of almost three times the S.E.E., while RCBILL tracks reasonably well. As the cost of deviation from the M1 target increases relative to the cost of interest rate deviations from target, the optimal track for M1 converges to its target track but, as expected, at a cost of greater deviation of RCBILL from its target. A surprising aspect of the results, however, is the potential for considerably improved short-run control of M1 with relatively little increase in the variability of market yields.

The M3/RCBILL tradeoff with zero cost of M1 deviations from target is reported in the second set of experiments and is similar to the M1/RCBILL tradeoff. Again close control of the M3 money stock is possible but the tradeoff in terms of interest variability is slightly more costly than for M1. The final set of results in Table 2 correspond to the case where policymakers view deviations of M1 and M3 from target as being equally costly. These results suggest that, even if we permit considerable interest rate variability, it is impossible to hit both M1 and M3 targets

TABLE 2:

TRADEOFF RESULTS BETWEEN M1 AND RCBILL, M3 AND RCBILL
AND M1 AND M3 EQUALLY WEIGHTED AND RCBILL:
BASE IS CONTROL VARIABLE WITH WEIGHT SET AT .001

WEIGHTS			ROOT-MEAN-SQUARED-DEVIATION			
M1	M3	RCBILL	M1	M3	RCBILL	BASE
1	0	1	.0313		.0428	.0991
5	0	1	.0171		.0609	.0505
10	0	1	.0130		.0699	.0365
50	0	1	.0060		.0884	.0244
100	0	1	.0038		.0944	.0257
200	0	1	.0022		.0988	.0278
500	0	1	.0010		.1023	.0299
1000	0	1	.0005		.1037	.0308
0	1	1		.0312	.0424	.1026
0	5	1		.0154	.0612	.0562
0	10	1		.0117	.0704	.0451
0	50	1		.0060	.0923	.0337
0	100	1		.0041	.1005	.0336
0	200	1		.0025	.1068	.0347
0	500	1		.0012	.1121	.0363
0	1000	1		.0007	.1143	.0371
1	1	1	.0247	.0230	.0499	.0757
5	5	1	.0141	.0113	.0704	.0387
10	10	1	.0114	.0083	.0793	.0306
50	50	1	.0069	.0043	.0962	.0264
100	100	1	.0058	.0039	.1009	.0275
200	200	1	.0051	.0038	.1039	.0286
500	500	1	.0048	.0039	.1061	.0295
1000	1000	1	.0047	.0040	.1069	.0299

simultaneously over time with the single BASE instrument. Thus the best that may be expected in terms of monetary control under these circumstances is a root-mean-squared-deviation from target of approximately half the S.E.E.

In Table 3 we present results with SRD as the sole instrument of monetary policy. It is clear from these results that, irrespective of which definition of the money stock is the target, it is not possible to closely control the money supply over time using SRD policy as the sole instrument. In this respect SRD changes are clearly inferior to open market operations as the (sole) instrument of monetary policy. On the other hand, a comparison of Tables 2 and 3 suggests that if it is only desired to reduce the root-mean-squared-deviation of M1 from target to .0070 and M3 from target to .0060 then use of SRD policy is superior to BASE policy in terms of limiting deviations of market yields from target. In other words, market yields do not appear to be as sensitive to SRD policy as to BASE policy.

However policymakers are not constrained to using either the BASE or SRD as the sole instrument. With two policy instruments assigned to two targets it is not surprising to find in Table 4 that tight control of the money stock is possible whilst also maintaining market yields at their target values. However the final set of results in Table 4 suggest that when we increase the number of targets to three so that attention is paid to deviations of each of the definitions of the money supply as well as market yields from their targets, close control of the money supply once again is not possible. Furthermore a comparison of these results with those using BASE as the sole instrument indicates

TABLE 3

TRADEOFF RESULTS BETWEEN M1 AND RCBILL, M3 AND RCBILL
AND M1 AND M3 EQUALLY WEIGHTED AND RCBILL:
SRD IS CONTROL VARIABLE WITH WEIGHT SET AT .001

WEIGHTS			ROOT-MEAN-SQUARED-DEVIATION			
M1	M3	RCBILL	M1	M3	RCBILL	SRD
1		1	.0104		.0027	.0642
5		1	.0092		.0108	.0587
10		1	.0084		.0178	.0539
50		1	.0070		.0412	.0410
100		1	.0068		.0503	.0393
200		1	.0068		.0553	.0403
500		1	.0068		.0532	.0413
	1	1		.0084	.0033	.0639
	5	1		.0068	.0136	.0576
	10	1		.0057	.0229	.0521
	50	1		.0048	.0539	.0423
	100	1		.0053	.0662	.0490
1	1	1	.0099	.0081	.0056	.0623
5	5	1	.0083	.0062	.0202	.0529
10	10	1	.0076	.0054	.0310	.0467
50	50	1	.0075	.0047	.0568	.0423
100	100	1	.0077	.0048	.0630	.0490

TABLE 4

TRADEOFF RESULTS BETWEEN M1 AND RCBILL, M3 AND RCBILL AND M1 AND M3 EQUALLY WEIGHTED AND RCBILL: BASE AND SRD DUAL CONTROL VARIABLES WITH WEIGHTS OF .001

WEIGHTS			ROOT-MEAN-SQUARED-DEVIATION		
M1	M3	RCBILL	M1	M3	RCBILL
1		1	.0007		.0001
5		1	.0002		.0001
10		1	.0001		.0002
50		1	.0000		.0002
	1	1		.0005	.0004
	5	1		.0001	.0006
	10	1		.0001	.0006
	50	1		.0000	.0006
1	1	1	.0064	.0040	.0007
5	5	1	.0062	.0041	.0028
10	10	1	.0061	.0040	.0052
50	50	1	.0056	.0040	.0199
100	100	1	.0053	.0039	.0332
200	200	1	.0049	.0039	.0530
500	500	1	.0043	.0037	.0915
1000	1000	1	.0039	.0037	.1289

that the addition of SRD as a policy instrument has done very little to improve short-run monetary control. In terms of our results the primary advantage of SRD policy is that it reduces the interest variability associated with any given degree of control of the money supply.

To this point we have assumed that variation of the policy instruments is almost costless by imposing a weight (cost) of .001 of deviations of BASE and SRD from their actual values. However a case can be made that frequent and large variations in the statutory reserve requirements of the Banking system involve costs. In the first place, variability of SRD policy may affect the portfolio preference of Banks as increased variability of SRD requirements is likely to lead to an increased demand for liquid assets. Secondly, there are welfare costs associated with the use of SRD policy. Increases in SRD requirements reduce Bank wealth and reduce the competitiveness of Banks vis-a-vis non-bank financial intermediaries.

As a consequence of these considerations, the experiments of Table 4 were repeated but with a cost of unity associated with deviations of SRD from actual levels. Implicitly we are assuming that a 10% change in the statutory reserve requirement is as undesirable as a 10% change in the level of market yields. Not surprisingly these results, which are summarised in Table 5, indicate that less use is made of SRD changes in the optimal control solution and thus greater variation in market yields must be accepted relative to the experiments of Table 4.

TABLE 5

TRADEOFF RESULTS BETWEEN M1 AND RCBILL, M3 AND RCBILL AND M1 AND M3 EQUALLY WEIGHTED AND RCBILL: BASE AND SRD DUAL CONTROL VARIABLES WITH WEIGHTS OF .001 AND 1.0 RESPECTIVELY

WEIGHTS			ROOT-MEAN-SQUARED-DEVIATION		
M1	M3	RCBILL	M1	M3	RCBILL
1		1	.0204		.0182
5		1	.0104		.0263
10		1	.0076		.0294
50		1	.0029		.0345
100		1	.0017		.0360
200		1	.0009		.0369
500		1	.0004		.0376
1000		1	.0002		.0379
	1	1		.0196	.0192
	5	1		.0087	.0286
	10	1		.0062	.0330
	50	1		.0026	.0427
	100	1		.0016	.0459
	200	1		.0009	.0482
	500	1		.0004	.0499
	1000	1		.0002	.0506
1	1	1	.0157	.0140	.0226
5	5	1	.0095	.0061	.0314
10	10	1	.0080	.0045	.0348
50	50	1	.0057	.0037	.0427
100	100	1	.0052	.0038	.0480
200	200	1	.0048	.0039	.0579
500	500	1	.0043	.0038	.0843
1000	1000	1	.0039	.0037	.1162

IV STOCHASTIC CLOSED-LOOP OPTIMAL CONTROL EXPERIMENTS

The tradeoff relationships derived in the previous section of the paper ignore the uncertainty associated with the parameter estimates of the model and the existence of residual errors. In this section we maintain the assumption that the parameters of the model are known for certain but permit random shocks on the model. Following Pindyck and Roberts (1974, p. 231) we assume the random shocks are additive noise terms which are not autocorrelated. The model then becomes:

$$x_{i+1} - x_i = Ax_i + B\mu_i + Cz_i + De_i \tag{11}$$

where the e_i are generated by either adding or subtracting the regression residuals of the estimated relationships in Table 1.

The stochastic closed-loop control procedure is then as follows. Firstly, given an initial value of x_o use the deterministic optimal control procedure to obtain μ_o^* and substitute the value of μ_o^* in equation (9) to determine x_1. Then either add or subtract the regression residual e_1 to obtain $\tilde{x}_1 = x_1 + e_1$. Deterministic optimal control techniques are then applied to obtain μ_1^* using x_1 in the linear feedback rule. This procedure is repeated to determine x_2, $\tilde{x}_2$ and μ_2^*, and so on.

Stochastic experiments corresponding to each of the sets of results in Tables 2 to 5 were undertaken but for space reasons we report only the M1/RCBILL tradeoffs with BASE and SRD the sole instruments. These are depicted in Figures 1 and 2 respectively together with the corresponding deterministic tradeoffs. We have also shown the M1/BASE and M1/SRD tradeoffs in order to indicate the variability in the instruments associated with improved monetary control.

It is clear from these results that when closed loop

FIGURE 1

OPTIMAL CONTROL TRADEOFFS
(BASE AS INSTRUMENT)

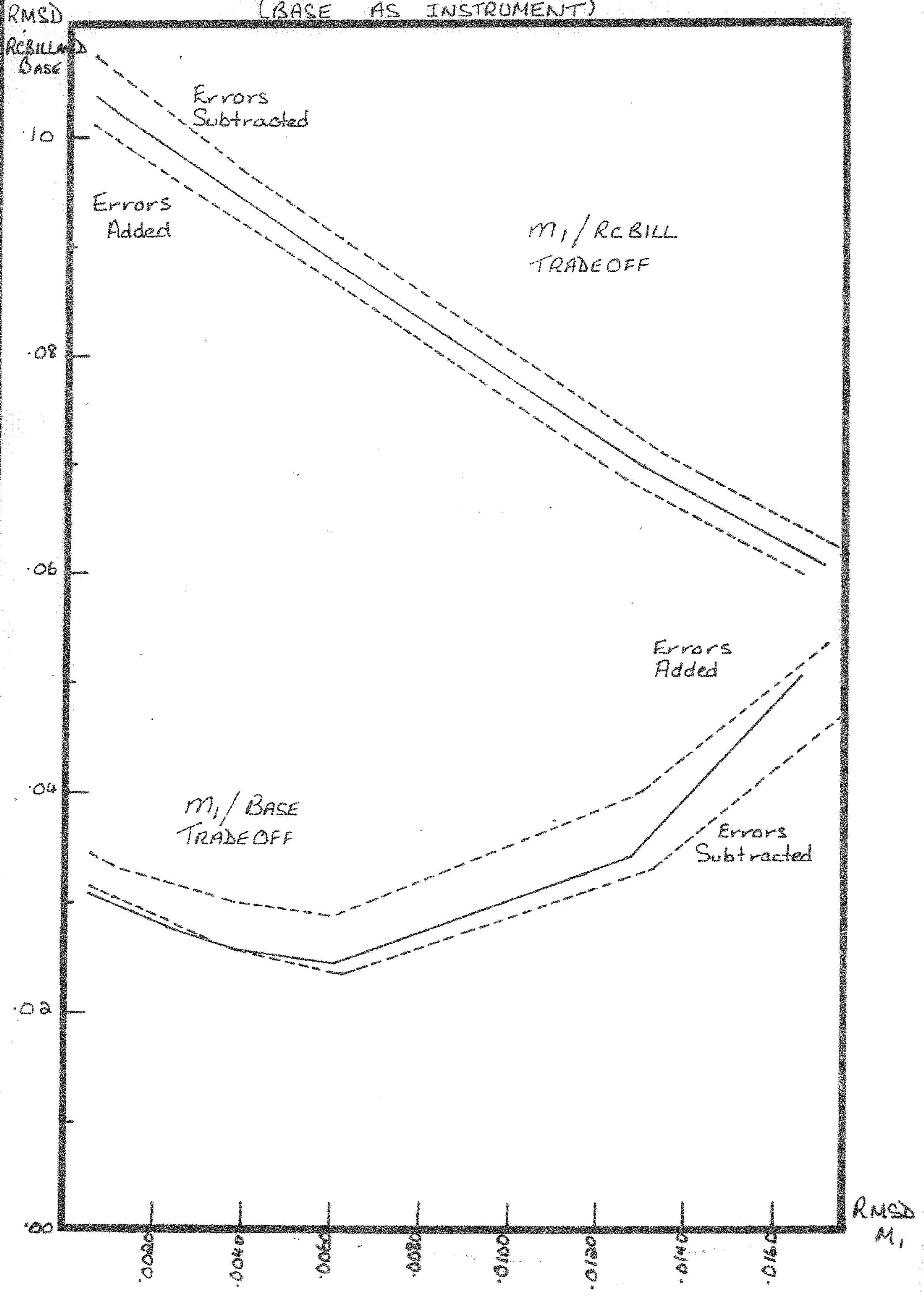
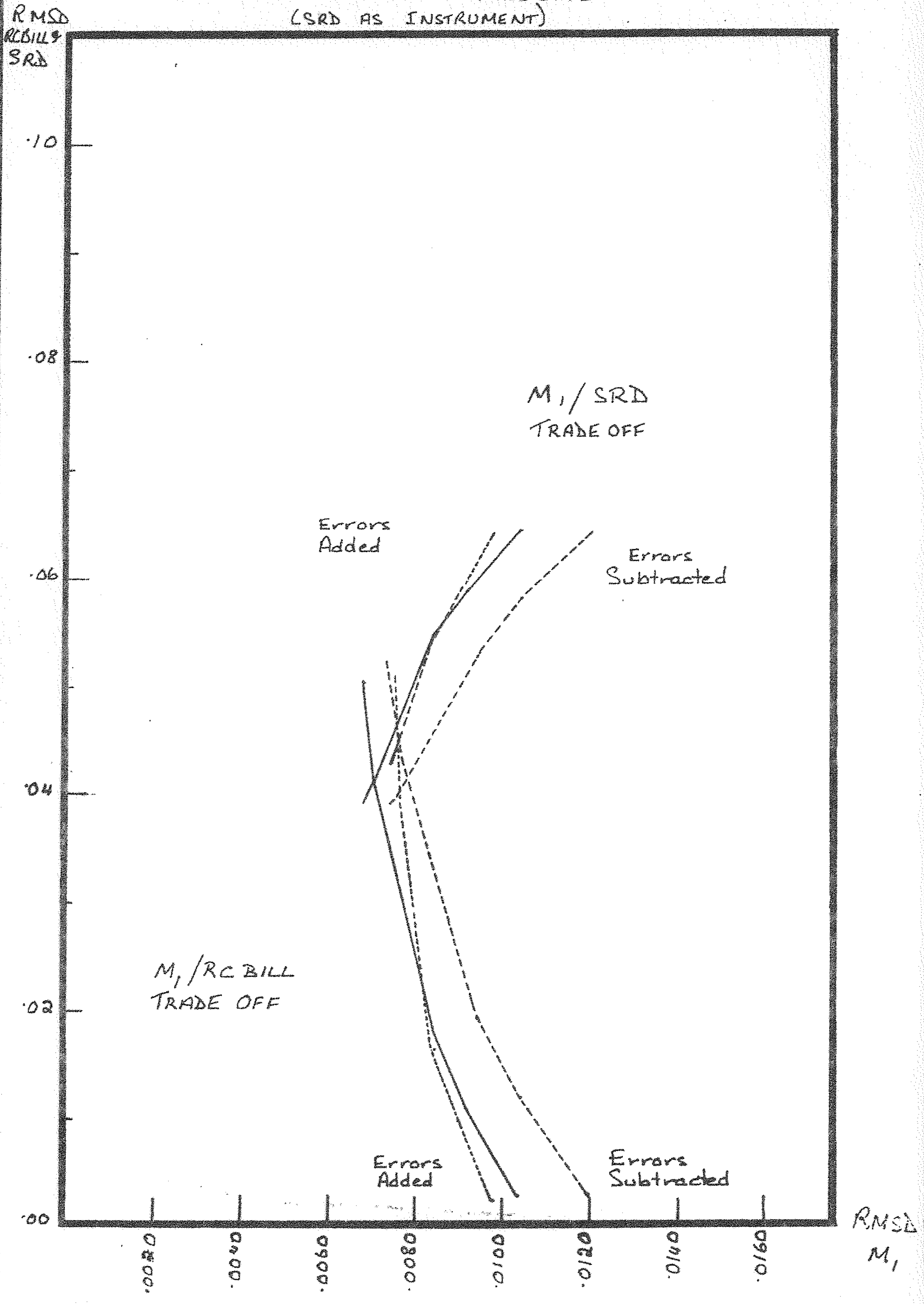


FIGURE 2.

OPTIMAL CONTROL TRADE OFFS
(SRD AS INSTRUMENT)



optimal control techniques are applied, there is little difference between the stochastic and deterministic tradeoff results. However the stochastic results require greater variation in the instruments, particularly when high costs are associated with deviations of the monetary aggregate from target. In this respect, the similarity between the Australian results and the U.S. results of Pindyck and Roberts (1974, pp. 233/4) is evident.

V CONCLUSIONS

As in any study of this type, the results reflect the structure of the model used and the various assumptions made in the analysis. Particularly important in the context of the present study has been the use of a reduced form model rather than a structural model of the money market. Also, the assumption that prices and output are exogenous, and thus independent of the control path selected, may be subject to criticism as is also the application of a quadratic cost function to evaluate deviations from target. Furthermore, while we have analysed the implications of the introduction of random shocks on the optimal control solution, the problem of uncertainty of the parameter estimates of the model has been ignored.

Bearing in mind such shortcomings of the analysis, the major conclusions of the study may be summarised as follows:

1. Using BASE as the sole monetary policy instrument, close control of either M1 or M3 is possible on a quarterly basis.
2. The monetary control/interest variability tradeoff curve in these cases is relatively flat and suggests that a root-mean-squared change in $\Delta \ln$ RCBILL of approximately .1 is necessary in order to track M1 or M3 targets very closely over the control horizon.
3. The tradeoff curve for M1 is marginally flatter than that of M3 suggesting a slight superiority of M1 relative to M3 as an intermediate target on the criterion of interest rate variability.
4. Unlike the U.S. results of Roberts and Margolis (1976), the strategy of establishing dual monetary aggregate targets does not improve the monetary control/interest variability tradeoff in Australia.

5. Close quarterly control of the monetary aggregates is not possible using SRD as the sole instrument.
6. Use of appropriate SRD changes in conjunction with BASE changes significantly reduces the interest variability associated with any degree of monetary control.
7. When the welfare costs associated with SRD changes are acknowledged, less use is made of SRD changes in the optimal control solution and there is an increase in the variation of market yields.
8. Provided greater variability is permitted in the policy instruments, the stochastic closed loop monetary control/interest variability tradeoffs are similar to the corresponding deterministic experiments.

FOOTNOTES

1. An advantage with working with reduced form estimates is the comparative ease of rearranging the equations in state-variable form relative to transforming an estimated structural model to state-variable form.

2. BASE is influenced by lender of last resort borrowings from the Reserve Bank of Australia. However because such statistics are unavailable it is not possible to use an "unborrowed" base concept as the policy instrument.

3. In order to concentrate on the relationship between alternative monetary policy instruments and targets we assume that the authorities can control the reserve base of the economy. This implies that for a small open economy the monetary authorities are willing to vary exchange rates and/or impose exchange controls in order to reduce the impact of balance of payments factors on the monetary base.

4. A corresponding equation exists for bank credit but is not used in this study.

5. This lag is largely attributable to the extensive use of the overdraft lending system in Australia.

6. These errors may be interpreted as quarterly rates of growth.

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