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Redistribution and Optimal Monetary Policy

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Abstract This paper departs from the representative-agent assumption and investigates how optimal monetary policy should be conducted in a two-agent New Keynesian (TANK) model. Relative to a price stability motive that typically appears as policy prescriptions in representative-agent New Keynesian (RANK) models, heterogeneity adds a motive to spread aggregate fluctuations equally across all households. We show that the latter motive hinges on how fiscal transfers are implemented with the business cycle.

Keywords optimal monetary policy, consumption dispersion, countercyclical transfers

JEL Classification D63, E52

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1. INTRODUCTION

Inequality in income and wealth is one of the defining features of our times (Piketty, 2014). Such inequality makes specific household groups more exposed to aggregate shocks than others, creating a large interest in understanding the macroeconomic consequences of transfers to specific income and wealth groups (Oh and Reis, 2012; Bilbiie, Monacelli, and Perotti, 2013). Figure 1 documents the relationship between real fiscal transfers and real GDP over the business cycle in the US.[1] During recessions, the government increases transfer payments as a way to reduce the disproportionate impact of aggregate shocks across different income and wealth groups. The presence of such countercyclical transfers raises the question whether the systematic response of monetary policy to the business cycle should focus on traditional inflation targeting and leave the inequality issue to the fiscal authority. The central goal of this paper is to understand how optimal monetary policy should look like in the presence of countercyclical transfers.

Toward this end, we construct a New Keynesian business cycle model that incorporates income and wealth heterogeneity and transfer rule. The aggregate shocks that we consider are the neutral technology shocks and the marginal efficiency of investment shocks. The model builds on two-agent New Keynesian (TANK) models by Galí, López-Salido, and Vallés (2007) and Debortoli and Galí (2017) to generate a tractable model of households heterogeneity. The model features non-Ricardian households that merely consume their labor income and do not hold any financial assets and Ricardian households who intertemporally optimize using capital and government bonds. Using the model as a laboratory, we study the rich relation between transfer rules and differential consumption responses across households, and their normative implication for monetary policy.

We obtain two main results. First, complete price stability is no longer socially optimal under the countercyclical transfer payments that is consistent with the data. Because the consumption dispersion that emerges after aggregate shocks is suboptimal, it is optimal for the Ramsey planner to give up complete stabilization of inflation and the output gap and partially reduce consumption inequality. Second, the cyclicality of transfers matters substantially for the properties of the optimal monetary policy. If transfer payments do not vary with the business cycle, then it is optimal to deflate and reduce the output gap. In con-

[1] Fiscal transfers correspond to government social benefits to persons. Both transfers and GDP are obtained from FRED and are HP-filtered.

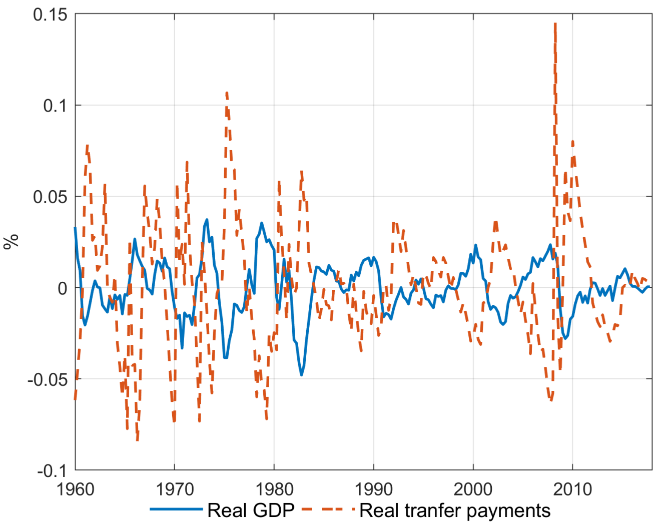

Figure 1: Real GDP and real government transfer payments

trast, if transfer payments are much more countercyclical than the data, then it is optimal to inflate (or deflate less) and have the output gap increased (or less decreased).

The intuition for these results is that the cyclicality of transfers governs the distribution of consumption in response to aggregate shocks. Consider a positive neutral technology shock as an example. If transfer payments are constant, then consumption of non-Ricardians increases more than that of Ricardians, which calls for the real wage gap to fall to dampen the spending of non-Ricardians. This leads to a fall in the inflation rate. If transfer payments are strongly countercyclical, then consumption of non-Ricardians increase less than that of Ricardians, which calls for the real wage gap to increase to stimulate the spending of non-Ricardians. Hence, a positive neutral technology is inflationary in this scenario.

Most studies of optimal monetary policy that are restricted to economies with a representative agent conclude that price stability is optimal in response to neutral technology shocks (Galí, 2015). In this environment, transfers are irrelevant for policy prescriptions. In our representative agent New Keynesian model which includes capital, we obtain the same result. Bilbiie and Ragot (2017), Nuno and Carlos (2016), Challe (2018), and Debortoli and Galí (2017) study optimal monetary policy in economies with heterogeneity in wealth. These papers find that strict inflation targeting is not optimal like ours. However, what sets our paper apart from theirs is that we emphasize the role of fiscal transfer rules, which are absent in these papers, on distributional consequences and thus in shaping the properties of optimal monetary policy.

The rest of the paper is organized as follows. Section 2 introduces the model. Section 3 highlights the calibration and the solution method. Section 4 highlights monetary policy trade-offs between consumption inequality and price stability which depends on the cyclicality of transfers. Section 5 concludes.

2. MODEL

There are two types of households, a continuum of firms producing differentiated intermediate goods, a perfectly competitive firm producing a final good, a central bank in charge of monetary policy, and a fiscal authority.

2.1. HOUSEHOLDS

The economy consists of a continuum of infinitely lived households. A fraction $1-\Omega$ of households can invest in physical capital and have access to asset markets where they can trade a full set of contingent securities. Following Galí, López-Salido, and Vallés (2007), we label them optimizing or Ricardian households. The remaining fraction Ω of households are completely isolated from asset and capital markets, and just consume their labor income. We refer to them as rule-of-thumb or non-Ricardian households.

Optimizing (Ricardian) households Ricardian households maximize:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{{C_t^o}^{1-\sigma}-1}{1-\sigma} - b\frac{\eta}{1+\eta} {N_t^o}^{\frac{\eta+1}{\eta}} \right), \tag{1}$$

where $\beta \in (0,1)$ is the subjective discount factor and C_t^o is its period t consumption. N_t^o denotes their labor inputs, b the relative disutility of supplying labor inputs, and η the Frisch elasticity.

The capital accumulation by Ricardian households is as follows:

$$K_{t+1}^{o} = \varphi_t I_t^{o}\left[1-\frac{\kappa}{2}\left(\frac{I_t^{o}}{I_{t-1}^{o}}-1\right)^{2}\right]+(1-\delta)K_t^{o} \tag{2}$$

where δ denotes the depreciation rate. K_t^o is their installed capital, I_t^o denotes their newly purchased investment goods, and κ captures the convex investment adjustment cost proposed by Christiano, Eichenbaum, and Evans (2005). φ_t is the marginal efficiency of investment (MEI), known to proxy for disturbances to the functioning of the financial sector (Justiniano, Primiceri, and Tambalotti, 2011). We assume the MEI shock follows the stochastic process

$$\log\varphi_t = \rho_\varphi \log\varphi_{t-1} + \varepsilon_{\varphi,t} \qquad \varepsilon_{\varphi,t} \overset{iid}{\sim} \mathcal{N}(0,\sigma_\varphi^2),$$

where ρ_φ and σ_φ denote the persistence and the standard deviation of the shock, respectively. Ricardian households' periodic budget constraint is given by

$$P_tC_t^o + P_tI_t^o + B_t^o + T_t^o \leq R_{t-1}B_{t-1}^o + W_tN_t^o + R_t^kK_t^o + D_t. \tag{3}$$

for $t = 0,1,2,\cdots,\infty$. Here, W_t is the nominal wage, R_t^k is the nominal rental rate of capital, B_t represents the quantity of one-period nominal bond purchased in period t, R_t is the gross nominal interest rate, D_t is the dividend, and T_t^o is the lump-sum tax paid to the government.

Rule-of-thumb (non-Ricardian) households Non-Ricardian households choose C_t^r and N_t^r that maximize:

$$E_0\sum_{t=0}^{\infty}\beta^t\left(\frac{C_t^{r\,1-\sigma}-1}{1-\sigma}-b\frac{\eta}{1+\eta}N_t^{r\,\frac{\eta+1}{\eta}}\right) \tag{4}$$

subject to

$$P_tC_t^r = W_tN_t^r - T_t^r, \tag{5}$$

where T_t^r is the lump-sum tax levied on non-Ricardian households.

Wage schedule Because we are interested in potential welfare losses of consumption heterogeneity, as in Debortoli and Galí (2017), we keep the labor supply side as simple as possible so that households' wage schedule satisfies

$$\frac{W_t}{P_t} = \mu^w bC_t^\sigma N_t^{\frac{1}{\eta}}, \tag{6}$$

where C_t is the aggregate consumption, N_t the aggregate labor input, and $\mu^w = \frac{\varepsilon^w}{\varepsilon^w - 1} > 1$ the wage markup. This wage rule would arise in a version of the representative-agent New Keynesian models with an imperfect labor market, in which a labor union sets the wage that maximizes the households utility. We assume that the wage markup is sufficiently large so that the conditions $\frac{W_t}{P_t} > bC_t^{type\,\sigma} N_t^{\frac{1}{\eta}}$ for $type = o, r$ are satisfied for all t, which guarantees that both types of households are willing to supply labor demanded by firms at the prevailing wage.

Aggregation Aggregate consumption and hours worked are given by a weighted average of the corresponding variables for each household type. That is, $C_t = \Omega C_t^r + (1-\Omega)C_t^o$ and $N_t = \Omega N_t^r + (1-\Omega)N_t^o$. Aggregate investment and the capital stock are $I_t = (1-\Omega)I_t^o$ and $K_t = (1-\Omega)K_t^o$, respectively.

2.2. FIRMS

A continuum of monopolistically competitive firms, indexed by $s \in [0,1]$, produce differentiated intermediate products $Y_t(s)$. We assume the existence of a representative final good firm that combines the differentiated products into a final output Y_t:

$$Y_t = \left[\int_0^1 Y_t(s)^{\frac{\varepsilon-1}{\varepsilon}} ds\right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{7}$$

where $\varepsilon > 1$ denotes the intratemporal elasticity of substitution across different varieties of intermediate goods. Solving the cost minimization problem for the final good firm yields the demand for each differentiated intermediate good:

$$Y_t(s) = \left(\frac{P_t(s)}{P_t}\right)^{-\varepsilon} Y_t, \tag{8}$$

where $P_t(s)$ is the price of intermediate good s. Because the final good firms operate in a perfectly competitive market, the aggregate price index P_t can be obtained by imposing the zero-profit condition:

$$P_t = \left[\int_0^1 P_t(s)^{1-\varepsilon} ds\right]^{\frac{1}{1-\varepsilon}}. \tag{9}$$

All monopolistically competitive firms that produce intermediate goods have an identical production technology

$$Y_t(s) = A_t K_t(s)^{\alpha} N_t(s)^{1-\alpha} \tag{10}$$

relation

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{A,t} \tag{11}$$

where $\varepsilon_{A,t}$ is $i.i.d.N(0,\sigma_A^2)$.

Intermediate-good firms are subject to nominal price rigidity. As in Calvo (1983), in every period, a fraction θ of these firms cannot optimally choose their prices and keep their prices unchanged from the previous period. The remaining fraction $1-\theta$ of these firms reset their optimal price $P_t^*(s)$ by maximizing their current and the present value of their expected future real profits

$$\max E_t \sum_{v=0}^{\infty} (\beta\theta)^v \frac{\lambda_{t+v}}{\lambda_t} \frac{1}{P_{t+v}} \left[P_t^*(s) Y_{t+v}(s) - (1-\tau)\left(R_{t+v}^k K_{t+v}(s) + W_{t+v} N_{t+v}(s) \right) \right],$$

subject to the sequence of demand constraints (8). Here λ_{t+v} is the marginal utility of real wealth of a Ricardian household that owns the firm. τ denotes the rate at which the cost of labor and capital is subsidized and is introduced to eliminate the distortions arising from monopolistic competition. These subsidies are financed by means of lump-sum taxes T_t^o and T_t^r. The inefficiency resulting from the presence of market power can be eliminated by setting $\tau = \frac{1}{\varepsilon}$.

Moreover, as in Galí, López-Salido, and Vallés (2007) and Debortoli and Galí (2017), we assume that intermediate-good firms hire labor uniformly across household types so that

$$N_{j,t}(s) = N_{j,t}^o(S) = N_{j,t}^r(s) \tag{12}$$

holds for all t.

2.3. FISCAL POLICY

Because the marginal propensity to consume differs across households, there is a non-negligible role for fiscal transfers on aggregate fluctuation. Following Leeper, Plante, Traum (2010), we consider a transfer rule which is given by

$$\log(trans_t/trans) = \phi_y \log(Y_t/Y), \tag{13}$$

where $trans_t \equiv -\Omega \frac{T_t^r}{P_t}$ denotes the total real government transfer payments, and ϕ_y determines the cyclicality of transfer payments.[2] $trans$ and Y are the steady

[2]More precisely, their fiscal rule takes the form of $\log(trans_t/trans) = \phi_y \log(Y_t/Y) + \log(B_t/B)$. However, because we assume net bond holdings are zero in equilibrium ($B_t = 0$), we omit terms that capture government debt.

state real transfer and output. If $\phi_y < 0$, transfers to non-Ricardian households are reduced during booms, which works to dampen an increase in their consumption and thus aggregate consumption. So, (13) can be interpreted as automatic stabilizers.

2.4. MARKET CLEARING

In equilibrium, net bond holdings are zero, $B_t = 0$. Marketing clearing in the goods markets requires that the quantity produced matches the quantity demanded for consumption and investment. Thus, in equilibrium, $Y_t = C_t + I_t$.

Using the labor market equilibrium condition, $N_{j,t} = \int_0^1 N_{j,t}(s)ds$ and demand equation (8), it can be shown that the aggregate output can be expressed as:

$$Y_t = A_t K_t^{\alpha} N_t^{1-\alpha} \frac{1}{\Delta_t} \tag{14}$$

where $\Delta_t \equiv \int_0^1 \left(\frac{P_t(s)}{P_t}\right)^{-\varepsilon} ds$ is a measure of price dispersion across firms.

3. PARAMETER VALUES AND THE SOLUTION METHOD

Table 1 summarizes our baseline parameter values used for deriving the optimal policy under commitment. It is assumed that the discount factor β is 0.99, implying a steady state real annual return of 4%, and the relative risk aversion coefficient σ is 1 (log utility). Following Chetty (2012), the Frisch elasticity of labor η is set to 1/2. The preference parameter b is set to match the steady state value of N, which is 1 for analytical convenience. It is assumed that there are no costs associated with changing the level of investment ($\kappa = 0$).[3] The annual depreciation rate is set to 10 percent ($\delta = 0.025$). Capital income share α is set to 0.33. Following Galí, López-Salido, and Vallés (2007), we set θ to 0.75, which corresponds to a price adjustment frequency of 4 quarters. It is also assumed that the degree of intratemporal elasticity of substitution between intermediate goods ε is 6. Elasticity of substitution between labor types ε_w is set equal to 6, implying a wage markup of 1.2. As for the parameter describing the government transfer rule ϕ_y, we use OLS estimates of equation (13) by regressing the HP filtered real government social benefits to persons on the HP-filtered real GDP. The

[3] All the qualitative properties of the optimal policy presented below are not affected by the presence of the investment adjustment costs.

share of non-Ricardian households Ω is 0.3, which is consistent with the fraction of hand-to-mouth households in the US over the period 1989-2010 estimated by Kaplan, Violante, and Weidner (2014). The persistence and the standard deviation of aggregate shocks are assumed to be 0.9 and 0.01, respectively.

Because the focus of our paper is the welfare implication of the differential consumption responses to aggregate shocks, as opposed to steady state consumption differences, we assume steady state consumption is the same across household types, that is, $C_r = C_o = C$, as in Galí, López-Salido, and Vallés (2007) and Debortoli and Galí (2017). This outcome can always be guaranteed by an appropriate choice of steady state lump sum tax on non-Ricardian households, T^r.

Table 1: Benchmark calibration

Parameter	**Description**	**Value**
β	Discount factor	0.99
η	Frisch elasticity	1/2
σ	Relative risk aversion	1
κ	Investment adjustment cost	0
δ	Depreciation rate	0.025
α	Capital income share	0.33
θ	Calvo price stickiness parameter	0.75
ε	Elasticity of substitution across intermediate goods	6
ε^w	Elasticity of substitution across labor types	6
Ω	Share of non-Ricardian households	0.3
ϕ_y	Cyclicality of transfer payments	-1.27
ρ_A	Persistence of the neutral tech. shock	0.9
ρ_μ	Persistence of the MEI shock	0.9
σ_A	Standard deviation of the neutral tech. shock	0.01
σ_μ	Standard deviation of the MEI shock	0.01

4. OPTIMAL MONETARY POLICY

In this section, we show that the presence of consumption heterogeneity leads to an optimal monetary policy prescription that deviates from perfect price stability. We then discuss how different transfer rules call for different optimal monetary policies. We assume that ex-ante commitment is feasible. For each process of aggregate shock, we assume that the Ramsey planner maximizes the following weighted utility function:

$$W_0 = (1-\Omega)\sum_{t=0}^{\infty}\beta^t\left(\frac{C_t^{o\,1-\sigma}-1}{1-\sigma}-b\frac{\eta}{1+\eta}N_t^{\frac{\eta+1}{\eta}}\right)$$
$$+\Omega\sum_{t=0}^{\infty}\beta^t\left(\frac{C_t^{r\,1-\sigma}-1}{1-\sigma}-b\frac{\eta}{1+\eta}N_t^{\frac{\eta+1}{\eta}}\right), \qquad (15)$$

by choosing plans for C_t, C_t^o, C_t^r, I_t, I_t^o, N_t, R_t, λ_t, μ_t, r_t, MRS_t, Π_t, w_t, K_t, K_t^o, Y_t, ψ_t, τ_t^r, τ_t^o, x_t^1, x_t^2, Δ_t, Π_t^* subject to the constraints from (A.1) to (A.22) for $t = 0, 1, \cdots, \infty$. We compute the equilibrium path under the optimal policy by applying a second-order approximation around a steady state of the Ramsey problem, following the approach pioneered by Schmitt-Grohé and Uribe (2004).

Neutral technology shock Figure 2 compares the impulse responses to a one standard deviation neutral technology shock in a RANK and a TANK model under the baseline fiscal rule. When prices are flexible in a TANK model (NT-Flexible (TANK)), consumption level of Ricardians (O. Consumption) and non-Ricardians (R. Consumption) rises due to an increase in factor prices. Because non-Ricardians cannot use assets to smooth out consumption as Ricardians can, their consumption level increases more than that of Ricardians causing a dispersion in cross-section consumption. This heterogeneous consumption response is the first distortion. When prices are sticky, there is an additional distortion that arises due to countercyclical markups which poses a further challenge for the Ramsey planner. The latter distortion, which manifests itself as the time-varying output gap, can be completely eliminated in a RANK model by keeping the inflation rate fully stable. However, in a TANK model, such strict inflation targeting would lead to a flexible price equilibrium, which involves consumption inequality. Therefore, the Ramsey planner strikes a balance between stabilizing the inflation rate and reducing consumption dispersion between Ricardians and non-Ricardians. Because non-Ricardians are more income-sensitive than Ricardians, in order to reduce the consumption dispersion, it is easier to bring non-Ricardians' consumption close to Ricardian's consumption than to bring Ricardians' close to non-Ricardians'. Therefore, the Ramsey planner seeks for an allocation that involves a smaller increase in real wages than its flexible equilibrium counterpart – a negative real wage gap – which induces a fall in real marginal costs and in turn the inflation rate (NT-Ramsey (TANK)).

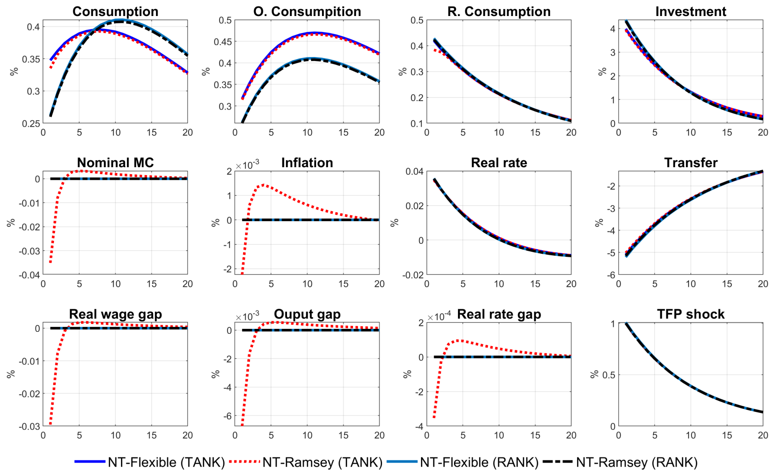

Figure 2: Effects of a neutral tech. shock in a RANK and a TANK with the baseline transfer rule ($\phi_y = -1.27$) under flexible prices and under Ramsey policy

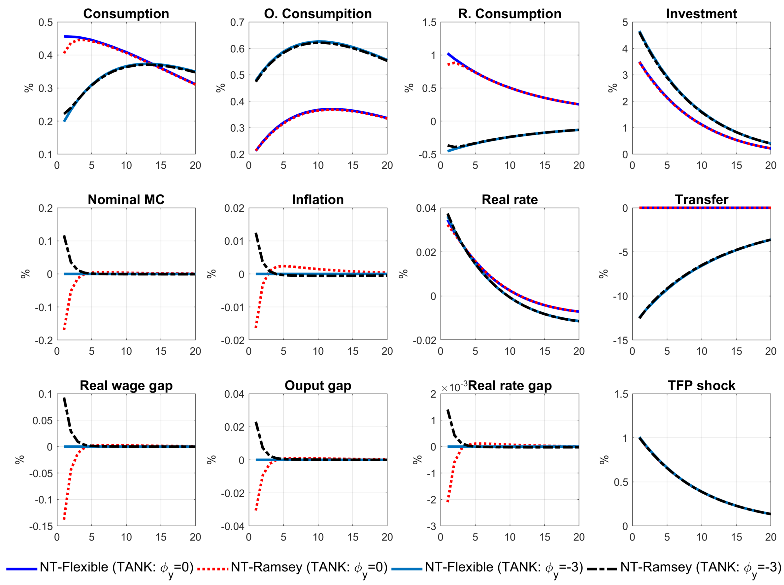

Figure 3: Effects of a neutral tech. shock in a TANK with different fiscal transfer rules under Ramsey policy

Figure 3 plots the Ramsey equilibrium in TANK models under two extreme fiscal transfer rules in response to a positive neutral technology shock. In the absence of fiscal transfers ($\phi_y = 0$), the responses of prices and quantities are qualitatively the same as those observed under the baseline transfer rule. The only difference is that, under no transfer, the Ramsey planner is more willing to bring down the real wage gap by allowing a larger fall in the inflation rate and the output gap because the consumption dispersion is larger due to the absence of automatic stabilizer. However, when transfers are more countercyclical than in the data (ϕ_y = -3), the Ramsey planner seeks for an increase in the real wage gap by inducing inflation and an inefficient boom. This is because the more powerful the automatic stabilizer is, the more income of non-Ricardians is redistributed to Ricardian households. Thus, non-Ricardians' increase in consumption is dampened more. With $\phi_y = -3$, non-Ricardians' consumption is lower than Ricardian's. As a result, the Ramsey optimal allocation is to have non-Ricardians' consumption closer to Ricardians' by raising the real wage gap.

Marginal efficiency of investment shock Figure 4 compares the impulse responses to a one standard deviation marginal efficiency of investment shock in a RANK and a TANK model under baseline fiscal rule. When prices are flexible in a TANK model (MEI-Flexible (TANK)), consumption of Ricardians falls whereas that of non-Ricardians rises in response to a positive marginal efficiency of investment shock. Ricardians exploit the increased expected return on capital by investing more and reducing consumption. This works to reduce aggregate consumption and so the marginal rate of substitution between labor and consumption, which induces an increase in aggregate labor input. This increases the labor income of non-Ricardians due to assumption (12) and so their consumption. The optimal policy is to bring non-Ricardians' consumption level close to Ricardians' consumption. Therefore, the Ramsey planner seeks for a policy that reduces the real wage gap to depress non-Ricardians' consumption, which induces deflation (MEI-Ramsey (TANK)).

Figure 5 plots the Ramsey equilibrium in TANK models under two extreme fiscal transfer rules in response to a positive marginal efficiency of investment shock. As in the case of the neutral technology shock, in the absence of fiscal transfers ($\phi_y = 0$), the Ramsey planner is more willing to bring down real wages by allowing a larger fall in the inflation rate and the output gap than under the baseline transfer rule. When $\phi_y = -3$, unlike the scenario of the neutral technology shock, the optimal policy still calls for deflationary policy. This is because the neutral technology shock directly affects the consumption of both non-Ricardians and Ricardians through changes in real wages, whereas the marginal efficiency of investment shock only directly affects the intertemporal decision of capital holders, Ricardian households. As a result, the consumption dispersion is larger under positive MEI shocks than under positive neutral technology shocks. Therefore, in order to have the consumption level of non-Ricardians fall below that of Ricardians and thus have an inflationary policy as the optimal policy, more countercyclical transfers are needed under MEI shocks than under neutral technology shocks.

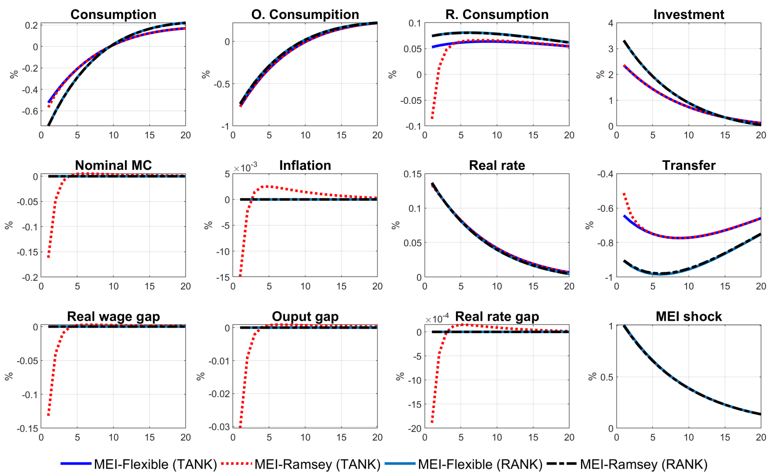

Figure 4: Effects of a MEI shock in a RANK and a TANK with the baseline transfer rule ($\phi_y = -1.27$) under flexible prices and under Ramsey policy

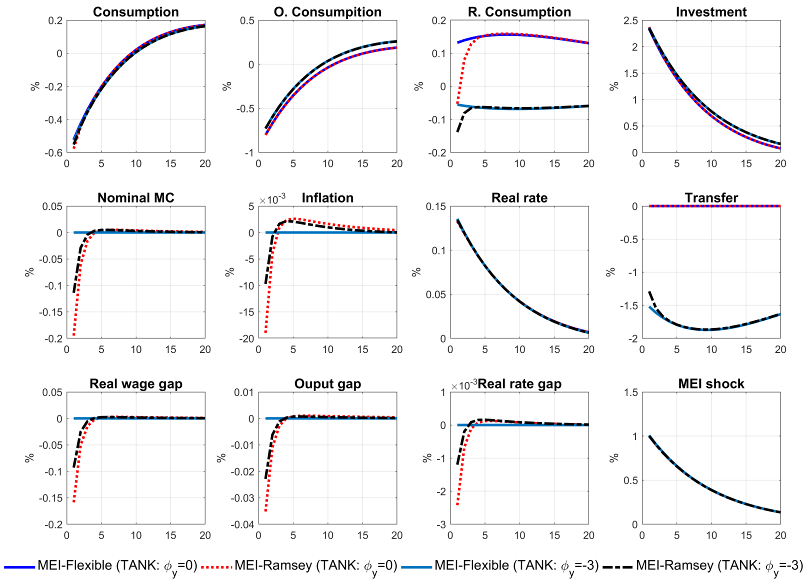

Figure 5: Effects of a MEI shock in a TANK with different fiscal transfer rules under Ramsey policy

Suboptimality of inflation targeting The impulse responses from Figure 2 to Figure 5 are suggestive that the behavior of the consumption distribution is relevant both for welfare and the characteristics of the optimal monetary policy under various transfer rules. This intuition is confirmed in Table 2, which reports welfare losses under inflation targeting relative to those under Ramsey optimal policy. The welfare loss reported in the table are computed for our benchmark calibration of the model in which inefficient fluctuations are driven by both the neutral technology and the marginal efficiency of investment shocks, and is expressed as a percentage of steady state aggregate consumption. The table clearly indicates that a monetary policy that ignores consumption distribution perform more poorly than Ramsey optimal policy.

Table 2: Welfare under inflation targeting

Welfare loss relative to Ramsey optimal policy		
$\phi_y = -1.27$	$\phi_y = 0$	$\phi_y = -3$
0.0024	0.0010	0.0053

Note: The welfare loss is expressed as a percent of steady state consumption.

5. CONCLUSION

This paper departs from the representative-agent assumption and explores how the presence of consumption distribution alters the optimal plans for the Ramsey planner who uses the nominal interest rate as an instrument. Relative to a price stability motive that typically appears as policy prescriptions in representative-agent New Keynesian models, heterogeneity adds a quantitatively important motive to spread aggregate fluctuations equally across all households. The latter motive crucially depends on how the fiscal transfer rules are constructed. The message of our finding is that monetary policy prescription is connected to redistributive fiscal policy.

A fruitful area for future work is the optimal design of both redistributive policy (or automatic stabilizers) and monetary policy. McKay and Reis (2016) argue that automatic stabilizers are effective given a suboptimal monetary policy rule. They continue to show that automatic stabilizers may be less effective when monetary policy rule becomes close to optimal. In contrast, we characterize optimal monetary policy given a suboptimal transfer rule and conclude that monetary policy prescription may look differently depending on fiscal rules. If automatic stabilizers and monetary policy are both optimally designed, then the outcome could be that automatic stabilizers focus on eliminating inefficiencies generated by the changes in the consumption distribution, and monetary policy concentrates on conventional price stability.

APPENDIX

A. FULL SET OF EQUILIBRIUM CONDITIONS

$$C_t^{o-\sigma} = \lambda_t \tag{A.1}$$

$$1 = \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{R_t}{\pi_{t+1}} \right) \tag{A.2}$$

$$\mu_t = \beta E_t \left[\lambda_{t+1} r_{t+1} + (1-\delta)\mu_{t+1} \right] \tag{A.3}$$

$$C_t^r = w_t N_t - \tau_t^r \tag{A.4}$$

$$C_t = \Omega C_t^r + (1-\Omega) C_t^o \tag{A.5}$$

$$MRS_t = b C_t^{\sigma} N_t^{\frac{1}{\eta}} \tag{A.6}$$

$$MRS_t \mu^w = w_t, \tag{A.7}$$

where $w_t = \frac{W_t}{P_t}$ and $\tau_t^r = \frac{T_t^r}{P_t}$.

Capital accumulation and investment demand

$$K_{t+1}^o = \varphi_t I_t^o \left[1 - \frac{\kappa}{2} \left(\frac{I_t^o}{I_{t-1}^o} - 1 \right)^2 \right] + (1-\delta) K_t^o \tag{A.8}$$

$$\begin{aligned} \lambda_t q_t = {} & \mu_t \varphi_t \left[1 - \frac{\kappa}{2} \left(\frac{I_t^o}{I_{t-1}^o} - 1 \right)^2 - \kappa \left(\frac{I_t^o}{I_{t-1}^o} - 1 \right) \frac{I_t^o}{I_{t-1}^o} \right] \\ & + \kappa \beta E_t \left[\mu_{t+1} \varphi_{t+1} \left(\frac{I_{t+1}^o}{I_t^o} - 1 \right) \left(\frac{I_{t+1}^o}{I_t^o} \right)^2 \right] \end{aligned} \tag{A.9}$$

$$K_t = (1-\Omega) K_t^o \tag{A.10}$$

$$I_t = (1-\Omega) I_t^o \tag{A.11}$$

Firms

$$(1-\tau) w_t = \psi_t (1-\alpha) A_t K_t^{\alpha} N_t^{-\alpha} \tag{A.12}$$

$$(1-\tau) r_t = \psi_t \alpha A_t K_t^{\alpha-1} N_t^{1-\alpha}, \tag{A.13}$$

where $r_t = \frac{R_t^k}{P_t}$. .

Price setting
Consider a price-setting problem faced by an intermediate-good firm which has the opportunity to reoptimize its price in period t. This price, which we denote by $P_t^*(s)$, is set so as to maximize the expected present discounted value of profits. The first- order condition for price setting problem for each sector can be expressed as follows.

$$(\varepsilon-1)E_t\sum_{v=0}^{\infty}(\theta\beta)^v\lambda_{t+v}\left(P_t^*(s)^{-\varepsilon_c}P_{t+v}^{\varepsilon-1}Y_{t+v}\right)=\varepsilon E_t\sum_{v=0}^{\infty}(\theta\beta)^v\lambda_{t+v}\Psi_{t+v}(s)P_t^*(s)^{-\varepsilon-1}P_{t+v}^{\varepsilon-1}Y_{t+v}$$

where $\Psi_t=\psi_t\times P_t$ denote nominal marginal costs. We introduce auxiliary variables $X_{c,t}^1$ and $X_{c,t}^2$:

$$X_t^1=E_t\sum_{v=0}^{\infty}(\theta\beta)^v\lambda_{t+v}\left(P_{t+v}^{\varepsilon-1}Y_{t+v}\right)$$

$$X_t^2=E_t\sum_{v=0}^{\infty}(\theta\beta)^v\lambda_{t+v}\left(\Psi_{t+v}(s)P_{t+v}^{\varepsilon-1}Y_{t+v}\right)$$

Using these auxiliary variables, the first-order condition can be expressed recursively:

$$x_t^1=\lambda_tY_t+(\theta\beta)E_t\Pi_{t+1}^{\varepsilon-1}x_{t+1}^1 \tag{A.14}$$

$$x_t^2=\lambda_t\psi_tY_t+(\theta\beta)E_t\Pi_{t+1}^{\varepsilon}x_{t+1}^2 \tag{A.15}$$

$$\Pi_t^*=\frac{\varepsilon}{\varepsilon-1}\Pi_t\frac{x_t^2}{x_t^1} \tag{A.16}$$

$$\Pi_t^{1-\varepsilon}=(1-\theta)\Pi_t^{*\,1-\varepsilon}+\theta \tag{A.17}$$

where $\Pi_t^*=P_t^*/P_{t-1}$ is reset price inflation, and where $x_t^1=\frac{X_t^1}{P_t^{\varepsilon-1}}$ and $x_t^2=\frac{X_t^2}{P_t^{\varepsilon}}$. Log-linearizing these equations around zero steady state inflation and putting the results together yield the usual Phillips curve.

Fiscal and monetary policy
Subsidies given to intermediate good producing firms are covered by lump-sum taxation collected from households. Moreover, the fiscal transfers vary with the macroeconomic condition.

$$\Omega t_t^r+(1-\Omega)t_t^o=\tau\left(\frac{W_t}{P_t}N_t+\frac{R_t^k}{P_t}K_t\right) \tag{A.18}$$

$$\log(trans_t/trans)=\phi_y\log(Y_t/Y) \tag{A.19}$$

where $t_t^o=\frac{T_t^o}{P_t}$.

Market clearing

$$Y_t = C_t + I_t \tag{A.20}$$

$$Y_t = (A_t K_t^{\alpha} N_t^{1-\alpha}) \frac{1}{\Delta_t} \tag{A.21}$$

$$\Delta_t = (1-\theta)\Pi_t^{*-\varepsilon}\Pi_t^{\varepsilon} + \theta\Pi_t^{\varepsilon}\Delta_{t-1} \tag{A.22}$$

where $\Delta_t \equiv \int_0^1 \left(\frac{P_t(s)}{P_t}\right)^{-\varepsilon} ds$ is a measure of price dispersion across firms.

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