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

Fernando Pérez-Cervantes\textsuperscript{1} and Aldo Sandoval-Hernández\textsuperscript{1,2}

\textsuperscript{1}Banco de México\textsuperscript{‡}
\textsuperscript{2}The University of Western Ontario\textsuperscript{§}

Abstract

We calculate the short-run effect that the construction of the 230km-long Durango-Mazatlán highway in the end of 2013 and of the 290km-long Mexico City-Tuxpan highway in the beginning of 2014 produced on welfare in every municipality as well as in market-access in every location of 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. The municipalities in the south of the country have net short run losses from the infrastructure construction due to losses in competitiveness. Our model is consistent with the observed sectoral growth in Sinaloa, Durango, and Veracruz in the year 2014. Qualitatively, market access and welfare change in the same direction and magnitudes, so this paper recommends to use the market access approach when doing short-run analysis of infrastructure, because it is much less computationally intensive.

JEL Classification: R1, R4, F15

Keywords: Market Access, Infrastructure, Public Investment, Mexico

\textsuperscript{*}We thank Óscar Cuéllar-Nevares and Claudia Velázquez (Dirección de Análisis Sobre Precios, Economía Regional e Información at Banco de México) for excellent research assistance.
\textsuperscript{†}Contact: Pérez-Cervantes: fernando.perez@banxico.org.mx, Sandoval-Hernández: asandov3@uwo.ca
\textsuperscript{‡}Dirección de Análisis Sobre Precios, Economía Regional e Información
\textsuperscript{§}Department of Economics
1 Introduction

Between 1995 and 2005, around 9% of total World Bank lending went to upgrading of roads and highways.\footnote{Calculated by the authors using data from Asturias et al. (2014).} Investments in transportation infrastructure have been a widely used policy aimed to reduce trade costs, enhance mobility and boost economic growth across regions. Moreover, these transportation policies have also targeted redistributional objectives, in which, previously disconnected areas now have access to a wider variety of goods, inputs and markets. Since infrastructure investment not only reduces the trade costs between the locations being connected but also on the rest of locations using that route, an approach that considers changes in optimal routing is useful in order to quantify its effects on economic outcomes.

In this paper, we study how improvements in the transportation infrastructure within a country can affect welfare and internal demand in the short run. In particular, we quantify the potential effects of two recently inaugurated 4-lane highways in Mexico: the Durango-Mazatlán and the Mexico City-Tuxpan highways. These two highways 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. Additionally, locations that are not necessarily close to the origin or the destination of the original highway, now have an opportunity to transport goods on the updated highway network.

At this point, it is too soon to have enough data at the local level to quantitatively...
calculate any observed effects of the two recently opened highways. To overcome that limitation, in this paper we use small changes in transportation infrastructure that reduce travel time between producers and consumers to calculate the short-run impact in every region in Mexico.\(^2\) Thus, we model improvements in transportation infrastructure as changes in travel times and, therefore, in transportation costs. This is possible because we can observe the speed of infrastructure similar to the one being built and compare it with the one observed before the construction. This new speed and the location of the infrastructure can be used to calculate the new fastest routes, and then 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.

This paper provides two sets of results. First, it does welfare analysis using a simple trade model, and second it calculates the changes in market access making use of the triangle inequality. As it will be shown in the document, market access and welfare are closely related, and, computationally, market access is an order of magnitude simpler to obtain than welfare. Our results suggests that the impacts of both highways are very different. On the one hand, the Durango-Mazatlán highway

\(^2\)There are many other short-run impacts that have been studied recently. See for example Asturias et al. (2014) for estimates of regional changes in competitiveness derived from the construction of the 5,846km long “Golden Quadrangle” highway in India.
produced 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 magnitude of these are greater than any of the ones produced by the Durango-Mazatlán highway.

This research is related to a growing literature that studies 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 for different time periods. Additionally, we find our paper joining important work studying infrastructure in Mexico. To the best of our knowledge, this is the first paper that does a market access analysis in a large number of regions (for any country) and the first one in Mexico for any number of regions. The usefulness of this measure, lies in the fact that it provides a parsimonious way to summarize the forces that contribute to the geographic concentration of economic activity (Hanson (2005)). Therefore, by measuring each location’s proximity to the consumer markets, we are able to identify which regions are more prone to attract new industries and economic activity in the following years. Also, in this paper we develop a set of tools which is able to compute travel time matrices of any size very efficiently. The latter constitutes an important step towards understanding the interaction between distance, size, and connectivity of large transportation networks.

The rest of the paper is organized as follows. Section 2 discusses specific aspects of the infrastructure projects being considered. Section 3 explains the methodology

---


4See Looney and Frederiksen (1981), Deichmann et al. (2004) and Dávila et al. (2002).
to obtain the travel times between every two locations of the country. Section 4 details how the transportation costs were calibrated and estimated. Welfare analysis is performed in section 5. Market access for every location in Mexico is studied in section 6. Finally, section 8 analyzes the results and concludes. The Online Appendix contains a detailed discussion about the numerical optimization problems referred in this paper, as well as a four-region example and complementary figures on market access, municipal population, income, and travel times.

2 Background

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.

To foresee the potential effects of the NIP projects on the regional economies, this paper studies the effect of two recently inaugurated high speed (average of 90km/hr) 4-lane highways in Mexico: the Durango-Mazatlán and the Mexico City-Tuxpan highways, pictured along with the other highways of the country in figure 1. These two highways, despite not being completely part of the NPI, are in many ways similar to the infrastructure projects considered, thus analyzing their potential effects
The 230 km-long Durango-Mazatlán highway, which is not part of the NIP, involved 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 constituting an informed forecast of what to expect after all the projects contained in the NPI are finished.

5All amounts and figures in the paper are in Mexican Pesos.
from vast regions west of the construction of the highway. 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 the Online Appendix). This highway 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 it.

After Hansen (1965) approached the problem of building infrastructure in specific areas as a trigger for unbalanced growth, Looney and Frederiksen (1981) were probably the first ones to explicitly test if the region where infrastructure was being built reduced inequality between Mexican states. 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 (income wise) regions, while economic overhead capital (the type of capital that supports productive activities, such as roads, electricity, water supply, etc.) only benefits advanced regions.

\footnote{See the Online Appendix for details.}
Deichmann et al. (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 et al. (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. 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 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, and so the NIP is a great head start.

3 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

7In 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.
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. For that purpose, 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.\(^8\)

The continental territory of Mexico was approximated with 1,977,537 squares, covering an area of 1km\(^2\) each, and where the centroid is the point of reference.\(^9\) The location of the 1,977,537 vertices correspond to the 1,977,537 centroids 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, an scheme commonly known as *king movements* in which the permitted displacements between each one 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.

We obtained georeferenced data on highways, pathways, maritime routes, and urban localities from INEGI (2010). This data is intersected with the grid, and this

---

\(^8\)The 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.

\(^9\)The area of Mexico is 1,972,550km\(^2\). The difference of 0.25% comes from rounding up areas of maps that include some sea, as well as the routes of the ferries.
procedure entailed a mapping from the vectorial data into vertices and edges. At this point, we were able to 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.), and classify it according to 21 categories. In order to calibrate the speeds, we use “Punto a Punto” travel planner from the Secretaría de Comunicaciones y Transportes for several hundreds of origin-destination pairs. This web application contains information about the toll cost, road classification, approximated travel time and distance for many Mexican cities, with a limited number of searches per day. Thus from all the routes consulted, we can infer the average speed for any type of infrastructure contained in our classification.

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 transportation “Rest of the territory”. All the speeds of every means of transportation are pictured in figure 2, 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, meaning that our grid is connected.

10 See the Online Appendix for more details.
11 Maritime 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.
12 This property is required for many of the "Shortest Path" algorithms such as the one used in this paper.
Figure 2: 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

Note: 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 2d, 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.

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,\textsuperscript{13} 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

\textsuperscript{13}A very simple task that had to be performed 7,875,594 times.
by the horizontal geodistance and the difference in altitudes. Thus, the distance in kilometers between vertex \( i \) and vertex \( j \) is given by:

\[
distance_{i,j} = \sqrt{(\text{Geodistance}(i, j))^2 + (\text{altitude}_i - \text{altitude}_j)^2}
\]  

(1)

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 (in hours) spent in moving from one vertex to another, based on the formula below:

\[
Time_{i,j} = \frac{distance_{i,j}}{speed_{i,j}}
\]  

(2)

Given the above, now we have characterized the Mexican territory and its transportation network as a graph 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. All the calculations that use Dijktra’s algorithm in this paper were performed using Gabriel Peyre’s Matlab Toolbox. Now define matrix \( \mathbf{D} \) as the \( 1,977,537 \times 1,977,537 \) matrix of travel times in which each one of the

\(^{14}\)The changes in altitude are an important factor not only to calculate instantaneous speed, but also to determine the location of transportation infrastructure.  

\(^{15}\)See the Online Appendix for a brief introduction to the “Shortest Path Problem”, and for a brief and simple example of an application of Dijkstra’s algorithm.  

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 $D$, 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 $D$ satisfy the triangle inequality, that is, $\delta (i, j) \leq \delta (i, k) + \delta (k, j) \forall k$. To illustrate this matrix $D$, 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 the Online Appendix.

4 Estimating the Iceberg Costs

With matrix $D$, we know the approximate optimal 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 prices data estimate the parameters of the function. This transportation cost function $TC (i, j)$ is modelled as an iceberg cost, and represents the percentage of goods that have to be shipped 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:

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

(3)

The costs function is formed by 2 parameters: one of them is a fixed cost $F$ incurred only when goods leave their location of production, and the other parameter is the
variable cost $\lambda$ 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). The fixed costs term is included in order to capture all the transportation cost shifters that are not related 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 $\lambda$, we follow the empiric strategy carried out by Donaldson (2008), in which the author uses a result present in most of the spatial models, suggesting that in the presence of transportation costs, the price of identical goods will differ among distant regions. That is:

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

(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. 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

\footnote{Other interesting approaches have been used too. Asturias et al. (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.}
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 \( p(i, j) \). 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:

\[
\ln p_{kot} = F_{i \neq j} + \lambda \delta(o, d) + \beta + \beta_{ot} + \beta_d + \beta_k + \epsilon_{kot}
\]

(5)

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.), \( \beta \) 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 1. The idea behind this estimation, which is the same as in Donaldson (2008), is that \( \beta + \beta_{ot} + \beta_d + \beta_k \) identify \( \ln p_{kot} \), 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, and also because it defines in some sense the initial conditions of the sale at the origin. We discard the ones that include the destination dummies, because we are assuming constant markups over the price at the origin, 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 \(\beta\). We do not think there is any location with such market power that could justify going in this direction.\(^{18}\)

The fact that states such as 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\%.

\(^{18}\) As shown in Atkin and Donaldson (2012) and Hummels et al. (2009), with homogeneous goods the constant markup result is obtained regardless of the market structure of the transportation industry.
Table 1: Estimation of Transport Cost Function

<table>
<thead>
<tr>
<th>Variables</th>
<th>$F$</th>
<th>$\lambda$</th>
<th>$\beta$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.9027**</td>
<td>0.0557***</td>
<td>-0.2965***</td>
<td>0.0859***</td>
</tr>
<tr>
<td></td>
<td>(0.0838)</td>
<td>(0.0067)</td>
<td>(0.0904)</td>
<td>(0.0066)</td>
</tr>
<tr>
<td></td>
<td>0.0498**</td>
<td>0.0024***</td>
<td>0.0799***</td>
<td>0.0018***</td>
</tr>
<tr>
<td></td>
<td>(0.0237)</td>
<td>(1.3e-4)</td>
<td>(0.0256)</td>
<td>(1.3e-4)</td>
</tr>
<tr>
<td></td>
<td>1.8296**</td>
<td>3.4370***</td>
<td>1.3695***</td>
<td>3.2188***</td>
</tr>
<tr>
<td></td>
<td>(0.7201)</td>
<td>(0.0128)</td>
<td>(0.6704)</td>
<td>(4.3e-7)</td>
</tr>
</tbody>
</table>

Fixed Effects

<table>
<thead>
<tr>
<th>origin-date</th>
<th>type</th>
<th>destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Note: Robust standard errors in parentheses. Number of observations: 29,124

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

5 Effect of the New Infrastructure on Welfare

In order to perform welfare analysis, we will increase the level of aggregation of the travel time calculations and do it at the municipal level. Thus, we assume that the entire economic activity of the municipality happens at a single point: the municipal head. This way, we will be able to get factor returns and obtain real income at this level of disaggregation. So, we get the $2456 \times 2456$ sub matrix that comes from the $1,977,537 \times 1,977,537$ and whose elements are the 2456 square kilometers that contain the coordinates of the municipal head, as published by INEGI. We obtain all the travel times between every pair of municipal heads in the country. To stress the complexity of obtaining this travel time matrix even if it has only 0.00015% of the number of elements of original large matrix, this would take 5 years using the free service of Google Maps in a single computer, and more than two months using a similar, but paid service. We are able to obtain all this information in a few
seconds with our weighted graph approach, and the whole 4 trillion elements in less than one hour.

Once we have a reliable estimation of the transportation costs at a municipality level, we use a standard Armington model of trade to properly address the general equilibrium effects of the provision of transportation infrastructure on factor payments, trade and welfare. Since we are only interested on the short-run effects, which are likely to occur in the first years after the construction of the highways, this model abstracts from possibility of migration of consumers and the reallocation of firms.

5.1 Consumers

Consider a representative agent that lives in municipality $n$, endowed with $L_n$ units of labor and $K_n$ units of capital, and has preferences for consuming goods produced in the 2456 municipalities of the following form:

$$U_n = \left( \sum_{i=1}^{2456} \gamma_i^\frac{1}{\sigma} c_{ni}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (6)$$

where $\sigma$ is the elasticity of substitution and $\gamma_i$ is the preference parameter for goods from municipality $i$ (common across all municipalities), and $c_{ni}$ are the purchases of municipality $n$ of consumption goods from municipality $i$. The budget constraint for each municipality is standard, and states that the purchases of goods from every municipality, inclusive of transport costs (as defined in previous sections), must not
exceed the returns to the representative consumer’s endowment:

\[
\sum_{i=1}^{2456} p_{ni} c_{ni} \leq w_n L_n + r_n K_n \tag{7}
\]

No-arbitrage conditions imply that the producer price at municipality \(i\) plus the transport cost must equal the price for the consumer at municipality \(n\), that is \(p_{ni} = p_{ii} TC(n, i)\) where \(p_{ii}\) equals the producer price of the good produced in municipality \(i\). We normalize \(p_{ii} = p_i\), that is, the price paid by consumers in municipality \(i\) for goods produced locally equals the producer price.

\subsection{5.2 Producers}

We assume a competitive industry in each municipality, so there will also be a representative firm, who takes factor prices and output prices as given. A firm in municipality \(n\) will hire the \(L_n\) units of labor and \(K_n\) units of capital and produce using a constant returns to scale production function

\[
y_n = A_n (K_n)^{\alpha_n} (L_n)^{1-\alpha_n} \tag{8}
\]

It is straightforward to calculate that the producer price in region \(n\), defined in the last subsection, is given by:

\[
p_n = \frac{1}{A_n} \left( \frac{r_n}{\alpha_n} \right)^{\alpha_n} \left( \frac{w_n}{1-\alpha_n} \right)^{1-\alpha_n} \tag{9}
\]
and from constant returns to scale we get that the zero profit condition gives:

\[ p_n y_n = w_n L_n + r_n K_n \]  

(10)

### 5.3 Equilibrium

The market clearing condition for the output prices and balanced trade is given by

\[ p_n y_n = \sum_{i=1}^{2456} \frac{\gamma_n (p_n TC(i,n))^{1-\sigma} p_i y_i}{\sum_{m=1}^{2456} \gamma_m (p_m TC(i,m))^{1-\sigma}} \]  

(11)

Defining the source effect as \( S_n = \gamma_n (p_n)^{1-\sigma} \) and defining \( Y_n = p_n y_n \) as the nominal income of municipality \( n \), a simple system of equations emerges:

\[ Y_n = \sum_{i=1}^{2456} \frac{S_n (TC(i,n))^{1-\sigma} Y_i}{\sum_{m=1}^{2456} S_m TC(i,m)^{1-\sigma}} \]  

(12)

whose solution \( S = (S_1, S_2, \ldots, S_{2456})^T \) is normalized up to a constant, and is obtained using the algorithm of Pérez-Cervantes (2014). It is possible to obtain the values of the source effect using the municipal population data from INEGI and the municipal per capita income from CONEVAL, both from 2010. The values of population and of income per capita at the municipal level are pictured in the Online Appendix. The product of these two numbers will be \( Y_n \) for every \( n \). Transport costs are as defined in previous sections.
Total welfare in municipality \( n \) is given by the real income of the endowment,

\[
\frac{w_n L_n + r_n K_n}{P_n} = \frac{p_n y_n}{P_n}
\]  

(13)

where \( P_n \) is the Armington price index, which solves:

\[
(P_n)^{1-\sigma} = \sum_{i=1}^{2456} \gamma_i (p_i TC(i,n))^{1-\sigma} = \sum_{i=1}^{2456} \frac{S_i}{TC(i,n)^{\sigma-1}}
\]  

(14)

Initial welfare is therefore, not identified because \( p_n \) is not identified for any \( n \) with this algorithm. Easily identifiable, however, are the gains from trade. That is, what is the percentage change in welfare from an imaginary counter-factual initial condition of

\[
TC(i,n) = \begin{cases} 
\infty & i \neq n \\
1 & i = n 
\end{cases}
\]

compared to the transport cost structure one obtained in section 4. The gains from trade in municipality \( n \) in the Armington model are exactly

\[
\left( \frac{S_n}{\sum_{m=1}^{2456} S_m (\delta_m)^{1-\sigma}} \right)^{\frac{1}{1-\sigma}}
\]  

(15)

so the smaller the number inside the parenthesis, the larger the gains. Recalling from the definition of the source effect, factor prices, productivity, and the production function, we have that it is larger for municipalities with low transport costs, high productivity, low factor prices, and high Armington preference parameter are the ones that gain the most from trade.
Then, closely following the proof in Pérez-Cervantes (2014), we obtain the counterfactual endowment prices, which as it will be shown, do not need any information or assumptions on the preference parameters \( \gamma_i \), the productivity parameter \( A_n \), or even the curvature of the production function \( \alpha_n \) or the size and return of the endowments \( K_n, L_n, r_n, \) and \( w_n \), respectively. 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 \( \lambda \) from the baseline case to obtain the new transport cost functions. Defining with \( \hat{x} \) the gross changes \( x'/x \) in the variable \( x \), where \( x' \) is the counterfactual value of \( x \), and \( \pi_{in} = \frac{S_i(\delta_{in})^{1-\sigma}}{\sum_{m=1}^{2456} S_m(\delta_{im})^{1-\sigma}} \) for every \( i, n \),\(^{19}\) the following system of equations has a unique solution \( \hat{p} = (\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_{2456})^T \) up to a scalar normalization:

\[
\hat{p}_n Y_n = \sum_{i=1}^{2456} \frac{\pi_{im} (\hat{p}_i \delta_{im})^{1-\sigma}}{\sum_{m=1}^{2456} \pi_{nm} (\hat{p}_m \delta_{fm})^{1-\sigma}} \hat{p}_i Y_i \tag{16}
\]

and the normalization that is chosen is \( \sum_{i=1}^{2456} \hat{p}_i Y_i = \sum_{m=1}^{2456} Y_m \). The percentage change in welfare will be given by the percentage change in gains from trade, that is,

\[
\hat{U}_n = \frac{U'_n}{U_n} = \frac{U'_n/U_{nAUTARKY}}{U_n/U_{nAUTARKY}} = \left( \frac{\pi_{ii}}{\pi_{ii}} \right)^{\frac{1}{1-\sigma}} \tag{17}
\]

\(^{19}\)Note that gains from trade are \( (\pi_{ii})^{\frac{1}{1-\sigma}} = \left( \frac{\sum_{m=1}^{2456} S_m(\delta_{im})^{1-\sigma}}{\sum_{m=1}^{2456} S_m(\delta_{im})^{1-\sigma}} \right)^{\frac{1}{1-\sigma}} \).
where $\pi'_{ii} = \frac{\pi_{ii}(\hat{p}_i)^{1-\sigma}}{\sum_{m=1}^{2456} \pi_{im}(\hat{p}_m \hat{\delta}_{im})^{1-\sigma}}$. And so we have a simple expression for welfare growth coming from our system of equations. We assume an elasticity of substitution between goods $\sigma = 9$, a value that is commonly used in the trade literature such as Caliendo and Parro (2009) Allen and Arkolakis (2014), Eaton and Kortum (2002), Feenstra (1994), and Hummels (1999). Our choice of the elasticity of substitution parameter responds to two reasons. First, we are working with very disaggregated data, thus a higher degree of substitutability among goods might be expected. Second, following the discussion in Ruhl (2008), it is important to identify the source of variation when estimating the Armington elasticity. In general, when the source of variation comes from a permanent (temporary) change, the estimates tend to be higher (smaller). Since changes in the transportation infrastructure can be thought as permanent, an elasticity of substitution equal to 9 which is high, is reasonable.

The results are depicted in figure 3. The whole state of Sinaloa has increases in welfare, and this being an agriculturally intensive state, we think our model predicts very well the observed outcome for 2014 in this state, and the same can be said for Durango. As for the state of Veracruz, the north is predicted to have a lot of growth and the south is predicted to take some losses. Weighted by population, our estimates show almost no growth in the state derived from the construction of the Mexico City-Tuxpan highway, and the interviews performed by Banco de México for their regional reports confirm that there was a large boom coming from the

---

20 Most of the empirical attempts to measure the Armington elasticity use country-level data, and as suggested by Ruhl (2008) an acceptable range of the estimates is 4 to 15.
touristic investment in Tuxpan and that many of the workers come from the south of the state, which is more agricultural.

We believe our results are consistent with the observed data for Veracruz too, since the highway, while not completely opened for all of 2014, produced investment of hotels anticipating the ending the construction of the highway, investment which started before April of 2014. As for the states in the west of the country, now the fastest route to Veracruz goes through Mexico City, the richest and most populated region in the country, so an indirect benefit for those states is the reduction in the prices of the goods sourced from the regions near Mexico City too. As an outside validation of our results, table 2 shows the annual GDP sectoral growth in 2014 for all the states that contain the ending points of the highways considered. The growth rates are consistent with figure 3, where Sinaloa exhibited high growth rates in Agriculture and Tourism related Services, and Veracruz showing a near zero growth in the total GDP, explained by the increases in Manufactures and Tourism related Services and the fall in Agriculture GDP.

Table 2: Sectoral GDP Growth by State (states containing the endpoints of the new highways)

<table>
<thead>
<tr>
<th>States</th>
<th>Total</th>
<th>Agriculture</th>
<th>Manufactures</th>
<th>Tourism related Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distrito Federal</td>
<td>0.49%</td>
<td>4.00%</td>
<td>-0.71%</td>
<td>-11.04%</td>
</tr>
<tr>
<td>Durango</td>
<td>1.29%</td>
<td>-0.11%</td>
<td>-2.48%</td>
<td>9.79%</td>
</tr>
<tr>
<td>Sinaloa</td>
<td>2.87%</td>
<td>6.22%</td>
<td>4.07%</td>
<td>6.25%</td>
</tr>
<tr>
<td>Veracruz</td>
<td>0.08%</td>
<td>-1.96%</td>
<td>2.37%</td>
<td>8.60%</td>
</tr>
</tbody>
</table>

Source: Authors calculations using data from INEGI.
Figure 3: Change in municipal welfare from the construction of the new highways

Note: Top: Changes in welfare from the construction of the Durango-Mazatlán highway. Bottom: Changes in welfare from the construction of the Mexico City-Tuxpan highway.
6 Calculating the Change in Market Access

The welfare analysis, although interesting and testable, implies a huge computational and time burden. While the results presented in this paper are the ones after every equation mentioned before converged to equilibrium, the iterative process took days until convergence. If what we are interested in is the impact of several changes in transport costs such as the ones that come from the NIP, which are more than 20 (a total of $2^{20}$ or around 1 million combinations can be tested) would simply not be possible to do. In this section we develop a technique that can get very similar results as the welfare analysis that does not need to solve for any equilibrium equations, and we show that it can be extended to an arbitrarily large number of regions without increasing the computational burden (bearing in mind that the calculation of the transport cost matrix is a sunk cost for both models). In fact, we will calculate the changes in market access derived from the construction of the highways in every square kilometer of the country. In the Online Appendix, we include 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 section.

We start by defining 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 use a measure that
summarizes the forces that contribute to the geographic concentration of economic activity as described in Hanson (2005). Moreover, it resembles a centrality measure used in network analysis (closeness centrality), that we believe is well suited to capture each location’s proximity to the consumer markets:

$$MA_i = \sum_{j=1}^{2,456} \frac{Y_j}{TC(i,j)^\sigma - 1}$$  \ (18)

With than in hand, 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. Again, we assume an elasticity of substitution between goods $\sigma = 9$.

### 7 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 the Online Appendix.

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.

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, in the Online Appendix we map the travel times to the nearest crossing border and port, before and after the construction of the highways. As can be seen there, there is no major change in travel times to the border, no major shift in the port of entry to the United
States, and analogous results for the sea ports. 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.

The change in market access derived from the construction of the new highways is pictured in figure 4. It is evident that both highways produce different results, but that qualitatively, figure 4 and figure 3 give exactly the same predictions. However, figure 4 cost thousands of times less time and computational burden than figure 3. So we have a model that gives the same predictions for much less cost. The Durango-Mazatlán highway increases the market access in an extensive region. The 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.
Figure 4: Change in market access (per km²) 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.
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.

8 Conclusions

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 welfare and market access to national products derived from the inclusion of the two infrastructure investments previously mentioned. Qualitatively, market access and welfare change in the same direction and magnitudes, however the former is less computational intensive than the latter, so we recommend to do this analysis of short-run impact of infrastructure using the market access approach.
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. The municipalities in the south of the country have net short run losses from the infrastructure due to losses in competitiveness. Our model is consistent with the observed sectoral growth in Sinaloa, Durango, and Veracruz in the year 2014.

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.

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. These and other important features are subject of a further research agenda.
References


Online Appendix

The Shortest Path Problem and Dijkstra’s Algorithm

The purpose of this section 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 5 below:

Figure 5: 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
\( N - 1 \) vertices\(^{21}\) is the following:

\[
\begin{align*}
\min_{x_{ij}} \sum_{(i,j) \in E} c_{ij} x_{ij} \\
\text{s.t.} \sum_{j : (A,j) \in E} x_{Aj} - \sum_{j : (j,A) \in E} x_{jA} &= N - 1 \\
\sum_{j : (i,j) \in E} x_{ij} - \sum_{j : (j,i) \in E} x_{ji} &= -1, \quad \forall i \in V \setminus \{A\}
\end{align*}
\] (21)

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 21, but takes much less computational resources. Dijkstra’s algorithm was invented in 1956 by Edsger W. Dijkstra, and the pseudocode (algorithm) is in table 3, 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.

\(^{21}\)If 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 3: Dijkstra’s algorithm pseudocode

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

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 6). 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 6 too.
Combining the data of distances and speed, it is easy to obtain the travel times for each edge (see figure 7). 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 4 (that is, the solution of equation 21). This table has the entire optimal travel time matrix, that is, the solution obtained from running Dijkstra’s algorithm 6 times.
Table 4: Optimal travel time matrix

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>4</td>
<td>6.5</td>
<td>7.7</td>
<td>10.2</td>
<td>12.2</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>0</td>
<td>2.5</td>
<td>3.7</td>
<td>6.2</td>
<td>8.2</td>
</tr>
<tr>
<td>C</td>
<td>6.5</td>
<td>2.5</td>
<td>0</td>
<td>1.2</td>
<td>3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>D</td>
<td>7.7</td>
<td>3.7</td>
<td>1.2</td>
<td>0</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>E</td>
<td>10.2</td>
<td>6.2</td>
<td>3.7</td>
<td>2.5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>12.2</td>
<td>8.2</td>
<td>5.7</td>
<td>4.5</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Market Access: a Four Region Example

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 8. 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.

Figure 8: Four regions and four roads

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
Another way to look at the extent of this discount, is that for the same transport costs, in order for every 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 9. 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.

Market access will not give any information on 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. This was partially calculated in section 5, because we assumed the factors of production fixed, so it was a short run analysis.

22Using the values of $F$, $\lambda$, and $\theta$ from Section 3.
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 9: Four regions and five roads

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Complementary Figures and Tables

In this section, we depict the 21 categories used for the road classification, as well as the calibrated speeds.
Table 5: Speed by Category of Infrastructure

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

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 4.

Additionally, we map the travel times from Mexico City to every other location in Mexico, as well as every location in Mexico to the nearest border crossing to the U.S., and maritime ports, before and after the construction of the highways. In order to determine the major border crossings and ports depicted in figure 13 and figure 14, we obtain data from the U.S. Department of Transportation and the Secretaria de Comunicaciones y Transportes from Mexico respectively.

Major 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. Major 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. From west to east, the ports are: Ensenada, Guaymas, Manzanillo, Lázaro Cardenas, Altamira, Veracruz, Coatzacoalcos, and

43
Figure 10: 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 1,977,537x1,977,537 with the travel times. Notice how the three ferries in Baja California are an important source of connection to the rest of the country.

Punta Venado. Interestingly enough, neither Mazatlán nor Tuxpan are major ports under this measure.
Figure 11: Municipal population and municipal income per capita, 2010
Figure 12: Market access to national products for each of the 1,977,537 locations of the grid
Figure 13: 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 14: Travel time to the closest major sea port

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.