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Short-Run Market Access and the Construction of Better Transportation Infrastructure in Mexico

ABSTRACT We calculate the short-run effect that the construction of the Durango-Mazatlán highway in late 2013 and the Mexico City-Tuxpan highway in early 2014 produced on welfare in every municipality and on 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 areas 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 2014. Qualitatively, market access and welfare change in the same direction and magnitudes. We thus recommend using the market access approach for short-run analysis of infrastructure, because it is much less computationally intensive.

JEL Codes: R1, R4, F15

Keywords: Market access, infrastructure, public investment, Mexico

Between 1995 and 2005, around 9 percent of total World Bank lending went to upgrading roads and highways.[1] Investment in transportation infrastructure is a widely used policy aimed at reducing trade costs, enhancing mobility, and boosting 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 reduces the trade costs not only between the locations being connected, but also for the rest of

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ACKNOWLEDGMENTS The authors thank Óscar Cuéllar-Nevares and Claudia Velázquez for excellent research assistance.

[1] Calculated using data from Asturias, García-Santana, and Ramos (2016).

the locations using that route, an approach that considers changes in optimal routing is useful to quantify the 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 four-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 two-lane highways (or worse roads) and shortened the route between origin and destination through the construction of 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 quantitatively calculate any observed effects of the two recently opened highways. To overcome the data limitation, 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] 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 speed observed before construction. This new speed and the location of the infrastructure can be used to calculate the new fastest routes, and the new transportation costs can be used to obtain the new short-run demand for products of different origins, which in turn defines the demand for goods in every location. That is, using the instantaneous speed that is implied from the infrastructure characteristics, we can back out the entire trade cost structure of the economic system, provided that we have a good measure of the cost of transportation and that the predicted fastest route is actually the one being used to transport goods.

The paper provides two sets of results: a welfare analysis using a simple trade model and the calculation of changes in market access. Market access and welfare are closely related, and, computationally, market access is an order of magnitude simpler to obtain than welfare. Our results suggest that the two highways have very different impacts. The Durango-Mazatlán highway produced gains in vast regions in the north of Mexico. In contrast, the Mexico City-Tuxpan highway mostly benefited regions near Tuxpan, but the magnitude of the impact is greater than any of the gains produced by the Durango-Mazatlán highway.

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[2] For an example of a short-run impact study, see Asturias, García-Santana, and Ramos (2016), who estimate regional changes in competitiveness derived from the construction of the 5,846-kilometer Golden Quadrilateral highway in India.

This research is related to a growing literature that studies the impact of transportation infrastructure both theoretically and quantitatively, in terms of productivity, transportation costs, or trade costs and for different time periods.[3] Additionally, we find our paper joining important work studying infrastructure in Mexico.[4] To the best of our knowledge, this is the first paper to include 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.[5] Therefore, by measuring each location's proximity to the consumer markets, we are able to identify which regions are more likely to attract new industries and economic activity in the following years. We also develop a set of tools that are able to compute travel time matrices of any size very efficiently. The latter constitutes an important step toward understanding the interaction between distance, size, and connectivity of large transportation networks.

The rest of the paper is organized as follows. The next section discusses specific aspects of the infrastructure projects being considered. We then explain the methodology for obtaining the travel times between every two locations of the country and for calibrating and estimating transportation costs. The welfare analysis and the market access study for every location in Mexico are presented in subsequent sections. Finally, we analyze the results and present our conclusions. The online appendix contains a detailed discussion of the numerical optimization problems discussed in this paper, as well as a four-region example and complementary figures on market access, municipal population, income, and travel times.

Background

On 29 April 2014, the Mexican Federal Government published the 2014–2018 National Infrastructure Program (NIP), which detailed the infrastructure projects that were going to be built in Mexico over the following years in order to achieve "equilibrated regional development, urban development, and

[3] See Donaldson (2010), Gonzalez-Navarro and Quintana-Domeque (2016), Kondo (2013), Allen and Arkolakis (2014), Gertler and others (2014), Chanda and Panda (2016), and Pérez-Cervantes (2014) for recent examples.

[4] See Looney and Frederiksen (1981), Deichmann and others (2004), and Dávila, Kessel, and Levy (2002).

[5] Hanson (2005).

FIGURE 1. The Durango-Mazatlán and Mexico City-Tuxpan Highways

logistic connectivity."[6] The NIP projected that investment in this sector would increase substantially with respect to the last twenty-three 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 four-lane highways in Mexico: the Durango-Mazatlán and the Mexico City-Tuxpan highways (figure 1). These two highways, though not completely part of the NIP, are in many ways similar to the infrastructure projects considered, so analyzing their potential effects constitutes an informed forecast of what to expect after all the projects contained in the NIP are finished.

The 230-kilometer Durango-Mazatlán highway, which is not part of the NIP, involved an investment of $28 billion and was opened in 2013.[7] This is a toll highway formed by four lanes, sixty-one tunnels, and 115 bridges (including the tallest cable-stayed bridge in the world). It reduces the travel time between the important locations of Durango and Mazatlán from six to three hours. The main objective of the construction of this highway was to improve

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[6] DOF (2014).

[7] All amounts and figures in the paper are in Mexican pesos.

the connectivity between the commercial and industrial zone of northern Mexico and the Pacific coast. According to our own calculations, there was also a significant reduction in the travel time to the northwestern border cities from vast regions east of the construction of the highway.[8] 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 Texas to the Pacific coast (see figure 1). Only a few months later, the Mexican Government finished the last section of the 290-kilometer highway of the corridor that connects Mexico City with the Gulf of Mexico. This highway, known as the Mexico City-Tuxpan highway, is aimed at boosting economic activity in eastern Mexico, while connecting the central region with other important corridors between the United States and Mexico. After the construction of this highway, Tuxpan became the closest seaport to Mexico City (although Tuxpan is not currently a major port). This highway was almost finished when the NIP was announced, so only the conclusion of the middle part of this highway is part of the program.

After Hansen approached the problem of building infrastructure in specific areas as a trigger for unbalanced growth, Looney and Frederiksen were probably the first to explicitly test whether building infrastructure reduced inequality between Mexican states.[9] They find that for the case of Mexico, the social overhead capital (which enhances human capital, such as education, public health facilities, and so on) has a greater impact on lagging (income-wise) regions, while economic overhead capital (which supports productive activities, such as roads, electricity, and water supply) only benefits advanced regions.

Deichmann and others find that southern Mexico is quite different from the rest of the country.[10] The size of firms, the quality of human capital, and other measures of productivity (such as skill upgrading opportunities for workers) all seem endogenous to the lack of transport infrastructure and the resulting limited access to markets. Dávila, Kessel, and Levy find that the infrastructure in the south is very poor relative to the rest of Mexico and that important changes are needed for the south to become more competitive.[11]

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[8] See the online appendix for details (www.dropbox.com/sh/o8mikpqs5b2z1jm/AAB9JAVSz52mu_ATwuAoKuCwa?dl=0).

[9] Hansen (1965); Looney and Frederiksen (1981).

[10] Deichmann and others (2004).

[11] In 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.

In particular, they mention that being better connected to the center of the country is the first step for any major and generalized improvement in economic conditions there. Finally, the Bank of Mexico conducted a set of interviews in which entrepreneurs in the southern region of the country indicated that better transport infrastructure would significantly improve productivity.[12] One year later, a follow-up quantitative exercise found that an important factor explaining lower relative total factor productivity in the south of Mexico is deficient infrastructure in that region.[13] These studies all seem to indicate that in order to achieve equilibrated regional development, the south would be an important area to improve first, so the NIP is a great head start.

Calibrating Travel Times

The objective of this section is to explain how we obtained 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 billion pairs, this section describes the set of tools we developed to make this problem feasible. First, we needed 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 of vertices, edges, and weights), where one can apply an algorithm of minimum paths 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.[14]

The continental territory of Mexico was approximated with 1,977,537 squares, covering an area of one square kilometer each, where the centroid is the point of reference.[15] The location of the 1,977,537 vertices corresponds to the 1,977,537 centroids of our grid. To define the edges, we restrict the movements between each of the cells, using the notion of neighborhood.

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[12] Bank of Mexico (2011).

[13] Bank of Mexico (2012).

[14] The order of magnitude reduction equals the power of one-tenth that gives the size of the reduction. The problem was reduced, per our calculations, 245 times in complexity and size.

[15] The area of Mexico is 1,972,550 square kilometers. The difference of 0.25 percent comes from rounding up areas of maps that include some parts of the ocean, as well as the routes of the ferries.

That is, we assume that any vertex of the grid will only have edges to connect with neighbors, a scheme commonly known as *king movements*, in which the permitted displacements between each 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 the National Institute of Statistics, Geography, and Information (INEGI).[16] The data were intersected with the grid, and this procedure entailed a mapping from the vectorial data into vertices and edges. At this point, we were able to identify the kind of road represented by each of the edges of the grid (for example, a four-lane federal toll highway, a one-lane unpaved road, and so on) and classify it according to twenty-one categories.[17] To calibrate the speeds, we used the Punto a Punto travel planner from the Secretariat of Communications and Transportation for several hundred origin-destination pairs. This web application contains information about the toll cost, road classification, approximate 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.[18]

We used a default speed of two kilometers per hour wherever there were no roads reported by INEGI, to avoid any conflicts such as INEGI's missing some road data and to have potential market access spread all over the grid, and not only in the regions with positive population. We call this means of transportation the rest of the territory. All the speeds of every means of transportation are pictured in figure 2, which shows 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 guarantees that every vertex of the grid can be reached from any other vertex in a finite time, meaning that our grid is *connected.*[19]

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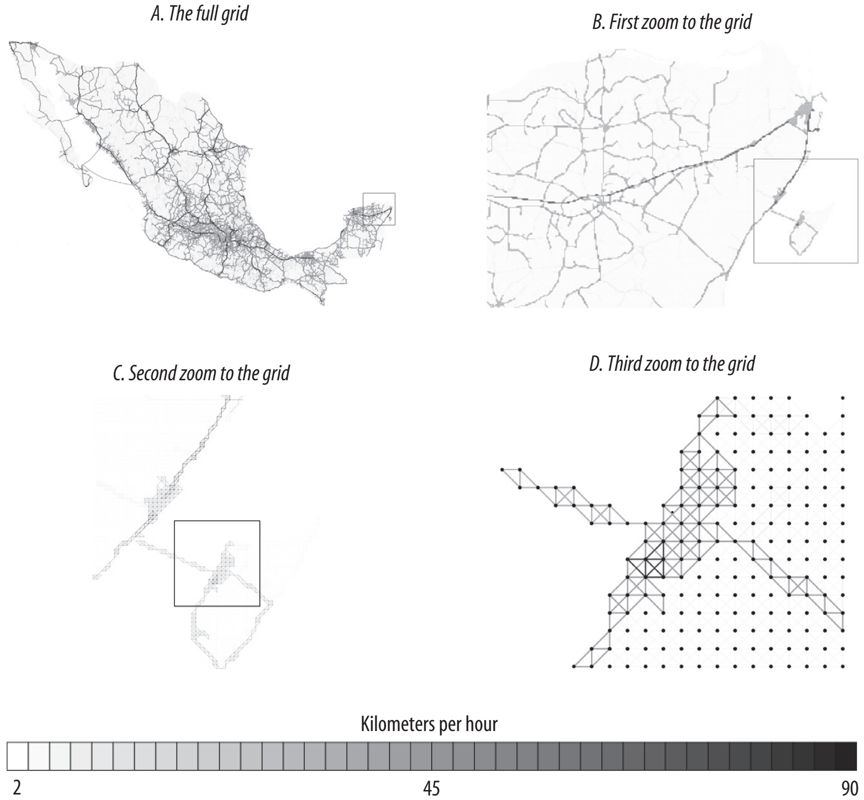
[16] INEGI (2010).

[17] See the online appendix for more details.

[18] Maritime routes are not included in INEGI (2010), so we used the four most important ferries: Mazatlán-La Paz, Topolobampo-La Paz, and Santa Rosalía-Guaymas in the Pacific Ocean and Cancún-Cozumel in the Atlantic Ocean. We averaged the travel times of their websites, as well as the actual routes.

[19] This property is required for many shortest-path algorithms, such as the one used in this paper.

FIGURE 2. Speed of Edges[a]



A. The full grid

B. First zoom to the grid

C. Second zoom to the grid

D. Third zoom to the grid

a. Panel A shows the full grid of 1,977,537 vertices and then looks at them closer; the remaining panels show increasing levels of detail. The scale is one horizontal or vertical edge per kilometer. The vertices are black dots in panel D, and the edges are shaded by their speed in every figure. The large proportion of "rest-of-the-territory" links appear as the image is zoomed in.

Now that we have all the vertices and all the speeds of every edge, and given 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, since every vertex that shares an edge is either one kilometer away or $\sqrt{2}$ kilometers away from the neighbor.[20] To capture slope changes and properly identify the Mexican topography, the distance between vertices is calculated as the

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[20] A very simple task that had to be performed 7,875,594 times.

hypotenuse of a right triangle formed by the horizontal geodistance and the difference in altitudes.[21] Thus, the distance in kilometers between vertex *i* and vertex *j* is given by

$$\text{(1)} \qquad \text{DISTANCE}_{i,j} = \sqrt{\begin{array}{c}\left(\text{GEODISTANCE}(i,j)\right)^2 \\ +\left(\text{ALTITUDE}_i - \text{ALTITUDE}_j\right)^2\end{array}},$$

where the geodistance is either 1 or $\sqrt{2}$. Finally, once we know the kind of road represented by each 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:

$$\text{(2)} \qquad \text{TIME}_{i,j} = \frac{\text{DISTANCE}_{i,j}}{\text{SPEED}_{i,j}}.$$

We have thus characterized the Mexican territory and its transportation network as a graph composed of 1,977,537 vertices, 7,875,594 edges, and a weight for each edge, which is given by the travel time between each 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 in the network.[22] All the calculations that use Dijktra's algorithm in this paper were performed using Gabriel Peyre's Matlab Toolbox.[23] We now define matrix **D** as the 1,977,537 × 1,977,537 matrix of travel times in which each 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 **D**, except its diagonal (the time of going from one vertex to itself), have values greater than zero 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.

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[21] The changes in altitude are an important factor not only for calculating instantaneous speed, but also for determining the location of transportation infrastructure.

[22] See the online appendix for a brief introduction to the shortest-path problem and a brief example of an application of Dijkstra's algorithm.

[23] Available for free to the public on his webpage (www.gpeyre.com) and on the Mathworks File Exchange (www.mathworks.com/matlabcentral/fileexchange/5355-toolbox-graph).

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 in a transportation cost function and, along with price data, estimate the parameters of the function. This transportation cost function $TC(i, j)$ is modeled as an iceberg cost; it represents the percentage of goods that have to be shipped from the origin *i* to the destination *j,* such that at the end of the travel a unity of the good is delivered. The functional form used in this paper is the one proposed by Gordon Hanson, adding the possibility of having fixed costs:[24]

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

The cost function is formed by two parameters: a fixed cost *F,* which is incurred only when goods leave their location of production, and a variable cost λ, which represents an extra cost for each hour of travel between *i* and *j*, where $\delta(i, j)$ is the travel time estimated in the previous section. The fixed-cost term is included to capture all the transportation cost shifters that are not related to distance.[25] 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 empirical strategy carried out by Donaldson, who uses a result present in most spatial models, suggesting that in the presence of transportation costs, the price of identical goods will differ among distant regions.[26] That is,

$$\ln TC(i,j)=\ln p(i,j)-\ln p(i,i), \tag{4}$$

where $p(i, j)$ is the price of the good consumed in *j* and produced in *i.* Donaldson estimates the parameters of the transportation cost function for India, where salt production has historically been concentrated in eight

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[24] Hanson (2005).

[25] Atkin and Donaldson (2012) show the importance of incorporating fixed costs in order to capture other important determinants such as information costs, bureaucracy, and so on.

[26] Donaldson (2010).

different regions.[27] An analogous product for Mexico would be the avocado: in 2010, 91 percent of the annual production was concentrated in only three states, with Michoacán contributing 85.9 percent of national production, according to data for 2012 from the Mexican Ministry of the Economy's National System of Information and Integration of Markets (SNIIM). This database provides daily information on the behavior of the wholesale prices of an ensemble of agricultural goods. The variety of avocado that is chosen is first-class Hass, for which we have daily data from 3 January 2011 to 21 January 2014. The database identifies the state of origin and the destination market, 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 us 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's identification strategy, we estimate the following equation:

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

where t is the date, o is the city of origin (twelve in total), d is the city of destination (forty-two in total), k is a dummy variable for each of the eight presentations of the avocado (box of twenty kilos, box of ten kilos, and so on), and β is the constant of the regression. Finally, we have dummy variables 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, 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.[28] 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 because it defines in some sense the initial conditions of the sale at the origin. We discard the estimates that include the destination dummy variables, because we are assuming constant markups over the price at

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[27] Donaldson (2010). Asturias, García-Santana, and Ramos (2016) use monopolies (of many products, in many regions) that sell to the rest of the regions of the same country, which helps identify transport costs by sector.

[28] Donaldson (2010).

TABLE 1. Estimation of Transport Cost Function[a]

Variable	*(1)*	*(2)*	*(3)*	*(4)*
F	−1.9027**	0.0557***	−0.2965***	0.0859***
	(0.0838)	(0.0067)	(0.0904)	(0.0066)
λ	0.0498**	0.0024***	0.0799***	0.0018***
	(0.0237)	(1.3e-4)	(0.0256)	(1.3e-4)
β	1.8296**	3.4370***	1.3695**	3.2188***
	(0.7201)	(0.0128)	(0.6704)	(4.3e-7)
Summary statistic				
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

*Statistically significant at the 10 percent level.
**Statistically significant at the 5 percent level.
***Statistically significant at the 1 percent level.
a. The table presents estimates of equation 5 in the text, based on 29,124 observations. Robust standard errors are in parentheses.

the origin. Consequently, including the destination biases the results, reducing the impact of the transportation industry (which is even 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.[29]

The fact that states such as the Federal District and Puebla have a large share of sales but are not producers could also bias the estimate for pure transportation cost because of measurement error. Treating avocados labeled as being produced in the Federal District or Puebla corrects for this problem, because it forces the transport costs to break the triangle inequality on both the dependent and independent variables. The estimates imply that product prices receive a markup of 5.57 percent, on average, when leaving the place of production, and increase an additional 5.76 percent every twenty-four hours in transit.

Effect of the New Infrastructure on Welfare

For the welfare analysis, we increase the level of aggregation of the travel time calculations to the municipal level. Thus, we assume that the entire economic activity of the municipality happens at a single point: the municipal

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[29] Atkin and Donaldson (2012) and Hummels, Lugovskyy, and Skiba (2009) show that with homogeneous goods, the constant markup result is obtained regardless of the market structure of the transportation industry.

center. This produces factor returns and real income at the municipal level. We generate the 2,456 × 2,456 submatrix that comes from the 1,977,537 × 1,977,537 matrix, whose elements are the 2,456 square kilometers that contain the coordinates of the municipal head, as published by INEGI, and 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 percent of the number of elements of the original large matrix, this would take five 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 the municipal 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 in the short-run effects, which are likely to occur in the first years after the construction of the highways, this model abstracts from the possibility of the migration of consumers and the reallocation of firms.

Consumers

Consider a representative agent who lives in municipality n, endowed with L_n units of labor and K_n units of capital, and who has preferences for consuming goods produced in the 2,456 municipalities of the following form:

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

where σ is the elasticity of substitution, γ_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.

Producers

We assume a competitive industry in each municipality, so there is also a representative firm, which 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:

$$y_n = A_n\left(K_n\right)^{\alpha_n}\left(L_n\right)^{1-\alpha_n}. \tag{8}$$

The producer price in region n, defined in the last subsection, is given by:

$$p_n = \frac{1}{A_n}\left(\frac{r_n}{\alpha_n}\right)^{\alpha_n}\left(\frac{w_n}{1-\alpha_n}\right)^{1-\alpha_n}. \tag{9}$$

Given constant returns to scale, the zero-profit condition yields

$$p_n y_n = w_n L_n + r_n K_n. \tag{10}$$

Equilibrium

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

$$p_n y_n = \sum_{i=1}^{2456} \frac{\gamma_n\left(p_n TC(i,n)\right)^{1-\sigma} p_i y_i}{\sum_{m=1}^{2456}\gamma_m\left(p_m TC(i,m)\right)^{1-\sigma}}. \tag{11}$$

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:

$$Y_n = \sum_{i=1}^{2456} \frac{S_n\left(TC(i,n)\right)^{1-\sigma} Y_i}{\sum_{m=1}^{2456} S_m TC(i,m)^{1-\sigma}}, \tag{12}$$

whose solution $\mathbf{S} = (S_1, S_2, \ldots, S_{2456})^T$ is normalized up to a constant and is obtained using Pérez-Cervantes's algorithm.[30] We obtain the values of the source effect using municipal population data from INEGI and municipal per capita income from the National Council for the Evaluation of Social Development Policy (CONEVAL), both from 2010. The values of population and 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:

$$\frac{w_n L_n + r_n K_n}{P_n} = \frac{p_n y_n}{P_n}, \tag{13}$$

where P_n is the Armington price index, which solves

$$\left(P_n\right)^{1-\sigma} = \sum_{i=1}^{2456} \gamma_i \left(p_i TC\left(i,n\right)\right)^{1-\sigma} = \sum_{i=1}^{2456} \frac{S_i}{TC\left(i,n\right)^{\sigma-1}}. \tag{14}$$

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, we find the percentage change in welfare from an imaginary counterfactual initial condition of

$$TC\left(i,n\right) = \begin{cases} \infty & i \neq n \\ 1 & i = n \end{cases}$$

compared to the transport cost structure obtained in the previous section. The gains from trade in municipality n in the Armington model are exactly

$$\left(\frac{S_n}{\sum_{m=1}^{2456} S_m \left(\delta_{im}\right)^{1-\sigma}} \right)^{\frac{1}{1-\sigma}}. \tag{15}$$

The smaller the number inside the parentheses, the larger the gains. Given the definition of the source effect, factor prices, productivity, and the production

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[30] Pérez-Cervantes (2014).

function, the largest gains from trade are in municipalities with low transport costs, high productivity, low factor prices, and a high Armington preference parameter.

We then obtain the counterfactual endowment prices, which do not need any information or assumptions on the preference parameters γ_i, the productivity parameter A_n, or even the curvature of the production function α_n or the size and return of the endowments K_n, L_n, r_n, and w_n, respectively.[31] We add one new highway at a time to the grid and update the speed of the edges so that they correspond to 85 kilometers per hour, the calibrated speed that corresponds to four-lane highways in Mexico. We recalculate the entire 1,977,537 × 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. Define as $\hat{x}$ the gross changes x'/x in the variable x, where x' is the counterfactual value of x, and

$$\pi_{in} = \frac{S_n\left(\delta_{in}\right)^{1-\sigma}}{\sum_{m=1}^{2456} S_m\left(\delta_{im}\right)^{1-\sigma}}$$

for every i, n.[32] Then, the following system of equations has a unique solution $\hat{\mathbf{p}} = (\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_{2456})^T$ up to a scalar normalization:

$$\hat{p}_n Y_n = \sum_{i=1}^{2456} \frac{\pi_{ni}\left(\hat{p}_n \hat{\delta}_{in}\right)^{1-\sigma}}{\sum_{m=1}^{2456} \pi_{nm}\left(\hat{p}_m \hat{\delta}_{im}\right)^{1-\sigma}} \hat{p}_i Y_i, \tag{16}$$

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,

$$\hat{U}_n = \frac{U'_n}{U_n} = \frac{U'_n / U_n^{AUTARKY}}{U_n / U_n^{AUTARKY}} = \frac{\left(\pi'_{ii}\right)^{\frac{1}{1-\sigma}}}{\left(\pi_{ii}\right)^{\frac{1}{1-\sigma}}} \tag{17}$$

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[31] Here, we closely follow the proof in Pérez-Cervantes (2014).

[32] Note that gains from trade are $\left(\pi_{ii}\right)^{\frac{1}{1-\sigma}} = \left(\frac{S_i}{\sum_{m=1}^{2456} S_m\left(\delta_{im}\right)^{1-\sigma}}\right)^{\frac{1}{1-\sigma}}$.

where

$$\pi'_{ii} = \frac{\pi_{ii}\left(\hat{p}_i\right)^{1-\sigma}}{\sum_{m=1}^{2456} \pi_{im}\left(\hat{p}_m \hat{\delta}_{im}\right)^{1-\sigma}}.$$

We thus 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.[33] Our choice of the elasticity-of-substitution parameter is based on two reasons. First, we are working with very disaggregated data, so a higher degree of substitutability among goods might be expected.[34] Second, it is important to identify the source of variation when one estimates the Armington elasticity.[35] In general, when the source of variation is a permanent (temporary) change, the estimates tend to be higher (smaller). Since changes in the transportation infrastructure are essentially permanent, an elasticity of substitution equal to nine is reasonable, although it is high.

The results are depicted in figure 3. In the case of the Durango-Mazatlán highway, the whole state of Sinaloa has increases in welfare. Given that this is an agriculturally intensive state, our model predicts very well the observed outcome for 2014 in this state, and the same can be said for Durango. In the case of the Mexico City-Tuxpan highway, the state of Veracruz is predicted to have a lot of growth in the north and some losses in the south. Weighted by population, our estimates show almost no growth in the state derived from the construction of the highway. Interviews performed by the Bank of Mexico for their regional reports confirm that there was a large boom from touristic investment in Tuxpan and that many of the workers come from the south of the state, which is more agricultural.

Our results are thus also consistent with the observed data for Veracruz, since the highway, while not completely opened in 2014, produced investment in hotels anticipating the end of construction, investment that started before April 2014. As for the states in the west of the country, the fastest route

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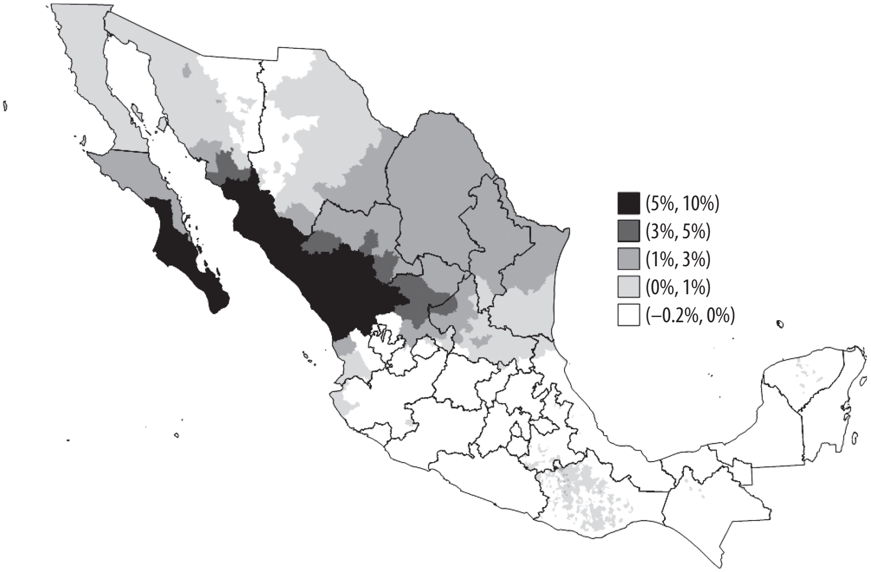
[33] For example, Caliendo and Parro (2015), Allen and Arkolakis (2014), Eaton and Kortum (2002), Feenstra (1994), and Hummels (1999).

[34] 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 four to fifteen.

[35] See the discussion in Ruhl (2008).

FIGURE 3. Change in Municipal Welfare from the Construction of the New Highways

A. Durango–Mazatlán Highway



B. Mexico City–Tuxpan Highway

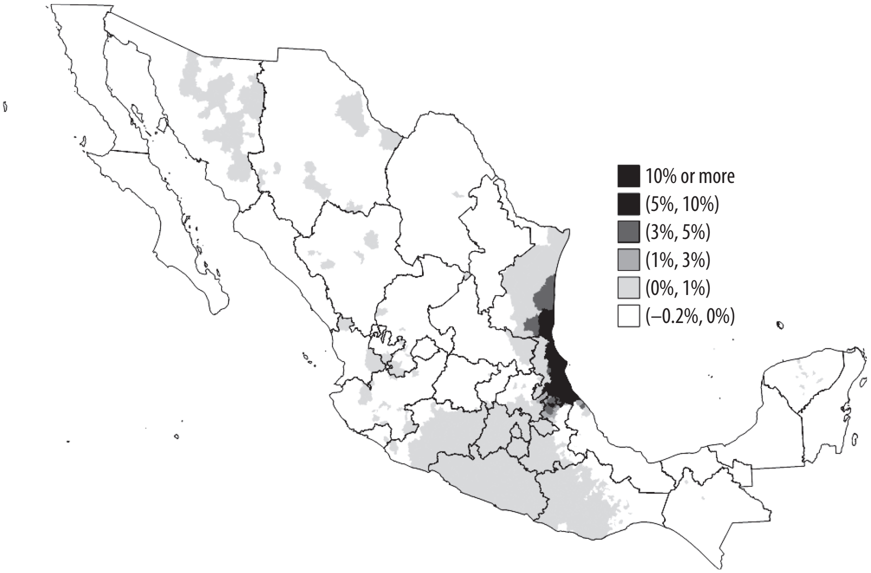


TABLE 2. Sectoral GDP Growth by State[a]
Percent

State	*Total*	*Agriculture*	*Manufacturing*	*Tourism-related services*
Federal District	0.49	4.00	–0.71	–11.04
Durango	1.29	–0.11	–2.48	9.79
Sinaloa	2.87	6.22	4.07	6.25
Veracruz	0.08	–1.96	2.37	8.60

Source: Authors' calculations, using data from INEGI.
a. The states included in the table contain the endpoints of the new highways.

to Veracruz now goes through Mexico City, the richest and most populated region in the country. Consequently, an indirect benefit for those states is the reduction in the price of goods sourced from the regions near Mexico City. As an outside validation of our results, table 2 shows the annual sectoral GDP 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 exhibits high growth rates in agriculture and tourism-related services, and Veracruz shows near-zero growth in total GDP, explained by increases in manufacturing and tourism-related services and a fall in agriculture.

Calculating the Change in Market Access

The welfare analysis, although interesting and testable, implies a huge computational and time burden. The results presented in this paper are the ones after every equation mentioned above converged to equilibrium—an iterative process that took days until convergence. It simply would not be possible to calculate the impact of several changes in transport costs such as the ones from the NIP, where there are more than twenty (a total of 2^{20}, or around a million combinations). In this section, we develop a technique that generates very similar results to the welfare analysis, but does not need to solve for any equilibrium equations. 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 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 identifies what it is exactly that we are and not measuring in this section.

We start by defining market access. We use a result from the economic geography literature, which states 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, weighted by the costs of transportation that it faces in order to sell its goods and services.[36] In particular, we use a measure that summarizes the forces that contribute to the geographic concentration of economic activity, as described by Gordon Hanson.[37] Moreover, it resembles a centrality measure used in network analysis (closeness centrality), which is well suited to capture each location's proximity to the consumer markets:

$$MA_i = \sum_{j=1}^{2456} \frac{Y_j}{TC(i, j)^{\sigma-1}}. \tag{18}$$

We can now calculate the market access for each 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 previous section. Again, we assume an elasticity of substitution between goods of $\sigma = 9$.

Baseline Scenario

Now that we have the matrix of transportation costs from every location in Mexico to every municipal center, 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 demand into 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 substantially changed 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

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[36] Harris (1954); Hanson (2005).

[37] Hanson (2005).

loss of generality. In any case, the impact of the highways might end up being underestimated, so this could have been an important caveat if the impact of the new highways was found to be small. This was not the case, however. 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 total market access, that is, the sum of market access MA_i (defined in the previous section) plus foreign market access, FMA_i which includes demands from foreign markets:

$$TMA_i = MA_i + FMA_i. \tag{19}$$

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

$$TMA_i' - TMA_i = \left(MA_i' - MA_i\right) + \left(FMA_i' - FMA_i\right), \tag{20}$$

which we claim will be 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 shown 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 seaports. This means that it is possible to think of the term $FMA_i' - FMA_i$ as 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 downward. Therefore, what we find is a lower bound of the benefits from the new infrastructure, and it is a very low bound for locations that changed travel times to the border or the ports.

The change in market access derived from the construction of the new highways is pictured in figure 4. 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. Thus, we have a model that gives the same predictions for a much lower cost. The Durango-Mazatlán highway increases market access in an extensive region. The benefits go all the way to the Baja California peninsula. The states of Sonora, Zacatecas, Coahuila, Nuevo León, San Luis Potosí, 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, receive the largest benefits of the highway.

F I G U R E 4 . Change in Market Access from the Construction of the New Highways[a]

A. Durango–Mazatlán Highway

B. Mexico City–Tuxpan Highway

[a] Change per square kilometer.

In contrast, the Mexico City-Tuxpan highway benefits mostly regions to the east of the construction, in particular, the area close to Tuxpan, the rest of northern Veracruz, and the eastern area 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.

To a large degree, the previous existence of infrastructure causes the impact of the new highways to spread over the territory, and 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 we are looking here at short-run effects. The increase in market access will increase the demand for products in every region, and this demand will increase more in regions with the largest average reduction in transportation costs to large markets. Another consideration is the extent to which the new infrastructure is creating new economic activity relative to just reorganizing existing activity.[38] The latter is an important issue, given that the total gains of some regions could be driven by net losses in others.

Conclusions

This paper analyzes the short-run effects of the construction of two important highways on 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 mentioned previously. Qualitatively, market access and welfare change in the same direction and magnitudes. However, the former is less computationally intensive than the latter, so we recommend using the market access approach for the analysis of short-run impacts of infrastructure.

Our estimates suggest that the Durango-Mazatlán highway produced benefits not only in the region where the new highway is located, but in vast areas of the north of the country. Analogous estimates show that the Mexico City-Tuxpan 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

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[38] See Fogel (1970).

competitiveness. Our model is consistent with the observed sectoral growth in Sinaloa, Durango, and Veracruz in 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. Two additional facts are worth mentioning. First, since the transportation infrastructure is subject to network effects, the current state of the network and of 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 to correctly determine the causal effect of the provision of new infrastructure, a wider approach is required so we can handle such 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 regional goods. For example, the port of Mazatlán could become a major port of entry from countries trading through the Pacific Ocean now that there is faster access to the northeastern border and therefore to the U.S. markets that are currently accessed through the Gulf of Mexico (and crossing the Panama Canal). Also, some regions might see an increase in value added just in being part of new trade routes, such as the corridor from Mazatlán to the Gulf of Mexico or from Mexico City to Matamoros (via Tuxpan). Therefore, 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 elements that could deal with three important aspects: namely, the general equilibrium effects caused by the reduction of transportation costs and the reorganization of the optimal trading routes; the fact that the infrastructure is not randomly provided, such that 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 the incorporation of the changes in the international trade structure. These and other important features are the subject of a further research agenda.

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