Regional Labor Markets, Commuting and the Economic Impact of Road Pricing

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Perspective

Urban areas are beset by economic externalities:

- Unpriced traffic congestion squanders time during morning and evening rush hours.
- Agglomeration drives up productivity in dense urban areas.
- Unemployment rates for unskilled workers in densely populated metropolitan areas often exceed national averages.

Road pricing deals with the externalities of traffic congestion, but it also impacts unemployment and urban agglomeration.

Jobs and Unemployment in Belgium

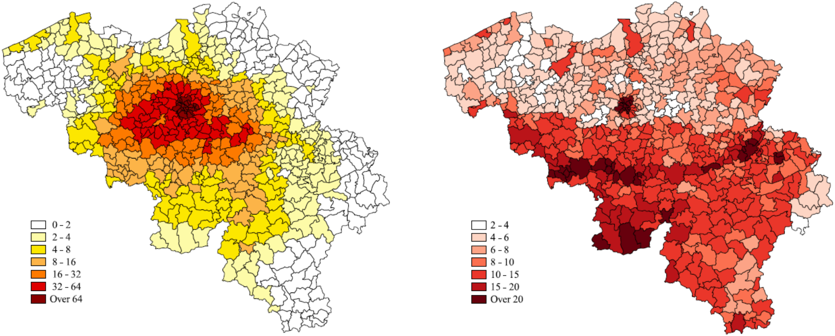


Fig. 1. Urban concentration of jobs and unemployment. Left: Percentage of workers with job location in Brussels, by region of residence. Right: Unemployment rates per municipality in 2010. Sources: Census 2001 and Steunpunt WSE.

Commuting and Traffic Congestion in Brussels

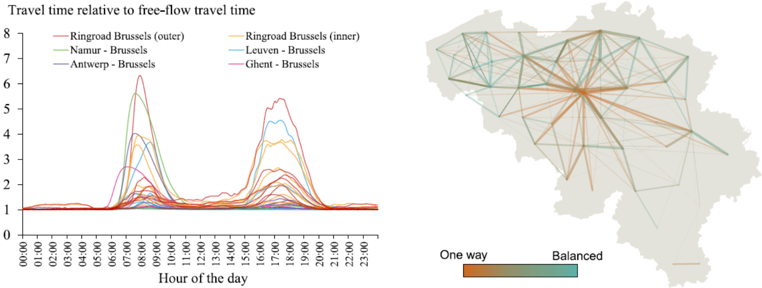


Fig. 2. Time profile and spatial pattern of travel. Left: Congestion over the course of the day on road segments to and from Brussels, average over 2010–2014, excluding school holidays. Right: The visualization of commuting patterns following Arribas-Bel and Gerritse (2012) shows strong commuting flows toward Brussels, while commuting between other cities appears to be more bidirectional. Sources: Own calculations based on data from Flanders Traffic Control Center Division and Census 2001.

The Model

We formulate a model which introduces the three features characteristic of urban and regional economies:

- regional labor markets for skilled and unskilled workers,
- traffic congestion and commuting delays,
- compensating wage differentials,
- unemployment among unskilled workers, and
- external economies of scale and agglomeration effects.

These factors have implications for effectiveness of congestion taxes and the return to investments in transportation infrastructure.

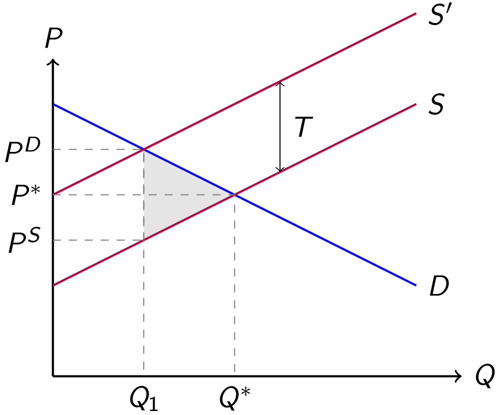
Key Findings

We calibrate a numerical version of our model to the city of Brussels and use the model to assess the extent to which second-best optimal pricing departs from first-best rules of thumb.

A congestion tax for commuting towards the urban area widens urban-rural wage gaps and unemployment differentials. Wages of skilled workers in the urban center rise as a toll restricts the supply of skilled labor in the city. Urban GDP falls, increasing unemployment.

White collar commuters, however, do not necessarily bear the burden of the tax, as it is shifted to less mobile factors of production in the urban area, including unskilled labor, land and capital. We demonstrate the usefulness of our model for assessing the returns to road network investments.

Definition: An *excise tax* (or a specific tax) is an amount paid by either the consumer or the producer per unit of the good at the point of sale.



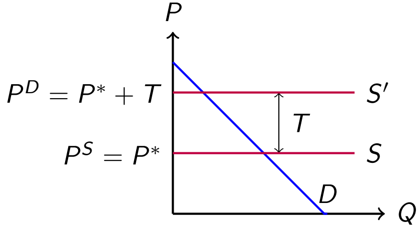
Tax incidence

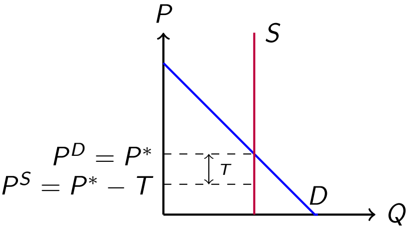
Definition: *tax incidence on consumers* is the amount by which the buyer price, P_D, rises over the non-tax equilibrium price, P^*, ; the tax incidence on producers is the amount by which the seller price, P_S, falls below P^*.

The total tax wedge equals the sum of the tax incidence on the buyer and on the seller. The shares depend on the elasticities of demand and supply. The tax incidence is larger in the less elastic side of the market.

Tax incidence in extreme cases

When supply is perfectly elastic, the tax incidence falls solely on the consumer; and when supply is perfectly inelastic, the tax incidence falls solely on the producer.





The Model

- Hourly and salaried workers are distinct. Further, salaried workers are distinguished by *region of residence* (an "Armington" model)
- Skilled workers commute, work for 8 hours per day, and give up morning and evening leisure in exchange for compensating wage differentials.
- Unskilled work where they live. They experience involuntary unemployment described by a *wage curve* with elasticity -0.1. (ala Blanchflower and Oswald)
- Total factor productivity in Brussels exhibits external economies of scale through urban agglomeration.
- Fixed factors of production in the short run include capital and land.

Labor Demand

- Salaried workers from Wallonia, Flanders and Brussels are imperfect substitutes in production.
- Benchmark wage differentials are are calibrated to a reference employment, commute delays and arbitrage constraints.

Salaried Workers

Welfare for salaried worker living in i and working in j:

$$U(c_{ij}, \ell_{ij}) = \left(\theta_\ell \ell_{ij}^\rho + (1-\theta_\ell)c_{ij}^\rho\right)^{1/\rho}$$

Extended income and budget constraint:

$$M_{ij} = 8W_{ij} + T_{ij} + \omega_{ij}(3 - D_{ij}) = c_{ij} + \omega_{ij}\ell_{ij}$$

which includes a term representing the difference between toll receipts less payments, T_{ij}.

Leisure is determined by the morning and evening time allocation (3 hours) less travel delay, D_{ij}:

$$\ell_{ij} = (3 - D_{ij})$$

Toll Receipts

The *net* distribution of toll revenue is returned lump sum to salaried workers:

$$T_{ij} = \frac{\bar{T}}{\bar{N}} - \tau_{ij}$$

in which τ_{ij} is the toll, $\bar{T}$ is aggregate toll revenue $(= \sum_{ij} \tau_{ij} N_{ij})$, and $\bar{N}$ is the population of salaried workers $(= \sum_{ij} N_{ij})$.

NB: Revenue is fully rebated, hence $\sum_{ij} N_{ij} T_{ij} = 0$.

Equilibrium Sorting

Two arbitrage conditions:

1. Commuter welfare is no higher than other salaried residents in region i:

$$\hat{U}_i \geq U_{ij} = \frac{M_{ij}}{p_{ij}} \quad \perp N_{ij} \geq 0$$

2. All salaried residents in i work somewhere:

$$\sum_j N_{ij} = \bar{N}_i \quad \perp \hat{U}_i$$

Traffic Congestion

- Delay on the ij arc consistent with the bureau of public roads congestion function:

$$D_{ij} = \alpha_{ij} + \beta_{ij} \left(\frac{N_{ij}}{S_{ij}} \right)^{\gamma}$$

  in which α_{ij} represents uncongested travel time, β_{ij} is the congestion parameter, S_{ij} is a capacity scale (=1 in benchmar), and $\gamma = 4$.
- The open road travel time based on the travel distance ($\mathcal{D}$) and the maximum speed (s^{max}):

$$\alpha_{ij} = \frac{\mathcal{D}_{ij}}{s^{max}}$$

- β_{ij} is calibrated to reference period flows, $\bar{N}_{ij}$, and commute times, $\bar{D}_{ij}$

A Pigouvian Tax

The travel delay created by one additional driver on the *ij* link is given by:

$$\frac{\partial(N_{ij}D_{ij})}{\partial N_{ij}} = D_{ij} + \gamma\beta_{ij}\left(\frac{N_{ij}}{S_{ij}}\right)^{\gamma} = D_{ij} + \gamma(D_{ij} - \alpha_{ij})$$

Congestion externality examines the marginal impact of driver for other commuters: $\gamma(D_{ij} - \alpha_{ij})$. In the absence of other distortions, the optimal (Pigouvian) toll is equal to the value of the induced delay, i.e.

$$\tau_{ij} = \gamma\omega_{ij}(D_{ij} - \alpha_{ij})$$

Unemployment

Unemployment in region j, u_j, depends on the hourly wage:

$$u_j = \bar{u}_j \left(\frac{v_j}{\bar{v}_j} \right)^{-\varepsilon}$$

where $\bar{u}_j$ is benchmark unemployment and $\bar{v}_j$ is the benchmark wage for unskilled workers.
A 10% drop in the real wage implies a doubling in the unemployment rate, hence:

$$\varepsilon = -\frac{\log(\frac{u_j}{\bar{u}_j})}{\log(\frac{v_j}{\bar{v}_j})} = -\frac{\log(2)}{\log(0.9)}$$

The market for hourly workers is then:

$$\bar{H}_j(1 - u_j) = N_j^H$$

Regional Production

$$
\begin{aligned}
Y_j &= F(N_j^H, L_j, K_j, N_{ij}) \\
&= \phi_j \left[\left(N_j^H \right)^{\theta_j^H} f(L_j, K_j, N_{ij})^{1-\theta_j^H} \right]^{\eta_j}
\end{aligned}
$$

Parameter $\eta_j \geq 1$ portrays external economies of scale through urban agglomeration. Firms take these agglomeration benefits as given.

Regional Production (cont.)

$$f(L_j, K_j, N_{ij}) = \left(\theta_j^L L_j^{\rho_L} + (1-\theta_j^L) g(K_j, N_{ij})^{\rho_L}\right)^{1/\rho_L}$$

$$g(K_j, N_{ij}) = \left(\theta_j^K K_j^{\rho_K} + (1-\theta_j^K) h(N_{ij})^{\rho_K}\right)^{1/\rho_K}$$

Skilled workers from different regions are traded off with an elasticity of substitution $\sigma_N (= \frac{1}{1-\rho_N})$.

$$h(N_{ij}) = \left(\sum_i \theta_{ij}^N N_{ij}^{\rho_N}\right)^{1/\rho_N}$$

Regional Production

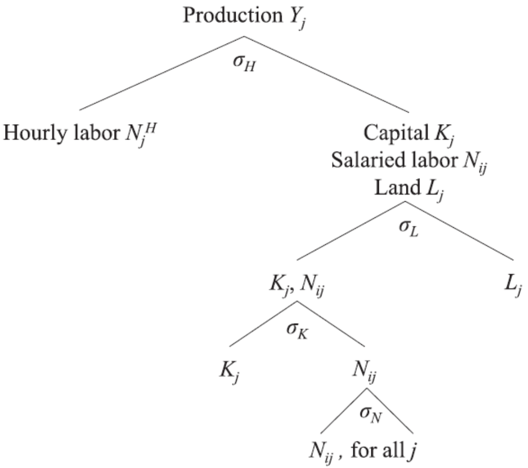


Fig. 3. Nested production structure.

Arbitrage

Representative firms set production levels that maximize profits, taking agglomeration externalities as given. The zero profit condition

$$C(v_j, p_j^L, p_j^K, W_{ij})Y_j^{1-\eta_j} = 1$$

where $C()$ is the unit cost function dual to F, p_j^L is the price of land in region j and p_j^K is the price of capital.

- In the short-run, land and capital are fixed and associated resource constraints determine p_j^L and p_j^K.
- In the long-run, the land constraint remains, and the price of capital is fixed. (Rents flow to absentee land and capital owners.)

Structural Sensitivity: Dynamic Congestion

Traffic congestion in the morning or evening peak hours is often caused or amplified by specific capacity constraints of the road network, such as a tunnel, an intersection, highway exits and ring roads around city centers. The bottleneck model, initiated by Vickrey (1969) and further developed by Arnott et al. (1993).

In equilibrium, all commuters face the same travel cost:

$$\alpha(t^* - \widetilde{t}) = \beta(t^* - t_F) = \gamma(t_L - t^*)$$

Average total travel cost from region i to region j in the no-toll equilibrium as

$$p_{ij} = c_{ij} + \delta_{ij} \frac{N_{ij}}{s_{ij}},$$

where $\delta_{ij} = \frac{\beta_{ij}\gamma_{ij}}{\beta_{ij}+\gamma_{ij}}$ and c_{ij} is a fixed cost per trip.

Income in the Bottleneck Model

The second term in the travel cost expression is variable, half due to queuing costs (in the aggregate). The other half corresponds to schedule delay costs.

We then represented extended income M_{ij} as:

$$M_{ij} = 8W_{ij} + T_{ij} + 2\omega_{ij}(3 - D_{ij})$$

Tolling Regime

The parameter Γ_{ij}^k changes according to the tolling regime:

$$\begin{aligned} \Gamma_{ij}^e &= \Gamma_{ij}^u = 1 \\ \Gamma_{ij}^c &= \frac{1}{4}\left[3 - \frac{(\gamma_{ij}-\alpha_{ij})\beta_{ij}}{(\beta_{ij}+\gamma_{ij})(\alpha_{ij}+\gamma_{ij})}\right] \\ \Gamma_{ij}^o &= \frac{1}{2} \end{aligned}$$

where the superscript $k = e, u, c, o$ indicates different tolling scenarios:

- the no-toll equilibrium (e),
- a uniform or flat toll (u),
- a coarse toll that only distinguishes between a peak and an off-peak road price (c) and the optimal,
- completely time-depending fine toll (o).

The Fine Toll

A fine toll eliminates all queuing costs by shifting departure times, without affecting the schedule delay costs (arrival times are determined by a constant outflow from the bottleneck at a rate $\frac{N_{ij}}{s_{ij}}$). The fine toll simply replaces the queuing costs. The optimal toll τ_{ij}^{k} (for $k = u, c, o$) can then be expressed as

$$\tau_{ij}^{k} = 2\Gamma_{ij}^{k}\delta_{ij}\frac{N_{ij}}{s_{ij}}.$$

The Optimal Pigouvian Toll

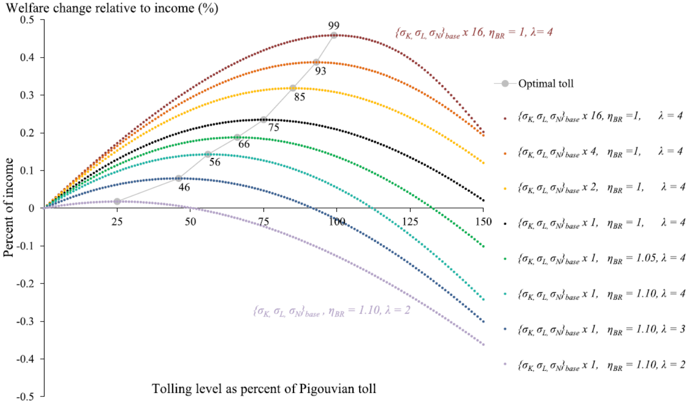


Fig. 4. The value of the optimal toll depends on rigidities in production technology, agglomeration externalities, and the intensity of congestion. Welfare is expressed as the utilitarian sum of equivalent variation over all regions.

Commuting, Wages and Income Impacts

Table 1

The effects (% change) of a Pigouvian congestion toll in second best. Results are shown for three cases: without agglomeration externalities ($\eta_{BR} = 1$ and $\lambda = 4$; upper numbers in small font), with 10% agglomeration externalities in the urban area ($\eta_{BR} = 1.10$ and $\lambda = 4$; middle), and under lower congestion intensity ($\eta_{BR} = 1.10$ and $\lambda = 2$; lower numbers in small font). All scenarios assume a short-run framework with fixed land and capital supply and wage curve unemployment.

Region of residence	Region of work					
	Brussels	Flanders	Wallonia	Brussels	Flanders	Wallonia
	Nr. of skilled workers N_{ij}			**Travel delay D_{ij}**		
Brussels	1.7	−4.9	−5.9		−9.6	−6.7
	1.3	−3.7	−4.5		−7.3	−5.2
	1.7	−4.9	−5.7		−5.1	−3.5
Flanders	−22.1	5.5	1.5	−32.3		1.6
	−22.5	5.7	1.6	−32.7		1.7
	−23.7	5.9	2.5	−21.4		1.3
Wallonia	−22.1	1.4	6.6	−24.4	1.3	
	−22.5	1.6	6.7	−24.7	1.5	
	−23.7	2.6	6.9	−16.1	1.2	
	Wage of skilled workers W_{ij}			**Extended income M_{ij}**		
Brussels	2.2	0.9	1.1	5.5	3.5	3.6
	1.3	0.4	0.6	4.4	2.9	3.0
	1.3	0.7	0.9	4.0	3.0	3.1
Flanders	9.2	−1.7	−0.8	−8.4	1.9	2.3
	8.3	−1.9	−0.9	−8.8	1.6	2.0
	8.8	−1.9	−1.2	−6.0	1.0	1.4
Wallonia	9.2	−0.7	−2.0	−8.4	2.4	1.9
	8.3	−0.9	−2.1	−8.9	2.1	1.6
	8.8	−1.2	−2.2	−6.1	1.4	1.0

Macroeconomic Impacts of Road Tolls

	Region of work			**Region of residence**		
	Brussels	Flanders	Wallonia	Brussels	Flanders	Wallonia
Production Y_j	−8.2	0.6	0.5			
	−9.4	**0.8**	**0.7**	**Utility**		
	−9.8	0.8	0.7	**of skilled worker U_{ij}**		
Land price p_j^L	−15.6	1.0	1.0	2.9	1.0	1.0
	−16.9	**1.4**	**1.3**	**2.4**	**0.9**	**0.9**
	−17.7	1.4	1.3	2.1	0.6	0.5
Capital price p_j^K	−1.5	0.0	−0.1			
	−2.6	**−0.1**	**−0.1**	**Utility**		
	−2.8	−0.1	−0.1	**of unskilled worker U_{ij}^H**		
Unemployment u_j[a]	4.6	−0.1	−0.2	−9.1	0.6	0.6
	4.8	**−0.2**	**−0.3**	**−9.4**	**0.8**	**0.8**
	5.0	−0.2	−0.3	−9.8	0.8	0.8
Wage unskilled v_j	−3.8	0.4	0.3			
	−3.9	**0.6**	**0.4**			
	−4.1	0.6	0.4			

[a] Changes in unemployment rate are expressed as percentage point difference w.r.t. the benchmark.

Welfare Impacts: Low Skilled Workers in Brussels

Share of toll revenue (%) redistributed to low-skilled

Time-invariant flat toll

Brussels	0	10	20	30	40	50
0	-8.5	-7.1	-6.0	-4.9	-4.0	-3.1
10	-8.0	-6.7	-5.5	-4.5	-3.5	-2.7
20	-7.5	-6.2	-5.1	-4.0	-3.1	-2.3
30	-7.0	-5.7	-4.6	-3.6	-2.7	-1.9
40	-6.6	-5.3	-4.2	-3.2	-2.3	-1.5
50	-6.1	-4.8	-3.7	-2.7	-1.9	-1.1
60	-5.6	-4.3	-3.3	-2.3	-1.4	-0.7
70	-5.1	-3.9	-2.8	-1.9	-1.0	-0.3
80	-4.6	-3.4	-2.3	-1.4	-0.6	0.1
90	-4.1	-2.9	-1.9	-1.0	-0.2	0.6
100	-3.6	-2.5	-1.4	-0.5	0.3	1.0

Coarse toll

Brussels	0	10	20	30	40	50
0	-4.4	-3.2	-2.2	-1.2	-0.4	0.3
10	-3.9	-2.8	-1.8	-0.9	-0.1	0.6
20	-3.5	-2.4	-1.4	-0.5	0.3	1.0
30	-3.1	-2.0	-1.0	-0.1	0.6	1.3
40	-2.7	-1.6	-0.6	0.2	1.0	1.7
50	-2.2	-1.1	-0.2	0.6	1.4	2.0
60	-1.8	-0.7	0.2	1.0	1.7	2.4
70	-1.4	-0.3	0.6	1.4	2.1	2.7
80	-0.9	0.1	1.0	1.8	2.4	3.0
90	-0.5	0.5	1.4	2.1	2.8	3.4
100	-0.1	0.9	1.8	2.5	3.2	3.7

Fine toll

Brussels	0	10	20	30	40	50
0	0.1	1.1	1.9	2.6	3.2	3.8
10	0.5	1.4	2.2	2.9	3.5	4.1
20	0.8	1.7	2.5	3.2	3.8	4.3
30	1.2	2.1	2.8	3.5	4.1	4.6
40	1.5	2.4	3.1	3.8	4.4	4.9
50	1.9	2.7	3.5	4.1	4.7	5.2
60	2.2	3.0	3.8	4.4	4.9	5.4
70	2.6	3.4	4.1	4.7	5.2	5.7
80	2.9	3.7	4.4	5.0	5.5	6.0
90	3.3	4.0	4.7	5.3	5.8	6.2
100	3.6	4.4	5.0	5.6	6.1	6.5

Expansion of road capacity to Brussels (%)

Welfare Impacts: Low Skilled Workers in Flanders

Share of toll revenue (%) redistributed to low-skilled (rows) × Expansion of road capacity to Brussels (%) (columns)

Time-invariant flat toll

Flanders	0	10	20	30	40	50
0	0.7	0.5	0.4	0.3	0.3	0.2
10	1.1	0.9	0.8	0.7	0.6	0.5
20	1.5	1.3	1.2	1.1	0.9	0.8
30	1.9	1.7	1.6	1.4	1.3	1.2
40	2.3	2.1	1.9	1.8	1.6	1.5
50	2.7	2.5	2.3	2.1	2.0	1.8
60	3.1	2.9	2.7	2.5	2.3	2.2
70	3.5	3.2	3.0	2.9	2.7	2.5
80	3.9	3.6	3.4	3.2	3.0	2.9
90	4.3	4.0	3.8	3.6	3.4	3.2
100	4.7	4.4	4.2	3.9	3.7	3.5

Coarse toll

Flanders	0	10	20	30	40	50
0	0.3	0.2	0.1	0.0	-0.1	-0.2
10	0.6	0.5	0.4	0.3	0.2	0.1
20	1.0	0.8	0.7	0.6	0.5	0.4
30	1.3	1.2	1.0	0.9	0.8	0.7
40	1.7	1.5	1.4	1.2	1.1	1.0
50	2.1	1.9	1.7	1.5	1.4	1.2
60	2.4	2.2	2.0	1.8	1.7	1.5
70	2.8	2.5	2.3	2.1	2.0	1.8
80	3.1	2.9	2.7	2.5	2.3	2.1
90	3.5	3.2	3.0	2.8	2.6	2.4
100	3.8	3.6	3.3	3.1	2.9	2.7

Fine toll

Flanders	0	10	20	30	40	50
0	-0.2	-0.3	-0.4	-0.4	-0.5	-0.6
10	0.1	0.0	-0.1	-0.2	-0.3	-0.4
20	0.4	0.3	0.2	0.0	-0.1	-0.1
30	0.7	0.5	0.4	0.3	0.2	0.1
40	1.0	0.8	0.7	0.5	0.4	0.3
50	1.3	1.1	0.9	0.8	0.6	0.5
60	1.6	1.4	1.2	1.0	0.9	0.7
70	1.9	1.6	1.4	1.3	1.1	1.0
80	2.1	1.9	1.7	1.5	1.3	1.2
90	2.4	2.2	2.0	1.8	1.6	1.4
100	2.7	2.5	2.2	2.0	1.8	1.6

Expansion of road capacity to Brussels (%)

Welfare Impacts: Low Skilled Workers in Wallonia

Share of toll revenue (%) redistributed to low-skilled

Expansion of road capacity to Brussels (%)

Time-invariant flat toll

Wallonia	0	10	20	30	40	50
0	0.6	0.5	0.4	0.3	0.2	0.2
10	1.1	0.9	0.8	0.7	0.6	0.5
20	1.5	1.3	1.2	1.1	1.0	0.9
30	1.9	1.8	1.6	1.5	1.4	1.2
40	2.3	2.2	2.0	1.9	1.7	1.6
50	2.8	2.6	2.4	2.2	2.1	2.0
60	3.2	3.0	2.8	2.6	2.5	2.3
70	3.6	3.4	3.2	3.0	2.8	2.7
80	4.0	3.8	3.6	3.4	3.2	3.0
90	4.5	4.2	4.0	3.8	3.6	3.4
100	4.9	4.6	4.4	4.2	3.9	3.7

Coarse toll

Wallonia	0	10	20	30	40	50
0	0.3	0.2	0.1	0.0	-0.1	-0.2
10	0.7	0.5	0.4	0.3	0.2	0.1
20	1.0	0.9	0.8	0.6	0.5	0.4
30	1.4	1.2	1.1	1.0	0.8	0.7
40	1.8	1.6	1.4	1.3	1.2	1.0
50	2.2	2.0	1.8	1.6	1.5	1.3
60	2.5	2.3	2.1	2.0	1.8	1.6
70	2.9	2.7	2.5	2.3	2.1	1.9
80	3.3	3.0	2.8	2.6	2.4	2.3
90	3.7	3.4	3.2	2.9	2.7	2.6
100	4.0	3.8	3.5	3.3	3.1	2.9

Fine toll

Wallonia	0	10	20	30	40	50
0	-0.2	-0.3	-0.3	-0.4	-0.5	-0.6
10	0.1	0.0	-0.1	-0.2	-0.3	-0.3
20	0.5	0.3	0.2	0.1	0.0	-0.1
30	0.8	0.6	0.5	0.4	0.2	0.1
40	1.1	0.9	0.7	0.6	0.5	0.4
50	1.4	1.2	1.0	0.9	0.7	0.6
60	1.7	1.5	1.3	1.1	1.0	0.9
70	2.0	1.8	1.6	1.4	1.2	1.1
80	2.3	2.1	1.8	1.7	1.5	1.3
90	2.6	2.3	2.1	1.9	1.7	1.6
100	2.9	2.6	2.4	2.2	2.0	1.8

Welfare Impacts: High Skilled Workers in Brussels

Rows: Share of toll revenue (%) redistributed to low-skilled. Columns: Expansion of road capacity to Brussels (%).

Time-invariant flat toll

Brussels	0	10	20	30	40	50
0	1.7	1.5	1.4	1.3	1.2	1.1
10	1.6	1.4	1.3	1.2	1.1	1.0
20	1.5	1.3	1.2	1.1	1.0	0.9
30	1.4	1.2	1.1	1.0	0.9	0.8
40	1.2	1.1	1.0	0.9	0.8	0.8
50	1.1	1.0	0.9	0.8	0.7	0.7
60	1.0	0.9	0.8	0.7	0.6	0.6
70	0.9	0.8	0.7	0.6	0.5	0.5
80	0.8	0.7	0.6	0.5	0.5	0.4
90	0.7	0.6	0.5	0.4	0.4	0.3
100	0.6	0.5	0.4	0.3	0.3	0.2

Coarse toll

Brussels	0	10	20	30	40	50
0	1.3	1.1	1.0	0.9	0.8	0.7
10	1.2	1.0	0.9	0.8	0.7	0.7
20	1.1	0.9	0.8	0.8	0.7	0.6
30	1.0	0.9	0.8	0.7	0.6	0.5
40	0.9	0.8	0.7	0.6	0.5	0.4
50	0.8	0.7	0.6	0.5	0.4	0.4
60	0.7	0.6	0.5	0.4	0.3	0.3
70	0.6	0.5	0.4	0.3	0.3	0.2
80	0.5	0.4	0.3	0.2	0.2	0.1
90	0.4	0.3	0.2	0.1	0.1	0.0
100	0.3	0.2	0.1	0.1	0.0	0.0

Fine toll

Brussels	0	10	20	30	40	50
0	0.8	0.7	0.6	0.5	0.4	0.3
10	0.7	0.6	0.5	0.4	0.3	0.3
20	0.6	0.5	0.4	0.3	0.3	0.2
30	0.5	0.4	0.3	0.3	0.2	0.1
40	0.4	0.4	0.3	0.2	0.1	0.1
50	0.4	0.3	0.2	0.1	0.1	0.0
60	0.3	0.2	0.1	0.1	0.0	-0.1
70	0.2	0.1	0.1	0.0	-0.1	-0.1
80	0.1	0.0	0.0	-0.1	-0.1	-0.2
90	0.0	0.0	-0.1	-0.1	-0.2	-0.2
100	0.0	-0.1	-0.2	-0.2	-0.3	-0.3

Expansion of road capacity to Brussels (%)

Welfare Impacts: High Skilled Workers in Flanders

Share of toll revenue (%) redistributed to low-skilled

Time-invariant flat toll

Flanders	0	10	20	30	40	50
0	0.3	0.4	0.5	0.6	0.7	0.7
10	0.2	0.3	0.4	0.5	0.5	0.6
20	0.0	0.2	0.3	0.4	0.4	0.5
30	-0.1	0.0	0.1	0.2	0.3	0.4
40	-0.2	-0.1	0.0	0.1	0.2	0.3
50	-0.3	-0.2	-0.1	0.0	0.1	0.2
60	-0.5	-0.3	-0.2	-0.1	0.0	0.1
70	-0.6	-0.5	-0.3	-0.2	-0.1	0.0
80	-0.7	-0.6	-0.5	-0.3	-0.2	-0.1
90	-0.9	-0.7	-0.6	-0.5	-0.4	-0.3
100	-1.0	-0.8	-0.7	-0.6	-0.5	-0.4

Coarse toll

Flanders	0	10	20	30	40	50
0	0.6	0.7	0.8	0.9	0.9	1.0
10	0.5	0.6	0.7	0.8	0.9	0.9
20	0.4	0.5	0.6	0.7	0.8	0.8
30	0.3	0.4	0.5	0.6	0.7	0.7
40	0.2	0.3	0.4	0.5	0.6	0.6
50	0.1	0.2	0.3	0.4	0.5	0.5
60	-0.1	0.1	0.2	0.3	0.4	0.5
70	-0.2	0.0	0.1	0.2	0.3	0.4
80	-0.3	-0.2	0.0	0.1	0.2	0.3
90	-0.4	-0.3	-0.1	0.0	0.1	0.2
100	-0.5	-0.4	-0.2	-0.1	0.0	0.1

Fine toll

Flanders	0	10	20	30	40	50
0	1.0	1.1	1.1	1.2	1.3	1.3
10	0.9	1.0	1.1	1.1	1.2	1.2
20	0.8	0.9	1.0	1.1	1.1	1.2
30	0.7	0.8	0.9	1.0	1.0	1.1
40	0.6	0.7	0.8	0.9	1.0	1.0
50	0.5	0.6	0.7	0.8	0.9	1.0
60	0.4	0.6	0.6	0.7	0.8	0.9
70	0.3	0.5	0.6	0.7	0.7	0.8
80	0.3	0.4	0.5	0.6	0.7	0.7
90	0.2	0.3	0.4	0.5	0.6	0.7
100	0.1	0.2	0.3	0.4	0.5	0.6

Expansion of road capacity to Brussels (%)

Welfare Impacts: High Skilled Workers in Wallonia

Share of toll revenue (%) redistributed to low-skilled

Expansion of road capacity to Brussels (%)

Time-invariant flat toll

Wallonia	0	10	20	30	40	50
0	0.3	0.4	0.5	0.6	0.7	0.7
10	0.1	0.3	0.4	0.5	0.6	0.6
20	0.0	0.1	0.2	0.3	0.4	0.5
30	-0.1	0.0	0.1	0.2	0.3	0.4
40	-0.3	-0.1	0.0	0.1	0.2	0.3
50	-0.4	-0.3	-0.1	0.0	0.1	0.2
60	-0.5	-0.4	-0.3	-0.1	0.0	0.1
70	-0.7	-0.5	-0.4	-0.3	-0.2	0.0
80	-0.8	-0.7	-0.5	-0.4	-0.3	-0.2
90	-0.9	-0.8	-0.6	-0.5	-0.4	-0.3
100	-1.1	-0.9	-0.8	-0.6	-0.5	-0.4

Coarse toll

Wallonia	0	10	20	30	40	50
0	0.6	0.7	0.8	0.9	1.0	1.1
10	0.5	0.6	0.7	0.8	0.9	1.0
20	0.4	0.5	0.6	0.7	0.8	0.9
30	0.3	0.4	0.5	0.6	0.7	0.8
40	0.2	0.3	0.4	0.5	0.6	0.7
50	0.0	0.2	0.3	0.4	0.5	0.6
60	-0.1	0.1	0.2	0.3	0.4	0.5
70	-0.2	-0.1	0.1	0.2	0.3	0.4
80	-0.3	-0.2	0.0	0.1	0.2	0.3
90	-0.4	-0.3	-0.1	0.0	0.1	0.2
100	-0.6	-0.4	-0.3	-0.1	0.0	0.1

Fine toll

Wallonia	0	10	20	30	40	50
0	1.0	1.1	1.2	1.3	1.3	1.4
10	0.9	1.0	1.1	1.2	1.3	1.3
20	0.8	0.9	1.0	1.1	1.2	1.2
30	0.7	0.9	0.9	1.0	1.1	1.2
40	0.7	0.8	0.9	0.9	1.0	1.1
50	0.6	0.7	0.8	0.9	0.9	1.0
60	0.5	0.6	0.7	0.8	0.9	0.9
70	0.4	0.5	0.6	0.7	0.8	0.9
80	0.3	0.4	0.5	0.6	0.7	0.8
90	0.2	0.3	0.4	0.5	0.6	0.7
100	0.1	0.2	0.3	0.5	0.6	0.6

Conclusions

- We demonstrate the feasibility of analyzing the general equilibrium (non-marginal) effects of congestion pricing and infrastructure investment in an economic model combining endogenous congestion, agglomeration externalities and unemployment.
- Numerical experiments calibrated to a three region model of Belgium highlight the distributional impacts of transport policy.
- Surprisingly, commuters can gain from the introduction of a congestion toll, as it improves the efficiency of the allocation of workers across regions.
- With per-capita allocation of toll revenue, salaried workers living in Brussels gain because they do not pay the congestion tax and their wage rises.
- Under a range of road pricing simulations, production in Brussels falls resulting in losses for land and capital owners. A congestion tax widens the urban-rural wage gap.
- In most cases, with road pricing neighboring regions Flanders and Wallonia see a relatively small increase in output and a decrease in unemployment rate.

Conclusions (cont.)

- With agglomeration externalities, the introduction of congestion taxes appears to be less beneficial for all salaried workers and more detrimental for all capital owners.
- When we consider two instruments for transport policy, congestion taxes and infrastructure investments, we find that a substantial increase in transport network capacity is needed to reduce travel times by as much as would be achieved by the congestion toll.
- Unlike congestion taxes, investments in transport infrastructure reduce unemployment in Brussels. The optimal mix of instruments will depends on the objectives of policymakers.

Two Other Applications

- Foxconn in Wisconsin
- Eucalyptus in Ethiopia

Background[1]

In July 2017, Wisconsin Governor Scott Walker and President Donald Trump announced the third-largest economic development incentive package in U.S. history: $3 billion of incentives for Foxconn to build a $10 billion, 1,000-acre factory complex that promised to employ 13,000 workers (3,000 direct jobs). At the time of the announcement many economists criticized the proposal questioning the the structure and financial wisdom of the plan which offered a package which essentially paid more than 100% of workers' wages for several years. While initial details on the Foxconn deal were opaque, subsequent disclosures have been even less encouraging – fewer jobs and a payback period for taxpayers that now stretches into centuries rather than decades.

Officials of the Taiwanese Company have acknowledged that many of these jobs would be outside of Racine, the factory location, and indeed outside Wisconsin. Moreover, the state's own fiscal analysis admits these are "multiplier jobs," not direct employees of Foxconn. These are some supplier jobs, but also the doctors, construction and retail jobs potentially created by 3,000 Foxconn workers.

Over the past 18 months the incentive package has ballooned well past $3 billion. Good Jobs First, an organization that keeps close accounting of tax incentives and other subsidies, reports that the total for Foxconn has grown more than 50% to $4.8 billion from Wisconsin while Foxconn's promised investment dropped from $10 billion to $9 billion. The Wisconsin Budget Project, a budget think tank, estimates the cost per job range from $220,000 to $587,000. These are for jobs that will pay an average of a little more than $53,000 per year. Subsidies of this magnitude indicate that Wisconsin taxpayers are paying between a third and all the wage bill for Foxconn for more than the next decade.

In the present assignment we will use a calibrated general equilibrium model to evaluate the regional distribution of benefits from additional jobs in Racine, Wisconsin. The model as implemented (see *model.gms*) is based on several data sources and assumptions:

1. Population figures for towns and cities in southeastern Wisconsin and northeastern Illinois[2]
2. Travel times between municipalities based on Google maps.[3]
3. Agglomeration spillovers relating worker productivity to municipal density[4].
4. Labor demand as iso-elastic function of the productivity-adjusted market wage with unitary compensated demand elasticity.
5. The central worker valuation of leisure is 50% of average wage earnings.
6. Heterogeneous marginal value of leisure, varying between 20% to 180% of the central valuation of leisure. In the absence of commuting, the value share of leisure then ranges from 10% to 90% of wage earnings.
7. An elasticity of substitution between leisure and consumption (σ) equal to 0.5.

The Model

The labor market at location i requires that aggregate labor supply equals aggregate labor demand:

$$\sum_{hj} X_{hji} = D_i(w_i) + \Gamma_i$$

Labor demand includes *endogenous* (price-responsive) demand (D_i) and *exogenous* demand Γ_i. The later enters only in the counterfactual simulation and corresponds to the employment of workers at the Foxconn plant in Racine.

Workers are utility maximizing, with preferences for consumption of goods and leisure. All workers are employed for eight hours per day. A higher paying job may require commuting a longer distance. The decision of how far to drive for work reflects a trade-off between consumption (higher income) and leisure (more free time in mornings and evenings).

Their utility function representing preferences of type h household is:

$$U_h(c,\ell) = \left((1-\theta_h)\left(\frac{c}{\bar{c}}\right)^{\rho} + \theta_h\left(\frac{\ell}{\bar{\ell}}\right)^{\rho}\right)^{1/\rho}$$

in which

c stands for consumption of goods

ℓ stands for consumption of leisure

θ_h is the value share of leisure at the reference point, i.e.

$$\theta_h = \frac{\bar{\mu}_h \bar{\ell}}{\bar{\mu}_h \bar{\ell} + \bar{c}}$$

where $\bar{\mu}_h$ is the marginal value of leisure for household type h at the reference point.

The utility maximization problem for a type h household located at node i then has two budget constraints, one for money and the other for time:[5]

$$\max_{c,\ell} U_{hi}(c,\ell)$$

subject to:

$$c = \sum_j w_j x_{hij}$$

$$\ell = \bar{\ell} - \sum_j \tau_{ij} x_{hij} \qquad \text{(Leisure)}$$

$$\sum_j x_{hij} = 1 \qquad \text{(Labor)}$$

$$x_{hij} \geq 0$$

Letting μ_{hi} represent the shadow price on the (Leisure) constraint and ω_{hi} be the shadow price on the (Labor) constraint, the arbitrage condition for a worker of type h living at i and working at j is:

$$\omega_{hi} + \mu_{hi}\tau_{ij} \geq w_j \quad \perp \quad X_{hij} \geq 0$$

with $\perp$ indicating complementary slackness: if X_{hij} is positive, then the wage rate in j exactly compensates for the value of labor supply in i and the shadow value of the time required to commute from i to j. Worker heterogeneity with respect to the value of leisure suggests that μ_{hi} differ with h, however all workers are perfect substitutes in production, so workers commuting to j all earn w_j.

The value of labor supply by household h in region i is associated with a market clearance condition:

$$\bar{E}_{hi} \geq \sum_j X_{hij} \quad \perp \quad \omega_{hi} \geq 0$$

and labor markets clear through adjustment of city-specific wages with iso-elastic labor demand:

$$D_i = \bar{D}_i \left(w_i/\phi_i\right)^{-\epsilon_i} \tag{Demand}$$

Productivity term ϕ_i is assumed to take the form:

$$\phi_i = \left(\frac{\delta_i}{\bar{\delta}}\right)^{\gamma}$$

in which δ_i is the density of location i and $\bar{\delta} = 1000$.

We calibate labor demand at location i assuming that $\bar{D}_i$ equals the population at location i, and ϵ_i equals unity $\forall i$. Extended household income depends on the value of labor income and the imputed value of leisure endowment:

$$M_{hi} = \omega_{hi} \bar{L}_{hi} + \mu_{hi} \bar{\ell}_{hi}$$

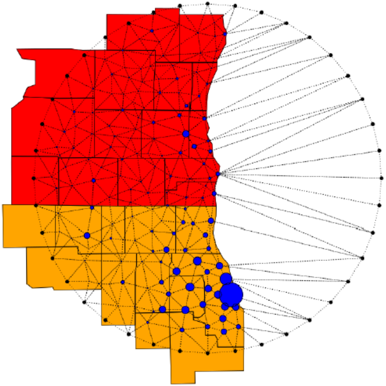
Leisure demand depends on income and relative prices:

$$\ell_{hi} = \bar{\ell}_h \frac{M_{hi}}{\bar{M}_{hi} c_{hi}} \left(\frac{\pi_{hi}}{\mu_{hi}} \right)^{\sigma}$$

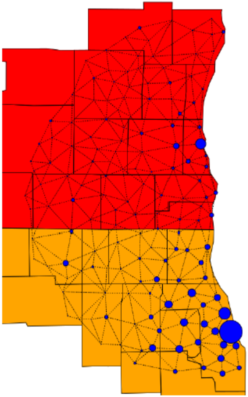
in which π_{hi}, the cost of living index, is a CES composite of the price of goods (=1) and the price of leisure (μ_{hi}):

$$\pi_{hi} = \left(\theta_h \mu_{hi}^{1-\sigma} + 1 - \theta_h \right)^{1/(1-\sigma)}$$

```
nonnegative
variables       U(h,i)          Utility index (money metric),
                D(i)            Labor demand,
                W(i)            Wage rate,
                PI(h,i)         Price index for utility,
                OMEGA(h,i)      Shadow value of labor supply,
                MU(h,j)         Shadow value of leisure
                X(h,i,j)        Commuting;

equations       demand, supply, market, commute, pricelevel, leisure, budget;

demand(i)..             D(i) =e= d0(i) * (W(i)/phi(i))**(-epsilon(i)) + gamma(i);

supply(h,i)..           x0(h,i) =e= sum(j,X(h,i,j));

market(i)..             sum((h,j),X(h,j,i)) =e= D(i);

commute(h,i,j)..        OMEGA(h,i) + tau(i,j)*MU(h,i) =g= W(j);

pricelevel(h,i)..       PI(h,i) =e= (theta(h,i)*(MU(h,i)/mu0(h))**(1-sigma(h)) + 1 - theta(h,i))**(1/(1-sigma(h)));

leisure(h,i)..          ell0(h,i) =e= U(h,i) * ell0(h,i) * (PI(h,i)/(MU(h,i)/*mu0(h)))**sigma(h) + sum(j,tau(i,j)*X(h,i,j));

budget(h,i)..           PI(h,i)*U(h,i) =e= MU(h,i)*ell0(h,i) + OMEGA(i)*x0(h,i);

model labor /demand.D, supply.OMEGA, market.W, commute.X, pricelevel.PI, leisure.MU, budget.U/;
```

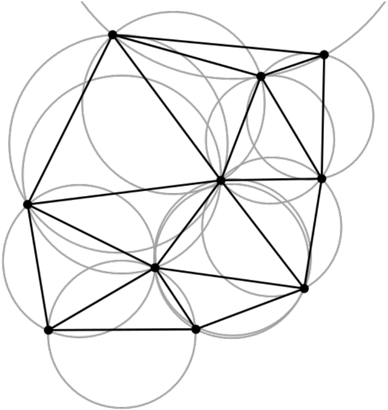


(a) Delaunay Triangulation with Boundary Nodes



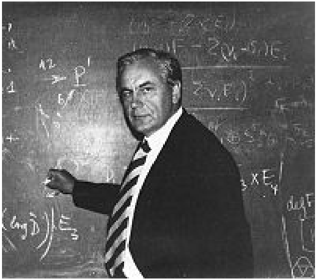
(b) Resulting Network

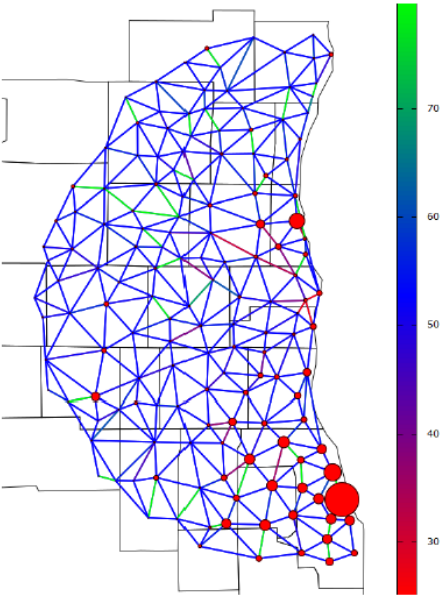
A Delaunay triangulation for a given set P of discrete points in a plane is a triangulation DT(P) such that no point in P is inside the circumcircle of any triangle in DT(P):



Delaunay Triangulation (cont.)

Delaunay triangulations maximize the minimum angle of all the angles of the triangles in the triangulation; they tend to avoid sliver triangles.
The triangulation is named after Boris Delaunay for his work on this topic from 1934.





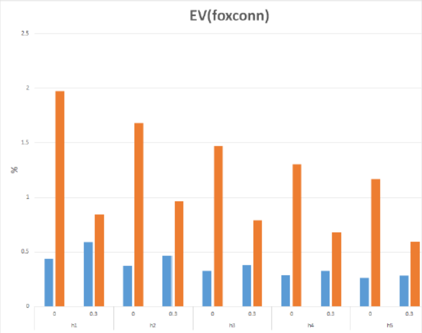
(c) Calibrated Travel Speeds (miles per hour)

Here is a linear programming formulation for calculating the shortest path through the nextwork:

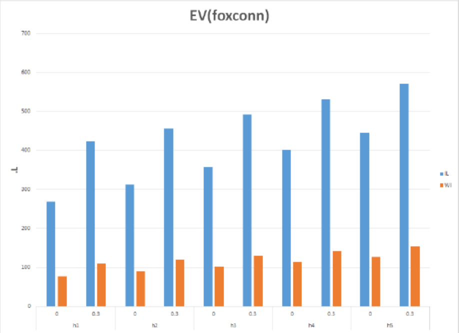
```
variable        OBJ        Dual objective;

equations        objdef, optimal;

objdef..                OBJ =e= sum((i,destination(k)), T(i,k));

optimal(a(i,j),destination(k))..        TAU(i,j) + T(j,k) =g= T(i,k);

model routechoice /objdef, optimal/;
```

We can evalauate travel times using Google's average speed, and then we set up a bilevel program to find arc speeds which come closest to matching the Google Map travel times:

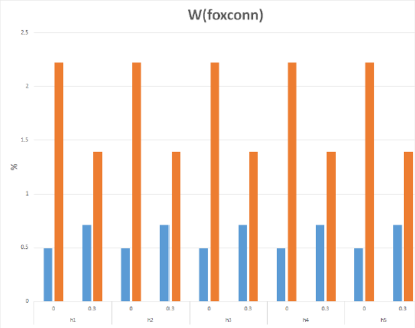
```
parameter        target(i,j)        Target of Google estimate of travel duration;

variable        OBJBL        Bilevel calibration problem (outer objective);

equation        objbilevel;

objbilevel..        OBJBL =e= sum(dcalc(i,j), sqr(T(i,j) - target(i,j)));

model bilevel /objbilevel, objdef, optimal/;

$onecho >"%emp.info%"
bilevel TAU
max OBJ T objdef optimal
$offecho

*        Choose speeds between 20 and 80 mph:

TAU.LO(a) = dist(a) / 80;
TAU.UP(a) = dist(a) / 20;

solve bilevel using EMP minimizing OBJBL;
```



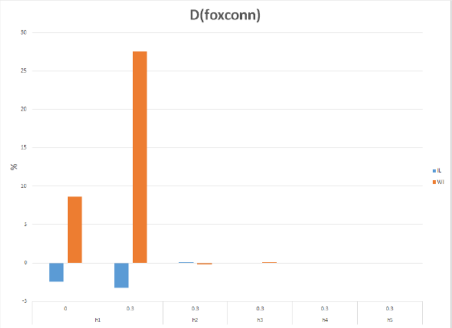
(a) Percentage Wisconsin Gains are Greater



(b) Value of Illinois Gains are Greater



(c) Wages Increase More in Wisconsin



(d) Job Gains in Wisconsin Offset by Losses in Illinois

Eucalyptus in East Afraica

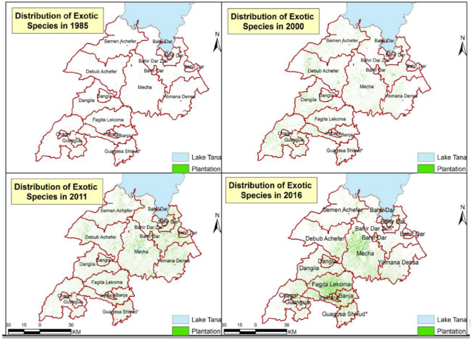
Ethiopia is the biggest and fastest growing Eucalyptus planter in East Africa (Dessie and Gessesse 2009)

Table 1 Current population, land and forests of East Africa

Countries	General Description					
	Population (1)	Land (ha) (1)	Forest (ha) (2)	Natural forest (ha) (2)	Plantation forest (ha) (2)	*Eucalyptus* forest (ha) (3)
Ethiopia	83099000	122148000	4593000	4377000	216000	506000
Somalia	8699000	63754000	na	na	na	na
Djibouti	833000	231800	6000	na	na	na
Sudan	38560000	250000000	61627000	60986000	641000	23000
Kenya	37538000	58265000	17096000	16864000	232000	60000
Uganda	30884000	24103800	4190000	4147000	43000	11000
Rwanda	9725000	2633800	307000	46000	261000	102765
Burundi	8508000	2783000	152000	67000	86000	40000
Total	217846000	523919400	95102000	86487000	1479000	742765

Source: (1) WPP (2007), (2) WRI (2000), (3) Amare (2002); FAO (1979); Oballa et al. (2005); CDF (2007)

- According to a study on 10 woredas in Amhara region (BoA, Barhir Dar 2017), the share of exotic species coverage rises from 0:4% in 1985 to 10% in 2016.
- The dominant land cover in the study area is cropland, which accounts for more than 50% from the total area.



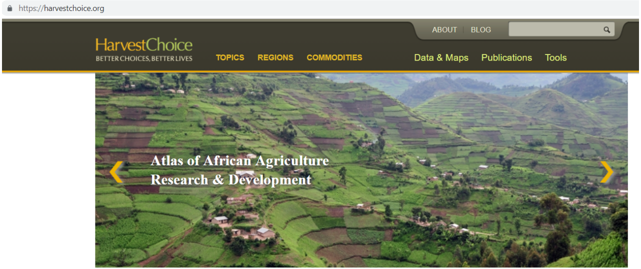
Problems with Eucalyptus Expansion

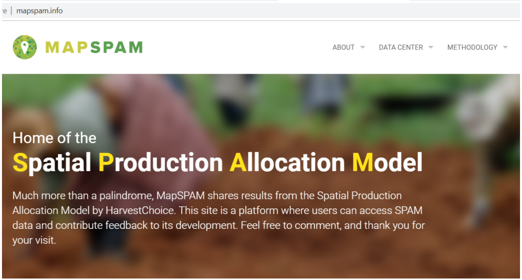
- Failure to protect watershed and provide soil conservation, wildlife habitat and recreational or aesthetic values
- Removal of too much water from streams and underground water, adverse effects of their leaf litter on soil humus, heavy consumption of soil nutrients, inhibition of growth of other plants
- Exhausting the once productive farmland because of its fast growth (Alemie 2009), and the eradication is difficult (Diez 2005)

Drivers of Eucalyptus Expansion

- Road infrastructure
- Increasing demand for fuel wood and construction material from home and abroad (FAO 2009)
- For small land holders, eucalyptus suits their limited resources and yields more money than other tree crops (FAO 2009)
- Land tenure

Demographic and Geographic Data





SPAM Dataset for 2010

HarvestChoice BETTER CHOICES, BETTER LIVES IFPRI HarvestChoice Dataverse (International Food Policy Research Institute (IFPRI)) HarvestChoice

Harvard Dataverse > International Food Policy Research Institute (IFPRI) Dataverse > IFPRI HarvestChoice Dataverse >
Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 1.0

Metrics | 1,729 Downloads   Contact Share

Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 1.0 Version 2.3

International Food Policy Research Institute, 2019, "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 1.0", https://doi.org/10.7910/DVN/PRFF8V, Harvard Dataverse, V2

Cite Dataset

Learn about Data Citation Standards.

SPAM Commodity Coverage

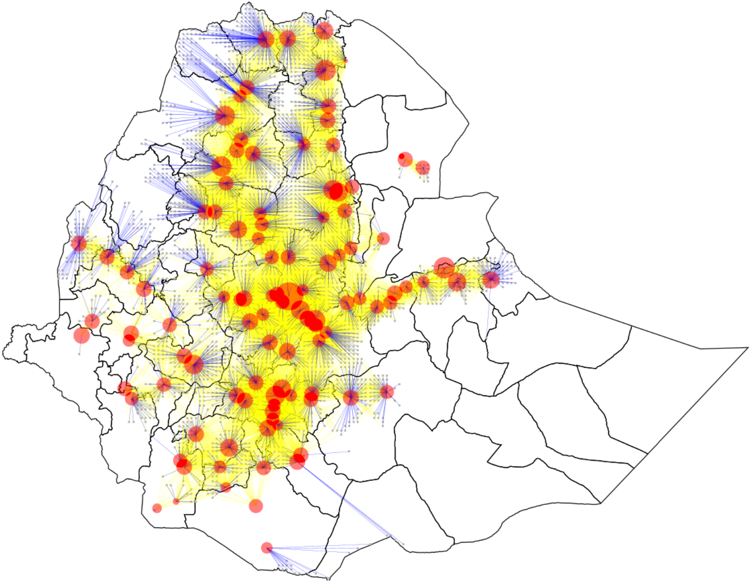
whea	Wheat	chic	Chickpea	sugb	Sugarbeet
rice	Rice	cowp	Cowpea	cott	Cotton
maiz	Maize	pige	Pigeonpea	ofib	Oth_Fibre
barl	Barley	lent	Lentil	acof	Ara_Coffee
pmil	Pearlmill	opul	Oth_Pulse	rcof	Rob_Coffee
smil	Smallmill	soyb	Soybean	coco	Cocoa
sorg	Sorghum	grou	Groundnut	teas	Tea
ocer	Oth_Cereal	cnut	Coconut	toba	Tobacco
pota	Potato	oilp	Oilpalm	bana	Banana
swpo	Sweet_Pot	sunf	Sunflower	plnt	Plantain
yams	Yams	rape	Rapeseed	trof	Trop_Fruit
cass	Cassava	sesa	Sesameseed	temf	Temp_Fruit
orts	Oth_Root	ooil	Oth_Oil	vege	Vegetable
bean	Bean	sugc	Sugarcane	rest	Rest_Crop

SPAM Technology and Value Data

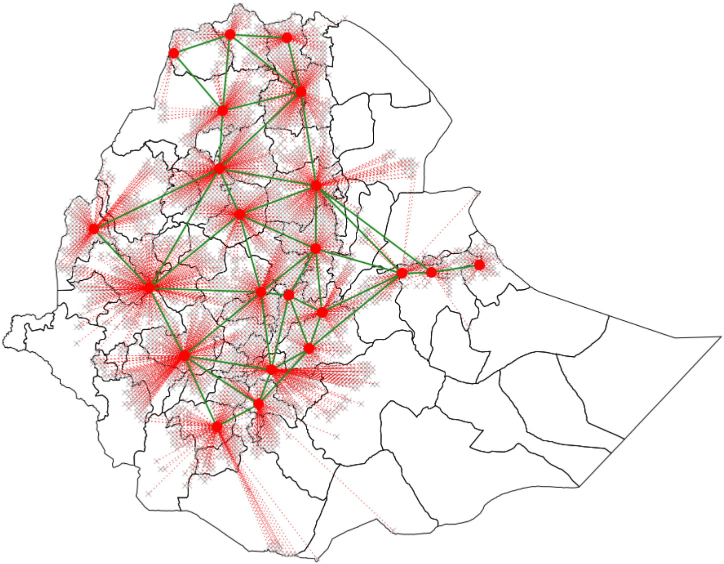
```
set     v       Variable in the dataset /
        A       Physical area
        H       Harvested area
        P       Production
        Y       Yield,
        V       Value of production
 /;

set     t       Technology /
        A       Total
        H       Rainfed high inputs
        L       Rainfed low inputs
        I       Irrigated
        S       Subsistence
        R       Rainfed (= A-I = H+L+S)
 /;

set     id              Spam pixel ID,
        fips2           Production level (FIPs code) ,
        cell5m          Cell 5m ID,
        cntr            Country,
        adm1            Administrative level 1,
        adm2            Administrative level 2,
        iso3            Country /%iso3%/;

set     adm(id,iso3,fips2,cell5m,cntr,adm1,adm2) Administrative assignments;

parameter       data(id,v,t,g)  "Dataset for region %iso3%";
```

```
set     vp      Value of production /
vp_crop         "Value of production of all 42 crops",
vp_food         "Value of production of food crops",
vp_nonf         "Value of production of non-food crops",
ha_crop         "Harvested area of all crops",
ha_food         "Harvested area of food crops",
ha_nonf         "Harvested area of non-food crops",
vpha_crop       "VoP per ha of all crops",
vpha_food       "VoP per ha of food crops",
vpha_nonf       "VoP per ha of non-food crops"/;
```

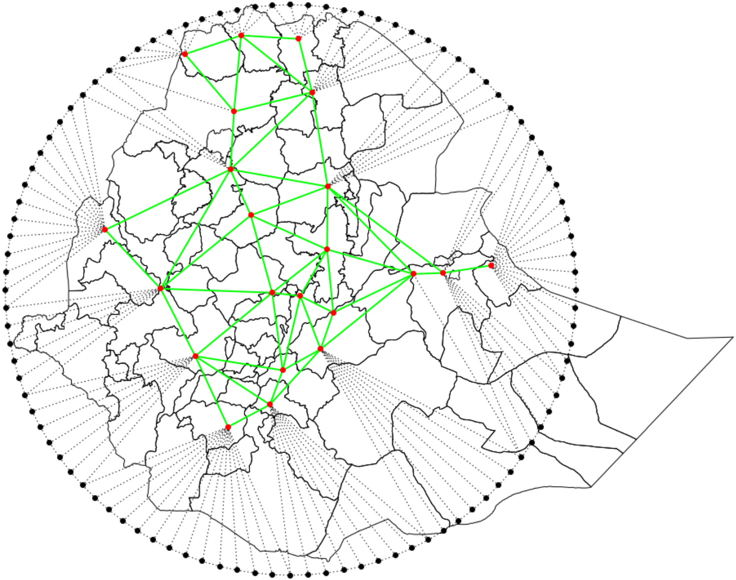
Ethiopian Cities and Harvest Choice Cells



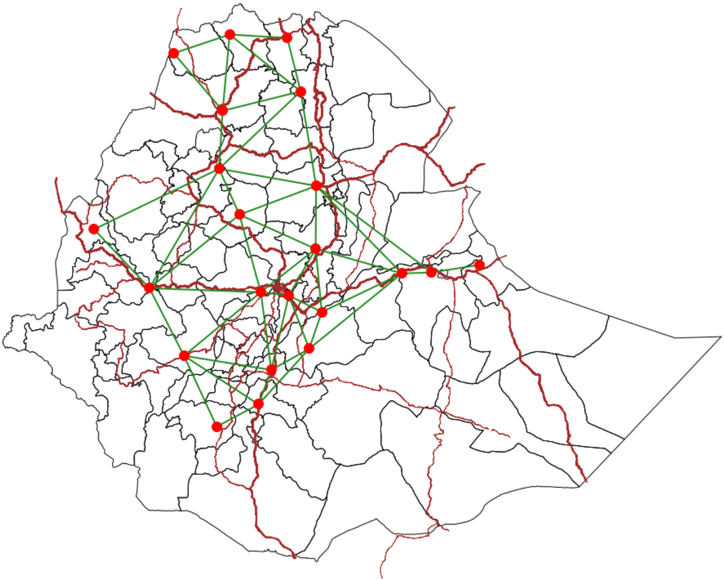
Harvest Choice Marketsheds



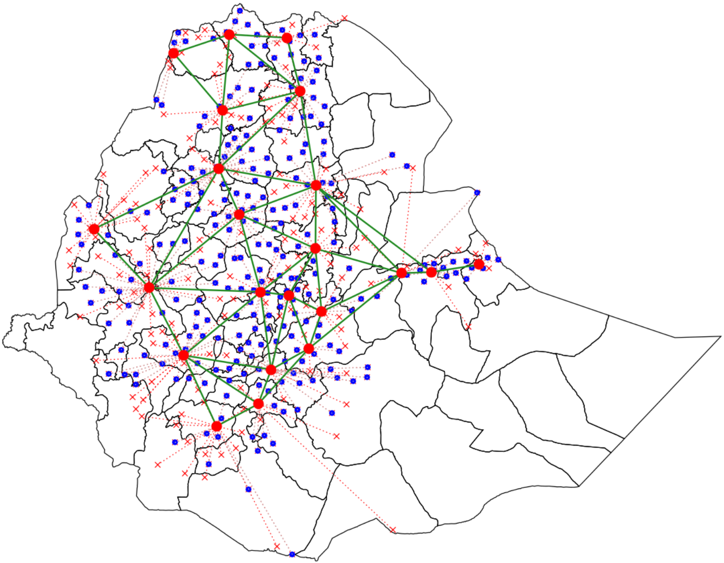
Construction of the Transportation Network



Comparison with Open Street Map Road Network



Clustered Rural Nodes



Simulations

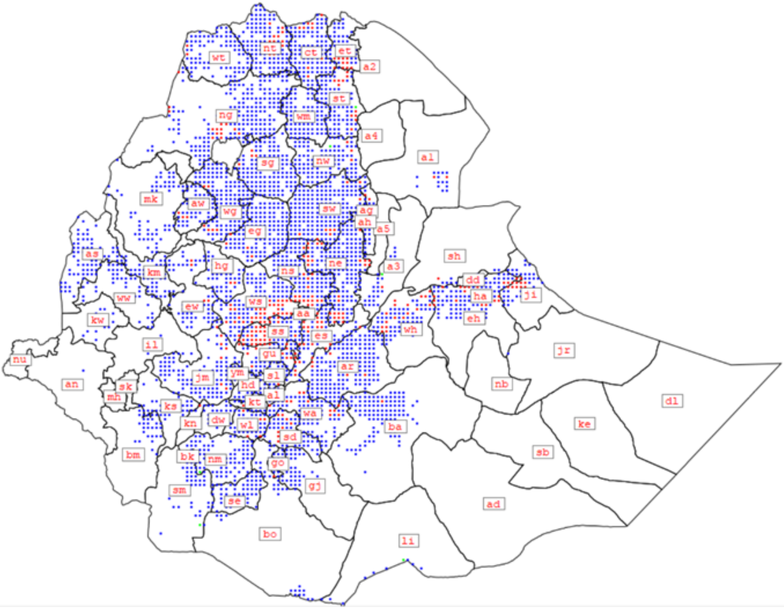
`bmk` Benchmark equilibrium, assuming neither eucalyptus cultivation nor land reform.

`exempt` Labor productivity shock in manufacturing with eucalyptus plantation providing an "exemption" for labor market migration.

`reform` Labor productivity shock with land reform – legalized land transfer, rural labor market and share cropping.

`ban` As in `reform` with a ban on cultivation of eucalyptus.

Exemption



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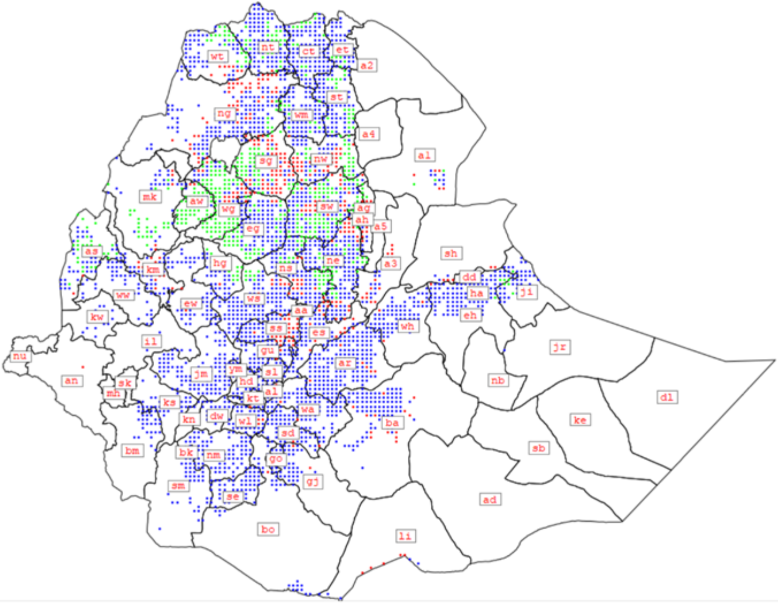
Land Reform



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Land Reform with Eucalyptus Ban