Econometrica Supplementary Material

SUPPLEMENT TO “TRADABILITY AND THE LABOR-MARKET IMPACT OF IMMIGRATION: THEORY AND EVIDENCE FROM THE UNITED STATES”

(*Econometrica*, Vol. 88, No. 3, May 2020, 1071–1112)

ARIEL BURSTEIN
Department of Economics, University of California, Los Angeles

GORDON HANSON
Kennedy School of Government, Harvard University

LIN TIAN
INSEAD

JONATHAN VOGEL
Department of Economics, University of California, Los Angeles

APPENDIX A: DERIVATION OF ANALYTIC RESULTS

IN THIS SECTION we derive the system of equations that allows us to solve for all endogenous variables as a function of small changes in immigrant and natives supplies in every region and education group and solkve for productivities in every region and occupation; we then derive the analytic results formally presented in Sections 3.2 and 3.3 as well as a range of other results described throughout the paper. In Appendix A.1, we begin by deriving the system in changes for small changes in $\{n_{re}^{k}\}_{r,e,k}$ and $\{a_{ro}\}_{r,o}$ for our baseline model of Section 2. We then impose the restrictions of Section 3.1 and simplify this system in changes in Appendix A.2. In Appendix A.3 we derive the analytic results presented in Sections 3.2 and 3.3. In Appendix A.4 we solve explicitly for all endogenous variables of interest in a special case of the model in Section A.2. Finally, in Appendix A.5 we deviate from the model of Section A.2 in the other direction and provide additional results in a version of the model that imposes fewer rather than more restrictions.

A.1. *System in Changes*

Here we derive a system of equations that we use to solve for changes in endogenous variables in response to infinitesimal changes in N_{re}^{I}, N_{re}^{D}, and A_{ro} in every region r, education cell e, and occupation o. We use lowercase characters, x, to denote the log change of any variable X relative to its initial equilibrium level: $x = d\ln X$.

Log-differentiating equation (8), we obtain

$$p_{ro} = -a_{ro} + \sum_{k} S_{ro}^{k} w_{ro}^{k}, \tag{32}$$

Ariel Burstein: arielb@econ.ucla.edu
Gordon Hanson: gordon_hanson@hks.harvard.edu
Lin Tian: lin.tian@insead.edu
Jonathan Vogel: jvogel@econ.ucla.edu

https://doi.org/10.3982/ECTA16196

where $S^k_{ro} \equiv \sum_e \frac{W^k_{reo} L^k_{reo}}{P_{ro} Q_{ro}}$ is the cost share of factor k (across all education cells) in occupation o output in region r. Log-differentiating equation (9), we obtain

$$l^D_{ro} - l^I_{ro} = -\rho \big(w^D_{ro} - w^I_{ro} \big). \tag{33}$$

Combining equations (10) and (11) and log-differentiating yields

$$l^k_{reo} = \theta w^k_{ro} - \theta \left(\sum_{j \in \mathcal{O}} \pi^k_{rej} w^k_{rj} \right) + n^k_{re}. \tag{34}$$

Log-differentiating $L^k_{ro} = \sum_e L^k_{reo}$, we obtain

$$l^k_{ro} = \sum_e \frac{L^k_{reo}}{L^k_{ro}} l^k_{reo}. \tag{35}$$

Log-differentiating equation (10), we obtain

$$n^k_{reo} = (\theta + 1) w^k_{ro} - (\theta + 1) \sum_o \pi^k_{ro} w^k_{ro} + n^k_{re}. \tag{36}$$

Log-differentiating equation (6), we obtain

$$p^y_{ro} = \big(1 - S^m_{ro}\big) p_{ro} + \sum_{j \neq r} S^m_{jro} p_{jo}, \tag{37}$$

where $S^m_{jro} \equiv \frac{P_{jo} \tau_{jro} Y_{jro}}{P^y_{ro} Y_{ro}}$ is the share of the value of region r's absorption in occupation o that originates in region j and $S^m_{ro} \equiv \sum_{j \neq r} S^m_{jro}$ is regions r's import share of absorption in occupation o. Log-differentiating equation (4) and using equation (37) yields

$$p_r = \sum_{o \in \mathcal{O}} S^A_{ro} \left(\big(1 - S^m_{ro}\big) p_{ro} + \sum_{j \neq r} S^m_{jro} p_{jo} \right), \tag{38}$$

where $S^A_{ro} = \frac{P^y_{ro} Y_{ro}}{P_r Y_r}$ denotes the share of occupation o in total absorption in region r.

Log differentiating equation (7), we obtain

$$q_{ro} = -\alpha p_{ro} + \sum_{j \in \mathcal{R}} S^x_{rjo} \big[(\alpha - \eta) p^y_{jo} + \eta p_j + y_j \big], \tag{39}$$

where $S^x_{rjo} \equiv \frac{P_{ro} \tau_{rjo} Y_{rjo}}{P_{ro} Q_{ro}}$ is the share of the value of region r's output in occupation o that is destined for region j. Equations (39) and (37) yield

$$q_{ro} = -\alpha p_{ro} + \sum_{j \in \mathcal{R}} S^x_{rjo} \left[(\alpha - \eta) \left(\big(1 - S^m_{jo}\big) p_{jo} + \sum_{j' \neq j} S^m_{j'jo} p_{j'o} \right) + \eta p_j + y_j \right].$$

Log-differentiating equation (1) and using equation (9), we obtain

$$q_{ro} = a_{ro} + \sum_k S^k_{ro} l^k_{ro}.$$

Combining the two previous expressions, we obtain

$$
\begin{aligned}
q_{ro} &= a_{ro} + \sum_{k} S^{k}_{ro} l^{k}_{ro} \\
&= -\alpha p_{ro} + \sum_{j \in \mathcal{R}} S^{x}_{rjo} \Big[(\alpha - \eta) \Big(\big(1 - S^{m}_{jo}\big) p_{jo} + \sum_{j' \neq j} S^{m}_{j'jo} p_{j'o} \Big) + \eta p_j + y_j \Big]. \qquad (40)
\end{aligned}
$$

Log-differentiating equation (12) yields

$$\sum_{o} S^{P}_{ro} \sum_{k} S^{k}_{ro} \big(w^{k}_{ro} + l^{k}_{ro}\big) = p_r + y_r, \qquad (41)$$

where S^{P}_{ro} denotes the share of occupation o in total absorption in region r, $S^{P}_{ro} = \frac{P_{ro} Q_{ro}}{P_r Y_r}$.

We can use equations (32), (33), (34), (35), (36), (38), (40), and (41) to solve for changes in employment allocations in efficiency units l^{k}_{reo} and l^{k}_{ro} and bodies n^{k}_{reo}, occupation wages w^{k}_{ro}, occupation prices p_{ro} and quantities q_{ro}, aggregate absorption price p_r, and quantity y_r, for all r, o, and k.

A.2. *Imposing the Restrictions of Section 3.1*

In Section 3.1, we impose three restrictions. First, we assume that region r is a small open economy in the sense that it constitutes a negligible share of exports and absorption in each occupation for each region $j \neq r$. Specifically, we assume that $S^{m}_{rjo} \to 0$ and $S^{x}_{jro} \to 0$ for all o and $j \neq r$. The small-open-economy assumption implies that, in response to a shock in region r only, prices and output elsewhere are unaffected in all occupations: $p^{y}_{jo} = p_{jo} = p_j = y_j = 0$ for $j \neq r$. Therefore, given a shock to region r alone, equation (40) simplifies to

$$q_{ro} = a_{ro} + \sum_{k} S^{k}_{ro} l^{k}_{ro} = -\epsilon_{ro} p_{ro} + \big(1 - S^{x}_{ro}\big)(\eta p_r + y_r), \qquad (42)$$

where

$$\epsilon_{ro} \equiv \big(1 - \big(1 - S^{x}_{ro}\big)\big(1 - S^{m}_{ro}\big)\big)\alpha + \big(1 - S^{x}_{ro}\big)\big(1 - S^{m}_{ro}\big)\eta \qquad (43)$$

is a weighted average of the elasticity of substitution across occupations, η, and the elasticity across origins, $\alpha > \eta$, where the weight on the latter is increasing in the extent to which the services of an occupation are traded, as measured by S^{x}_{ro} and S^{m}_{ro}. The parameter ϵ_{ro} is the partial demand elasticity of region r's occupation o output to its output price. It is a partial elasticity because it holds fixed region r's aggregate output and price index (but lets its absorption price of occupation o change). Equation (38) simplifies to

$$p_r = \sum_{o \in \mathcal{O}} S^{A}_{ro} \big(1 - S^{m}_{ro}\big) p_{ro}. \qquad (44)$$

Second, we assume that occupations are grouped into two sets, g for $g = \{T, N\}$, where $S^{x}_{ro} = S^{x}_{ro'}$ and $S^{m}_{ro} = S^{m}_{ro'}$ for all $o, o' \in g$. According to (43), the assumption that $S^{x}_{ro} = S^{x}_{ro'}$ and $S^{m}_{ro} = S^{m}_{ro'}$ for all $o, o' \in g$ implies that the elasticity of local output to the local producer price, ϵ_{ro}, is common across all occupations in g. We refer to ϵ_{rg} as the common elasticity for all $o \in g$ within region r. The assumption that that $S^{x}_{ro} = S^{x}_{ro'}$ for all $o, o' \in g$

also implies that the term $(1 - S^x_{ro})(\eta p_r + y_r)$ in (42) is common across all occupations in g.[50]

Third, we restrict comparative advantage by assuming that education groups within each k differ only in their absolute productivities, $Z^k_{reo} = Z^k_{re}$. This assumption and equation (10) imply that education groups within k are allocated identically across occupations: $\pi^k_{reo} = \pi^k_{ro}$ for all e. Hence, equation (34) becomes

$$l^k_{reo} = \theta w^k_{ro} - \theta\left(\sum_{j\in\mathcal{O}} \pi^k_{rj} w^k_{rj}\right) + n^k_{re}.$$

The previous expression and equation (35) yield[51]

$$l^k_{ro} = \theta w^k_{ro} - \theta\left(\sum_{j\in\mathcal{O}} \pi^k_{rj} w^k_{rj}\right) + \sum_e \frac{S^k_{reo}}{S^k_{ro}} n^k_{re}.$$

Under the assumption that $Z^k_{reo} = Z^k_{re}$, the ratio S^k_{reo}/S^k_{ro} is common across o, so

$$l^k_{ro} = \theta w^k_{ro} - \theta\left(\sum_{j\in\mathcal{O}} \pi^k_{rj} w^k_{rj}\right) + n^k_r, \tag{45}$$

where the vector of changes in labor supplies by education level in region r, $\{n^k_{re}\}_e$, is summarized by a single sufficient statistic,

$$n^k_r \equiv \sum_e \frac{S^k_{re}}{S^k_r} n^k_{re},$$

with weights given by the share of labor income in region r accruing to type k labor with education e, $S^k_{re} \equiv \frac{W^k_{ro} L^k_{re}}{\sum_{e',k'} W^{k'}_{ro} L^{k'}_{re'}}$, relative to the share of labor income in region r accruing to all type k labor, $S^k_r = \sum_{e'} S^k_{re'}$.

Hence, under the first and third restrictions of Section 3.1, we can use equations (32), (33), (36), (41), (42), (44), and (45) to solve for changes in employment allocations l^k_{ro} and n^k_{ro}, occupation wages w^k_{ro}, occupation prices p_{ro} and quantities q_{ro}, and aggregate absorption price p_r and quantity y_r, for all r, o, and k. With shocks to region r alone, log changes in all endogenous variables are linear functions of shocks in region r: $\{n^I_{re}\}_e$, $\{n^D_{re}\}_e$, and $\{a_{ro}\}_o$.

---

[50] Under the assumption that α is infinite, as in the Rybczynski theorem, ϵ_{ro} is infinite and the assumption that r is a small open economy implies that $p_{ro} = 0$. In this case, we obtain our analytic results in Section 3.2 without requiring common trade shares across goods. Of course, in this case crowding in obtains.

[51] In this derivation, we use

$$\sum_e \frac{L^k_{reo}}{L^k_{ro}} n^k_{re} = \frac{1}{W^k_{ro}\sum_{e'} L^k_{re'o}} \sum_e W^k_{ro} L^k_{reo} n^k_{re} = \frac{\sum_{e',k'} W^{k'}_{ro} L^{k'}_{re'o}}{W^k_{ro}\sum_{e'} L^k_{re'o}} \sum_e S^k_{reo} n^k_{re}$$

and the definitions in the main text $S^k_{reo} \equiv \frac{W^k_{ro} L^k_{reo}}{\sum_{e',k'} W^{k'}_{ro} L^{k'}_{re'o}}$ and $S^k_{ro} \equiv \sum_e S^k_{reo}$.

A.3. *Proofs for Sections 3.2 and 3.3*

Deriving equations (18)–(21): Combining equations (33) and (45), we obtain

$$(\theta+\rho)\left(w_{ro}^{D}-w_{ro}^{I}\right)=\theta\left(\sum_{j\in\mathcal{O}}\pi_{rj}^{D}w_{rj}^{D}-\sum_{j\in\mathcal{O}}\pi_{rj}^{I}w_{rj}^{I}\right)+n_{r}^{I}-n_{r}^{D}, \tag{46}$$

so that $\tilde{w}_r \equiv w_{ro}^{D}-w_{ro}^{I}$ is common across occupations o. With shocks to region r alone, it follows from the system of equation in changes that $\tilde{w}_r$ is a linear combination of region r shocks, as in equation (21). We do not explicitly solve for the change in relative wages per efficiency unit, $\tilde{w}_r$, in general; we do so under the assumption of a single g in Appendix A.4.

Equation (42) is equivalent to

$$p_{ro}=\frac{1}{\epsilon_{ro}}\left(1-S_{ro}^{x}\right)(\eta p_r+y_r)-\frac{1}{\epsilon_{ro}}a_{ro}-\frac{1}{\epsilon_{ro}}S_{ro}^{I}\left(l_{ro}^{I}-l_{ro}^{D}\right)-\frac{1}{\epsilon_{ro}}l_{ro}^{D}.$$

The previous expression and equation (33) yield

$$p_{ro}=\frac{1}{\epsilon_{ro}}\left(1-S_{ro}^{x}\right)(\eta p_r+y_r)-\frac{1}{\epsilon_{ro}}a_{ro}-\frac{\rho}{\epsilon_{ro}}S_{ro}^{I}\tilde{w}_r-\frac{1}{\epsilon_{ro}}l_{ro}^{D},$$

which, together with equation (32), yields

$$w_{ro}^{D}=\frac{1}{\epsilon_{ro}}\left(1-S_{ro}^{x}\right)(\eta p_r+y_r)+\left(\frac{\epsilon_{ro}-1}{\epsilon_{ro}}\right)a_{ro}+\left(\frac{\epsilon_{ro}-\rho}{\epsilon_{ro}}\right)S_{ro}^{I}\tilde{w}_r-\frac{1}{\epsilon_{ro}}l_{ro}^{D}.$$

The previous expression and equation (45) yield

$$\begin{aligned} w_{ro}^{D}={}&\left(\frac{\epsilon_{ro}-\rho}{\epsilon_{ro}+\theta}\right)\tilde{w}_r S_{ro}^{I}+\left(\frac{\epsilon_{ro}-1}{\epsilon_{ro}+\theta}\right)a_{ro}\\ &+\frac{1}{\epsilon_{ro}+\theta}\left[\left(1-S_{ro}^{x}\right)(\eta p_r+y_r)+\theta\sum_{j\in\mathcal{O}}\pi_{rj}^{D}w_{rj}^{D}-n_{r}^{D}\right]. \end{aligned} \tag{47}$$

We similarly obtain

$$\begin{aligned} w_{ro}^{I}={}&\left(\frac{\epsilon_{ro}-\rho}{\epsilon_{ro}+\theta}\right)\tilde{w}_r\left(S_{ro}^{I}-1\right)+\left(\frac{\epsilon_{ro}-1}{\epsilon_{ro}+\theta}\right)a_{ro}\\ &+\frac{1}{\epsilon_{ro}+\theta}\left[\left(1-S_{ro}^{x}\right)(\eta p_r+y_r)+\theta\sum_{j}\pi_{rj}^{I}w_{rj}^{I}-n_{r}^{I}\right]. \end{aligned} \tag{48}$$

Imposing the second restriction from Section 3.1, equations (36), (47), and (48) yield equation (20), where $\epsilon_{rg}=\epsilon_{ro}$ for all $o\in g$. Under the same restriction, equations (36) and (20) yield equation (19). Equations (19) and (20) simplify to equations (16) and (17) if $a_{ro}=a_{ro'}$ for all $o, o'\in g$ and $n_{re}^{D}=0$ for all e.

Using equations (32) and (20), we obtain

$$p_{ro}-p_{ro'}=-\frac{\theta+\rho}{\theta+\epsilon_{rg}}\tilde{w}_r\left(S_{ro}^{I}-S_{ro'}^{I}\right)-\frac{\theta+1}{\theta+\epsilon_{rg}}(a_{ro}-a_{ro'})$$

for any $o, o' \in g$. Combining the previous expression and equation (42), we obtain

$$q_{ro} - q_{ro'} = \frac{\epsilon_{rg}(\theta + \rho)}{\theta + \epsilon_{rg}} \tilde{w}_r \left(S^I_{ro} - S^I_{ro'}\right) + \frac{\epsilon_{rg}(\theta + 1)}{\theta + \epsilon_{rg}} (a_{ro} - a_{ro'})$$

for any $o, o' \in g$. The two previous expressions yield equation (18). Equation (18) simplifies to equation (15) if $a_{ro} = a_{ro'}$ for all $o, o' \in g$ and $n^D_{re} = 0$ for all e.

Deriving equation (22). Consider $o, o' \in g$. Equation (19) implies

$$n^k_{reo} = \frac{(\epsilon_{rg} - \rho)(\theta + 1)}{\epsilon_{rg} + \theta} \tilde{w}_r \left(S^I_{ro} - S^I_{ro'}\right) + \frac{(\epsilon_{rg} - 1)(\theta + 1)}{\epsilon_{rg} + \theta} (a_{ro} - a_{ro'}) + n^k_{reo'}.$$

The previous expression is equivalent to

$$\begin{aligned} \frac{\pi^k_{reo'}}{\pi^k_{reg}} n^k_{reo} = {} & \frac{(\epsilon_{rg} - \rho)(\theta + 1)}{\epsilon_{rg} + \theta} \tilde{w}_r \left(\frac{\pi^k_{reo'}}{\pi^k_{reg}} S^I_{ro} - \frac{\pi^k_{reo'}}{\pi^k_{reg}} S^I_{ro'} \right) \\ & + \frac{(\epsilon_{rg} - 1)(\theta + 1)}{\epsilon_{rg} + \theta} \left(\frac{\pi^k_{reo'}}{\pi^k_{reg}} a_{ro} - \frac{\pi^k_{reo'}}{\pi^k_{reg}} a_{ro'} \right) + \frac{\pi^k_{reo'}}{\pi^k_{reg}} n^k_{reo'}. \end{aligned}$$

Letting $n^k_{reg} \equiv \sum_{o' \in g} \frac{\pi^k_{reo'}}{\pi^k_{reg}} n^k_{reo'}$ denote the log change in labor allocated to g and summing the previous expression over all $o' \in g$, we obtain

$$\begin{aligned} n^k_{reo} = {} & \frac{(\epsilon_{rg} - \rho)(\theta + 1)}{\epsilon_{rg} + \theta} \tilde{w}_r \left(S^I_{ro} - \sum_{o' \in g} \frac{\pi^k_{reo'}}{\pi^k_{reg}} S^I_{ro'} \right) \\ & + \frac{(\epsilon_{rg} - 1)(\theta + 1)}{\epsilon_{rg} + \theta} \left(a_{ro} - \sum_{o' \in g} \frac{\pi^k_{reo'}}{\pi^k_{reg}} a_{ro'} \right) + n^k_{reg}. \end{aligned}$$

The previous expression, equation (21), and $a_{ro} \equiv a_o + a_{rg} + \tilde{a}_{ro}$ yield equation (22), where

$$\begin{aligned} \alpha^k_{reg} \equiv {} & -\frac{(\epsilon_{rg} - \rho)(\theta + 1)}{\epsilon_{rg} + \theta} \tilde{w}_r \sum_{o' \in g} \frac{\pi^k_{reo'}}{\pi^k_{reg}} S^I_{ro'} \\ & - \frac{(\epsilon_{rg} - 1)(\theta + 1)}{\epsilon_{rg} + \theta} \sum_{o' \in g} \frac{\pi^k_{reo'}}{\pi^k_{reg}} a_{ro'} + \frac{(\epsilon_{rg} - 1)(\theta + 1)}{\epsilon_{rg} + \theta} a_{rg} + n^k_{reg}. \end{aligned}$$

The partial own labor demand elasticity. We can solve for the partial own labor demand elasticity at the level of the region–occupation, l^D_{ro}/w^D_{ro}, in which we allow for native and immigrant labor to reallocate across occupations and occupation prices to change, but hold immigrant wages, aggregate output, and aggregate prices fixed. Combining equations (32), (33), and 42, we obtain

$$\left| l^D_{ro}/w^D_{ro} \right| = \epsilon_{ro}\left(1 - S^I_{ro}\right) + \rho S^I_{ro}.$$

This partial elasticity is increasing in ρ (as is standard) and also ϵ_{ro} (consistent with Hicks–Marshall's rules of derived demand). Moreover, it is increasing in S^I_{ro} if and only if $\rho > \epsilon_{ro}$.

A.4. *Explicit Solutions if All o Have Common Trade Shares*

Here we consider a version of our baseline model in which we assume that there is a single grouping of occupations so that all occupations o have a common export share of output, $S^x_r = S^x_{ro}$, and import share of absorption, $S^m_{ro} = S^m_r$. This formulation nests the case in which bilateral trade costs are infinite, in which case $S^x_{ro} = S^m_{ro} = 0$ for all o.

We begin by solving explicitly for $\tilde{w}_r$ and n^D_{reo}. We then sign Ψ^I_{ro}, Ψ^D_{ro}, and Ψ^A_{ro}.

Solving explicitly for $\tilde{w}_r$ and n^k_r. Equation (43) simplifies to

$$\epsilon_r \equiv \epsilon_{ro} = \big(1 - \big(1 - S^x_r\big)\big(1 - S^m_r\big)\big)\alpha + \big(1 - S^x_r\big)\big(1 - S^m_r\big)\eta \quad \text{for all } o. \tag{49}$$

Equations (47) and (49) imply

$$\sum_o \pi^D_{ro} w^D_{ro} = \left(\frac{\epsilon_r - \rho}{\epsilon_r}\right)\tilde{w}_r \sum_o \pi^D_{ro} S^I_{ro} + \left(\frac{\epsilon_r - 1}{\epsilon_r}\right)\sum_o \pi^D_{ro} a_{ro} + \frac{1}{\epsilon_r}(\eta p_r + y_r)\big(1 - S^x_r\big) - \frac{1}{\epsilon_r} n^D_r.$$

We similarly obtain from equations (48) and (49),

$$\begin{aligned}\sum_o \pi^I_{ro} w^I_{ro} = {} & \left(\frac{\rho - \epsilon_r}{\epsilon_r}\right)\tilde{w}_r \sum_o \pi^I_{ro}\big(1 - S^I_{ro}\big) \\ & + \left(\frac{\epsilon_r - 1}{\epsilon_r}\right)\sum_o \pi^I_{ro} a_{ro} + \frac{1}{\epsilon_r}(\eta p_r + y_r)\big(1 - S^x_r\big) - \frac{1}{\epsilon_r} n^I_r.\end{aligned}$$

The previous two expressions and equation (46) yield an explicit solution for $\tilde{w}_r$:

$$\tilde{w}_r = \frac{(\theta + \epsilon_r)\big(n^I_r - n^D_r\big) + \theta(\epsilon_r - 1)\sum_o \big(\pi^D_{ro} - \pi^I_{ro}\big)a_{ro}}{\epsilon_r(\theta + \rho) + \theta(\rho - \epsilon_r)\left[1 + \sum_o \big(\pi^D_{ro} - \pi^I_{ro}\big)S^I_{ro}\right]}.$$

This can be reexpressed as

$$\tilde{w}_r = \Phi^I_r\big(n^I_r - n^D_r\big) + \sum_o \Phi^A_{ro} a_{ro}, \tag{50}$$

where

$$\Phi^I_r = \frac{\theta + \epsilon_r}{\epsilon_r(\theta + \rho) + \theta(\rho - \epsilon_r)\left[1 + \sum_o \big(\pi^D_{ro} - \pi^I_{ro}\big)S^I_{ro}\right]}$$

and

$$\Phi^A_{ro} = \frac{\theta(\epsilon_r - 1)}{\epsilon_r(\theta + \rho) + \theta(\rho - \epsilon_r)\left[1 + \sum_o \big(\pi^D_{ro} - \pi^I_{ro}\big)S^I_{ro}\right]}\big(\pi^D_{ro} - \pi^I_{ro}\big).$$

Equation (50) provides an explicit solution for the log change in the relative occupation wage of natives to immigrants, $\tilde{w}_r$, as a function of the relative log change in the supply of immigrant to native workers, $n_r^I - n_r^D$, and the log change in the change in occupation productivities, $\sum_o(\pi_{ro}^D - \pi_{ro}^I)a_{ro}$, where Φ_r^I and Φ_r^A represent the corresponding elasticities. Finally, we can also solve explicitly for log changes in labor allocations as

$$n_{reo}^D = \frac{\theta+1}{\epsilon_r+\theta}\left[(\epsilon_r-\rho)\tilde{w}_r\left(S_{ro}^I - \sum_o \pi_{ro}^D S_{ro}^I\right) + (\epsilon_r-1)\left(a_{ro} - \sum_o \pi_{ro}^D a_{ro}\right)\right] + n_{re}^D.$$

Signing Φ_r^I. Here, we prove that $\Phi_r^I \geq 0$. Let

$$z_r \equiv \sum_j (\pi_{rj}^I - \pi_{rj}^D) S_{rj}^I. \tag{51}$$

The numerator of Φ_r^I is weakly positive. We consider two cases: (i) $\rho \geq \epsilon_r$ and (ii) $\rho < \epsilon_r$. In the first case ($\rho \geq \epsilon_r$), we clearly have $\Phi_r^I \geq 0$, since $z_r \leq 1$. In the second case ($\rho \geq \epsilon_r$), $z_r \geq 0$ is a sufficient condition for $\Phi_r^I \geq 0$ since $\Phi_r^I \geq 0 \iff \frac{\epsilon_r\rho}{\rho-\epsilon_r}(\frac{1}{\epsilon_r}+\frac{1}{\theta}) \leq z_r$. Order occupations such that

$$o \leq o' \quad \Rightarrow \quad S_{ro}^I \leq S_{ro'}^I.$$

By definition, $S_{ro}^I = W_{ro}^I L_{ro}^I/(W_{ro}^I L_{ro}^I + W_{ro}^D L_{ro}^D)$. Equations (10) and (11) imply

$$W_{ro}^k L_{reo}^k = \gamma N_{re}^k \pi_{reo}^k \left(\sum_{j\in\mathcal{O}} (Z_{rej}^k W_{rj}^k)^{\theta+1}\right)^{\frac{1}{\theta+1}},$$

which, together with our restriction that $Z_{reo}^k = Z_{ro}^k$, yields

$$W_{ro}^k L_{ro}^k = \gamma \pi_{ro}^k \left(\sum_{j\in\mathcal{O}} (Z_{rj}^k W_{rj}^k)^{\theta+1}\right)^{\frac{1}{\theta+1}} N_r^k,$$

where $N_r^k \equiv \sum_e N_{re}^k$. Hence, we have

$$o \leq o' \quad \Rightarrow \quad \frac{\pi_{ro}^D}{\pi_{ro}^I} \geq \frac{\pi_{ro'}^D}{\pi_{ro'}^I}. \tag{52}$$

Let $\Pi_r^k(o) \equiv \sum_{o'=1}^{o} \pi_{ro}^k$. Condition (52) is equivalent to stating that $\Pi_r^I(o)$ dominates $\Pi_r^D(o)$ in terms of the likelihood ratio. This implies that $\Pi_r^I(o)$ (first-order) stochastically dominates $\Pi_r^D(o)$. Since S_{ro}^I is increasing in o, equation (51) therefore implies $z_r \geq 0$, which implies $\Phi_r^I \geq 0$ if $\rho < \epsilon_r$. Combining the two cases ($\rho \geq \epsilon_r$ and $\rho < \epsilon_r$), we obtain the result that $\Phi_r^I \geq 0$.

Signing Φ_{ro}^A. Here we prove that $\Phi_{ro}^A > 0 \iff (\pi_{ro}^D - \pi_{ro}^I)\epsilon_r > 1$. The denominator of Φ_r^A is strictly positive, since $z_r \leq 1$ and $\rho, \theta, \epsilon_r > 0$. The numerator of Φ_r^A is positive if and only if $(\pi_{ro}^D - \pi_{ro}^I)\epsilon_r > 1$.

A.5. *Relaxing Restriction (iii): Education-Specific Occupation Comparative Advantage*

In our baseline analytic results we assumed that education cells did not differ in their relative productivities across occupations: $Z_{reo}^k/Z_{reo'}^k = Z_{re'o}^k/Z_{re'o'}^k$ (restriction (iii)). Here we discuss the conditions for crowding in or out when we relax this assumption (as is the case in the data we use in our quantitative analysis). We impose that $a_{ro} = 0$.

By equation (34) and (35),

$$l^k_{ro} = \theta w^k_{ro} + \sum_e \frac{L^k_{reo}}{L^k_{ro}}\left(-\theta \text{wage}^k_{re} + n^k_{re}\right), \tag{53}$$

where

$$\text{wage}^k_{re} = \sum_{o \in \mathcal{O}} \pi^k_{reo} w^k_{ro}.$$

Equations (32), (33), and (42) (which do not use restriction (iii)) imply that

$$l^D_{ro} + (\rho - \epsilon_{ro}) S^I_{ro} \tilde{w}_{ro} = -\epsilon_{ro} w^D_{ro} + \left(1 - S^x_{ro}\right)(\eta p_r + y_r),$$

where $\tilde{w}_{ro} \equiv w^D_{ro} - w^I_{ro}$. For two occupations $o, o' \in g$,

$$l^D_{ro} - l^D_{ro'} + \epsilon_{rg}\left(w^D_{ro} - w^D_{ro'}\right) = (\epsilon_{rg} - \rho)\left[S^I_{ro}\tilde{w}_{ro} - S^I_{ro'}\tilde{w}_{ro'}\right]. \tag{54}$$

Consider first the case in which $Z^k_{reo}/Z^k_{reo'} = Z^k_{re'o}/Z^k_{re'o'}$ for $k = D$ (satisfying restriction (iii)) but not for $k = I$. In this case, $\frac{L^D_{reo}}{L^D_{ro}} = \frac{L^D_{reo'}}{L^D_{ro'}}$ and equation (53) implies that $l^D_{ro} - l^D_{ro'} = \theta(w^D_{ro} - w^D_{ro'})$. Using (33), (54) can be rewritten as

$$w^D_{ro} - w^D_{ro'} = \frac{(\epsilon_{rg} - \rho)}{(\epsilon_{rg} + \theta)}\left(S^I_{ro}\tilde{w}_{ro} - S^I_{ro'}\tilde{w}_{ro'}\right).$$

If $\epsilon_{rg} = \rho$, then $w^D_{ro} = w^D_{ro'}$ so by equation (34), $l^D_{reo} - l^D_{reo'} = 0$ for $o, o' \in g$; that is, there is neither crowding in or out for native workers in g. If $\epsilon_{rg} \neq \rho$, then the sign and magnitude of $l^D_{reo} - l^D_{reo'}$ depend on S^I_{ro}, $S^I_{ro'}$, $\tilde{w}_{ro}$, and $\tilde{w}_{ro'}$.

Consider now the more general case in which we do not impose restriction (iii) for either $k = D$ or $k = I$. We aim to understand under what conditions $\rho = \epsilon_{rg}$ implies neither crowding in nor out in g, as under the assumption that restriction (iii) holds. If $\rho = \epsilon_{rg}$, then equation (54) (and the analogous equation for immigrant labor) implies that for $o, o' \in g$,

$$l^k_{ro} - l^k_{ro'} + \epsilon_{rg}\left(w^k_{ro} - w^k_{ro'}\right) = 0,$$

which combined with equation (53) implies

$$w^k_{ro} - w^k_{ro'} = \frac{1}{\epsilon_{rg} + \theta}\sum_e \left(\frac{L^k_{reo}}{L^k_{ro}} - \frac{L^k_{reo'}}{L^k_{ro'}}\right)\left(\theta \text{wage}^k_{re} - n^k_{re}\right) \tag{55}$$

for $k = D, I$ and $o, o' \in g$. If $\theta \text{wage}^k_{re} - n^k_{re}$ is common across education levels e, then $w^k_{ro} - w^k_{ro'} = l^k_{reo} - l^k_{reo'} = 0$ for all $o, o' \in g$; that is, there is neither crowding in nor out across occupations in g for worker k type.

We can use this result to understand why, in the calibrated model of Section 5 (in which we do not impose restriction (iii)), setting $\epsilon_{rT} \approx \rho$ results roughly in neither crowding in nor crowding out for native workers within the set of tradable occupations, as in the model with a single education group. This is because immigration induces only small differential changes across education groups in native populations across space (via endogenous mobility of native workers) and in average wages within a region: that is, $n^D_{re} \approx n^D_{re'}$ and

TABLE V

THE MOST AND LEAST TRADABLE OCCUPATIONS, IN ORDER[a]

	Most and Least Tradable Occupations	
Rank*	Twenty-Five Most Tradable Occupations	Twenty-Five Least Tradable Occupations
1	Fabricators$^+$	Social, recreation and religious workers$^+$
2	Printing machine operators$^+$	Cleaning and building service$^+$
3	Metal and plastic processing operator$^+$	Electronic repairer$^+$
4	Woodworking machine operators$^+$	Lawyers and judges$^+$
5	Textile machine operator	Vehicle mechanic$^+$
6	Math and computer science	Police$^+$
7	Precision production, food and textile	Housekeeping$^+$
8	Records processing	Teachers, postsecondary$^+$
9	Machine operator, other	Health assessment$^+$
10	Computer, communication equipment operator	Food preparation and service$^+$
11	Office machine operator	Personal service$^+$
12	Precision production, other	Firefighting$^+$
13	Metal and plastic machine operator	Related agriculture$^+$
14	Technical support staff	Extractive$^+$
15	Science technicians	Production, other$^+$
16	Engineering technicians	Guards$^+$
17	Natural science	Construction trade$^+$
18	Arts and athletes	Therapists$^+$
19	Misc. administrative support	Supervisors, protective services$^+$
20	Engineers	Teachers, non-postsecondary
21	Social scientists, urban planners and architects	Transportation and material moving
22	Managerial related	Librarians and curators
23	Secretaries and office clerks	Health service
24	Sales, all	Misc. repairer
25	Health technologists and diagnosing	Executive, administrative and managerial

[a] To construct the 50 occupations used in our baseline analysis, we start with the 69 occupations based on the subheadings of the 1990 Census Occupational Classification System and aggregate up to 50 to concord to David Dorn's occupation categorization (http://www.ddorn.net/) and to combine occupations that are similar in education profile and tradability but whose small size creates measurement problems (given the larger number of CZs in our data). *For most (least) traded occupations, rank is in decreasing (increasing) order of tradability score. $^+$Occupations that achieve either the maximum or minimum tradability score.

$\text{wage}^D_{re} \approx \text{wage}^D_{re'}$ for all e, e'. In contrast, in Appendix F of the online Appendix we show that setting $\epsilon_{rT} \approx \rho$ implies that immigrant workers reallocate systematically across tradable occupations in response to an inflow of immigrants. As shown in Appendix F, this is also the case in the data when we consider the allocation regressions for immigrant workers.

APPENDIX B: SUMMARY STATISTICS AND OCCUPATION DETAILS

We list the 50 occupations used in our baseline analysis, as well as their tradability ranking from Blinder and Krueger (2013), in Table V. We provide balance tables across tradable and nontradable occupations using 1980 occupation characteristics and 2012 occupation characteristics in Table VI. We provide summary statistics for immigrant intensity, S^I_{ro}, for the most and least tradable occupations both at the national level and in Los Angeles, CA in Table VII.

TABLE VI

CHARACTERISTICS OF WORKERS[a]

			1980			**2012**		
	Characteristics of Workers		Natives	Immigrants	**Total**	Natives	Immigrants	**Total**
Tradable	Share of female		0.49	0.47	0.49	0.51	0.46	0.51
	Share of college and above		0.17	0.23	0.17	0.34	0.43	0.34
	Share of non-white		0.10	0.25	0.11	0.17	0.57	0.24
		16–32	0.44	0.37	0.44	0.30	0.25	0.29
	Age distribution	33–49	0.33	0.40	0.33	0.37	0.48	0.39
		50–65	0.23	0.23	0.23	0.33	0.28	0.32
	Share in routine-intensive		0.45	0.39	0.44	0.40	0.35	0.39
	Share in abstract-intensive		0.30	0.22	0.29	0.34	0.27	0.33
	Share in communication-intensive		0.27	0.22	0.27	0.34	0.27	0.33
	Total		**0.46**	**0.03**	**0.50**	**0.37**	**0.07**	**0.44**
Nontradable	Share of female		0.31	0.33	0.31	0.42	0.38	0.41
	Share of college and above		0.20	0.18	0.20	0.34	0.24	0.32
	Share of non-white		0.11	0.22	0.12	0.18	0.50	0.24
	Age distribution	16–32	0.41	0.35	0.41	0.28	0.24	0.28
		33–49	0.35	0.40	0.35	0.39	0.49	0.40
		50–65	0.24	0.24	0.24	0.33	0.27	0.32
	Share in routine-intensive		0.07	0.10	0.07	0.07	0.11	0.08
	Share in abstract-intensive		0.24	0.22	0.24	0.28	0.19	0.26
	Share in communication-intensive		0.33	0.28	0.32	0.41	0.25	0.39
	Total		**0.47**	**0.03**	**0.50**	**0.46**	**0.10**	**0.56**

[a] The source for data is the 1980 Census for the left panel and the 2011–2013 ACS in the right panel. Values are weighted by annual hours worked times the sampling weight.

APPENDIX C: WAGE ANALYSIS

To estimate regression (29) replacing unobserved occupation wages with observed average wages and to estimate regression (30), we require measures of average wages by education group, occupation, and CZ (*reo*) cell. To obtain these, we first regress log hourly earnings of native-born workers in each year on a gender dummy, a race dummy, a categorical variable for 10 levels of educational attainment, a quartic in years of potential experience, and all pairwise interactions of these values (where regressions are weighted by annual hours worked times the sampling weight). We take the residuals from this Mincerian regression and calculate the sampling weight and hours-weighted average value for native-born workers for an education group, occupation, and CZ. Finally, we use these values to calculate changes in average wages in each *reo* cell.

APPENDIX D: ADDITIONAL DETAILS OF THE EXTENDED MODEL

D.1. *System of Equilibrium Equations in Changes*

We describe a system of equations to solve for changes in prices and quantities in the extended model. We consider the specification of the model that incorporates agglomeration externalities governed by the parameter λ; see footnote 45. We use the "exact hat algebra" approach that is widely used in international trade (Dekle et al. (2008)). We denote with a "hat" the ratio of any variable between two time periods. The two driving

TABLE VII

SUMMARY STATISTICS OF S^I_{ro} FOR THE MOST AND LEAST TRADABLE OCCUPATIONS IN LOS ANGELES AND ACROSS ALL CZS[a]

		Occupation Immigrant Intensity Within CZ, S^I_{ro}					
		1980			2012		
		LA	All CZs		LA	All CZs	
Occupations			Mean	Std. Dev.		Mean	Std. Dev.
10 Most tradable*	Fabricators^{+}	0.324	0.027	0.054	0.628	0.068	0.095
	Printing machine operators^{+}	0.153	0.019	0.051	0.433	0.042	0.093
	Metal and plastic processing operators^{+}	0.352	0.038	0.133	0.646	0.053	0.158
	Woodworking machine operators^{+}	0.457	0.023	0.09	0.72	0.073	0.163
	Textile machine operators	0.714	0.053	0.103	0.899	0.14	0.178
	Math and computer science	0.125	0.026	0.086	0.364	0.053	0.065
	Precision production, food and textile	0.218	0.024	0.034	0.464	0.085	0.096
	Records processing	0.136	0.016	0.024	0.301	0.03	0.044
	Machine operators, other	0.262	0.027	0.058	0.589	0.11	0.11
	Computer, communication equipment operators	0.104	0.012	0.024	0.274	0.034	0.088
19 Least tradable**	Social, recreation, and religious workers	0.093	0.023	0.037	0.284	0.032	0.042
	Cleaning and building service	0.242	0.025	0.042	0.527	0.076	0.093
	Electronic repairer	0.1	0.01	0.022	0.267	0.025	0.047
	Lawyers and judges	0.055	0.006	0.031	0.124	0.019	0.051
	Vehicle mechanic	0.207	0.018	0.033	0.441	0.039	0.063
	Police	0.054	0.014	0.048	0.119	0.016	0.029
	Housekeeping	0.537	0.04	0.068	0.823	0.165	0.174
	Teachers, postsecondary	0.148	0.046	0.056	0.283	0.109	0.078
	Health assessment	0.215	0.03	0.046	0.484	0.042	0.065
	Food preparation and service	0.337	0.034	0.044	0.527	0.092	0.085
	Personal service	0.175	0.023	0.031	0.325	0.05	0.053
	Firefighting	0.027	0.008	0.026	0.03	0.01	0.023
	Related agriculture	0.442	0.041	0.077	0.679	0.142	0.134
	Extractive	0.11	0.02	0.06	0.164	0.042	0.092
	Production, other	0.186	0.019	0.033	0.374	0.043	0.057
	Guards	0.08	0.014	0.031	0.225	0.026	0.042
	Construction trade	0.144	0.019	0.031	0.396	0.054	0.067
	Therapists	0.11	0.027	0.087	0.287	0.037	0.051
	Supervisors, protective services	0.03	0.008	0.066	0.117	0.016	0.056

[a] *The most tradable occupations ordered by decreasing tradability score. $^{+}$Occupations that achieve the maximum tradability score. **The least tradable occupations that achieve the minimum tradability score.

forces are changes in the national supply of foreign workers (denoted by $\hat{N}^I_e$) and domestic workers (denoted by $\hat{N}^D_e$).

We proceed in two steps. First, for a given guess of changes in occupation wages for domestic and immigrant workers in each region, $\{\hat{W}^D_{ro}\}$ and $\{\hat{W}^I_{ro}\}$, changes in the supply of domestic workers by education in each region, $\{\hat{N}^D_{re}\}$, and changes in the supply of immigrant workers by education and source country in each region, $\{\hat{N}^{Ic}_{re}\}$, we calculate in each region r changes in the supply of immigrant workers by education e,

$$\hat{N}^I_{re} = \sum_c \frac{N^{Ic}_{re}}{N^I_{re}} \hat{N}^{Ic}_{re},$$

TABLE VIII

AVERAGE OCCUPATION WAGE FOR DOMESTIC WORKERS[a]

	(1)	(2)	(3)	(1)	(2)	(3)
		Low Ed.			High Ed.	
	OLS	2SLS	RF	OLS	2SLS	RF
x_{ro}	0.038	0.046	0.038	0.003	−0.008	0.001
	(0.014)	(0.023)	(0.017)	(0.021)	(0.031)	(0.030)
$\mathbb{I}_o(N)x_{ro}$	−0.057	−0.083	−0.076	0.007	−0.022	−0.0189
	(0.028)	(0.052)	(0.037)	(0.028)	(0.037)	(0.0311)
Obs.	33,723	33,723	33,723	26,644	26,644	26,644
R^2	0.639	0.639	0.639	0.613	0.613	0.613
Wald test: P-values	0.34	0.38	0.18	0.64	0.36	0.52
AP F-stats (first stage)						
x_{ro}		102.77			65.90	
$\mathbb{I}_o(N)x_{ro}$		75.21			48.48	

[a] The dependent variable is the change in the average wage of domestic workers in a region–occupation, 1980–2012. Observations are for CZ–occupation pairs. The dependent variable is the log change in the average CZ–occupation wage for native-born workers; the immigration shock, x_{ro}, is in (23); $\mathbb{I}_o(N)$ is a dummy variable for the occupation being nontradable. All regressions include dummy variables for the occupation and the CZ–group (tradable, nontradable). Column 1 reports OLS results, column 2 reports 2SLS results using (26) to instrument for x_{ro}, and column 3 replaces the immigration shocks with the instruments. Robust standard errors (in parentheses) are clustered on state. Models are weighted by start of period CZ–occupation–education group native-born population. For the Wald test, the null hypothesis is that the sum of the coefficients on x_{ro} and $\mathbb{I}_o(N)x_{ro}$ is zero.

changes in the total population in each region,

$$\hat{N}_r = \sum_{k,e} \frac{N_{re}^k}{N_r} \hat{N}_{re}^k,$$

changes in average group wages,

$$\widehat{\text{Wage}}_{re}^k = \hat{N}_r^{\lambda} \left(\sum_o \pi_{reo}^k \left(\hat{W}_{ro}^k \right)^{\theta+1} \right)^{\frac{1}{\theta+1}},$$

changes in occupation output prices,

$$\hat{P}_{ro} = \left(S_{ro}^I \left(\hat{W}_{ro}^I \right)^{1-\rho} + \left(1 - S_{ro}^I\right) \left(\hat{W}_{ro}^D \right)^{1-\rho} \right)^{\frac{1}{1-\rho}},$$

changes in allocations of workers across occupations,

$$\hat{\pi}_{reo}^k = \frac{\left(\hat{N}_r^{\lambda} \hat{W}_{ro}^k \right)^{\theta+1}}{\left(\widehat{\text{Wage}}_{re}^k \right)^{\theta+1}},$$

changes in occupation output,

$$\hat{Q}_{ro} = \frac{1}{\hat{P}_{ro}} \sum_{k,e} S_{reo}^k \hat{\pi}_{reo}^k \widehat{\text{Wage}}_{re}^k \hat{N}_{re}^k,$$

and change in aggregate expenditures (and income),

$$\hat{E}_r = \sum_{k,e} S_{re}^k \widehat{\text{Wage}}_{re}^k \hat{N}_{re}^k.$$

TABLE IX

CONSTRUCTED OCCUPATION WAGE FOR DOMESTIC WORKERS[a]

	(1)	(2) Low Ed. 2SLS	(3)	(1)	(2) High Ed. 2SLS	(3)
	OLS		RF	OLS		RF
x_{ro}	0.075	0.039	0.033	0.019	−0.021	−0.006
	(0.023)	(0.045)	(0.031)	(0.032)	(0.057)	(0.052)
$\mathbb{I}_o(N)x_{ro}$	−0.189	−0.204	−0.171	−0.167	−0.234	−0.203
	(0.038)	(0.070)	(0.050)	(0.061)	(0.087)	(0.077)
Obs.	33,723	33,723	33,723	26,644	26,644	26,644
R^2	0.798	0.797	0.797	0.712	0.711	0.712
Wald test: P-values	0.01	0.01	0.00	0.00	0.00	0.00
AP F-stats (first stage)						
x_{ro}		102.77			65.90	
$\mathbb{I}_o(N)x_{ro}$		75.21			48.48	

[a] The dependent variable is the log change in the constructed occupation wage of domestic workers in a region–occupation, 1980–2012. Observations are for CZ–occupation pairs. The dependent variable is the constructed changes in native occupation wages in (30); the immigration shock, x_{ro}, is in (23); $\mathbb{I}_o(N)$ is a dummy variable for the occupation being nontradable. All regressions include dummy variables for the occupation and the CZ–group (tradable, nontradable). Column 1 reports OLS results, column 2 reports 2SLS results using (26) to instrument for x_{ro}, and column 3 replaces the immigration shocks with the instruments. Robust standard errors (in parentheses) are clustered on state. Models are weighted by start of period CZ–occupation–education group native-born population. For the Wald test, the null hypothesis is that the sum of the coefficients on x_{ro} and $\mathbb{I}_o(N)x_{ro}$ is zero.

Here, S_{re}^k is defined as the total income share within region r of workers of group k, e (such that $\sum_{k,e} S_{re}^k = 1$), S_{reo}^k is defined as the cost (or income) share within region r of workers of group k, e in occupation o (such that $\sum_{k,e} S_{reo}^k = 1$), and S_{ro}^I denotes the cost (or income) share of immigrants in occupation o in region r (i.e., $S_{ro}^I = \sum_e S_{reo}^I$). If $S_{ro}^I = 0$ ($S_{ro}^I = 1$), then we set $\hat{W}_{ro}^I = 1$ ($\hat{W}_{ro}^D = 1$).

Second, we update our guess of changes in occupation wages and changes in the supply within each region r of domestic and immigrant workers by education (and, for immigrants, also by source country) until the following equations are satisfied:

$$\hat{Q}_{ro} = (\hat{P}_{ro})^{-\alpha} \sum_{j \in \mathcal{R}} S_{rjo}^x \big(\hat{P}_{jo}^y\big)^{\alpha-\eta} (\hat{P}_j)^{\eta-1} \hat{E}_j,$$

$$\frac{\big(1 - S_{ro}^I\big)}{S_{ro}^I} \frac{\sum_e S_{reo}^I \hat{\pi}_{reo}^I \widehat{\text{Wage}}_{re}^I \hat{N}_{re}^I}{\sum_e S_{reo}^D \hat{\pi}_{reo}^D \widehat{\text{Wage}}_{re}^D \hat{N}_{re}^D} = \left(\frac{\hat{W}_{ro}^I}{\hat{W}_{ro}^D}\right)^{1-\rho},$$

$$\hat{N}_{re}^D = \frac{\left(\dfrac{\widehat{\text{Wage}}_{re}^D}{\hat{P}_r}\right)^{\nu}}{\sum_{j \in \mathcal{R}} \dfrac{N_{je}^D}{N_e^D} \left(\dfrac{\widehat{\text{Wage}}_{re}^D}{\hat{P}_j}\right)^{\nu}} \hat{N}_e^D,$$

$$\hat{N}^{Ic}_{re} = \frac{\left(\frac{\widehat{\text{Wage}}^{I}_{re}}{\hat{P}_r}\right)^{\nu}}{\sum_{j\in\mathcal{R}} \frac{N^{Ic}_{je}}{N^{Ic}_{e}}\left(\frac{\widehat{\text{Wage}}^{I}_{re}}{\hat{P}_j}\right)^{\nu}}\hat{N}^{Ic}_{e},$$

where changes in absorption prices are given by

$$\hat{P}^{y}_{ro} = \left(\sum_{j\in\mathcal{R}} S^{m}_{jro}(\hat{P}_{jo})^{1-\alpha}\right)^{\frac{1}{1-\alpha}},$$

$$\hat{P}_r = \left(\sum_{o\in\mathcal{O}} S^{A}_{ro}(\hat{P}^{y}_{ro})^{1-\eta}\right)^{\frac{1}{1-\eta}}.$$

Here S^A_{ro} is defined as the total absorption share in region r of occupation o, $S^A_{ro} \equiv \frac{P^y_{ro}Y_{ro}}{E_r}$, S^x_{rjo} is the share of the value of region r's output in occupation o that is destined for region j, $S^x_{rjo} \equiv \frac{P_{ro}\tau_{rjo}Y_{rjo}}{P_{ro}Q_{ro}}$, and S^m_{jro} is the share of the value of region r's absorption within occupation o that originates in region j, $S^m_{jro} \equiv \frac{P_{jo}\tau_{jro}Y_{jro}}{P^y_{ro}Y_{ro}}$.[52] If $N^{Ic}_{re} = 0$, then we set $\hat{N}^{Ic}_{re} = 1$.

In this second step, we solve for $|\mathcal{O}| \times |\mathcal{R}|$ unknown occupation wage changes for domestic workers and the same for foreign workers. We also solve for $|\mathcal{E}^D| \times |\mathcal{R}|$ unknown changes in population of domestic workers by region $\{\hat{N}^D_{re}\}$ and for $|\mathcal{E}^{IC}| \times |\mathcal{R}|$ unknown changes in population of immigrant workers by region $\{\hat{N}^{Ic}_{re}\}$, using the same number of equations.

The inputs required to solve this system are (i) values of initial equilibrium shares π^D_{reo}, π^I_{reo}, S^D_{re}, S^I_{re}, S^A_{ro}, S^m_{jro}, and S^x_{rjo}, and population levels for natives and immigrants by education and source country N^D_{re}, N^{Ic}_{re}; (ii) values of parameters θ, η, α, ν, and λ; and (iii) values of changes in aggregate domestic supply by education $\hat{N}^D_e$ and changes in aggregate immigrant supply by education and source country $\hat{N}^{Ic}_e$. We have omitted S^k_{reo} and S^I_{ro} from the list of required inputs because they can be immediately calculated given π^k_{reo} and S^k_{re} as

$$S^k_{reo} = \frac{\pi^k_{reo}S^k_{re}}{\sum_{k',e'} S^{k'}_{re'}\pi^{k'}_{re'o}}$$

and $S^I_{ro} = \sum_e S^I_{reo}$. In the model, π^k_{reo} equals both the share of labor income earned and the share of employment in occupation o by nativity k in region r (because average wages are equal across occupations). In practice, we measure π^k_{reo} as the share of labor income.

D.2. *Bilateral Trade and Absorption Shares*

Given the difficulty of obtaining bilateral regional trade data by occupation that is required to construct initial equilibrium trade shares S^m_{jro} and S^x_{rjo}, we construct them given

---

[52] In terms of our model's primitive parameters, regions vary in their occupational output composition due to variation in labor productivities, A^k_{ro} and T^k_{reo} (for $k = D, I$ and by education e), amenities, U^D_{re} and U^{Is}_{re} (by source country and education group), and bilateral trade costs, τ_{rj}.

assumptions on trade costs, as described in Section 5.2. For nontradable occupations, we assume that trade costs are prohibitive across CZs ($\tau_{rjo} = \infty$ for all $j \neq r$). This implies that $S^x_{rro} = S^m_{rro} = 1$ and $S^x_{rjo} = S^m_{rjo} = 0$ for all $j \neq r$. Absorption shares for each nontradable occupation, S^A_{ro}, are given by

$$S^A_{ro} = \frac{P_{ro}Q_{ro}}{E_r},$$

where occupation revenues, $P_{ro}Q_{ro}$, are measured by labor payments of this occupation in the data, and E_r is equal to total expenditures in region r (which, by the assumption of balanced trade, is equal to the sum of revenues—labor payments—across all occupations). For tradable occupations, we assume instead that trade costs between a given origin–destination pair are common across occupations, $\tau_{rjo} = \tau_{rjo'}$ for all $o, o' \in T$, and are parameterized as $\tau_{rjo} = \bar{\tau} \times \ln(\text{distance}_{rj})^{\varepsilon}$ for $j \neq r$. We also assume that occupation demand shifters are common across regions for tradable occupations, $\mu_{ro} = \mu_o$ for $o \in T$. Equations (3) and (5) imply that region r's sales to region j in occupation o are given by

$$\begin{aligned} E_{rjo} &= (\tau_{rjo}P_{ro})^{1-\alpha}\big(P^y_{jo}\big)^{\alpha-1}P^y_{jo}Y_{jo} \\ &= \mu_o(\tau_{rjo}P_{ro})^{1-\alpha}\big(P^y_{jo}\big)^{\alpha-\eta}\big(P^y_{jT}\big)^{\eta-1}E_{jT}, \end{aligned} \tag{56}$$

where E_{rT} denotes total expenditures on tradable occupations in region r, which by trade balance equals the sum of revenues across tradable occupations and is related to aggregate expenditures and prices by $E_{rT} = E_r(P_r/P_{rT})^{\eta-1}$. We now describe how we solve for E_{rjo} given measures of E_{rT}, τ_{rjo}, and $P_{ro}Q_{ro}$ and parameter values α, η.

Defining $\tilde{P}_{ro} = (\mu_o^{\frac{1}{1-\eta}}P_{ro})^{1-\alpha}$ and $\tilde{P}^y_{jo} = (\mu_o^{\frac{1}{1-\eta}}P^y_{jo})^{1-\alpha}$, E_{rjo} in equation (56) can be rewritten as a function of $\{\tilde{P}_{ro}\}$,

$$E_{rjo} = (\tau_{rjo})^{1-\alpha}\tilde{P}_{ro}\big(\tilde{P}^y_{jo}\big)^{\frac{\alpha-\eta}{1-\alpha}}\big(P^y_{jT}\big)^{\eta-1}E_{jT}, \tag{57}$$

where, by equations (4) and (6),

$$\tilde{P}^y_{jo} = \sum_{j' \in \mathcal{R}}(\tau_{j'jo})^{1-\alpha}\tilde{P}_{j'o},$$

$$\big(P^y_{jT}\big)^{1-\eta} = \sum_{o \in \mathcal{O}^T}\big(\tilde{P}^y_{jo}\big)^{\frac{1-\eta}{1-\alpha}}.$$

Given measures of E_{rT}, τ_{rjo}, and $P_{ro}Q_{ro}$ and parameter values α, η, we solve for $|\mathcal{O}^T| \times |\mathcal{R}|$ values of $\tilde{P}_{ro}$ using an equal number of equations

$$P_{ro}Q_{ro} = \sum_{j \in \mathcal{R}} E_{rjo}, \tag{58}$$

where E_{rjo} is given by equation (57). Once we solve for tradable occupation prices $\tilde{P}_{ro}$, we calculate E_{rjo}, which allows us to construct import, export, and absorption shares as

$$S^m_{rjo} = \frac{E_{rjo}}{\sum_{r'} E_{r'jo}},$$

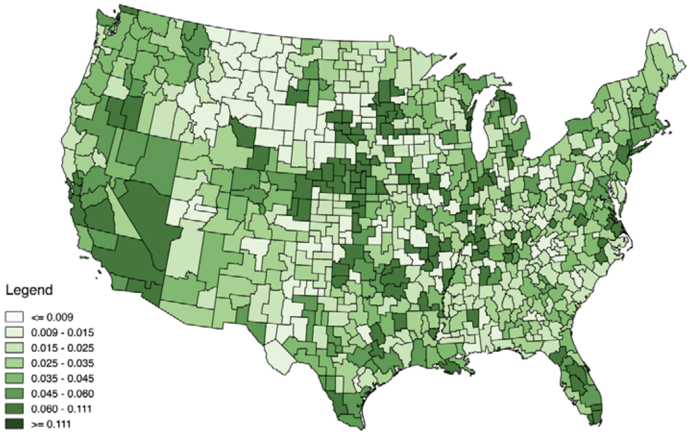

FIGURE 9.—Doubling of high education immigrants: highest minus lowest occupation wage increase for nontradable occupations across CZs.

$$S^x_{rjo} = \frac{E_{rjo}}{P_{ro}Q_{ro}},$$

and

$$S^A_{ro} = \frac{\sum_j E_{jro}}{E_r}.$$

The own export share of region r across all tradable occupations is defined as

$$S^{\text{own}}_r = \frac{\sum_{o\in\mathcal{O}^T} E_{rro}}{E_{rT}}.$$

In our model calibration, we assume $(1-\alpha)\delta = -1.29$ and set $\bar{\tau}$ to target a weighted average of own export shares S^{own}_r equal to 40% across a selected subset of regions, as described in the online Appendix.

REFERENCES

BLINDER, A. S., AND A. B. KRUEGER (2013): "Alternative Measures of Offshorability: A Survey Approach," *Journal of Labor Economics*, 31 (S1), S97–S128. [10]

DEKLE, R., J. EATON, AND S. KORTUM (2008): "Global Rebalancing With Gravity: Measuring the Burden of Adjustment," *IMF Staff Papers*, 55 (3), 511–540. [11]

Co-editor Fabrizio Zilibotti handled this manuscript.

Manuscript received 20 March, 2018; final version accepted 4 December, 2019; available online 13 January, 2020.