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Estimating the Short-Run Effect on Market-Access of the Construction of Better Transportation Infrastructure in Mexico*

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Abstract: We calculate the short-run effect that the construction of the 230km-long Durango-Mazatlán highway in 2013 and of the 290km-long Mexico City-Tuxpan highway in 2014 produced on market-access in every location in Mexico. Our estimates suggest that the former highway produced benefits not only in the region where the new highway is located, but in vast regions in the north of the country. Analogous estimates show that the latter highway mostly benefited regions near Tuxpan, but these focalized benefits were larger than any of the benefits derived from the construction of the Durango-Mazatlán highway.

Keywords: infrastructure, market access, transport costs

JEL Classification: R4, F1, H5

Resumen: Calculamos el efecto de corto plazo que la construcción de la autopista Durango-Mazatlán de 230km en 2013 y de la autopista México-Tuxpan de 290km en 2014 produjeron en el acceso al mercado en todas las localidades de México. Nuestras estimaciones sugieren que la primera autopista produjo beneficios no sólo en la región donde la nueva autopista está ubicada, sino en vastas regiones en el norte del país. Estimaciones análogas muestran que la segunda carretera benefició principalmente las regiones cercanas a Tuxpan, pero estos beneficios focalizados fueron mayores que cualquiera de los beneficios derivados de la construcción de la autopista Durango-Mazatlán.

Palabras Clave: Infraestructura, acceso al mercado, costos de transporte

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1 Introduction

Between the years of 1992 and 2011, Mexico invested an average of 1.1% of its GDP on infrastructure of communications and transport every year. Over the last 5 years, this average decreased to 1.07%. On April 29, 2014, the Mexican Federal Government published the “National Infrastructure Program 2014-2018” (NIP hereafter), which, based on the “National Development Plan 2013-2018”, detailed the infrastructure projects that were going to be built in Mexico the following years in order to achieve “equilibrated regional development, urban development, and logistic connectivity” (DOF (2014)). The NIP projected that investment on this sector would increase substantially with respect to the last 23 years.

The NIP does not have large projects on the north of Mexico, and the longest, most ambitious projects are on the south of the country. The center of Mexico, which is richer and more populated than the south has relatively shorter projects. It also has better previous connectivity, as seen in [figure 1](#) and [figure 3](#). The mountain formations makes them sophisticated engineering projects on their own. It would make it look that the NIP is looking to hard-wire the connectivity of the country in order to give it better access to trading with the center of the country by land, even if this is not mentioned explicitly in the NIP.

In this paper we study how do previous efforts of this de-facto hard-wiring affects demand internally in the short run, without calculating any impact on foreign demand or the impact that foreign demand has on shifting demand internally either in the short or in the long run. In particular, we study the effect of two recently inaugurated 4-lane highways in Mexico: the Durango-Mazatlán and the Mexico City-Tuxpan highways, pictured along with the other 4-lane highways of the country in [figure 1](#). In this paper, we focus on these two large infrastructure projects that were recently finished to shed some light on what could be the impact of the rest of the projects on regional economies. These two highways are in many ways similar to the infrastructure projects of NPI: they both connect important regions of the country that were previously connected with 2-lane highways (or worse roads), and shorten the route between origin and destination by building large bridges and tunnels over natural barriers, which mean that previously disconnected areas (for geographical reasons) that are

not necessarily close to the origin or the destination and the original highway, now have an opportunity to transport goods on the updated highway network. The first one, the Durango-Mazatlán highway (230km), inaugurated in 2013, is not part of NIP. The second one, the Mexico City-Tuxpan highway (290km), was almost finished by the time of the announcement of NIP, so only the conclusion of the middle part of this highway is part of NIP. These two highways, combined, would imply an addition of 5.9% to the length of all 4 or more lane highways in Mexico built up to 2010 (see [figure 1](#)).¹ We focus on the short run change in potential market access to national products that is produced by the highways.

Between 1995 and 2005, around 9% of total World Bank lending went to upgrading of roads and highways.² This has shifted the regional economics literature to study the impact of transportation infrastructure both in a theoretic and in a quantitative way. Depending on the topic of interest, the effect in productivity, transportation costs, or trade costs is studied, and not only for this time period.³ In this paper, we calibrate a small change in transportation infrastructure that reduces travel time between producers and consumers and calculate the short-run impact in market access in every region in Mexico.⁴ The results of this paper rely on two key assumptions: first, assuming route optimality forces the triangle inequality to hold for every route, we have that small changes in the transportation network can imply huge changes in routing, which in turn imply larger gains from trade, as extensively discussed in [Pérez-Cervantes \(2014\)](#). Second, we assume that the toll rate of the new highways is relatively low such that the net effect of the reduction in travel time because of the toll roads is a reduction in transport costs.⁵ The second assumption implies that only studying the cost

¹Calculations made by the authors assuming [INEGI \(2010\)](#) contains all the 4 lane (or more) highways in Mexico up to 2010, and using GIS software to calculate the length of those highways.

²Calculated by the authors using data from [Asturias, García-Santana, and Ramos \(2014\)](#).

³See [Donaldson \(2008\)](#), [Gonzalez-Navarro and Quintana-Domeque \(2012\)](#), [Kondo \(2013\)](#), [Allen and Arkolakis \(2014\)](#), [Gertler, Gonzalez-Navarro, Gracner, and Rothenberg \(2014\)](#), [Chanda and Panda \(2014\)](#), and [Pérez-Cervantes \(2014\)](#) for recent examples.

⁴There are many other short-run impacts that have been studied recently. See for example [Asturias, García-Santana, and Ramos \(2014\)](#) for estimates of regional changes in competitiveness derived from the construction of the 5,846km long “Golden Quadrangle” highway in India.

⁵The toll of the Durango-Mazatlán highway to this day is around \$300 for a regular car, and up to \$2,000 for a 60-ton truck, and for the Mexico City-Tuxpan highway it is around \$300 for a regular car and \$1750 for a 60-ton truck. All money figures in the paper are in Mexican Pesos.

of time overestimates the real benefits of the highway as the cost of the new tolls is only captured indirectly from the utilization of the new highways in longer routes whose total cost, including toll, is known.⁶

This paper, however, does not do quantitative analysis. It only calculates changes in market access making use of the triangle inequality. To the best of our knowledge, it is the first paper that does this exercise in a large number of regions (for any country) and the first one in Mexico for any number of regions. As noted and documented by [Cuéllar-Nevarés and Pérez-Cervantes \(2015\)](#), geodesic distance between two localities does not correlate with transportation costs for geodesic distances less than 500km, so to the extent that this paper develops tools to further understand the interaction between distance, size, and connectivity is an important step towards understanding these effects. It is too soon to have enough data at the local level and quantitatively calculate any observed effects of any of the two recently opened highways on demands for products, but recently [Banco de México \(2014\)](#) conducted a set of interviews related to the Durango-Mazatlán highway, finding that the entrepreneurs who said that they benefited extensively from the highway were from vast regions of the north of the country and not just from regions near the highway. This contrasts with the results of [Ghani, Goswami, and Kerr \(2014\)](#), who find that only the regions near the recently built “Golden Quadrilateral” in India benefited from the construction of this 5,846km long highway. Our estimates of increments in market access due to the construction of the Durango-Mazatlán highway confirm the answers collected from the interviews, and suggest that even huge infrastructure projects can partially lack the proper assessments of their impact without a good measure of transport cost and the use of the triangle inequality.

In this paper, we model improvements in transportation infrastructure as transport cost changes, because the observed speed of infrastructure similar to the one being built can be compared to the observed old one. This new speed and the location of the construction can be used to

⁶Since the toll is only a fraction of the total transport cost, this overestimate is low and less than proportional to the share of the utilization of the new highways on the total length of all the routes. All the other tolls are incorporated in our transport cost measurements. The new Durango-Mazatlán and Mexico City-Tuxpan highways add 5.7% and 4.5% respectively to the total length of all the tollways in Mexico, and 3.3% and 2.6% respectively to all the 4-lane (or more) highways in Mexico (up to 2010), therefore they represent only a small share of the total transport costs.

calculate the new fastest routes, and the new transportation costs can be used to obtain the new short-run demands for products of different origins, which in turn define the demand for goods on every location. That is, using the instantaneous speed that is implied from the infrastructure characteristics, it is possible to back out the entire trade cost structure of the economic system, provided a good measure of the cost of transportation is given, and that the predicted fastest route is actually the one being used for transportation of goods.⁷

We find our paper joining important work studying infrastructure in Mexico. **Looney and Frederiksen (1981)** were probably the first ones to explicitly test if the Mexican region where infrastructure was being built made economic sense in the **Hansen (1965)** approach, which evaluates if a justification for building infrastructure in only a small region of a country that triggers unbalanced growth exists. They find that for the case of Mexico the social overhead capital (the one that enhances human capital, such as education, public health facilities, etc) has great impact on lagging (incomewise) regions, while economic overhead capital (the type of capital that supports productive activities, such as roads, electricity, water supply, etc.) only benefits advanced regions. **Deichmann, Fay, Koo, and Lall (2004)** find that the south of Mexico is quite different from the rest of the country. The size of the firms, the quality of the human capital, and several other measures of productivity such as skill upgrading opportunities for workers all seem endogenous to the lack of transport infrastructure and access to markets derived from this situation. **Dávila, Kessel, and Levy (2002)** find that the infrastructure in the south of Mexico is very poor relative to the rest of the country, and that important changes must be done in order for the south to become more competitive.⁸ In particular, they mention that being better connected to the center of the country is the first step to follow for any major and generalized improvement in economic conditions to happen there. **Banco de México (2011)** conducted a set of interviews and found that the entrepreneurs in the southern region of the county believe that better transport infrastructure would be a main

⁷As mentioned previously in this introduction, the results of this paper do not account for the toll of the new highways. However, the econometric estimation of the trade costs includes the tolls of all the previously constructed highways, and isolates the marginal cost of an additional hour of transportation, which is the key parameter in the analysis.

⁸In terms of income per capita, they are also poor relative to the rest of the country. The economic cycle is also lagged in the south with respect to the rest of the country.

factor to improve productivity. One year later, **Banco de México (2012)** did a quantitative exercise and found that an important factor explaining lower relative total factor productivity in the south of Mexico is deficient infrastructure in that region. Following these diagnoses it would look that in order to achieve equilibrated regional development, the south would be an area to improve first.

Between the years of 2013 and 2014, the Mexican federal government finalized the two previously mentioned investments in road infrastructure, none of them in the south. We focus on the construction of these two highways because they were aimed to improve the connectivity of two of the most important commercial corridors of Mexico, and because there is no municipal level data to calibrate the effect other large infrastructure projects from the past. The 230 km-long Durango-Mazatlán highway constitutes an investment of \$28 billion and was opened in 2013. This is a toll highway formed by 4 lanes, 61 tunnels, 115 bridges (where one of them is the tallest cable-stayed bridge in the world) and constitutes a better alternative of transportation, since it reduces the fastest travel time between important locations of Durango and Mazatlán from 6 to 3 hours. The main objective of the construction of this highway was to improve the connectivity between the commercial and industrial zone of the north of Mexico and the Pacific coast. According to our own calculations, there was also a significant reduction in the traveling time to the northwestern border cities from vast regions west of the construction of the highway.⁹ Moreover, this highway represents the second-to-last part of the trade corridor that goes from the Gulf coast to the Pacific coast, and the last part of a corridor that goes from the Pacific coast to Texas (see **figure 1**). Only a few months later, the Mexican Government finished the last section of the 290 km-long highway of the corridor that connects Mexico City with the Gulf of Mexico reducing considerably the travel times relative to the former route. This highway, known as the Mexico City-Tuxpan highway, is aimed to boost economic activity in the east of Mexico, while connecting the center of Mexico with other important corridors between the United States and Mexico. After the construction of this highway, Tuxpan became the closest sea port to Mexico City (although Tuxpan is not one of the major ports of Mexico, for now, as mentioned and illustrated in

⁹See **figure 9** for details.

Figure 1: The Durango-Mazatlán and the Mexico City-Tuxpan highways and the other 4-lane (or more) highways of Mexico

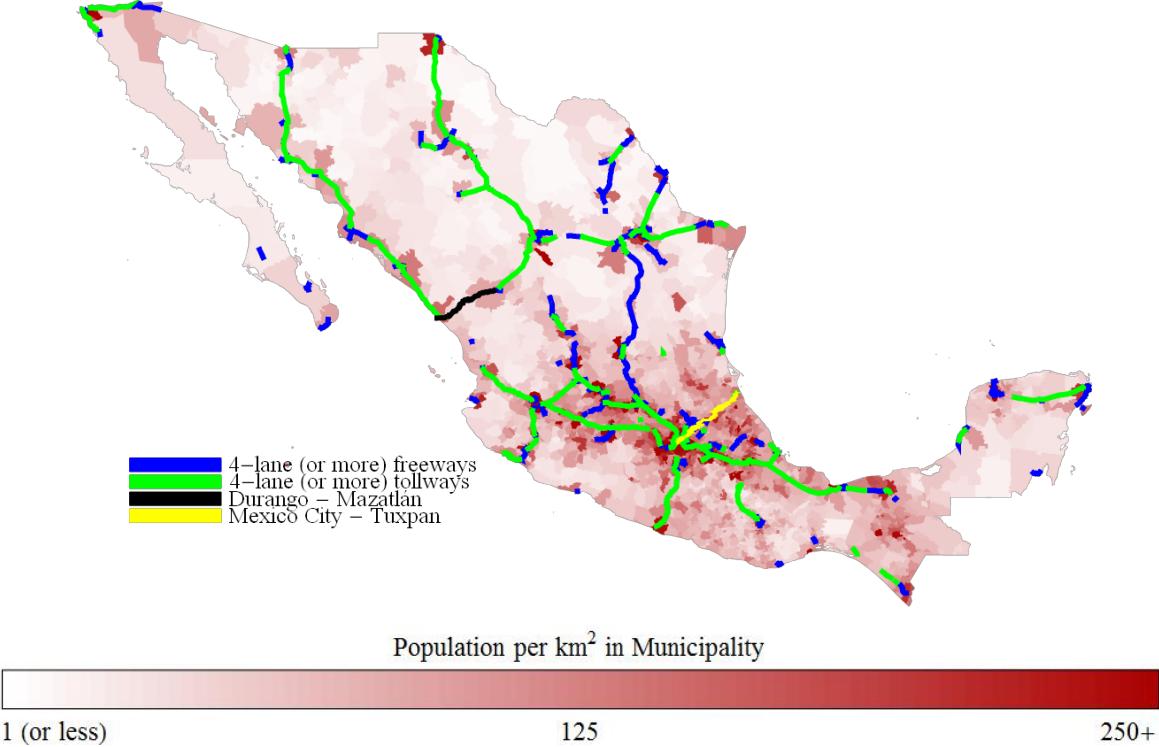


figure 10).

We calculate the market access to national products of every location in Mexico using municipal level GDP data and transportation infrastructure data in GIS format from 2010, and then calculate the new, short-run level of this measure incorporating the new highways to estimate the change in market access of every location in Mexico.¹⁰ We find and discuss that the impacts of both highways are very different. On the one hand, the Durango-Mazatlán highway produces gains in vast regions in the north of Mexico. On the other hand, we find that the Mexico City-Tuxpan highway mostly benefited regions near Tuxpan, but the areas with the largest benefits have larger benefits than any area benefited from the Durango-Mazatlán highway.

The paper is organized as follows. Section 2 explains the methodology to obtain the travel

¹⁰For a brief discussion on why the difference between market access to national products and the counterfactual market access to national products gives the change market access, see section 5.

times between every two locations of the country. [Section 3](#) details how the transportation costs were calibrated and estimated. Market access for every location in Mexico is calculated in [section 4](#). [Section 5](#) describes the baseline scenario and the identification strategy to obtain changes in market access. Finally, [section 6](#) analyzes the results and concludes. A brief introduction to the numerical optimization processes discussed throughout the paper can be found in [appendix A](#).

2 Calibrating Travel Times

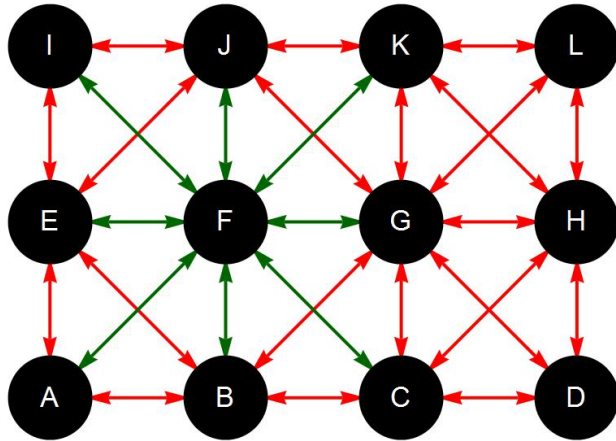
The objective of this section is to explain how to obtain travel times for every pair of locations in Mexico. Travel time web services such as Google Maps only allow for 2,500 pairs of travel times per day. Since we needed to calculate several billions of pairs, this section describes the tools we developed to obtain travel times too. The first thing that was needed was to reduce the size of the mathematical problem while maintaining precision of travel times. We discretized the continuous space represented by the territory of Mexico and its transportation network, so it could be defined as a grid (composed by vertices, edges and weights) whereby one can apply an algorithm of minimum paths in order to approximate the fastest route between two points. The computational burden of dealing with a grid compared to a continuous surface is more than two orders of magnitude smaller.¹¹

The continental territory of Mexico was approximated with 1,977,537 vertices, representing 1km^2 each.¹² The location of the 1,977,537 vertices correspond to the 1,977,537 vertices of our grid. To define the edges, we restrict the movements between each one of the cells, using the notion of neighborhood. That is, we will assume that any vertex of the grid will only have edges to connect with neighbors. For that instance we will assume a neighborhood scheme known as *king movements* in which the permitted displacements between each one

¹¹The order of magnitude reduction equals the power of 1/10 that gives the size of the reduction. The problem was reduced, per our calculations, 245 times in complexity and size.

¹²The area of Mexico is $1,972,550\text{km}^2$. The difference of 0.25% comes from rounding up areas of maps that include some sea, as well as the routes of the ferries.

Figure 2: King Movements



Note: King movements, just as in chess, allow going from vertex F to vertices A, B, C, E, G, I, J, and K using only one edge at a time, in any direction. The 8 edges for the king movements allowed from vertex F and the 8 edges allowed to vertex F are pictured in solid green. In order to go from F to vertices D, H, or L, then more than one movement is needed, that is, at least one red edge in combination with the green edges is needed.

of the vertices are in a pattern of an asterisk (up, down, right, left and diagonals). Any vertex can be reached from any other vertex using the edges, but if the vertices are not neighbors, they will require more than one edge (see figure 2).

Then, the grid is intersected with data obtained from INEGI (2010). We obtained georeferenced data of highways, pathways, maritime routes, and urban localities from INEGI (2010) and turn them into vertices and edges in the grid. We identify the kind of road that represents each one of the edges of the grid (for example, if it is a 4-lane federal toll highway, a 1-lane unpaved road, etc.). For this, we intersect our grid with the transportation data, so it is grouped according to the 21 categories in table 1, which were calibrated using optimal route data from the Secretaría de Comunicaciones y Transportes’s “Punto a Punto” web application for several hundreds of origin-destination pairs.¹³ We used a default speed of 2km/hr wherever there were no roads reported by INEGI (2010), to avoid any conflicts such as INEGI missing some road data, and to have potential market access to be spread all over the grid, and not only in the regions with positive population. We call this mean of transporta-

¹³Maritime routes are not included in INEGI (2010), so we used the four most important ferries: Mazatlán-La Paz, Topolobampo-La Paz, and Santa Rosalia-Guaymas in the Pacific Ocean, and Cancun-Cozumel in the Atlantic Ocean and used an average of the travel times of their websites, as well as the actual routes.

Table 1: Speed by Category of Infrastructure

Category	Lanes	Speed (km/hr)	Category	Lanes	Speed (km/hr)
Federal Toll Highways	5+	90	State Free Highways	6	90
	4	85		4	85
	3	70		3	60
	2	50		1-2	40
	1	40	State Toll Highways	5+	90
Federal Free Highways	6+	90		4	85
	4	85	2	40	
	3	70	Urban Roads	N/A	40
	1-2	50	Maritime Routes	N/A	35
Rural Pathways	N/A	3	Unpaved Roads	2	8
Rest of the territory	N/A	2		1	5

Note: The only aspect that was calibrated in these categories was the speed as a function of infrastructure. Other variables such as highway capacity, or truck capacity as a function of the road were not specifically included in this analysis throughout the paper. However, this effect is captured in the estimation of the transportation cost function, as discussed in [section 3](#).

tion “Rest of the territory”. All the speeds of every means of transportation are pictured in [figure 3](#), where it is possible to observe how the surface of the country was transformed into a grid with links and the speed corresponding to each link. The existence of the “Rest of the territory” roads guarantee that every vertex of the grid can be reached from any other vertex in a finite time.

Now that we have all the vertices and all the speeds of every edge, and that we know that any vertex is reachable from any other vertex, we calculate the distance between two vertices that share an edge. This was a very simple task,¹⁴ since every vertex that shares an edge is either 1 km away or $\sqrt{2}$ km away from the neighbor. In order to capture slope changes, and then properly identify the Mexican topography, the distance between vertices is calculated as the hypotenuse of a right triangle formed by the horizontal geodistance and the difference in altitudes.¹⁵ Thus, the distance in kilometers between vertex i and vertex j is given by:

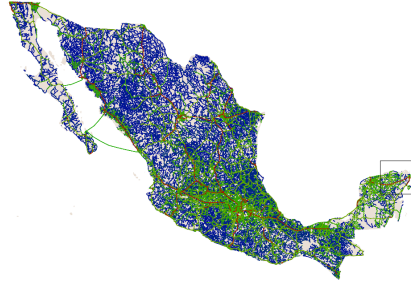
$$distance_{i,j} = \sqrt{(Geodistance(i,j))^2 + (altitude_i - altitude_j)^2} \quad (1)$$

¹⁴A very simple task that had to be performed 7,875,594 times.

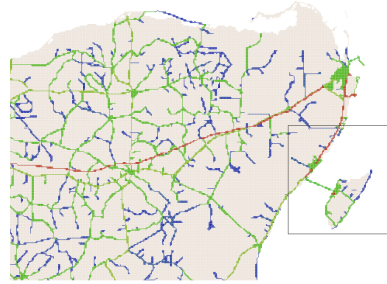
¹⁵The changes in altitude are an important factor not only to calculate instantaneous speed, but also to determine the location of transportation infrastructure.

Figure 3: Speed of edges

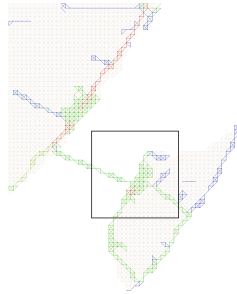
(a) All the grid. Looks almost like the surface of Mexico



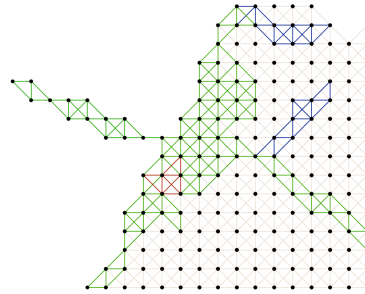
(b) First zoom to the grid



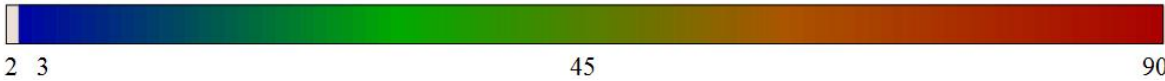
(c) Second zoom to the grid



(d) Third zoom to the grid



Kilometers per hour



Note: In [figure 2](#) it was possible to visualize 12 vertices of a grid. Here it is possible to visualize the 1,977,537 vertices and then look at them closer and closer every time. The scale is 1 horizontal or vertical edge per kilometer. The vertices are colored as black dots in [figure 3d](#), and the edges are colored by their speed in every figure. Note the large proportion of “Rest of the territory” links that appear as the image is zoomed in.

where the geodistance is either 1 or $\sqrt{2}$. Finally, once we know the kind of road that represent each one of the edges and the distance between vertices, we build the weights in such a way that they represent the time (hours) spent in moving from one vertex to another, based on the formula below:

$$Time_{i,j} = \frac{distance_{i,j}}{speed_{i,j}} \quad (2)$$

Given the above, now we have characterized the Mexican territory and its transportation network as a grid composed by 1,977,537 vertices, 7,875,594 edges, and a weight for each edge, which is given by the travel time between each one of the vertices. We have all the

elements to solve the “Shortest Path Problem”, so we apply Dijkstra’s Algorithm and obtain the minimum travel time for any pair of vertices of the network.¹⁶ All the calculations that use Dijkstra’s algorithm in this paper were performed using Gabriel Peyre’s Matlab Toolbox.¹⁷ Now define matrix \mathbf{D} as the $1,977,537 \times 1,977,537$ matrix of travel times in which each one of the entries $\delta(i, j)$ represents the total time of travel from the vertex i to the vertex j , through the fastest route found by Dijkstra’s Algorithm. All the elements of matrix \mathbf{D} , except from its diagonal (the time of going from one vertex to itself), have values greater than 0 and less than infinity. Also, the elements of matrix \mathbf{D} satisfy the triangle inequality, that is, $\delta(i, j) \leq \delta(i, k) + \delta(k, j) \forall k$. To illustrate this matrix \mathbf{D} , the travel times from Mexico City to every other location in the country (one row of the $1,977,537$ rows of this matrix) are pictured in [figure 4](#).

3 Estimating the Iceberg Costs

With matrix \mathbf{D} , we know the approximate time of going from vertex i to vertex j through the Mexican transportation network. The next step is to include those calibrations into a transportation costs function and along with data of the prices estimate the parameters of the function. This function $TC(i, j)$ is an iceberg cost, and represents the percentage of goods that have to be delivered from the origin i to the destination j , such that and the end of the travel a unity of the good is delivered. The functional form used in this paper is the one proposed by [Hanson \(2005\)](#), adding the possibility of having fixed costs:

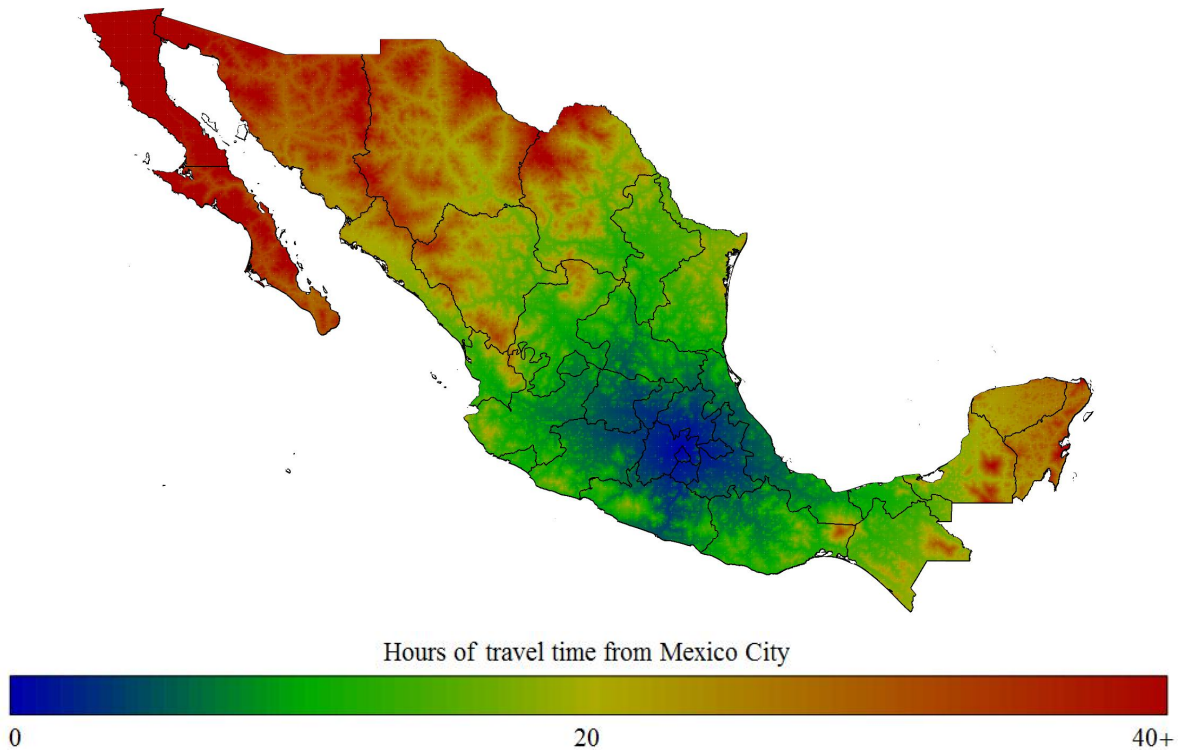
$$TC(i, j) = \begin{cases} e^{F+\lambda\delta(i,j)} & i \neq j \\ 1 & i = j \end{cases} \quad (3)$$

The costs function is formed by 2 parameters: one of them is a fixed cost F incurred only

¹⁶See [appendix A](#) for a brief introduction to the “Shortest Path Problem”, and [subsection 4.1](#) for a brief and simple example of an application of Dijkstra’s algorithm.

¹⁷Available for free to the public in his webpage: <http://www.ceremade.dauphine.fr/~peyre/> and on the Mathworks File Exchange: <http://www.mathworks.com/matlabcentral/fileexchange/5355-toolbox-graph>

Figure 4: Travel time from Mexico City to every other location in Mexico



Note: This diagram depicts the optimal travel times and not the routes, although they can be partially inferred from the travel times. The picture corresponds to one row of the matrix of size $1,977,537 \times 1,977,537$ with the travel times. Notice how the three ferries in Baja California are an important source of connection to the rest of the country.

when goods leave their location of production, and the other parameter is the variable cost λ which represents an extra cost for each hour of travel between i and j (where $\delta(i, j)$ is the time of travel estimated in the previous section). Usually, fixed costs are not assumed in the transportation costs function, however in this methodology we decided to do so, to capture any reduction in percentage price variation that could not be attributed to distance. This fact has its foundation on [Atkin and Donaldson \(2012\)](#), that show the importance of incorporating fixed costs in order to capture other important determinants such as information costs, bureaucracy, etc. Transport costs are normalized such that there is no cost to transport goods between producers and consumers in the same location.

To calibrate the parameters F and λ , we follow the empiric strategy carried out by [Donaldson \(2008\)](#), in which the author uses a result present in most of the spatial models, which suggests

that in the presence of transportation costs, the price of identical goods will differ among distant regions. That is:

$$\ln TC(i, j) = \ln p(i, j) - \ln p(i, i) \quad (4)$$

Where $p(i, j)$ is the price of the good consumed in j and produced in i . Donaldson (2008), does an estimation of the parameters of the transportation costs function in which he identifies, for India, that the salt production has been concentrating historically in eight different regions.¹⁸ Searching for an analogue product for Mexico, the avocado seems to be a very good candidate because, in 2010, 91% of the annual production was concentrated only in three states, being Michoacán the state that contributed the most with a 85.9% of the national production, according to Mexico's Secretaría de Economía (Ministry of Economy) data for 2012. Thus, we use the information generated by the Mexican Ministry of Economy in their project denominated SNIIM (Sistema Nacional de Información e Integración de Mercados), which offers daily information about the behavior of the wholesale prices of an ensemble of agriculture goods. The variety of avocado that is chosen is first class Hass avocado, for which we have daily data from 01/03/2011 to 01/21/2014. This database identifies the state of origin and the market of destination, where the price is being collected. That is, from equation 4, we only observe $\ln p(i, j)$. Table 2 shows the fraction of the total collected prices by state of origin. While the origin of the avocado in the data set may not be exactly the location of its production, the functional form of equation 4 allows to correctly identify the average markup charged for transportation per unit of time between the location where the price was collected and the location that is reported as the origin of the product.

Using Donaldson (2008) identification strategy, the equation we estimate is the following:

$$\ln p_{kodt} = F_{i \neq j} + \lambda \delta(o, d) + \beta + \beta_{ot} + \beta_d + \beta_k + \epsilon_{kodt} \quad (5)$$

¹⁸Other interesting approaches have been used too. Asturias, García-Santana, and Ramos (2014) use monopolies (of many products, in many regions) that sell to the rest of the regions of the same country, and this helps identify transport costs by sector.

Table 2: Observations by State of Origin

States	% of the Total
Michoacan	64.8%
Distrito Federal	12.7%
Puebla	10.8%
Jalisco	7.8%
Nuevo Leon	2.9%
Rest of country	1.0%

where t is the date, o is the city of origin (12 in total), d is the city of destination (42 in total), k is a dummy for each one of the 8 presentations of the avocado (box of 20kg, box of 10kg, etc.), β is the constant of the regression. Finally, we have dummies that control for all combinations of origin and date. The results of the regression are summarized in [table 3](#). The idea behind this estimation, which is the same as in [Donaldson \(2008\)](#), is that $\beta + \beta_{ot} + \beta_d + \beta_k$ identify $\ln p_{koot}$, so we correctly measure the impact of transport time and of the fixed costs. We chose the second column ($F = 0.0557$, $\lambda = 0.0024$), since it includes the effect of the different presentations of the avocado, which might be correlated with the type of transportation used, as well as defines in some sense the initial conditions of the sale at the origin. We discard the ones that include the destination, because we are assuming competitive pricing, so including it biases the results, reducing the impact of the transportation industry (it even makes it negative in the third column) and the average origin price β . We do not think there is any location with such market power that could justify going in this direction. The fact that Distrito Federal and Puebla have a large share of the sales but are not producers could also bias the estimate for pure transportation cost because of measurement error, but treating avocados labeled as being produced in Distrito Federal or Puebla corrects for this problem, because it forces the transport costs to break the triangle inequality both on the dependent and on the independent variables. The estimates imply that product prices, when leaving the place of production, receive a markup of 5.57% on average, and that every 24 hours in transit, products increase its prices an extra 5.76%.

Table 3: Estimation of Transport Cost Function

Variables				
F	-1.9027** (0.0838)	0.0557*** (0.0067)	-0.2965*** (0.0904)	0.0859*** (0.0066)
λ	0.0498** (0.0237)	0.0024*** (1.3e-4)	0.0799*** (0.0256)	0.0018*** (1.3e-4)
β	1.8296** (0.7201)	3.4370*** (0.0128)	1.3695** (0.6704)	3.2188*** (4.3e-7)
R^2	0.833	0.7653	0.8213	.7138
Fixed Effects				
origin-date	Yes	Yes	Yes	Yes
type	Yes	Yes	No	No
destination	Yes	No	Yes	No

Note: Robust standard errors in parentheses

Number of observations: 29,124

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

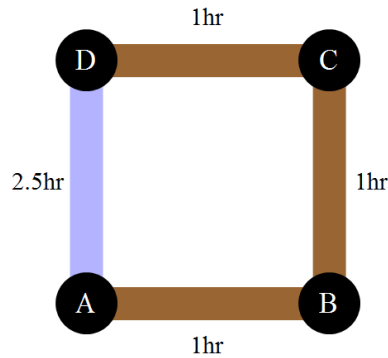
4 Calculating the Market Access

In order to calculate the market access, we use a result that comes from the economic geography literature, such as [Harris \(1954\)](#) and [Hanson \(2005\)](#) that state that the access or market potential of a region or locality, is an average of the income of the regions to which it has access to, weighted by the costs of transportation that it faces in order to sell its goods and services. In particular we take the functional form proposed by [Hanson \(2005\)](#):

$$MA_i = \sum_{j=1}^{2,456} \frac{Y_j}{TC(i, j)^{\sigma-1}} \quad (6)$$

Thus, we calculate the market access for each one of the 1,977,537 cells (represented by subscript i) relative to the 2,456 existent municipalities in 2010 (represented by subscript j). For Y_j we use the 2010 per capita income published by CONEVAL times the total population calculated in the 2010 census realized by INEGI. Meanwhile $TC(i, j)$ is the transportation cost from the the previous section. We assume an elasticity of substitution between goods $\sigma = 9$, a value that is chosen based on what is commonly used in the trade literature such as [Caliendo and Parro \(2009\)](#) [Allen and Arkolakis \(2014\)](#), [Eaton and Kortum \(2002\)](#), [Feenstra \(1994\)](#),

Figure 5: Four regions and four roads



Optimal Travel Times

	A	B	C	D
A	0	1	2	2.5
B	1	0	1	2
C	2	1	0	1
D	2.5	2	1	0

and [Hummels \(1999\)](#), all of whom obtain very similar estimates based on very different trade models and cost assumptions. In fact, [Caliendo and Parro \(2009\)](#) analyze specifically the case of Mexico with Mexican data and get a value very close to $\sigma = 9$.

4.1 A Four Region Example

Now we construct a simple example that not only illustrates the output of Dijkstra’s algorithm, but also what is it exactly that we are measuring and what is it exactly that we are not measuring in this paper. Assume that this economy consists of four regions: A, B, C, and D. These four regions are connected by four roads with the direct travel times as illustrated in the left part of [figure 5](#). Notice there are multiple ways of going to and from any region of the economy. Running Dijkstra’s algorithm over this transportation network yields the 4x4 *optimal* travel times matrix (in hours) on the right of the same figure.

For now, let’s focus on region A. This region’s market access is directly proportional to the GDP of the 4 regions, and inversely proportional to the travel time. For same values of GDP, region A’s market access is affected first by its own GDP (no discount), then by B’s (a discount of 37%), C’s (a discount of 38%), and then D’s (a discount of 39%).¹⁹ Another way to look at the extent of this discount, is that for the same transport costs, in order for every

¹⁹Using the values of F , λ , and θ from the previous section.

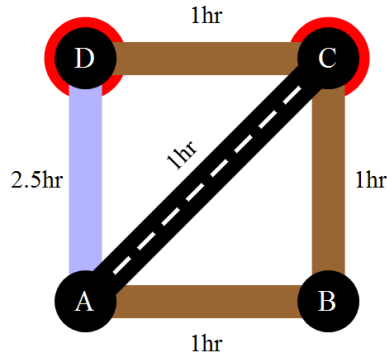
region to be exactly 1/4 of region A's market access, it must be that the GDP of regions B, C, and D to be larger than region A's by 59%, 61%, and 64% respectively.

Now let's add a fifth road to this economy: a fast, direct link from region A to region C, as pictured on the left of [figure 6](#). The new optimal travel times are on the matrix on the right. Note that for region A, the optimal travel time to region C has decreased, but also, because of the triangle inequality, so has the optimal travel time to region D. Assuming that the GDP of none of the regions changes (short run), then, from region A's perspective, the discounting from region C goes from 38% to 37%, and from region D goes from 39% to 38%. The market access of region A went up. And that's it. That is all we measure in this paper. Just as described in this example, this paper will only measure the increment in the market access of region A due to the reduction in the row corresponding to A of the optimal travel times matrix.

It will not study possible long-run outcomes such as the following:

1. Region B is not part of the trade route between A and C anymore. This means region B lost some market power. In the long run equilibrium, one might expect some migration from B to A, C, and even D. In the short-to-medium run, a reduction in the wages of region B is expected.
2. The road that directly connects A and D is abandoned. The road that connects B and C has a drastic reduction in flow because A no longer trades with C using that road. The road that connects C and D has an increase in flow because now A trades with D using that road. This paper will not study congestion, including lane capacity, or possible changes in travel times due to congestion. It will also not study the volume of the flows and compare it to theoretical capacity of every type of road.

Figure 6: Four regions and five roads



Optimal Travel Times

	A	B	C	D
A	0	1	1	2
B	1	0	1	2
C	1	1	0	1
D	2	2	1	0

5 Baseline Scenario

Now that we have the matrix of transportation costs from every location in Mexico to every Municipal Head, it is possible to obtain the values of market access using the municipal population data from INEGI and the municipal per capita income from CONEVAL. The values of population and of GDP per capita at the municipal level are pictured in [figure 7](#). The calculated market access values are in [figure 8](#).

The first thing to notice in [figure 8](#) is that since demand from foreign countries is ignored, border regions seem less connected (or with a reduced value of potential markets) than they really are. Incorporating foreign demands to the measure of market access can provide a more realistic starting point for the actual value of the demand for goods in every region. We claim that neither of the new highways changed substantially the cost of access to foreign markets. That is, if we measure the short-run change in market access, the component of foreign demand will not change much, leaving almost correct measures for changes in market access without loss of generality. In any case, the impact of the highways might end up being underestimated, so this could have been an important caveat had the impact of the new highways was found to be small. But this was not the case. The results, for both highways, were found to be quite large.

Figure 7: Municipal population and municipal GDP per capita, 2010

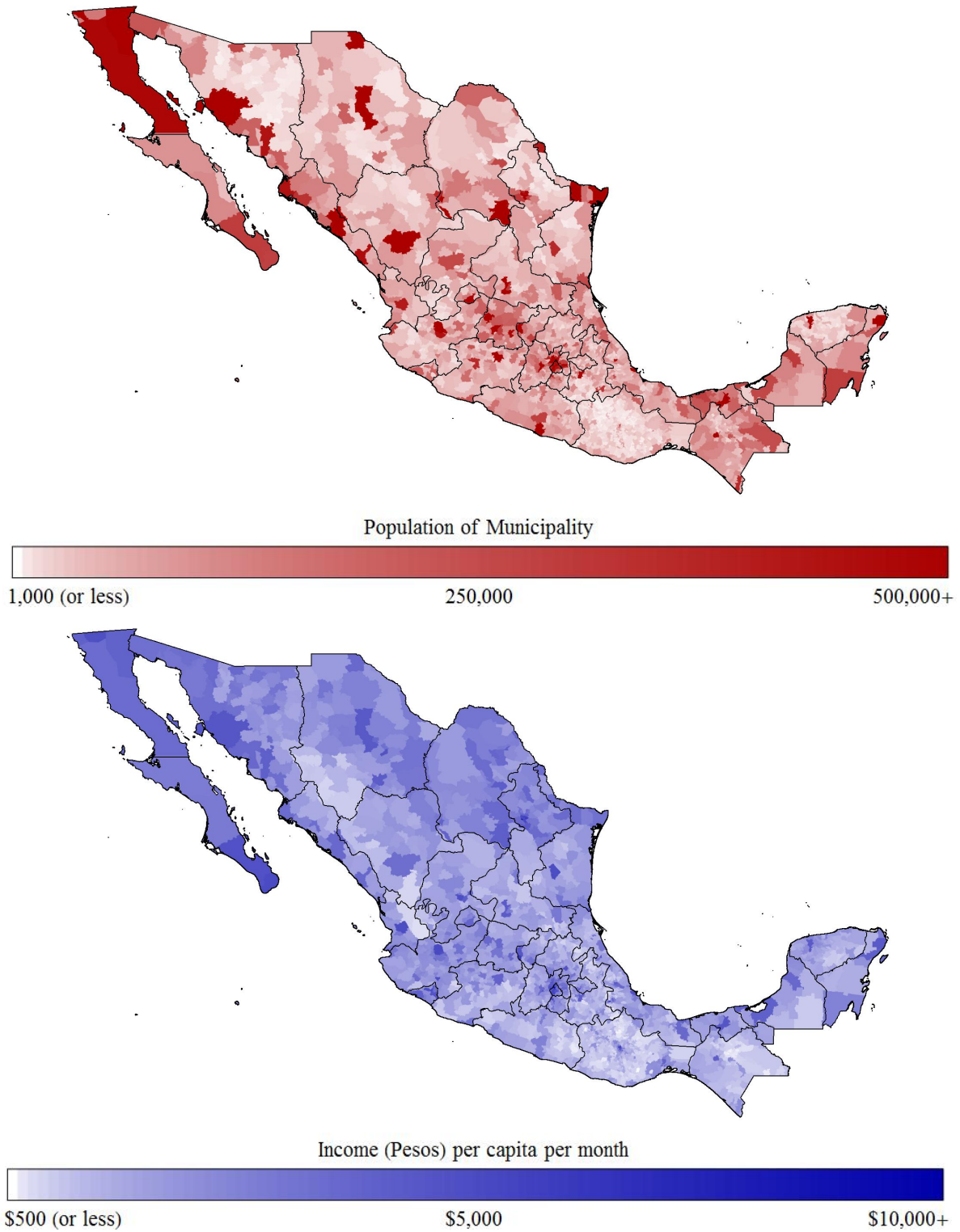
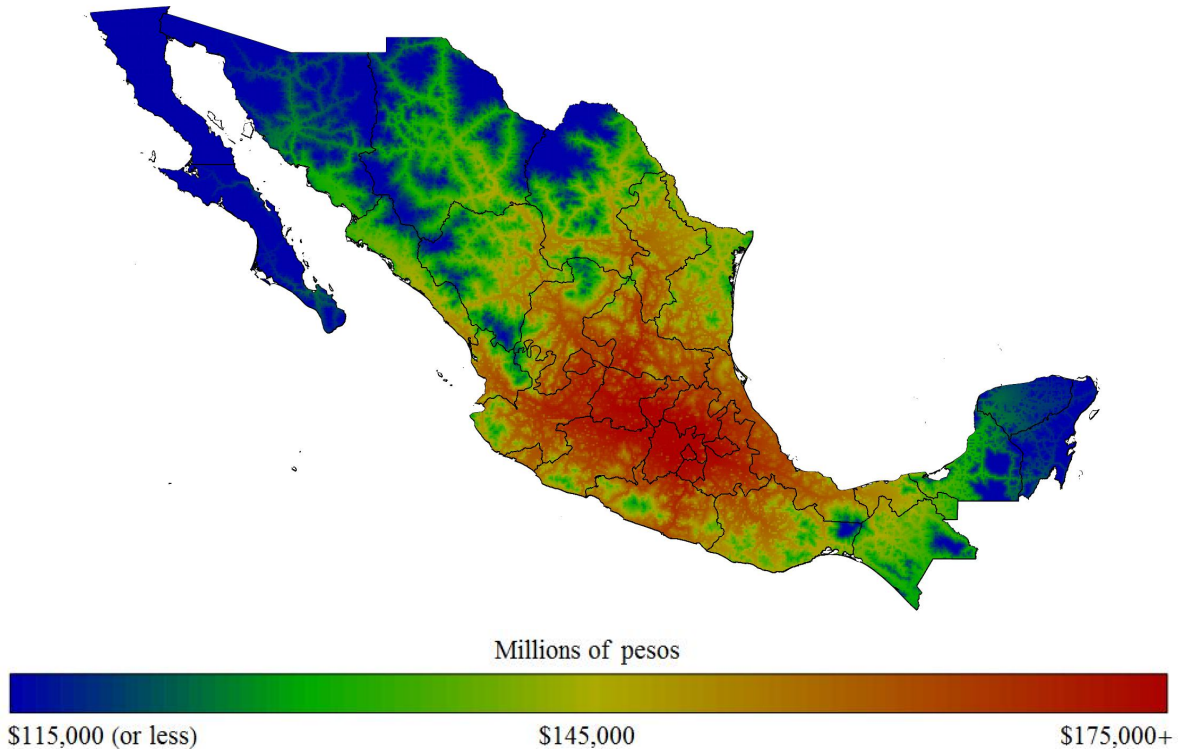


Figure 8: Market access to national products for each of the 1,977,537 locations of the grid



To see why foreign demand can be ignored to calculate the short run impact of these new highways, define TMA_i as the total market access, that is, the sum of the market access MA_i (defined in the previous section) plus the foreign market access, FMA_i which includes demands from foreign markets:

$$TMA_i = MA_i + FMA_i$$

Then, define X' as the new short run value of any variable X after incorporating any of the new highways. The change in market access becomes

$$TMA'_i - TMA_i = (MA'_i - MA_i) + (FMA'_i - FMA_i)$$

which we claim will be have a good measure of $TMA'_i - TMA_i$ using only $MA'_i - MA_i$, as defined in the previous section. To support our claim, notice [figure 9](#) and [figure 10](#), where

there is no major change in travel times to the border,²⁰ no major shift in the port of entry to the United States,²¹ and analogous results for the sea ports.²² This means that it is possible to think of the term $FMA'_i - FMA_i$ to be close to zero for almost every i , and for the locations where this term could be positive (the term cannot be negative, by construction), our measure of change in market access is biased downwards. Therefore, what we find is a lower bound of the benefits from the new infrastructure, and that it is a very low bound for locations that changed travel times to the border and/or the ports.²³

6 Results and conclusion

We add one new highway at a time to the grid, and update the speed of the edges so that they correspond to 85km/hr, the calibrated speed that corresponds to 4-lane highways in Mexico. Then, we recalculate the entire $1,977,537 \times 1,977,537$ matrix of travel times with the new highways, and reuse the values of F and λ from the baseline case to obtain the new transport cost functions. The change in market access derived from the construction of the new highways is pictured in [figure 11](#). It is evident that both highways produce different results.

The Durango-Mazatlán highway increases the market access in an extensive region. The

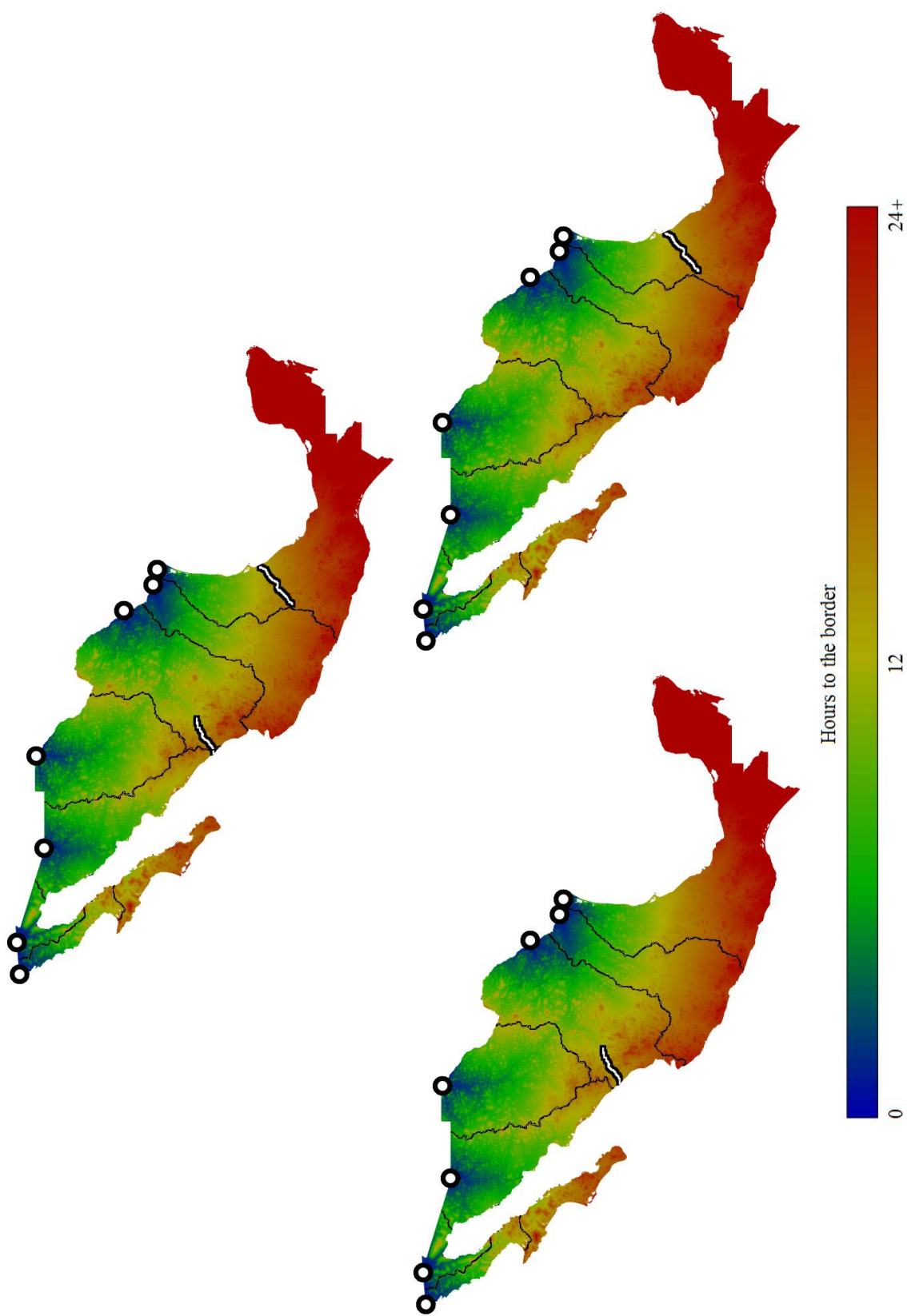
²⁰Major border crossings are ranked by the number of trucks passing through in 2010, and the 7 selected account for the 90.7% of the total. From west to east, the crossings are: Otay Mesa, Calexico, Nogales, Paso del Norte, Laredo, Hidalgo and Brownsville. The corresponding Mexican names are Tijuana, Mexicali, Nogales, Ciudad Juárez, Nuevo Laredo, Reynosa, and Matamoros. See [DoT \(2010\)](#) for details on this calculations.

²¹Notice how Mazatlán's closest border used to be Nogales and with the new highway it is Nuevo Laredo. Tepic and Puerto Vallarta used to have Reynosa as closest border, now it is Nuevo Laredo too.

²²Major ports are defined by the volume of exports and imports (not including petroleum) in 2010, and the 8 selected account for 91.1% of the total ([SCT \(2010\)](#)). From west to east, the ports are: Ensenada, Guaymas, Manzanillo, Lázaro Cardenas, Altamira, Veracruz, Coatzacoalcos, and Punta Venado. Interestingly enough, neither Mazatlán nor Tuxpan are major ports under this measure.

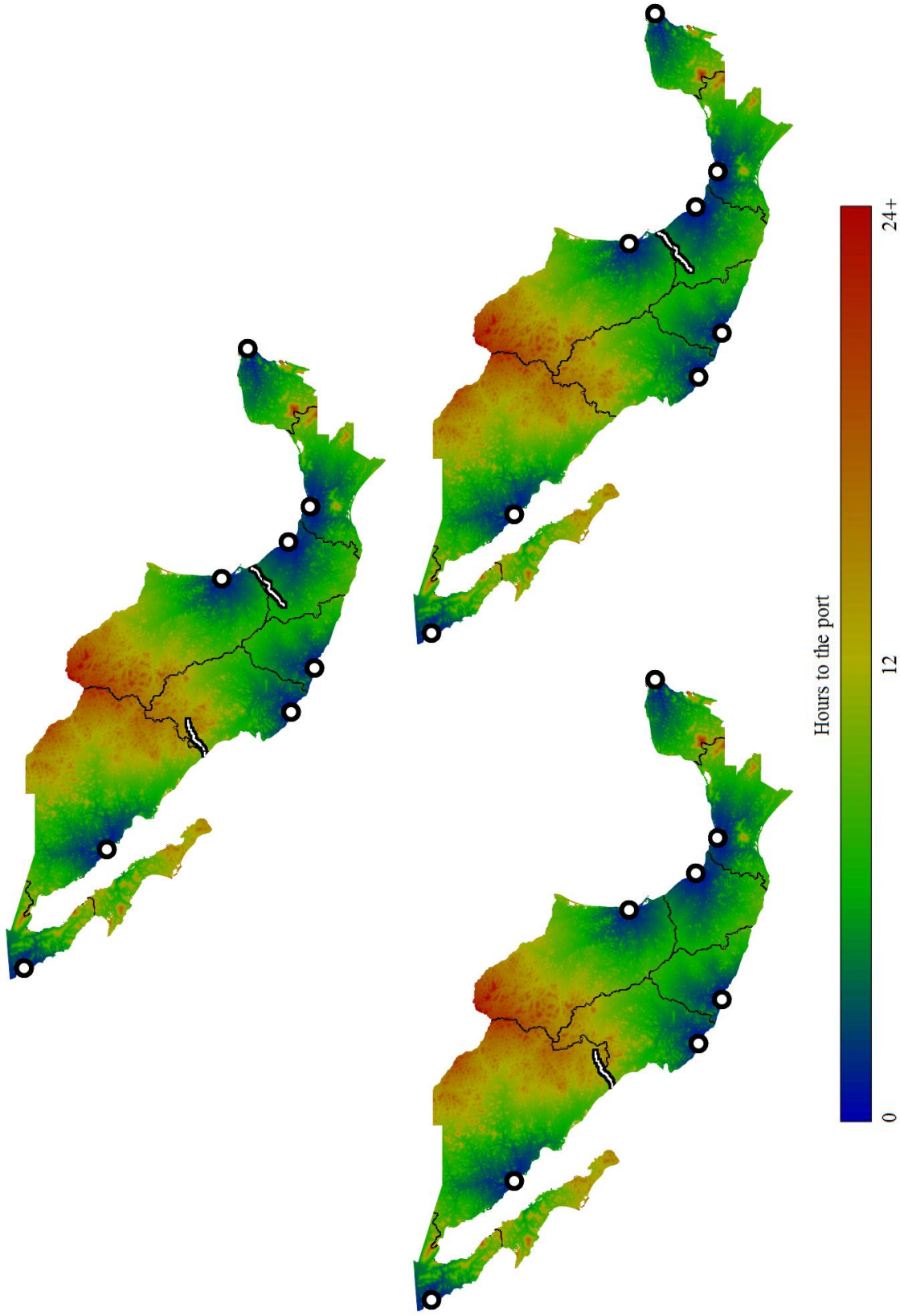
²³There can, of course, be omitted terms that do not imply optimal routing. For example, a firm in southern Mexico may export to the United States via Tijuana to be able to reach the California market without intermediaries. We partially capture this via the component of market access in large cities like Tijuana and Mexicali that comes from southern Mexico. We tried several other measures of access to the borders, with similar results as the case presented. There are other instances that the total market access measure cannot capture, such as a shift in production towards local or foreign markets. We think that those shifts may not necessarily happen in the short run and are partially measured in the change on market access from the demand side.

Figure 9: Travel time to the closest major border crossing to the United States



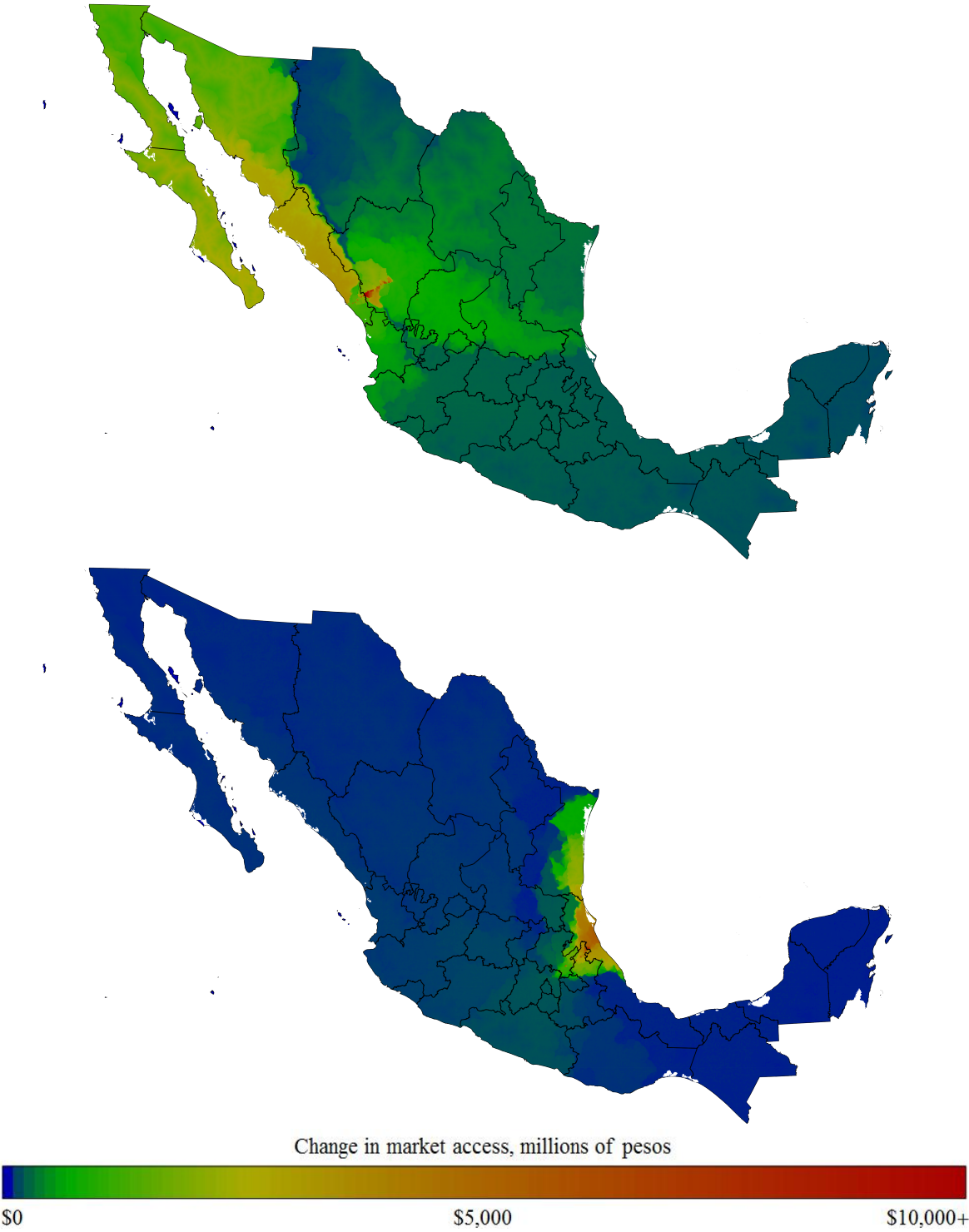
Notes: Top: baseline case. Bottom-left: baseline incorporating Durango-Mazatlán. Bottom-right: baseline incorporating Mexico City-Tuxpan. The top case has representations of the new highways to visualize any changes in the identity of the closest border due to the construction of the highways. The borders are, from west to east: Tijuana, Mexicali, Nogales, Ciudad Juárez, Nuevo Laredo, Reynosa, and Matamoros.

Figure 10: Travel time to the closest major sea port



Notes: Top: baseline case. Bottom-left: baseline incorporating Durango-Mazatlán. Bottom-right: baseline incorporating Mexico City-Tuxpan. The top case has representations of the new highways to visualize any changes in the identity of the closest port due to the construction of the highways. The ports are, from west to east: Ensenada, Guaymas, Manzanillo, Lazaro Cardenas, Altamira, Veracruz, Coatzacoalcos, and Punta Venado. Notice how Mazatlán's closest port used to be Guaymas and with the new highway it is Manzanillo.

Figure 11: Change in market access from the construction of the new highways



Note: Top: Changes in market access from the construction of the Durango-Mazatlán highway. Bottom: Changes in market access from the construction of the Mexico City-Tuxpan highway.

benefits go all the way to the Baja California peninsula. The states of Sonora, Zacatecas, Coahuila, Nuevo Leon, San Luis Potosi and Tamaulipas also get large benefits, even if they are hundreds of kilometers away from the new highway. The regions near the construction of the highway, but mostly between the endpoints of this new infrastructure get the largest benefits of the highway. On the other hand, the Mexico City-Tuxpan highway benefits mostly regions to the east of the construction. In particular, the area close to Tuxpan, the rest of the north of Veracruz, and the east of Tamaulipas. The benefits of this highway, however, are much larger in the north of Veracruz than in any region obtaining benefits from the Durango-Mazatlán highway.

It is in great measure the previous existence of infrastructure what causes the impact of the new highways to spread over the territory and that the magnitude of the impact is affected by the GDP of the regions that suddenly became cheaper to trade with. It is not trivial to evaluate which of the projects is more beneficial, since it is a short-run effect. The increase in the market access will increase the demand for products in every region, and this demand will increase more in regions whose average reduction in transportation to large markets was the largest. On the other hand, it should be considered to what extent the new infrastructure is creating new economic activity relative to just reorganizing the existent one, as discussed in [Fogel \(1970\)](#). The latter is an important issue, given that the total gains of some regions could be driven by net losses of the other ones.

Then, even if the short-run approach offers a plausible explanation of the first mechanisms triggered after the construction of new infrastructure, it does not take into account other possible long-run effects related to the backward and forward linkages affecting the production and consumption of the regional goods. For example, the port of Mazatlán can become a major port of entry from countries trading through the Pacific Ocean now that there is faster access to the northeastern border and into the U.S. markets that typically imply entering through the Gulf of Mexico (and crossing the Panama Canal). Also, some regions might get more value added than before, just for being part of new trade routes that previously were not in use, such as the corridor Mazatlán-Gulf of Mexico or Mexico City-Matamoros (via

Tuxpan). Therefore, in order to fully understand all the implications of the provision of infrastructure a more structural approach is required. That is, we need a theoretical framework able to endow our empirical strategy with the elements so it could deal with three important aspects. First, with the general equilibrium effects caused by the reduction of transportation costs and the reorganization of the optimal trading routes. Second, to properly address the issue that the infrastructure is not randomly provided, so the current state of the transportation network and, in general, of the economy, are important determinants of the causal effects of new infrastructure projects. And third, to incorporate the changes in the international trade structure.

This paper analyzes the short-run effects of the construction of two important highways produced on the market-access in every location in Mexico. By characterizing the Mexican territory and its transportation network as a weighted graph, we provide an estimation of the changes in market access to national products derived from the inclusion of the two infrastructure investments previously mentioned.

Our results support the idea that transportation infrastructure is an important determinant of the organization of economic activity within a country provided it is supplied at a competitive cost, and they enlighten two important facts that are worth-mentioning. First, since the transportation infrastructure is subject to network effects, the current state of the network and of the economic agents could drive the magnitude of the total effects of adding a new highway. Second, the heterogeneity of our results suggest that other important mechanisms could be acting along with the mere increase in market access. Thus in order to correctly determine the causal effect of the provision of new infrastructure, a wider approach is required so we can handle issues as the second order effects and the endogeneity in the construction of the new highways. Once we get data on regional output, the outcome at various levels of model sophistication can be tested. These and other important features are subject of a further research agenda.

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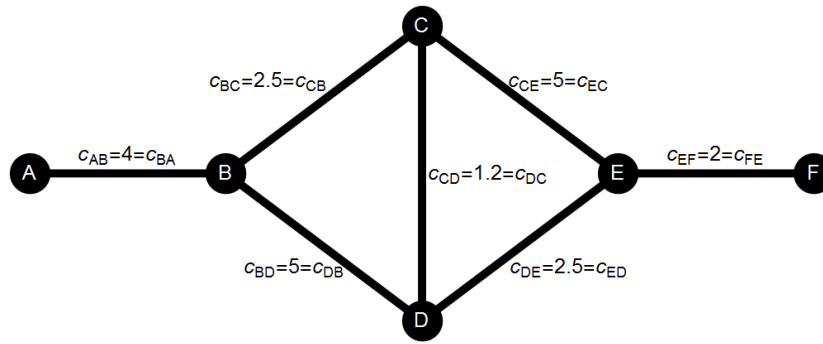
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A The Shortest Path Problem and Dijkstra's Algorithm

The purpose of this appendix is to briefly introduce Dijkstra's algorithm to a reader that has some experience on computer programming, some experience on theoretical optimization, but none on numerical optimization. The general problem to be solved is to find the fastest way of connecting a source vertex with a destination vertex using the best possible combination of the edges of a grid. This problem is known as the "Shortest Path Problem". The edges of the grid each one of them have source and destination vertices, and travel times associated to them. To illustrate the problem, see [figure 12](#) below:

Figure 12: Vertices, edges, and travel times



Defining V the set of vertices (A, B, C, D, E, and F), E the set of edges (AB, BA, BC, CB, BD, DB, CD, DC, CE, EC, DE, ED, EF, and FE), c_{ij} the travel time between vertex i and j using a direct edge (4, 4, 2.5, 2.5, 5, 5, 1.2, 1.2, 5, 5, 2.5, 2.5, 2, and 2 respectively), x_{ij} as the number of times that edge ij is used as part of an optimal path, and N is the number of vertices (6), we have that the mathematical problem to be solved to find the shortest paths

that start in vertex A to all the other $N - 1$ vertices²⁴ is the following:

$$\begin{aligned}
& \min_{x_{ij}} \sum_{(i,j) \in E} c_{ij} x_{ij} \\
& \text{s.t.} \quad \sum_{j:(A,j) \in E} x_{Aj} - \sum_{j:(j,A) \in E} x_{jA} = N - 1 \\
& \quad \quad \sum_{j:(i,j) \in E} x_{ij} - \sum_{j:(j,i) \in E} x_{ji} = -1, \quad \forall i \in V \setminus \{A\}
\end{aligned} \tag{7}$$

This is a computationally intensive problem, and for grids with a large number of vertices and edges it might take some time, even for a modern computer. A simplification of the problem is Dijkstra's algorithm, whose solution is the same as the one of [equation 7](#), but takes much less computational resources. Dijkstra's algorithm was invented in 1956 by Edsger W. Dijkstra, and the pseudocode (algorithm) is in [table 4](#), where the only new piece of notation is $n(i)$, the set of vertices that are one edge away from vertex i . This algorithm has a complexity of $O(N^2)$. This means that the number of computational operations grows as a polynomial of degree 2 in number of vertices.

Now we will illustrate the two steps required in our analysis of [section 2](#) to calculate optimal travel times between every two locations in Mexico. The first thing to do was to obtain the distance between every pair of vertices that share an edge. For the purposes of this example, there are 6 vertices and 14 edges (see [figure 13](#)). The distance between vertices is written next to each edge. Then, using the digitized data set of Mexican roads, we obtain the speed of the edge that connects each pair of vertices. The speeds are colored in [figure 13](#) too.

Combining the data of distances and speed, it is easy to obtain the travel times for each edge (see [figure 14](#)). This matrix of travel times is the input for Dijkstra's algorithm, and it is easily verifiable that the optimal travel time from source A is the first row of [table 5](#) (that is, the solution of [equation 7](#)). This table has the entire optimal travel time matrix, that is, the solution obtained from running Dijkstra's algorithm 6 times.

²⁴If only one destination vertex is needed, the mathematical problem is similar, but has the same complexity as the one for $N - 1$ vertices, so in general it is preferred to write the problem for the whole set of destination vertices.

Table 4: Dijkstra's algorithm pseudocode

```

 $S \leftarrow \emptyset$ 
 $\hat{S} \leftarrow V$ 
 $d(i) \leftarrow \infty \forall i \in V$ 
 $d(A) \leftarrow 0; \text{pred}(A) \leftarrow 0$ 
while  $|S| < N$  do
  let  $i \in \hat{S}$  be a node such that  $d(i) = \min d(j) : j \in \hat{S}$ 
   $S \leftarrow S \cup i$ 
   $\hat{S} \leftarrow \hat{S} - i$ 
  for all  $e \in n(i)$  do
    if  $d(i) + c_{ij} < d(j)$  then
       $d(j) \leftarrow d(i) + c_{ij}$ 
       $\text{pred}(j) \leftarrow i$ 
    end if
  end for
  mark current as visited
   $\text{current} \leftarrow \underset{v \in \text{unvisited}}{\text{argmin}} \text{dist}[v]$ 
end while

```

Figure 13: Distance between vertices (kilometers) and speed of the edges

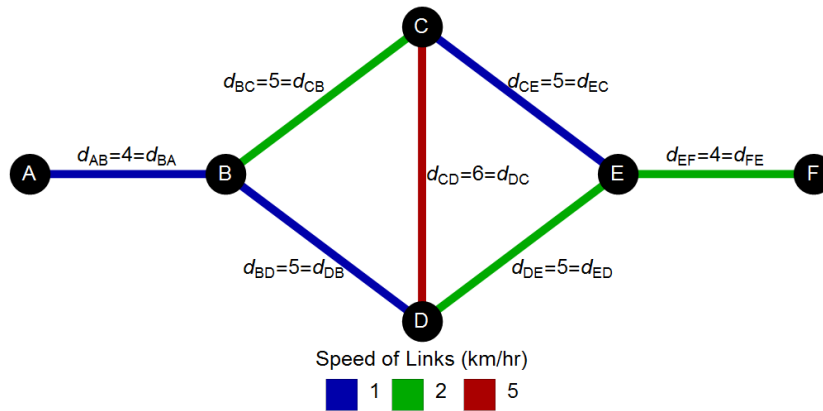


Table 5: Optimal travel time matrix

	A	B	C	D	E	F
A	0	4	6.5	7.7	10.2	12.2
B	3	0	2.5	3.7	6.2	8.2
C	6.5	2.5	0	1.2	3.7	5.7
D	7.7	3.7	1.2	0	2.5	4.5
E	10.2	6.2	3.7	2.5	0	2
F	12.2	8.2	5.7	4.5	2	0

Figure 14: Travel time between vertices that share an edge, using that edge

